Doctoral Thesis

Control and stability in velocity of individually driven drawing godets for thermoplastic filament yarns

Author(s):
Castiglioni, Matteo

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CONTROL AND STABILITY IN VELOCITY OF INDIVIDUALLY DRIVEN DRAWING GODETS FOR THERMOPLASTIC FILAMENT YARNS

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CASTIGLIONI MATTEO

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von Italien

Angenommen auf Antrag von

Prof. Dr. Urs Meyer
Prof. Dr. Paolo Ermanni

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Negli ultimi 20 anni quasi nessuno sviluppo ed innovazione del processo di stiro e stiro-testurizzazione di fili termoplastici è stato introdotto negli impianti di produzione.

La necessità di riduzione di consumo energetico, di una produttività più alta e di una maggiore flessibilità di produzione ha portato a pensare a soluzioni non convenzionali per l’azionamento dei godet di stiro. Importanti sviluppi sono stati brevettati e presentati alla ITMA (International Textile Machinery Exposition) nel 2003 a Birmingham in un prototipo dimostrativo sviluppato all’ETH.

L’uso di piccoli godet azionati singolarmente con motori sincroni a magneti permanenti è una soluzione adatta alle alte velocità ed al risparmio energetico. L’uso di questi motori per i godet di stiro, dove il filo può essere considerato un elemento elastico di accoppiamento di due godet successivi, pone nuovi quesiti sulla stabilità del controllo di velocità.

Attraverso l’utilizzo di un modello astratto, basto su elementi di massa, molla e smorzatori, il comportamento dinamico di differenti costruzioni di motori e di fili è stato misurato e simulato nel processo di stiro.

I valori di molla e smorzatore di un motore sincrono a magneti permanenti con e senza avvolgimento ammortizzante, e di un motore asincrono ad induzione sono stati misurati con esperimenti innovativi.

Le oscillazioni torsionali misurate per i due motori sincroni a magneti permanenti rivelano un rischio di instabilità nel controllo in velocità nel range di frequenze di 30-110 Hz.

L’effetto positivo dell’avvolgimento ammortizzante è confermato da una riduzione delle oscillazioni e da un margine di fase più elevato.

Ulteriori esperimenti eseguiti su un impianto di produzione per monofil, dove per l’azionamento di godet ad alta inerzia vengono utilizzati motori sincroni a riluttanza, hanno confermato il problema delle oscillazioni torsionali.

La valutazione di una soluzione stabile per l’azionamento di godet di stiro comandati singolarmente è il risultato dell’uso di strumenti innovativi e del confronto del comportamento dinamico, dei costi e del consumo energetico degli azionamenti analizzati e proposti in questo lavoro.
ABSTRACT

In filament drawing and filament draw-texturing, over the past 20 years almost no developments and innovations have been introduced into production machines. The increasing need of energy saving, of higher production speed, and of production flexibility has brought to think about unconventional solutions for the drive of the drawing godets. Important developments have been patented and presented at the ITMA (International Textile Machinery Exposition) in 2003 in Birmingham in a demonstration machine developed at the ETH.

Small individually driven godets using permanent magnet synchronous motors is a solution suited for high speed and energy saving. The use of these motors for drawing godets, where the yarn can be considered as an elastic coupling element between two consecutive godets, poses new questions about stability in the velocity control. With the use of an abstract model based on mass-spring-damper elements, the dynamic behavior of different designs of motors and processed yarns is measured and simulated in a drawing process.

The spring and damper parameters of a permanent magnet synchronous motor with and without damper winding, and of an asynchronous induction motor are found by innovative experiments made in labor.

The measured torsional oscillations of the two permanent magnet synchronous motors face a risk of instability in the range of 30-110 Hz.

The positive effect of the damper winding is stated by reduced oscillations and higher phase margin, showing the goodness of this solution.

Experiments done in an industrial production line for monofilament yarns, where synchronous reluctance motors are used for the drive of big inertia godets, state the problems of torsional oscillations.

The evaluation of a future stable solution for the drive of the individually driven drawing godets is the results of the use of innovative design tools and of the comparisons of the dynamic behavior, of the cost, and of the energy consumption of the analyzed and proposed drive solutions of this work.
### SYMBOLS AND ABBREVIATIONS

- Par. = paragraph
- Subpar. = subparagraph
- BCF Bulked Continuous Filament
- FDY Fully Drawn Yarn
- LOY Low Oriented Yarn
- PET Polietilene Tereftalato
- POY Partially Oriented Yarn
- RDY Ready Drawn Yarn
- $R_1$ radius of the godet or transfer roll
- $T_{in}$ tension of the yarn before entering the Hotbox
- $T_{out}$ tension of the yarn exiting the Hotbox
- $V_i$ linear speed of the yarn
- $CV_m$ coefficient of variation of mass of yarn
- dtex yarn count
- $d\varepsilon$ strain increment
- $\varepsilon$ axial tow strain
- $E_c$ specific dynamic modulus
- $E$ [N/m²] = Young’s modulus
- $N$ number of laps around the godet-duo or the godet and transfer roll
- $K_{spring \, upper/lower}$ = sum of the upper or lower $N$ wraps of yarn
- $K_{spring}$ average spring constant of the yarn
- $\rho$ [kg/m³] = density of the material
- $V$ = Volume
- $v$ = velocity of propagation of the stress pulse
- $\phi$ = Diameter of a godet or roll
- $M$ = Mass
- $J$ = Inertia
- $r$ Radius of the cylinder or of the disk
- $r_1, r_2$ internal and external radius of a long cylinder with open ends
- emf electromagnetic force
- mmf magneto motive force
- ALA Axially Laminated Structure
- BLDC Brushless Direct Current
- EC Electronic Commutation
- PM Permanent Magnet
- PMDC Permanent Magnet Direct Current
- SMC Soft Magnetic Composite
- SynR Synchronous Reluctance Motor
- FOC Field-Oriented Control
- P.I.D. Proportional, integral, derivative control
- $B_R$ = rotor magnetic field
- $B_S$ = stator magnetic field
- $B_w$ winding magnetic field
- $D_e$ disturbance
- $\varepsilon$ = amplitude of the rotational oscillation of the rotor
- $\theta$ = rotational position
- $\theta_R$ = rotational position of the rotor
\( \theta_S \) = rotational position of the stator
\( \theta_0 \) = mean rotor position
\( \lambda \) = frequency of the rotational oscillation of the rotor around the mean value \( \theta_0 \)
\( r_s \) = stator resistance
\( r_r \) = rotor resistance
\( \omega \) = rotational speed
\( \omega_R \) = rotational speed of the rotor
\( \omega_S \) = rotational speed of the stator magnetic field
\( X \) = Reactance
\( I_d, I_q \) d- and q-axis component of stator current
\( I_s \) = stator current
\( L_{md}, L_{mq} \) d- and q-axis magnetizing inductance
\( \phi \) = saliency ratio of synchronous motors
\( \Phi_m \) = air-gap magnetic flux
\( T_{add} \) = additional torque given by a change from the steady state condition
\( T_e \) = electromagnetic torque
\( T_{ind} \) = torque generated on the rotor
\( T_{ind} \) = steady state torque induced in the rotor (in asynchronous motor proportional to the steady state slip)
\( V_S \) = stator voltage
\( X_S \) = stator reactance
\( k \) = constant depending on the construction of the machine
\( n_{add \ slip} \) = additional slip speed to the steady state slip
\( n \) = actual slip speed
\( n_{slip} \) = Slip speed of the machine at steady state
\( n_{sync} \) = Speed of the magnetic field
\( n_m \) = mechanical shaft speed of the motor at steady state
\( n_m \) = mechanical speed of the motor shaft
1. INTRODUCTION

1.1 EVIDENCE AND CALL FROM PRACTICE

The whole textile manufacturing pipeline, from yarn to finished garment, which previously took two years, is today reduced to a 6 month cycle or even less. The main market forces driving the whole of today’s textile chain are identified in six trends:

- increase in product diversity;
- shortening of delivery time;
- production of smaller lot sizes;
- frequent change of lots;
- production of improved quality;
- and all these at lower cost.

These driving forces influence the producers of fabric and yarn, and also have their impact on the machinery suppliers.

Approximately 28 million tons of filament yarns are consumed annually, split up as follows: 45 % in apparel, 31 % in home textiles, 13 % in industrial applications and 11 % in carpets and floor coverings. [16]

Even though the world economic situation impacts strongly the textile industry, and since some years the market is depressed, the long term growth trend in the consumption of filament yarn is positive.

![Fig.1: Worldwide textile fiber consumption. [16]](image)
There is no doubt, however, that the main growth area for transforming synthetic yarns is in Asia, and that in order to remain competitive the Western companies must concentrate on new technologies in fibers and manufacturing equipments. [26] [73] In the continuous filament manufacturing, the thermoplastic filament drawing is a very important and very used process to increase fiber properties. The thermoplastic filament drawing process is based on a crystallization of the molecular chain in the polymer. Due to the increase in the crystallization and in the orientation of the molecular chain, an increased in the tenacity is achieved. Through the drawing, from a low oriented yarn (LOY) it can be obtained a partially oriented yarn (POY) or a fully oriented yarn (FDY).

![Fig.2: Comparison of the stress-strain diagram of a LOY, POY, and an FDY yarn.](image)

During the crystallization, the tension of each filament and the temperature represent the two most important parameters that have to be controlled. Problems connected to yarn tension irregularities are in the homogeneity of the color after dyeing, in the mechanical properties (i.e. stress-strain curve) and in the regularity of yarn fineness. This very high sensitivity, given by the very small mass and section of a yarn leads to strict requirements in the precision of the drawing drive. The stretch of the partially or low oriented polymer chains is induced by a set of rolls, also called godets, which follow each other, rotating at increasing speed. In the stretching zone a heating device is installed in order to heat the yarn to a given temperature for the drawing. The speed ratio of the drawing elements is called draw-
ratio, and the quality of the stretched yarn depends directly on the draw-ratio regularity.

In industrial application, there are a multitude of different type and design of godets. Commonly available godets have a diameter between 80 and 300 mm, and a width between 40 and 300 mm. Depending on their use, there are cold godets and internally heated godets. There are godets using a transfer roll and godets without transfer roll. [Annex 4]

Among all types of godets, there are also less conventional systems like for example those made of twin godets, also called godet-duos.

![Heated godet, Cold godet, Twin godet]

*Fig. 3: Different godet designs.*

The process of filament drawing is often connected to another very important process of thermoplastic filament treatment, called texturizing. The draw-texturizing machines are mainly used to process multifilament yarns and are characterized to be multiposition machines with the simultaneous processing of more than one yarn. [77]

The conventional drive solution for multiposition machines consists of common through shafts. Using a single motor at one side of the machine and a long shaft (up to 30 m), a multitude of processing positions is driven.

The use of the godets is becoming state of the art also for multiposition processing machines, substituting little by little the through shafts. [4] [26]

Synchronous reluctance motors are typically used for the drive of the individually driven godets, in order to achieve synchronism of the multitude of independent processing positions. In fact, some machinery suppliers use a common inverter for all
the motors of a set of godets, rotating at the same speed (solution called “common power bus”).\[76][77]\n
Besides through shaft and power bus methods, there is the solution adopted by other machinery suppliers, of individual driven godet. With this method, each godet is driven by an individual motor with its inverter/controller. The type of motor in use can be of different type: synchronous reluctance, synchronous permanent magnet (D.C. or A.C.), or asynchronous induction motors.

Generally speaking, the continuous advances in drive technology have radically changed the lay-out, the performance, and the efficiency of production machines. The drastic reduction of the costs of electric motors and electronics together with the increase in their efficiency and reliability has brought engineers to install gearless electric drives in many areas. New developments on electric motors such as permanent magnet and reluctance motors have disclosed new fields of application. Direct drives without transmission gears in open and closed loop control are not only more efficient than a single motor with gear boxes, but they also give a better fine tuning, production flexibility and in some cases they are also cheaper. [46] [54] [23]

In this scenario, a new high-speed draw-texturizing machine has been developed since 1998 at Institute for Textile Machinery and Textile Industry (now Institute for Manufacturing Automation). It was displayed in its two steps of development, at the ITMA International Textile Machinery Exhibition in Paris, June 1999, and at the ITMA in Birmingham, October 2003.
The key advancements of the machine have been applied for patent (EP1526196A2) in October 2003. A new layout of a draw-texturing machine, a water cooling device for the yarn, “full-floating” individually-driven spindles for the friction unit, and a new twin-godet system (the Hotbox), are the main claims of the patent. The use of very small elements, for less inertia, for high efficiency and for long lifetime of the bearings has been the basic method to design the machine. The general aims of the project were to achieve higher production speed, higher efficiency and energy saving. In the synthetic fiber drawing process, a lot of energy is lost for the heating and the stretching of the yarn, resulting in a very poor efficiency of the process. Generally, the energy costs for the production and transformation of a yarn have a heavy impact on the final costs, increasing as the yarn becomes finer. The size and the inertia of all the mechanical elements of a filament yarn processing machine that have to be driven, make the process much less efficient. The need of higher production speed, finer tuning, and flexibility of the drawing and draw-texturizing process, has led to consider the use of smaller individual drives.
The target of 2000 m/min of the Fastex.EDU for a production of drawn-textured yarn has brought to think about new and unconventional solutions. The use of very small godets using an individual motor with its individual controller, directly clamped on the godet shaft is a first development toward a more suitable drive for high speed and low energy consumption. Since the yarn is transported by the godets, the dynamic behavior of the motors, directly clamped on the godet shafts, have an impact on the tension of the yarn being processed. Due to the inherent magnetic principle, synchronous motors tend to develop rotational instability. In different works published in the past [11] [44], it has been demonstrated that synchronous motors are characterized by so called sub- and super-synchronous oscillations. During the rotation at constant speed, the rotor oscillates with a frequency, generally different from the frequency of rotation. The so called damper windings, often used in synchronous power generators, are also integrated in the construction of the rotor of the synchronous reluctance motors. Their function is to reduce the amplitude of the sub- and super-synchronous oscillations, besides allowing the start up at full speed (needed by the power bus solution). Those oscillations, typical for synchronous motors, are much more important for permanent magnet motors where low energy dissipation and high torque density are present. The use of godets without any internally heating, like in the Hotbox, has given the chance to reduce the inertia to more than 1000 times less than the value of the standard godets. Since the yarn applies with its tension a torque on the godet, any variation in the yarn tension might cause a disturbance in the dynamic of the godet. In case of big inertia godets, the force of the yarn might be neglected, but in case of very low inertia godets its impact might be important. Moreover, electric disturbances in the stator winding voltage, or in a non symmetrical construction of the motor cause disturbances on the rotor behavior. From the dynamic analysis of second order systems, it is known that, theoretically, in a system without energy dissipation and dampening, under certain circumstances, the oscillations grow up to infinite amplitude. It means that, considering the individually driven godets with the processing yarn as a second order system, the use of motors with very high efficiency and no dampening may reveal high oscillations and even instability in the dynamic behavior.
The inertia of the godet, the type of motor, the concept of the drive, and the dynamic characteristics of the yarn, define the dynamic behavior of the system, and thus the tension of the yarn in process.

The Hotbox, with a godet duos system, made of two very small identical rolls, driven by individual permanent magnet synchronous motors, represents a drive solution for future drawing components, but poses new questions about the stability of the drive.

### 1.2 RESEARCH QUESTIONS

During the studying and the experiments on thermoplastic multifilament yarn, a first research question that came out is:

*due to the development of new drive methods for the thermoplastic filament yarn drawing, as individually driven godets, which may be the consequences in quality of the yarn?*

A non uniform rotational behavior of the driving elements of the yarn during the drawing may cause an oscillating yarn tension. The use of other geometry and other drives, like very low inertia elements and high efficient motors may not only result in an oscillating system but even in an unstable system. It follows thus a second question:

*what theoretical model is available to explain these stability problems?*

In a system with very less energy dissipation and elements with elastic behaviors, the risk of oscillations and even instability are important to be studied.

There are systems that are very similar to the case of individually driven drawing godets with thermoplastic filament yarns that may be already modeled. Models of the dynamic behavior of different design and construction of electric motors may be helpful for the dynamic analysis and for explaining the stability of the whole system. Existing models of yarns may be used to analyze and simulate its behavior during the drawing. The study of the dynamic of the yarn leads to the following question:

*which is the interaction between the yarn and the drive?*

The dynamic of different yarns might have different impacts on the dynamic of the godets, depending also on the type of drive in use.
The use of synchronous reluctance motors, overrated in power, driven in open loop control, is the actual state of the art for the drive of individually driven godets. The losses of the overrated reluctance motors and the big inertia of the godets result at one side in a very poor efficient system, but at the other side, in a very dampened and stable drive.

Very small individual drives with high efficiency permanent magnet motors may have the big advantage in energy savings but at the other side they may reveal big problems for the stability. In fact, with less inertia and no dampening, any external disturbance may influence much easier the dynamic of the drive.

What kind of drive is able to overcome these stability problems?

Solution like closed loop control, which call for more expensive components, should be compared to other motor technology and other drive solutions. Induction asynchronous motors, besides being cheaper and less efficient than permanent magnet motors, may reveal an advantage in the dynamic behavior and in the stability. Due to their natural dampening behavior, their use even in open loop control might also be a solution. Thus the final questions:

which could be the most suitable drive in terms of stability, efficiency, assembling costs, manufacturing costs, maintenance costs, energy costs, and cost of the control, for an application like the individually driven drawing godets?

In the design and construction of a motor for individually driven godets, and also for similar applications, which are the parameters and the tools that might be used?

1.3 RESEARCH APPROACH AND DESIGN

Theoretically, a dynamic system comprising spring-type elements and masses, with their inertia, represents an oscillating system. By the stiffness, the dampening and the inertia of the components of the system, the dynamic behavior is analyzed.

Using the knowledge summed up by the studying of other works, a model of the elements of the drawing process has been created. The linearized model, made of
mass-spring-dampening elements is aimed to be used to simulate different drives by the processing of different yarns. The parameters to fit the model have been searched by dedicated experiments on the yarn and on the dynamic properties of different drives. [78]

Specially designed sensors have been developed and adopted for the experiments on different prototypes of the drive of the drawing elements and on the drive of standard godets.

Using the mass-spring-damper model, different yarns and drawing parameters with different drive solutions have been simulated in Working Model 2D.

A mathematical expression of the simplified model is written in form of state-space representation and used for the theoretical analysis of the stability of the simplified system. Frequency and time response analysis represent the basis for the conclusions on the stability.

**1.4 OUTLINE OF THE THESIS**

The whole thesis is structured in seven main chapters and 6 annexes.

The first chapter is aimed to give the reader an overview of the work, showing the actual problems which appear in practice, the research questions, the methods used in the work and here the structure of the chapter.

The second chapter is an introduction in the manufacturing processes and drive technologies used in synthetic fiber production.

Showing the actual processes and elements for the production of thermoplastic filament yarn, a comparison with the solutions proposed in the FasTex projects is done. Synchronous and asynchronous motors, in open and closed loop control are then analyzed and described. Their dynamic properties and their stationary behavior are then pointed out. The chapter 2 ends with a concept of filament yarn processing machine using individual drives, which is compared with a traditional through shaft multiposition machines.

Chapter 3 starts with the analysis of previous works connected to the topics dealt in this work: model of belt and pulleys, filament drawing process, behavior and modeling of electric motors, torsional oscillations of synchronous motors, and
dynamic behavior of thermoplastic filament yarns. The second part of the chapter describes the creation of the simplified model of the individually driven elements for the drawing of thermoplastic filament yarns. Starting from the hypothesis and the element identification, the mass-spring-dampering model is presented.

Chapter 4 deals with the experiment campaign made on the selected motors. Starting with the description of the concept of the experiments and of the tools, proceeds by showing the stationary and free oscillation tests made on permanent magnet and induction motors. The chapter ends by summing up the results of the experiments and by showing the values of the parameters that are used in the computer simulation.

In Chapter 5, the simulations in Working Model show the differences in dynamic between the analyzed drive solutions. Starting from the element identification and the specification of the coefficients and parameters, a resonance analysis shows the eigenfrequencies of the system for different operating conditions. The study of the dynamic system behavior under different conditions, such as different yarn counts, draw ratios, and motor type have been done with the simulations in Working Model.

The chapter proceeds dealing with the analytical model. With the hypothesis of a linear system, the state-space equations of the model are written. Using those equations in MatLab, the frequency and the step response analysis are done. The results of this analysis are then used to formulate a stability analysis by showing the limits of stability.

In chapter 6, the analysis of the dynamic behavior of conventional godets using synchronous reluctance motors demonstrates the possible problems in quality of the yarn, due to torsional oscillations. The critical dampening value is presented as a parameter to be used by designing electric motors. The block diagrams of the linearized model are sketched in MatLab Simulink and are presented as a suitable tool to optimize the parameters of the controllers.

Finally, chapter 7 is aimed to answer the research questions of Paragraph 1.2 and give some considerations on future research and development on individually driven drawing godets. The recipe for the drive solution of individually driven drawing godets is proposed together with possible future development and studies on this subject.
2. SYNTHETIC FIBERS PRODUCTION: MANUFACTURING PROCESSES AND DRIVE TECHNOLOGIES

This chapter is an introduction to the processes, the technologies, and the components used in the production of synthetic fibers and yarns.

The first paragraph describes the synthetic fibers production, discussing the creation and the transformation of thermoplastic filament yarns. The drawing and the draw-texturizing is described for conventional process and for the FasTex prototype developed at the ETH.

The paragraph 2.2 deals with the traditional and the new drive technologies. A stationary and a dynamical analysis of the most interesting drives for individually driven godets are proposed.

Paragraph 2.3 is a comparison between common draw-texturizing machines and new machines using individual drives. In Subparagraph 2.3.1 a concept of the drive and of the control of a modular machine is discussed.
2.1 SPINNING AND PROCESSING OF THERMOPLASTIC FILAMENT YARNS

Today’s annual production of synthetic fibers is approximately 30 million t/year, accounting for about 50% of the world fiber production. The average annual growth in the last twenty years (1980 to 2000) was 5.2%. Related global fiber market shares in 2000 by fiber type were: polyester 56%, olefin 18%, nylon 12%, acrylic 8% and cellulosics 6%. These shares compared with shares in 1980 of 35%, 7%, 22%, 14%, and 22%, respectively, show an increase of more than 50% for polyester, a doubling for olefin and a decrease for all the other listed fibers.

Textile yarns and technical yarns and fibers have to fulfill certain requirements that are primarily determined by the end use, and in the case of textile products, also by environmental conditions. In any case, they need to be cost efficient, and it must be possible to produce them in sufficient quantities and consistent quality.

The properties of synthetic fibers are primarily determined by their chemical structure, their degree of polymerization, the orientation of the chain molecules, their crystallinity, the packing density, and the cross links between individual chain molecules. In general they consist of threadlike long macromolecules that are arranged more or less parallel to the fiber axis and pass through crystalline and amorphous areas.

In the melt, the chain molecules have almost no orientation. When they cool during the spinning process they become partially oriented. For melt spun fibers, an additional drawing process is required. This can be done either in a primary spinning after cooling below the glass transition temperature, or in a following separate process at a suitable temperature. This drawing and orientating change considerably the tenacity and the modulus of the fiber.

According to the studies of Ulrich [16], to make a fiber useful for production and industrial use as a textile material, the following conditions have to be fulfilled:

- Raw materials must be available or producible in sufficient quantities and at reasonable cost.
- Existing methods must allow processing of these raw materials to polymers and then to filaments or fibers at acceptable cost and low impact to the environment.
• The intermediate and final products must have sufficient continuity in terms of quality and quantity.
• The final price of the yarn made from the fibers or filaments must be acceptable for the market.
• The fiber has to be either continuous and possibly capable of being textured, or must be capable of being processed in a mechanical spinning process, and must fulfill the following requirements:
  • The resulting yarn has to show sufficient tenacity and elasticity, and the initial elastic modulus must not be too low.
  • Flexibility and elasticity are relevant for the mechanical spinning, twisting and subsequent processes.
  • The fiber limits the fineness of the yarn, as well as the hand, breath ability, comfort etc. of the fabric.
  • The fiber should be easily dyeable; if conventional dyeing is not possible, it must at least allow spun dyeing.
  • Also relevant are luster, durability, insulation properties, recovery and many more properties that are difficult to measure.

These conditions can be fulfilled more or less satisfactorily by chemical and synthetic fibers; with some fibers, difficulties in some aspects cannot be avoided. Therefore they are only used in special applications, where the missing properties are unimportant. This means that each textile fiber has certain optimal applications and may be less suitable or inappropriate for other applications.

This is even truer for technical yarns where the range of properties needed for the applications can be defined much more distinctively.

Polymers suitable for the production of synthetic fibers are the so-called thermoplastic polymers that are all created by linking atoms or atomic groups. This is done by three reactions differing in their chemo-physical process: polymerization, polycondensation, and polyaddition.

Polymerization is the linking of low molecular monomers to long chain molecules with uniform links, e.g. Polyamide, PA. If different links are combined, the process is called co-polymerization. Heat and catalysts are needed to activate the monomers.
Polycondensation is the linking of low molecular compounds while simultaneously splitting off byproducts, e.g. water, alcohols etc., which are then removed. Typical products are PA66, PA 610, and PA11 etc.

Polyaddition is the linking of low molecular polyfunctional compounds. A typical product is Polyurethane.

After the production the polymer ribbon and strands are normally formed to be cut by the so called granulating machines and stored in form of chips. In large plants the melt is fed directly from the finisher of the continuous polycondensation to the spinning process. In most of the cases, the chips coming from granulation are dried and shipped in bags or barrels to the spinning mills. The thus prepared chips are then melted again in the extruder and fed to the filament forming elements.

Mixing and homogenization elements like filters and spin packs are arranged in the necessary surrounding temperature, typical 250°C and connected by pipes adequate to the respective high pressure (typical around 150-200 bar).

Spinnerets convert the melt into the final number of filaments, and determine together with the winding speed the filament cross-section and the single filament uniformity.

Filaments extruded from the spinneret holes are quenched as single filaments almost parallel to one another, and are cooled and solidified below the glass transition temperature.

*Fig. 5: A compact spinning machine for POY.*
The multifilament yarn in the form of LOY (Low Oriented Yarn) is not stable and must be processed immediately. Due to this, the LOY, in most of the cases, is directly drawn on the spinning plant. The resulting yarn is either a POY (Partially Oriented Yarn) or an FDY (Fully Drawn Yarn).

On high speed spinning machines the product is already a POY yarn, since it is wound at high speed, thus creating a drawing effect before winding.

The POY, wound on the bobbin, is then transformed in a multitude of ways on very different machines and processes.

The processes following the synthetic fiber spinning change the yarn in the mechanical, in the chemical, and in the aspect. Depending on the final destination of the yarn, different processes are adopted to give to the yarn the requested properties.

In Fig. 6 some of the most important transformations of the spun yarn are shown.

The process of yarn drawing is the first process that follows the melt spinning. For the production of multifilament yarns a first drawing is already applied on the spinning plant before the winding. A second drawing process with godets can also be integrated in the spinning plant but usually it is done on draw-winding or draw-texturing machines.

For the production of monofilaments, since no texturing follows, the process of drawing is always integrated in the spinning plant.
2.1.1 Drawing with conventional godets

In order to produce a filament yarn with a desired strength, the spinning of the polymer is followed by a process of drawing. The drawing is performed to induce sufficient orientation of the polymer molecules along the axial direction of the filament.
During the spinning process the polymer exits the capillary of the spinneret with a die swell, which removes any orientation in the polymer. This isotropic polymer melt is then stretched in the spin line while it cools, inducing so orientation of the molecules before the solidification of the fiber.

The relaxation time of the polymer melt is typically comparable to the time available for the fiber before it solidifies however, thereby remaining much of this orientation, and hence the amount of orientation that can be induced in the fiber during spinning is insufficient to produce the desired strength.

The orientation of the polymer molecules can be increased after the spinning process by a subsequent drawing process, in which the solidified fiber is heated to a temperature above the glass transition and drawn with a series of rollers. The purpose of the draw process is to convert relatively weak fibers to fibers with greater molecular orientation and the resulting greater strength. This happens in the drawing due to the new crystals that are formed and to the redistribution of existing crystals.

In a drawing machine, the process of filament drawing takes place between two elements called “Drawing groups”. In industrial environment, it is typical to use the expression “drawing ratio” $R_{\text{draw}} > 1$, which is defined as the ratio between the linear outgoing and incoming speed of the yarn.

$$R_{\text{draw}} = \frac{T_{\text{in}}}{T_{\text{out}}} = \frac{\omega_2 \cdot r_2}{\omega_1 \cdot r_1} = \frac{V_2}{V_1} \quad \text{Eq.1}$$

A wide variety of drawing processes and components are in common use in industry. A distinction can although be made between monofilament and multifilament drawing.

For monofilament drawing a set of feed rollers and a set of take-up rollers process a multitude of monofilaments in parallel (Multi-drum parallel roll work). The surface of the rollers is heated by an internal electrical resistance or by induction. The single filament is wound on each roller, from now on called godet, for about $180^\circ$ as shown in the Fig.7. Parallel to this yarn several others can be laid in the same way (parallel drawing).
Fig. 7: The typical monofilaments drawing.

Each set of godets rotates with the same angular velocity, and draw is achieved by rotating the second set of rollers faster than the first set. Between these two groups of godets a yarn heater is typically positioned. The heater is normally an oven with two openings for the entrance and the exit of the yarn. To increase the surface of contact between the godet and the yarn for both sets of feed and take up roller a multitude of godets is used. The increased surface reduces at one side the problem of the slip of the yarn and at the other increases the heat transferred from the godet to the yarn.

A different layout of drawing machine is used for the drawing of multifilament yarns. For this process, in order to increase the contact surface, instead of the set of rollers at the same speed, a single godet with an idler roll, also called transfer or separator roll, is used. By this layout the yarn is wound several times around both the godet and the transfer roll (Fig. 8). In order to make several yarn wraps around the godet and the transfer roll, the axis of the transfer roll is slightly inclined to the godet. Between two consecutive godet-transfer rolls at increasing speed the yarn is stretched. The heating is supplied by the godet, which is internally heated, but in addition it is also common to find a contact heater between two consecutive godets. [31]
Unlike the monofilament drawing, where a parallel drawing of a multitude of monofilaments is done, the multifilament drawing processes only a single or maximum two yarns.

The final denier of the drawn yarn is calculated from the draw-ratio (ratio of the feed and take-up roll speeds) with Eq.1.

The godets used for monofilament and multifilament plants are generally the same. Commonly available godets have a diameter between 80 and 300 mm, and a width between 40 and 300 mm (Annex 4).

The smallest godets are typically non heated and the godet shaft is either clamped directly to the motor shaft or connected to a motor with chain or belts.

In the heated godets a resistive or inductive heater is internally mounted. The surface temperature that can be achieved is for resistive heating around 250°, and for inductive around 400°. Besides the maximum temperature, the biggest difference is that the induction heating system is characterized by short heating up time and low control delay, the reasons why they are generally preferred.
The generally used drive for those individually driven godets is typically a synchronous reluctance motor, driven by an inverter.

In the production of monofilaments it is still common that a single motor drives all the godets of a set. Since they all rotate at the same speed (Fig.7), the transmission is made from the motor shaft by belts. This drive concept results at one side very cost efficient but at the other it allows only a very slow process speed (yarn speed around 200 m/min).

Generally, the use of individually driven godets has drastically increased the production speed to a yarn speed of around 1500 m/min and in case of cold godets even beyond 3000 m/min. [26]

The cost of an individually motorized solution is obviously higher than the solution with a single motor and transmission belts. The difference is basically given by the high expense of the synchronous reluctance motor, which normally has to be overrated in power, and whose production is nowadays still poorly automated.

However, the use of individually motorized godets has become now state of the art. There are still differences from supplier to supplier in the controller concept. The cheapest and most used solution is a common inverter for few godets. This concept is especially used for godets rotating at the same speed, like for the monofilament drawing plant, those of the same group of speed (Fig.7).
A more expensive solution consists in the use of individual inverter for each motor. This is used by some suppliers of monofilament plants and by modular multifilament plants (Par.2.4).

The use of a godet with a transfer roll (Fig.10) instead of a set of godets, like in the monofilament plants, results in a much more compact and inexpensive construction.

![Fig. 10: Heated godet with transfer roll.](image)

The use of this not driven and not heated transfer roll leads to a poor precision in the control of the yarn temperature and also of the yarn tension. Because of that, the application of this design with a godet and a transfer roll is normally limited to the multifilament plants. In fact, the production of monofilament is generally for technical applications and the processed yarn is very fine and sensitive. The multifilaments are on the other hand much less sensitive, and such solution is in this application much spread.

[77]

In order to make more wraps of yarn lapping, the axis of the transfer roll is slanted towards the godet (Fig.10). The angle between the two axis defines the distance between each wrap and thus for a given godet surface the maximum wraps that can be done.

In Fourné [31], reported measurements of the yarn temperature along the turns around the godet and the transfer roll have confirmed an oscillating temperature course (Fig.11).
Fig. 11: Yarn path (3 turns) versus yarn temperature. 0-T₁= part of the yarn on the godet (first turn); T₁-T₂= part of the yarn in the air between the godets and the transfer roll (first turn); T₂–T₃= part of the yarn on the transfer roll (first turn); T₃-T₄= part of the yarn in the air between the transfer roll and the godet (first turn); T₄-T₅= part of the second turn on the godet. [31]

This oscillating temperature is very harmful for the quality of the final yarn. For technical applications, like filters fabrics, a very high regularity of the denier is required. Very small changes in the yarn temperature cause an irregular distribution of the crystalline areas and thus irregular mechanical properties, but also an irregular fineness ($CV_m$). To reduce this for monofilament production plants, the set of all heated godets and the additional heater between the feed and take up set of godets are used.
2.1.2 Conventional draw texturing process

A further very much used transformation of melt spun synthetic yarns is the texturing. Made only on multifilament yarns, it is normally combined with the process of drawing. Texturizing (or texturing) aims to convert the “synthetic” appearance of flat yarns to a more acceptable textile aspect and hand and to confer on these yarns the properties associated with natural yarns such as wool and cotton, which have an inherent crimp or bulk. Further characteristics and effects, such as high voluminosity or high elasticity, are also provided.

The texturing acts directly on the filaments that constitute the filament yarn, creating curls and crimp. These alterations impact inevitably the aspect and the “hand” of the fabrics using this kind of yarn. The improvements in the quality of the woven or of the knitted fabric have brought a wide use of the textured yarn. [16]

There are two ways used for draw-texturing: the sequential and the simultaneous process. If the input yarn is an LOY yarn, it needs to be drawn in one stage and be continuously texturized in a second, following stage (sequential draw-texturizing). When the input yarn is already a POY yarn, it can be drawn and texturized in one step (simultaneous draw-texturizing). Since the POY yarn is the most common state in which to find a synthetic yarn, the simultaneous draw-texturizing is the most used process. [76]

In order to have a more versatile machine and a better control, some machinery suppliers keep the two processes, the drawing and the texturing, separated also for a POY transformation.

The draw-texturing process combines generally 9 different operations together:

- The unwinding
- the drawing,
- the heating,
- the cooling,
- the twisting,
- the detwisting,
- the heat setting,
- the interlacing,
- the application of spinfinish,
- and the winding.
The unwinding is the process of removing yarn from a package and is fundamental to many operations in the textile industry. The surface generated by a loop of yarn rotating rapidly about a fixed axis is called a balloon. The balloon shape characteristics and operating speeds govern the yarn tension. Yarn strength limits the maximum tension and therefore the operating speed and productivity of the system. The properties of such balloons are important in designing new machinery, improving the efficiency of existing processes, and determining the limit of performance of these processes.

As seen in the previous Subparagraph, the drawing is the process by which the orientation of the polymer molecules along the filament axis is increased. The process comprises the heating of the yarn and its stretching by a series of rollers rotating at increasing speed.

The twisting is the operation responsible for the texturing of the yarn. This can be made with two different technologies: the airjet and the friction texturing. The difference between the two processes is in the way how to impact the crimp effect to the yarn. In the air jet texturing this is made by airflow, while in the friction twist by a mechanical friction.

The yarns produced by air jet are, for the aspect and for the mechanical properties, totally different from those coming from the friction texturing.

![Fig. 12: Structure and stress-strain diagram of airjet and friction textured yarn.](image-url)
For friction texturizing, also called false twist texturizing, a three spindle friction disk aggregate is typically used to impart the twist to the yarn. Before the yarn enters the friction unit, it is first heated and then cooled. The heating is applied before the point of the maximum twist, in order to better deform the molecular orientation. Since the twist proceeds opposite to the yarn movement, heater is placed before the friction unit.

For a proper transfer of the twist from the friction disks to the yarn, before entering the friction unit the yarn is cooled by a cooling device; typically a cooling plate.

The twist, impacted in the friction unit, solves automatically just after it, while a crimp remains in the structure of the yarn, thus the name false twist texturing.

After the crimp is impressed, another heater for the thermal setting follows.

Spin finish is then applied before the yarn is wound on a bobbin.

For the drawing and for the feeding of the yarn, cold rolls covered by rubber mounted on shafts going through the whole machine are typically used. For these conventional draw-texturing machines, it is common to have a single motor driving the through-shaft (Subpar. 2.3.1).
Fig. 14: Typical layout of conventional draw-texturing machine.

Draw-texturing machines are very high (until 5-6 meters) and long (until 300 yarn positions).

The width of those machines is basically given by the length of the heating and cooling zones that are up to 3 meters.

2.1.3 FasTex.EDU texturing principle

In the FasTex project, as already explained in Par.1.1, pointing far into the future, a delivery speed beyond 2'000 m/min was set for target of the texturizing process. Since the disc units did not impose a basic obstacle for increasing speed, the decision was taken to remain stay with them. However, the spindles had to be redesigned. A completely new concept had to be chosen for heating, cooling, friction device and yarn path.
The POY bobbin is positioned on the back side of the machine to facilitate its change. The yarn coming to the front side goes down vertically to enter the first heating unit (Hotbox 1). From this device it goes horizontally to the second heating unit (Hotbox 2), while it is pre-drawn. The hot yarn reaches now a cooling pin, where it floats on the coolant fluid without loosing twist. This controlled flow of coolant allows a very fast cooling of the yarn. Moreover, the cooling fluid helps to control surface friction in the twisting unit, reducing the known problem of “snow”. The “snow” is the accumulation of broken parts of fibers that form polymer dust, similar in the aspect to the snow. The thread passes from bottom to top through the friction unit and reaches the third Hotbox, where it is set. The draw-textured yarn is interlaced by an interlacing jet and enters a fourth Hotbox without heater, acting as a brake to separate the yarn tension between the interlacing and the winding zone. The yarn is finally wound on a Comoli take up winder. A long winding triangle reduces the difference in yarn tension created by the traverse motion. The whole machine uses a personal computer to control all the devices. The set point for the godet speed is calculated by the controlling program, written in Visual Basic, and it is sent to the drives through serial RS 485 and USB interfaces.
The integration of the components has been made in order to obtain a no-friction contacts yarn path. All the changes of directions of the yarn are 90° angles, arranged in a way that the yarn doesn’t touch any other surface than the rotating godets.

Modern individual drive technology is used all over on this machine. Each component with its specific requirement is developed for a target of a yarn speed of 3000 m/min (Tab.1).

With the use of individually driven drawing components, it is possible that some of them work in 4-Quadrant operation. This means that in the case of the Hotbox 1, Hotbox 3, and Hotbox 4, the motors of the twin godets may be operating as generators. Therefore, a common D.C. bus is used and the energy produced by the Hotbox operating as generators is directly transferred to other Hotbox operating as motors.
<table>
<thead>
<tr>
<th>Function</th>
<th>Target requirements</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Motor</td>
</tr>
<tr>
<td>Hotbox 1</td>
<td>Yarn speed 2000 m/min Temperature up to 120°C</td>
<td>Twin godets with synchronous</td>
</tr>
<tr>
<td></td>
<td>4-Quadrant operation</td>
<td>motors 2 x 200 W</td>
</tr>
<tr>
<td>Hotbox 2</td>
<td>Yarn speed 2500 m/min Temperature up to 200°C</td>
<td>Twin godets with synchronous</td>
</tr>
<tr>
<td></td>
<td>1-Quadrant operation</td>
<td>motors 2 x 200 W</td>
</tr>
<tr>
<td>Cooling system</td>
<td>Computer controlled metering pump</td>
<td>Diaphragm pump with magnetic</td>
</tr>
<tr>
<td>Friction unit</td>
<td>30,000 RPM, direct drive, minimum vibration, 1-Quadrant</td>
<td>Single motor-spindle Maxon</td>
</tr>
<tr>
<td></td>
<td>operation</td>
<td>motor 30,000 RPM, direct drive</td>
</tr>
<tr>
<td>Hotbox 3</td>
<td>Speed of 3000 m/min Temperature up to 100°C</td>
<td>Twin godets with synchronous</td>
</tr>
<tr>
<td></td>
<td>4-Quadrant operation</td>
<td>motors 2 x 200 W</td>
</tr>
<tr>
<td>Hotbox 4</td>
<td>Speed of 3000 m/min</td>
<td>Twin godets with synchronous</td>
</tr>
<tr>
<td></td>
<td>No heating</td>
<td>motors 2 x 200 W</td>
</tr>
<tr>
<td></td>
<td>4-Quadrant operation</td>
<td></td>
</tr>
<tr>
<td>Winder Traverse</td>
<td>Step precision winding</td>
<td>Asynchronous squirrel cage</td>
</tr>
<tr>
<td></td>
<td>1-Quadrant operation</td>
<td>motor 130 W</td>
</tr>
<tr>
<td>Winder Friction roll</td>
<td>Yarn speed 2700 m/min</td>
<td>Asynchronous squirrel cage</td>
</tr>
<tr>
<td></td>
<td>1-Quadrant operation</td>
<td>motor 950 W</td>
</tr>
</tbody>
</table>

*Table 1: Drive requirements and solutions used in the FasTex.EDU.*

The essential new features are described in the patent WO2005038107, applied in 2005 by the company Rieter A.G.. [79]

One of the main claims of this patent is the new solution for the friction unit (Fig.18).

The use of individual drives for this component is the key factor for the increase of the rotating speed of the friction spindles.

The actual most used texturing apparatus for friction texturing is produced by Temco and uses one motor for the three spindles (Fig.17). The motor is placed behind the three spindles and with a belt it drives the shaft of one of the three spindles. The other two spindles are driven by the first spindle through two other belts.
In the new texturing unit, the friction discs are arranged on the three spindles, directly coupled to the three individual motors. Maxon EC 22 motors are used with hall sensors. This brushless DC motor has a maximum power of 50 Watt at its speed limit of 40’000 RPM, as tested by texturing a 298/167 f 30 POY polyester yarn.

The speed of each of the three motors is individually controlled by an electronic commutation board. This board receives from the motor the signal of the three hall sensors and controls the speed of the spindle. The set point, identical for the three drives, comes to this board from the PC through an analog output.
By this, the mechanical losses and vibrations created by the traditional belt drives could be eliminated. Working without belts means that radial forces are basically eliminated and smaller diameter bearings with longer life can be chosen. The spindle geometry has also been changed. Due to the radial load imposed by the driving belt, the classical layout of a spindle has two ball bearings mounted close to each other on one end of the spindle. Now the two bearings of the brushless DC motor on one end and a 608 2Z ball bearing on the opposite end provide a more rigid design. By O-rings used for holding the motor and bearing, vibration is dampened and virtually absent.

2.1.4 A new solution for a godet duos: the Hotbox

The new solution for the heating and feeding of the yarn, introduced in the FasTex.EDU, is an enclosed box with a twin godet. This Hotbox is heated internally by a convection heater. The two godets have no internally heater and are only in charge of feeding the yarn to the following device. In this Hotbox the thread is wound for several laps around both godets. By touching the surface of the godet and by being exposed to the ambient air, both at the same temperature, the thread has ample time to assume the desired temperature.

Fig. 19: Hotbox: construction and yarn path.
Due to the enclosure, there is a minimum loss of energy and the temperature inside the box is uniform, both points being decidedly better than a standard open godet.

The good uniformity of temperature inside the box avoids yarn temperature oscillations, typical of common godets with transfer roll (Fig. 11). It can thus be supposed that with the Hotbox the quality of the processed yarn is increased.

On the other hand, the use of stone wool insulation in the frame of the box increases the heating efficiency. In the following figure, the results of experiments made in De Crescenzo [75] shows a mean energy saving in comparison to inductive heated godet of about 40%.

![Fig. 20: Heating power for standard godets and for the Hotbox, in comparison to the calculated yarn power consumption (values calculated and measured at yarn speed of 500 m/min).](image)

If the efficiency of the heating process is calculated from the energy needed by a yarn to get to a given temperature, it can be found that the heating process is a very poor process. For common godets, the average efficiency, calculated from the data in De Crescenzo [75], is 16.7%, while for the Hotbox is 34.3% with a maximum of about 40%. Considering that the energy consumption impacts for more than 30% on the final cost of the produced yarn, an increase in the efficiency is a great cost reduction for yarn producers.

The temperature control of the box is done with a PT100 sensor mounted next to the exit of the box (Fig.19). It can be assumed that after enough time, depending on the yarn speed and on the number of wraps around the twin godets, the yarn has assumed the
temperature of the box. By controlling the temperature of the box, it is then possible to control the temperature of the yarn leaving the box. The two godets are independently driven by a motor, directly clamped on the godet shaft. The two motors are mounted externally of the box on the rear side. Due to the absence of the internal heating, the design of the godets is very compact, simple and much cheaper than a common godet. The diameter of such godet is in fact 60 mm and the axial length as well. In order to obtain multiple yarn wraps on the two godets, their axis have to be tilt. The first godet of the pair has its axis perpendicular to the machine face, while the second has its axis inclined to the first one.

![Diagram of Tilt godet and Tilt disk for the clamping of the motor](image)

**Fig.21: The positioning and clamping of the two individual motors.**

The motor of the tilt godet is clamped on the machine frame through a disk with a tilt surface. By rotating the motor and the clamping disk, the angle between the two godet axes can be adjusted. As it happens by a godet with transfer roll, by changing the angle between the two elements, the yarn wraps are nearer or more far away from one another. With nearer wraps, more space for other wraps is available and more yarn can be introduced inside the box. By having a longer path inside the box, the yarn has more time to heat up and to reach the inside temperature. The drive of the two godets is done by individual motor but the type of motor is still a matter of investigation. The efficiency, the cost, the dynamic properties and even the risk of instability in the control are important arguments that influence the decision.
On the prototype of the Hotbox, presented in 2003 together with the FasTex.EDU at the ITMA (Subpar.2.2.3), brushless D.C. motors were adopted. During the following years, different Semester and Diploma works at the Institute for Manufacturing Automation have been focused on the design and construction of A.C. brushless motors and asynchronous induction motors.

### 2.2 DRIVE TECHNOLOGIES FOR DRAWING PROCESSES

In literature and in industrial applications plenty types of electric motors can be found. [34] Their distinction and characteristics can be described by considering different kind of parameters. The most used way to describe them is by considering the type of current supplied to the non-rotating part of the electric motor (typically called stator): the direct current (simply called D.C.), and the alternating current (A.C.).

Another way to define and call electric motors is to use the expression synchronous/asynchronous, by considering the dynamics between the rotating part, the rotor, and the stationary part, the stator.

Industrial motors come in a variety of basic types. These variations are suitable for many different applications. Naturally, some types of motors are more suited for certain applications than other motor types are.

The most common electric motors in today’s market are summed up in the following scheme:

- DC Motors
  - Brushed DC Motors
    - Separately excited DC Motors
    - Series wound DC Motors
  - Brushless DC Motors
- AC Motors
  - Asynchronous Induction AC Motors
    - Squirrel cage AC Motors
    - Wound rotor AC Motors
  - Synchronous AC Motors
• Permanent magnets Motors
• Field wound Motors
• Stepper Motors
• Reluctance Motors
• Universal Motors
• Linear Motors

The brushed DC motor is one of the earliest motor designs and until some years ago it was the motor of choice in the majority of variable speed and torque control applications. The design of the brushed DC motor is quite simple. A permanent magnetic field is created in the stator by either of two means:

• Permanent magnets
• Electro-magnetic windings

If the field is created by permanent magnets, the motor is said to be a "permanent magnet DC motor" (PMDC). If created by electromagnetic windings, the motor is often said to be a "shunt wound DC motor" (SWDC). Today, because of cost-effectiveness, efficiency, and reliability, the PMDC motor is the motor of choice for applications involving fractional horsepower DC motors. The drawback of the PMDC motor is in the use of the brushes to commutate the armature field. The maintenance, the short life of the brushes, and the limited rotational speed are in fact the negative aspects of this motor that are overcome by brushless DC motor. [29]

Brushless DC motor uses an external electronically commutation and the rotor poles are made of permanent magnets. Since the use of this motor is interesting for the Hotbox, more detailed information is shown in the following Subparagraph 2.3.3.

The most common and simple industrial motor is the three phase AC induction motor, sometimes known as the "squirrel cage" motor. Induction motors are simple, rugged, reliable and easy-to-manufacture, thus interesting for a drive of the godets and of the Hotbox. Substantial information on this motor can be found in the following Subparagraph 2.3.5.

Synchronous AC motor is not as widely used as Asynchronous induction motors, because of having a more complex and expensive rotor design. In case of AC permanent magnet motor, its advantages are similar to the PMDC motors, i.e. efficiency and reliability. Its characteristics are showed and analyzed together with the PMDC in Subparagraph 2.3.3.

AC stepper motors permit rotation in small angle increments (steps) in response to
individual control pulses applied to its windings. Due to the high pole count, hysteresis and eddy current losses are high and increase with the rotational speed.

The reluctance motor offers a simple, and low cost motor choice. This motor consists of a shaped, highly permeable material for the rotor and two- or more-phase windings in the stator. The shape of the rotor concentrates magnetic flux lines into "poles" on the rotor which then interact with the rotating field being developed in the stator windings. The potential for its low-cost application into many areas makes it an extremely desirable motor. Its characteristics are shown in Subparagraph 2.3.3.

The universal motor presents a special case for a small-series motor that can be driven by either an AC or DC current source. This motor type, which represents another class of the commutating machine, consists of a series-wound fractional-horsepower motor. The universal motor's maximum speed is developed without load, while its greatest torque is developed at lowest speed. Universal motors are often found in vacuum cleaners, portable power tools, food processors, mixers and other small devices operating over a speed range of 3,000 to 10,000 rpm.

A linear motor is essentially a multi-phase ac electric motor that has its stator "unrolled" so that instead of producing a torque (rotation), it produces a linear force along its length. The linear motor market is in rapid evolution and also for this type of motors there are different design and constructions: synchronous, asynchronous, AC, DC and permanent magnet linear motors.
## 2.2.1 Electro-mechanical power conversion

The geometric arrangement of the magnetic circuit and windings defines how the motor converts the electrical input power into mechanical output power.

![Block diagram of the power conversion](image)

*Fig. 22: Block diagram of the power conversion.*

In the power conversion process, power losses are always present through different mechanisms:

- Resistance of the windings: “copper loss”.
- Magnetic hysteresis in the iron core: hysteresis loss.
- Eddy currents induced in the iron core: “eddy current loss”.
- Mechanical vibration of the core and windings (magnetic friction, mechanical vibration due to magnetic pull): additional mechanical loss.
- Dielectric loss in materials used to insulate the core and windings.

Hysteresis and eddy current losses are together known as *iron loss* or core loss.

In induction motors, the resistive losses in the rotor represent an additional effect that has to be added to those listed. This is the consequence of the construction and the principle of operation of induction motors. Compared to synchronous motors it causes generally a lower efficiency. [84]

The stationary analysis done in this work consists of an investigation of the system behavior and stability at defined steady-state conditions.

The electromagnetic interaction between the stator and the rotor magnetic field is a subsystem in the definition of the dynamic behavior of the rotor-godets.
If we would take an observer rotating at the speed of the magnetic field of the stator, he would see, by synchronous motors a rotor revolving synchronously, while by asynchronous motors a slower revolving rotor. However, the real relative behavior of a rotor is characterized by the typical rotor angle pulsation. In fact, it is well known that mainly for synchronous machines, the rotor exhibits small oscillations around the mean value $\theta_0$ between $\theta_0-\varepsilon$ and $\theta_0+\varepsilon$ with relative frequency $\lambda$. It means that the rotor behavior is not a uniform rotational movements but it decelerate and accelerate within a rotation.

The model proposed in this paragraph is intended to explain the relative behavior and interaction between stator and rotor in a stationary state. By using spring-dampening elements, the relative rotor oscillations are explained.

It is assumed that the stator magnetic field of the motor rotates at a nominal rotational speed and that the rotor supplies the nominal torque requested in static equilibrium with the load. Small variations of the steady-state conditions are then introduced and the electric motor reaction is studied.

In the spring dampening model, models are made for synchronous motors (PM and reluctance) and for asynchronous motors (induction motor).

### 2.2.2 Open loop and closed loop controlled drives

Electric motor dynamics is not only dependent on motor design but mostly on its control. Control systems are divided into two categories: open-loop control and closed-loop control.

The elements of an open-loop control system are divided into two parts: the controller and the controlled process, as shown by the following block diagram (Fig.23).
In simple cases, the controller is an amplifier, mechanical linkage, filter, or other control elements, depending on the nature of the system. In more sophisticated cases, the controller is a computer, such as a microprocessor. Because of the simplicity and economy of open-loop control systems, they are found in many noncritical applications. What is missing in the open-loop control system for more accurate and more adaptive control is a link or feedback from the output to the input of the system.

To obtain more accurate control, the controlled signal $y$ should be fed back and compared with the reference input, and an accurate signal proportional to the difference of the input and output must be sent through the system to correct the error (Proportional controller). The output signal of a controller is the sum of more correcting signals. Besides the signal from a proportional controller there is the signal of an integral controller and the signal of a derivative controller. The output of the integral controller is proportional to the integration of the error over the time. The output of the derivative controller is proportional to the derivative of the error over the time. A system with one or more feedbacks paths such as those just described is called closed-loop system.
Systems that work on the negative feedback principle to induce an action to cause the output to follow or track the input are called servos or servomechanism. Industrial servos had their real beginning during the World War II.

Measuring devices in general are called transducers. A transducer is a device, usually electrical, electronic, or electro-mechanical, that converts one type of energy to another for various purposes including measurement or information transfer.

There are many examples of transducers that convert mechanical energy into electrical signals: hall effect sensors, electroactive polymers, potentiometer, accelerometer, piezoelectric crystals, thermocouple, etc.. These electrical signals are the feedback information to the control system in a language the control can understand.

A classification of feedback devices is shown in Figure 25. There are two basic types of feedback signals, which also define the control system as to the data representation used within the system. Analog signals directly represent some physical quantity and are continuous in representation. Digital signals are discrete-time signals, and the control system is usually referred to as a digital system. Physical quantities are represented through the medium of digits or numbers, which correspond to discrete electrical pulses in the digital control system.

In industrial applications, the most used transducers are: the potentiometer, the tachometer, the incremental encoder, and the resolver.

Fig. 25: Feedback devices.
The potentiometer is an electromechanical transducer that converts mechanical energy into electrical energy. The input of the device is in the form of a mechanical displacement. When a voltage is applied across the fixed terminals of the potentiometer, the output voltage, which is measured across the variable terminal and the ground, is proportional to the input displacement, either linearly or according to some nonlinear relation. [80]

Tachometers work essentially as a voltage generator, with the output voltage proportional to the magnitude of the angular velocity of the input shaft. In control systems, most of the tachometers used are of the dc variety.

Incremental encoders are frequently found in modern control systems for converting linear or rotary displacement into digitally coded or pulse signals. Incremental encoders provide a pulse for each increment of revolution, analyzing 2 or more the signals it is possible to know the position and the speed of the object measured.

The resolver is a precision induction-type device acting like a variable transformer, with the amount of coupling varying as the sine and cosine of the angular position of its rotor shaft. [65]

The significance of the effects of feedback in control system is more complex than the simple reduction of the error between the reference input and the system output. Feedback has also effects on such system performance characteristics as stability, bandwidth, overall gain, impedance, and sensitivity. [66]

The type of motor, the drive and the controlled process, together with the controller define the dynamic performance of the system output.

### 2.2.3 Synchronous motors

The name synchronous motor results from the interaction between the stator and the rotor. Under steady-state conditions, if the rotor rotates at the same speed as the stator magnetic field, the motor is considered a synchronous motor.

There are different designs of synchronous motors but the most actual and interesting for a drive of the Hotbox and of individually driven godets are: the permanent magnet brushless motors (A.C. and D.C.) and the reluctance motors.

Even though the rotor magnetic field of synchronous reluctance motor and permanent magnet motor is generated in different ways, their dynamic behavior is very similar.
A brushless permanent magnet motor is a motor whose poles are made of permanent magnets and no commutator or brushes are used (thus also the name brushless motors).

Since no power loss is associated with machine excitation, permanent magnet motors have high efficiency and also high power/weight ratio, when compared with other motors.

Depending on the stator supply and construction, brushless motors can be divided into two categories: the permanent magnet D.C. (also called BLDC or electronic commutated EC) and the permanent magnet A.C.. The stator magnetic field of the three-phase motor is considered to be, in both cases of a D.C. or A.C. current, a rotating field with constant amplitude.

In case of D.C. current, the rotation of the stator magnetic field is done by electronic commutation. To generate the control voltage to the stator windings an external amplifier with a rotor position sensor and a solid-state electronic switching circuit is connected.

![Fig. 26: Brushless DC motor using Hall sensors for rotor position feedback. [81]](image)

In brushless DC motor constructions the stator may also do not have slots. Maxon, a Swiss leading company in small DC motors patented the ironless windings, System Maxon®. With no magnetic detent and minimal electromagnetic interference, such windings are up to 90% more efficient than other motor systems. [82]
In both cases of external commutation for DC current or of alternating current, the rotating stator magnetic field create a magnetic flux that interacts with the permanent magnet rotor field and generates torque:

$$T_{ind} = k \, B_R \times B_S$$  \hspace{1cm} \text{Eq. 2 [35]}

where \( B_R \) = permanent magnet magnetic field

\( B_S \) = magnetic field created by the stator

\( k \) = constant depending on the construction of the machine

In case of a brushless DC motor, this torque tends to align the rotor magnetic field \( B_R \) with the stator magnetic field \( B_S \). If a coil remained energized all of the time, the rotor would turn until the two magnetic fields are aligned, and then it would stop, just like a stepper motor. The key to the operation of a brushless D.C. motor is that the control circuit will know through the position sensor when the rotor is almost aligned with the stator magnetic field. At that time a coil will be turned off and the following coil will be turned on, causing the rotor to experience again a torque, and to continue rotating. This process of electronic commutation continues indefinitely with the coils turned on in order, so that the motor turns continuously. The electronics of the control circuit can be used to control both the speed and the direction of rotation of the motor.

In case of A.C. permanent magnet motors, the fundamental operation principle is not generated by electronic commutation but by using the alternating current.

If a three-phase set of currents, each of equal magnitude and differing in phase by 120°, flows in a three-phase winding, then it will produce a rotating magnetic field of constant
magnitude. The three-phase winding consists of three separate windings spaced 120 electrical degrees apart around the surface of the machine.

![Diagram showing three-phase winding](image)

*Fig. 28: Three phase, 4-pole synchronous motor [81]*

The alternating current in the stator windings create continuously a rotating magnetic field to which the rotor tends to align.

In both cases of AC and DC brushless motors, without having an external field circuit, it is not possible to control the speed of a permanent magnet motor by varying the field current or flux. The only methods of speed control available are armature voltage and frequency control.

Besides being very efficient, small, and almost without the need of maintenance, brushless motors also have disadvantages. The cost of the rotor assembly with the difficulty of fixing the permanent magnet is one of these. The risk of demagnetization of the permanent magnet because of high temperature represents also another drawback. However, modern magnets using Neodymium can support temperature up to 150°C and this problem is rather the case.

These kinds of problems do not affect the synchronous reluctance motor.

The synchronous reluctance motor is considered as a special brushless motor, without PM excitation. A synchronous reluctance motor (SynR) consists of a wound-stator and a magnetically anisotropic (salient pole) rotor. The excitation is drawn from the power source through the sinusoidal distributed stator winding and the torque is developed by virtue of a change in the reluctance with the rotor position. The stator structure is analog to that of a three-phase induction motor. The operation principle is based on the so called reluctance torque. Reluctance torque is the torque induced in an iron object in the presence of an external magnetic field. This torque occurs because the external field
induces an internal magnetic field in the iron of the object, and a torque appears between the two fields, twisting the object around to line up with the external field. Figure 29 illustrates the d-q axis equivalent circuits of the SynRM in a synchronously rotating reference frame and is referred to balanced steady-state operation. [84]

Fig. 29: Phasor diagram of synchronous reluctance motors. [84]

Where:

- $L_{mq}$ is the magnetising inductance in the q-axis
- $L_{md}$ is the magnetising inductance in the d-axis
- $L_{IS}$ is the stator inductance
- $\gamma$ is the saliency ratio ($L_{md}/L_{mq}$)
- $I_q$ and $I_d$ are the d- and q-axis component of stator current
- $V_s$ stator voltage
- $\omega_s$ = supply frequency (stator magnetic field frequency)
- $r_s$ = stator resistance

The axis $d$ lies along the rotor flux vector direction while the axis $q$, orthogonal to axis $d$, is 90° ahead of it in the trigonometric (positive) direction of motion. In terms of $d$-$q$ variables, the electromagnetic torque is given by:

$$T_{md} = L_{mq}(\gamma - 1)I_qI_d$$  

Eq. 3 [83]
The magnetic anisotropy of the rotor can be obtained in different ways. The first way has been called *Transverse-Laminate Rotor Design* or even *Multiple-flux-barrier-rotor* and is characterized by the number of flux barriers per pole. Figure 30 (a) shows a three flux barrier per pole, as an example. Mechanical strength is guaranteed by the thin ribs, disposed at the air gap and also in the inner rotor, important in the case of large speed values and/or large rotor diameters. The ribs are saturated, at load, by the stator mmf (magneto motive force) thus allowing the various rotor segments to have different values of magnetic potential. This type of rotor has many advantages, i.e., it is suited to rotor skewing, is practically free from rotor core loss, and is definitely suitable for mass production. As it can be seen from the figure, the permeances of the various flux barriers can easily be tailored by design, which is practically impossible in the ALA rotor (described in the following). This results in a near-sinusoidal flux-density behavior at the air gap, with obvious advantages for torque ripple and core loss behaviors. [20] [85]

The second type of rotor construction is called *Axially Laminated Structure* (ALA) and is represented in Figure 30 (b). The main part consists of axially arranged magnetic laminations, interleaved with nonmagnetic ones. The stack is held by a non magnetic pole-holder, connected to a magnetic central spider structure.

![Fig. 30: Traverse (a) and axially (b) laminated rotor design. [30]](image)

The adoption of the ALA structure certainly allows high anisotropy through proper design. On the other hand, a stator slotted structure with open slots enhances flux oscillations in the ALA rotor iron, leading to important core losses in the rotor, since the axially arranged laminae cannot oppose eddy currents induced by the harmonic fields. Moreover, the torque ripple due to stator slotting cannot be reduced by rotor skewing and
the stator must be skewed, if a low-ripple design is wanted. This has prevented to adopt ALA motors for industrial use.

The magnetic poles on the rotor can be of either salient or nonsalient construction. The term *salient* means “protruding” or “sticking out” and a *salient pole* is a magnetic pole that sticks out from the surface of the rotor. A *nonsalient* pole is a magnetic pole flush with the surface of the rotor. [85]

Regarding the performance of the synchronous reluctance motor, it is closely related to the method of control, which in turn depends on its nonlinear magnetic behavior. Synchronous reluctance motors (SynR) can be used under closed-loop control, supplied by dedicated power-electronic apparatus (inverter). The closed-loop mechanism controls the phase displacement between either the stator mmf wave or the flux wave and the rotor, thus ensuring torque performance under all working conditions. If an over torque is required, it is required to drive the SynR in closed loop control otherwise it is possible to drive those motors in open loop control.

Among the other A.C. machines, the synchronous reluctance motor exhibits the peculiarity that the flux linkage depends only on the current, by an algebraic relationship. In other words, disregarding the small delay due to eddy currents, the flux follows the driving current in real-time. This is different for induction motors, because of the delaying action of the rotor cage. This property of the synchronous reluctance motor may be seen as both an advantage and a drawback.

In closed loop control, real time flux control capability allows real time optimization of the operating point which is a welcome feature. On the other hand, the real-time flux control capability could constitute a drawback, e.g. because of the enhanced sensitivity of the flux to various ripples and disturbances. This high sensitivity can lead to too strong reactions, to a loss of synchronism and to problems of stability. On the contrary, an induction motor would be inherently protected in such a case, by the filtering action of the rotor cage. In some cases to avoid this problems, an additional induction cage, the so called *damper winding*, for starting and dampening rotational oscillations is integrated in the rotor of the synchronous reluctance motor (Subparagraph 2.3.4). [54] [55] [83] [87]
2.2.4 Damper windings for synchronous motors

Damper windings on synchronous motors are inserted in slots in the pole face iron. The windings consist of cast aluminum bars or bars of copper, bronze, or other alloys, inserted axially into slots on the pole face slots and connected at the ends to form a complete short circuit winding, quite similar to the squirrel-cage winding of an induction motor. The end connections are either complete rings of conducting material or a high conductivity pole end lamination, to which the pole faces are brazed.

The winding is required to produce an induction motor torque, when the motor is started from standstill at a given fixed frequency. This induction torque is also used, at steady-state, to dampen the typical rotational oscillations, especially known in synchronous motors.

When three-phase alternating voltage is applied to the armature terminals, the stator magnetic field sweeps along in a rotating direction and induces a voltage in the bars of the damper windings:

\[ e_{ind} = (v \times B_s) \cdot I \]  

Eq. 4

This voltage produces a current flow in the bars resulting then in an induced torque:

\[ T_{ind} = kB \times I \]  

Eq. 5

Even though a rotor cannot speed up till the synchronous speed, it can get so close that the rotor can be pulled into step with the stator magnetic field by the reluctance torque or by the interaction with the rotor field provided by excitation winding or permanent magnets.

Another advantage of the damper windings is to dampen the rotor oscillations at steady-state. If the rotor turns slower or faster than the synchronous speed, there will be relative motion between the rotor and the stator magnetic field that induces a voltage in the damper windings. The voltage produces a current flow that interacts with the stator magnetic field with the following acceleration or brake of the rotor. The acceleration and respectively the brake tend to place back the rotor to the synchronous speed.

These windings therefore tend to dampen out the load or other transients on the machine, thus the name *damper windings*.

Damper windings are mostly used on synchronous generators, where they serve a similar stabilizing function when a generator is operating in parallel with other generators on the main grid. If a variation in shaft torque occurs on the generator, its rotor will momentarily
speed up or slow down, and these changes will be opposed by the damper windings. They reduce therefore the magnitude of power and torque transients. Damper windings are responsible for the subtransient current in a synchronous machine. A short circuit at the terminals of a generator is just another form of transient, and the damper windings respond very quickly to it.

2.2.5 Asynchronous induction motors

Induction motors are A.C. machines whose field current is generated by magnetic induction (transformer action) in their field windings. The field circuit of most induction machines is located in their rotors.

The fundamental principle of A.C. machine operation is that, if a three-phase set of currents, each of equal magnitude and differing in phase by 120°, flows in a three-phase winding, then it will produce a rotating magnetic field of constant magnitude. The three-phase winding consists of three separate windings spaced 120 electrical degrees apart around the surface of the machine. [30]

There are two different types of induction motor rotors that can be placed inside the rotor. One is called the wound rotor, while the other is called cage rotor.

A wound rotor has a complete set of three-phase windings that are mirror images of the windings on the stator. The ends of the three rotor wires are tied to slip rings on the rotor’s shaft. The rotor windings are shorted through brushes riding on the slip rings. Because of the complexity and cost wound rotor are nowadays rare and substituted by cage rotor.

A cage induction rotor consists of a series of conducting bars laid into slots carved in the face of the rotor and shorted at either end by large shorting rings. The squirrel cage induction motor is probably the most widely used motor in industry today. The rotor construction looks like a squirrel cage, hence the traditional name. This is the simplest to manufacture and the easiest to maintain.

An induction motor can be basically described as a rotating transformer. For an ordinary transformer, the output is electric power from the secondary windings. The secondary windings in an induction motor (the rotor) are shorted, so no electrical output exists. Instead, the output is mechanical.
The magnetic induction principle of asynchronous motors is characterized by a difference in the rotational speed between the stator and rotor magnetic field. The rotor rotates slower than the stator magnetic field. It is this relative motion of the rotor to the stator magnetic field that produces the induced voltage in the rotor. The rotor current produces then the torque.

It is possible to use the equivalent circuit of an induction motor and the power-flow diagram to derive a general expression for induced torque (torque generated by the internal electric-to-mechanical power conversion) as a function of speed.

There is a finite upper limit to the motor’s speed. If the induction motor’s rotor were turning at synchronous speed, then the rotor bars would be stationary relative to the magnetic field and there would be no induced voltage, no rotor current and no rotor magnetic field. With no rotor magnetic field, the induced torque would be zero, and the rotor would slow down. An induction motor can speed up to near-synchronous speed, but it can never exactly reach synchronous speed.

The difference between the stator magnetic field speed (synchronous speed) and the rotor speed is defined as *slip speed*. Another term used to define the relative motion is the *slip*, which is the relative difference in speed:

\[ s = \frac{n_{\text{slip}}}{n_{\text{sync}}} (\times 100\%) \]  
\[ \text{Eq.6} \]

where \( n_{\text{slip}} = \text{slip speed of the machine (n}_{\text{sync}}-n_{\text{m}}) \)
\( n_{\text{sync}} \) = speed of the magnetic field
\( n_m \) = mechanical shaft speed of the motor

The torque-speed curve is nearly linear between no load and full load. There is a maximum possible torque that cannot be exceeded (pullout torque). The starting torque is slightly larger than its full-load torque, so this kind of motor will start carrying any load that it can supply at full power.

The simplified equation of the induced torque in the rotor is the following:

\[
T_{\text{ind}} \equiv k \cdot V_s^2 \frac{r_r \cdot s}{r_r^2 + [X_2 \cdot s]^2}
\]  

Eq.7 [29]

where

\( k \) = constant depending on the number of poles and on the stator field frequency

\( V_s \) = stator voltage

\( X_2 \) = rotor reactance

\( r_r \) = rotor resistance

\( s \) = slip

![Fig. 32: A typical induction motor torque-slip characteristic curve. [29]](image)

By using variable frequency control (inverter) it is possible to control the speed of an induction motor over a range from as little as 5% of the base speed up to about twice and more base speed. However, in order to have a constant working point of the magnetic
field and in order to prevent saturation and excessive magnetization currents, the terminal voltage applied to the stator is decreased/increased linearly with decreasing/increasing stator frequency. [84]

This easiness to control, together with the inexpensiveness of the construction fulfill the requirements of the majority of industrial applications, and pose the AC squirrel cage induction motor as the most widely accepted motor.

The continual improvements in the casting techniques and the construction features used in induction motors resulted in a considerable savings in manufacturing costs, leading to consider the induction motor as a norm motor.

2.2.6 Stationary and dynamic behavior of motors

Under the condition of small displacements from the steady-state, the dynamic characteristics of the synchronous and asynchronous motors are analyzed. With the linearization of the torque characteristic, their stationary behaviors are found and compared to typical mechanical elements like springs and dampers.

Due to the different design and torque characteristic curve, synchronous and asynchronous motors have different dynamic behavior.

The dynamic behavior of synchronous reluctance motor and permanent magnet motor is very similar, even though the rotor magnetic field is generated in different ways.

While for reluctance motor the magnetic field is generated by the reluctance principle, by the permanent magnet motor is already in the magnets.

In the steady-state of permanent magnet motors, the rotating stator magnetic field interacts with the rotating rotor magnetic field supplying the requested load torque (Eq.2).

Any change in the rotor position, caused by an external disturbance, means a change in the generated torque.

In Bianchi [35] (Subpar. 3.1.2), it has been demonstrated that the torque applied to the rotor of a two pole synchronous motor is proportional to \( \sin^2 \delta \), where \( \delta \) is the angle between the rotor and the stator magnetic fields. As long as the pullout torque of the motor is not exceeded, the rotor will be locked into the stator magnetic fields, so that the rotor rotates synchronously with the stator field.
In figure 33, the torque vs. the rotor position for a synchronous motor shows the sinusoidal dependence of the generated torque for a relative rotation of the rotor from the stator magnetic field.

By small rotor oscillations, the curve in Figure 33 is linearized and the linear spring constant \( K_s \) is calculated. Considering this linear dependence of the torque from the rotor relative position, it can thus be assumed that synchronous motors have, under small rotor oscillations, the behavior of a spring.

So that any change in the rotor steady state position would generate an additional torque:

\[
T_{add} = K_s (\theta_R - \theta_S)
\]

Eq. 8

Differently from the synchronous motor, the asynchronous induction rotor rotates at steady-state with a given slip (related to the stator magnetic field) of typically some percent (the first part of the curve in Fig.32).

If an external torque counteracts the rotation of the rotor, the slip increases and as a consequence the torque of the motor increases as well. The increase in the torque can be seen as the sum of a constant torque (the torque supplied at steady-state) and a second variable torque proportional to the difference of the rotational speed of the rotor.

On the other side, if a torque accelerates the rotor, the torque supplied by the motor decreases, until it is zero when the rotor rotates synchronously with the stator magnetic field. This effect can also be seen as a difference between the constant torque at steady-
state and a second variable torque proportional to the difference of the rotational speed of the rotor.

\[ T_{ind} = \overline{T}_{ind} + T_{add} \quad \text{Eq.9} \]

\[ \overline{T}_{ind} \sim n_{slip} \]

\[ T_{add} \sim n_{add \, slip} \]

\[ n_{add \, slip} = n - \overline{n}_{slip} \]

\[ n = n_{sync} - n_m \]

\[ \overline{n}_{slip} = n_{sync} - \overline{n}_m \]

\[ T_{add} \sim \overline{n}_m - n_m \quad \text{Eq.10} \]

where

\[ T_{ind} = \text{torque induced in the rotor} \]

\[ \overline{T}_{ind} = \text{steady state torque induced in the rotor (proportional to the steady state slip)} \]

\[ T_{add} = \text{additional torque given by a change in the rotor rotational speed from the steady state condition} \]

\[ n_{add \, slip} = \text{additional slip speed to the steady state slip (}\overline{n}_{slip}\text{)} \]

\[ n = \text{actual slip speed} \]

\[ \overline{n}_{slip} = \text{slip speed of the machine at steady state} \]

\[ n_{sync} = \text{speed of the magnetic field} \]

\[ \overline{n}_m = \text{mechanical shaft speed of the motor at steady state} \]

\[ n_m = \text{actual mechanical shaft speed of the motor} \]

The additional torque is proportional to the difference of the steady state rotor rotational speed and the actual rotor rotational speed and is opposite in sign to the actual rotor rotational speed.

It means that any external torque that would accelerate the rotor over the rotor steady state speed (\( \overline{n}_m \)) would cause an additional negative torque that decreases the total induced torque.\( (T_{ind}) \). It follows that from steady-state, any change in the rotor rotational speed is compensated by an increase or decrease in the supplied torque proportional to the speed difference and opposite in sign. This reflects a typical dampening behavior. Thus, for small displacements from steady-state position, the asynchronous motor is considered as a viscous damper.
Similar to the induction motor, the effect of damper winding is assumed as a torque counteracting the relative speed between the rotor and the stator magnetic field, and proportional to the slip.

If the rotor rotates slower than the stator magnetic field the generated torque is in the direction of the rotation. At the other side, if the rotor is faster, the generated torque is opposite to the direction of the rotation.

In both cases of positive and negative slip, the generated torque is thus always opposing the relative motion between the rotor and the stator magnetic field.

This generated torque can then be modeled as the torque supplied by a viscous dampening element.
2.3 MULTIPOSITION TEXTILE MACHINES FROM TROUGH-SHAFT TO INDIVIDUAL DRIVES

The trend of the “all electrics” with dedicated drives for each axis, already applied or under investigation for production machinery and automotive is becoming more and more interesting also for textile machineries.

The use of individual drives has replaced gear drives and belts. The choice of dedicated motors offer in some cases higher efficiency, higher speed and also higher flexibility of the process. These reasons together with the decrease of the price of electric motors have made machinery designer think about using individual drives.

2.3.1 Single motor with belts and inverter controlled motors in trough-shaft multiposition machines

All the major draw-texturing machinery producers, Barmag, Giudici and Murata, have adopted until some years ago a through-shaft multiposition layout.

In drawing and draw-texturing, it is typical to process simultaneously up to 300 yarns. Depending on the machine type and process, each machine has normally between 5 and 8 drive axes. On these machines, each axis uses a single motor, driving the through-shaft.

Each shaft is set to a speed and is used for the same function through the whole machine. All over the machine, the same yarn with the same properties is produced.

The typical through-shafts axes are: feed and take up rollers, texturing units, and winders (traverse and friction roll).

The drive of these trough-shafts is changed from the traditional design with a single motor and belt transmission to inverter controlled motors.

The traditional drive with a single big motor connected to the through-shafts by belts and pulleys is nowadays almost not used any more.

In this design, in order to produce different yarn properties (like for example other yarn fineness) the change of the processing parameters is connected to the change of the pulleys and of the belts, leading to very complex and long operations.
In case of inverter controlled motors, for each axis there is a motor at one side of the machine (in case of very long machines there could be a motor at both side). For each motor, an inverter controls the speed of each axis. Depending on the quantity of the axes, there are between 5 and 8 motors-inverters for up to 300 positions.

**Fig. 34: Schematic design of through-shaft machine using belts and pulleys.**

**Fig. 35: Example of layout of typical through-shaft axes in a multiposition machine.**
Due to these very long shafts, the machines are split in sections. Depending on the length of the machine and on the design of each manufacturer, the length of each shaft is determined. Between each zone of typically of 1-3 meter length, the shafts are then coupled to each other.

Due to the drive placed at one side of the machine, the through-shaft design has an advantage in a reduced space between each processing position. Further advantage, which nowadays may be questionable, is the inexpensiveness of the drive, above all in middle/long machines.

The production of long shafts, the use of coupling elements and the use in some cases of reduction gears may not result in a more cost efficient solution than direct drives. For short machines with less than 50 positions the use of a motor with long shafts may not be cheaper than direct drives with a single motor and its dedicated controller.

The processing positions through the whole machine have the same set-up; it is thus not possible to produce different yarns on the same machine. It follows that this type of machines is not flexible and thus only suitable for mass production. In fact, in order to test a new set-up on the machine, all the processing positions have to be stopped and restarted simultaneously. The same problem arises for maintenance. For sure, for production plants where a change in the programmed article happens very seldom, the flexibility does not represent an important argument of choice.
A further disadvantage of this design is the limit of the processing speed. It is stated that on such machine the speed limit is about 1500 m/min. The causes of this limit are in vibrations of the machine and torsional oscillation of the shafts, resulting in a poor quality of the drawn yarn. [77]

### 2.3.2 Modular machines with individually driven godets

The changes in drive technologies and the need in flexibility have put some questions on the applicability of individual drives also for filament yarn machines. The rising of small and very efficient motors, the potential of electronic devices such as inverters, together with their reduced costs, have brought the introduction of individual drives also for textile machines. A first step in the use of individual drives has been done in the draw-winding machines with the use of individual motors driven by a common inverter. As in the monofilament drawing plants (Subpar.2.1.1), the set of godets, all rotating at the same speed, are driven by individual motors. All these motors are then connected in parallel to a common inverter.

![Diagram showing individual motors using a common inverter](image)

*Fig.37: Individual motors using a common inverter (typical for monofilament plants).*

The use of this drive method is strictly connected to the use of synchronous motors with damper winding. The need of the synchronism of all the godets in the same set requires the use of synchronous motors. The damper winding is mainly asked to help the motors to accelerate at full speed.
The method of individually driven godets, which from the individual motor with common inverter represents a further development, is the use of individual motors connected to individual inverters.

Individually driven godets (Subpar.2.1.1) are nowadays used by the major machinery manufacturer also for draw-texturing machines, replacing little by little the long through-shafts. [4] [26] [88] [89]

The first draw-texturing machine using godets was the Tex2000, presented in 1999 at the ITMA in Paris by Retech AG together with the Institute of Manufacturing Automation of the ETH. This single position machine faced among an innovative yarn path, the use of individually driven godets. Those individually driven godets were known until then in melt spinning machines for the production of POY and FDY but they were never installed and used in texturing machines.

Following the concept presented on the Tex2000, other companies have started to design modular machines with individual godets.

SSM AG, a leading Swiss company in filament processing und winding machines, presented in 2003 at the ITMA in Birmingham different modular machines, among them also an air jet texturing machines with modular positions. One year later, the same company presented a friction texturing machine with individual drive.

![Fig.38: DP3, draw-texturing machine of SSM. [88]](image-url)
Barmag AG, a German company belonging to the Saurer Group, very known for melt spinning and texturing machines, brought in 2003 a new texturing machine to the market, using individual godets similar to those installed on its spinning machines.

![Fig.39: Comoli’s draw-winding modular machine with individually driven godets. [89]](image)

Later on, the same technical choices were taken by most all other machine manufacturers, confirming this choice and the need of the market.

The use of individual godets has not only increased the flexibility of the draw-winding and draw-texturing machines, but it has leaded to a higher productivity and to a better set-up of the machines.

Another big advantage is the possibility to build very small machines (also with 8 positions) to be used as machines for samples, with positions identical to production machines. The cost of such machines is more or less proportional to the number of positions (plus a standard basic equipment independent on the number of positions).

### 2.3.3 Concepts for the drive and process control in multiposition machines

In fiber drawing process, the tension of the yarn and the temperature of the yarn represent the two most important parameters that have to be controlled.
The temperature of the yarn is given by the temperature of the surface of the godets, or by the air in the heating box.

In case of multiposition machines, the temperature has to be set and controlled in each heating element. This is typically done through PT100 or thermocouple sensors, placed in each heating element.

The draft of the yarn, which is responsible of the fiber tension, is set by the speed of the feeding and of the taking-up rollers.

In case of multiposition machines, it is possible to set different speeds for each feeding and take up rollers. It follows that at each position it is possible to set different parameters and then to produce different yarns with different properties.

Machinery manufacturers, producing multiposition machines, have adopted different drive concepts.

The simplest, most expensive solution is to have for each motor its controller. This choice has to be taken in case of servo motors, where each motor has to be controlled by its dedicated controller. In this case, there would be a number of drives corresponding to the number of godets/axes. This solution has been adopted for the FasTex.EDU for the drive of the brushless D.C. motors.

Another solution is to have a common controller for all godets of the same function, i.e. a controller for all the godets 1, another controller for all the godets 2 and so on.

This method is used for monofilament extrusion lines (Subpar.2.2.1), where more than one godet belonging to a group are driven by a common inverter. This method is only applicable to synchronous reluctance motors, to asynchronous motors and, in case of stable open loop control, to A.C. permanent magnet motors. For any need of samples or machine maintenance, each position may be switched off/on, through a local switch.

Following this kind of solution, the company Reel s.r.l. presented in 2006 in the Seminar “Seminario interattivo sugli azionamenti elettrici” in Bressanone, a similar concept of the drive. With an example of cotton spinning machines and cotton twisting machines, each spindle and axes are driven by a dedicated motor-drive. The drive is made of a central master and a multiple of distributed slaves. The electrical energy is transmitted through the whole machine by a D.C. bus. [90]

Using the same concept, presented by Reel, it is possible to implement a similar drive concept for the Hotboxes in a draw-texturing machine, as proposed in Figure 40. The power is transmitted to each Hotbox by a D.C. bus. Locally, by each Hotbox, i.e. distributed along the machine, there are the local drives.
Fig. 40: Individually driven motors concept for the Hotboxes in multiposition machine.

Following another cheaper drive solution, the two godets of the same Hotbox are driven in parallel by a common inverter in open loop control, as in Figure 41.

Fig. 41: Common inverters drive solution for the Hotbox in multiposition machine.
This solution may develop, under circumstances stability problems due to the elastic coupling of the inertia of the rotating godets.
A detailed stability analysis of the whole mechatronic system, staring from the analysis of the dynamic behavior of the godets with their inertia, the yarn with its elastic behavior and the different motor design with their spring and dampening behavior will help to understand the limits of stability and will help to choose to most suitable drive.
3. MECHATRONIC MODEL OF INDIVIDUALLY DRIVEN DRAWING GODETS

This chapter shows, starting from the analysis of previous works on this subject, the method used for the dynamic modeling of the components that constitute the drawing process.

In Paragraph 3.1, previous work on the modeling of the drawing process, of the dynamics of electric motors, and of filament yarn is described and analyzed.

Paragraph 3.2 is a definition of all elements acting in the drawing process, with particular attention on the specific case of the Hotbox.

Finally, in chapter 3.3 the stationary analysis of asynchronous and synchronous motor behavior is explained using a mass-spring-damper model.

3.1 PREVIOUS WORKS ON THE SUBJECT

In literature, no reports are found regarding the study of stability and dynamics of two individually driven godets coupled by a yarn and driven by different types of electric motors.

Some studies were done almost 40 years ago, in modeling the torque transmission between pulleys. [40], [41], [42]

New developments in this field have been made and applied in the past years also for textiles. Bechtel [6], using the results of Firbank [42], has developed an extended model for the dynamics of fibers on rolls.

In a totally different field of research, literature on the dynamics of electric motors and generators has been published. Particular attention has been put on the study of the torque-speed behavior and on the problem of non-linearity in motor dynamics.

In Canay [10], [11], [58], a model of the torsional oscillations of a synchronous generator was developed and the equations of motion derived. In some other works [14] [15] [19] the subsynchronous oscillations are analyzed and the resonances with other connected
systems are found. Some other reports [21], [50], [57] have studied methods to dampen torsional oscillations, and some others [22], [35], [36], [47], [57] have found methods for obtaining motor parameters optimization.

3.1.1 Models of belt drive dynamics and fiber draw process

Stretching and sliding of belts on pulleys or fibers and films on rollers have significant industrial implications. Even though they are more and more substituted by direct drives, belt drives are still widely used to transmit power between rotational machine elements. The life of a belt drive in all applications depends critically on the tension in the belt spans and the extent of belt creep on the pulley. Torque transmission between pulleys is affected by the stretching and slipping of the belt. Even in a belt drive transmitting a constant torque between machine shafts, the translating belt is subject to cyclic belt tension variations. Its tension changes from a larger to a smaller tension on the driver pulley, and then from a smaller to a larger tension on each driven pulley, before returning again to the driver pulley. During tension changes, the belt is subjected to sliding wear as the belt creeps against the pulley, resulting in belt fatigue and subsequent creep and loss of compliance. In a fiber manufacturing process, polymeric fibers are drawn between feed and take-up rollers. Stretching and slipping of the fibers on the drawing roller is very similar to the behavior of belts on pulleys. In Bechtel [6], the belts are treated as linear elastic coupling elements between a driving and a driven pulley. This represents a very similar system to that of a yarn wound around a driving godet and an idler roller (Fig.10). The cases of a Hotbox, and also of two consequent godets running at the same speed in the drawing process of monofilaments (Fig.7, Fig.19), are also very similar; the only difference is that in both cases all godets are driven, there are no non-driven godets in the system. Adopting the Euler formula, the equations for mass conservation and for momentum in tangential and normal directions of belt motion can be set up. The angles on the driving and driven pulley, where the belt may slip can mathematically be expressed in a function of given parameters, as: the Coulomb friction coefficient
between the belt and the pulley, the initial belt tension, the belt stiffness, the driving pulley angular velocity, and the transmitted moment.

Unlike Amijima [40] [41], the equations in Bechtel [6] account also for centrifugal acceleration and the effect of stretching inertia in the belt.

At lower stiffness of the belt (like in the case of textile fibers) and higher speed, the centrifugal acceleration and the stretching inertia become more and more important.

These extended equations of motion are then applied in a subsequent work of Bechtel [1] on modeling the drawing of filaments in an isothermal process. A complete theory characterizing the behavior of a moving, stretching fiber tow on feed and take-up rollers is presented.

The fiber tow is here characterized as elastic-plastic, i.e. the increment $dT$ of tensile force in a fiber at a certain point depends proportionally on the axial tow strain $\varepsilon$ and strain increment $d\varepsilon$ at that point:

$$dT = k(\varepsilon)d\varepsilon$$

Eq. 11

The full solution, accounting for both centrifugal acceleration and stretching inertia of the fiber is compared with the quasistatic simplified solution where these two effects are neglected. The conclusion is that the approximate solution always underestimates the fiber tension increase and thus the amount of draw.

A further work of Bechtel [8] studies and models a two-stage filament fiber draw process. Three rollers at specific constant angular velocities, each faster than the other, draw fiber tow in a sequence of two stages.

Starting from the same equations for conservation of mass and momentum [1] a theoretical framework to predict the thermo-mechanical behavior of the fibers during drawing is then presented.

In the cited work, the fiber tow is characterized as thermoelastic-plastic, i.e. the increment $dT$ of tensile force in the fiber at a point depends not only on the axial tow strain $\varepsilon$, and strain increment $d\varepsilon$, but also on the temperature $\theta$ at that point. The tension of the fiber tow can then be written as a function of strain and temperature.

Distinguished by the temperature profile, three different two-stage draw processes are calculated. In each case, the fiber speed and the tension are computed throughout the drawline.
The outcome of this analysis of Bechtel is the velocity and tension at any point along the length of the yarn, and the forces acting from the rollers on the yarn for specific drawing conditions.

The micro-structure developed in the fiber during the drawing process is mainly responsible for the final fiber properties. As yarn velocity and tension profile are altered, vastly different micro-structure in the fiber may result.

The limitations of the model presented by Bechtel are the pre-assumption of constant speed and torque of the feed and take-up rollers. This is justified when the drawing rollers are characterized by extremely large inertia and their speed is considered as constant.

When instead, small and light godets driven by individual motors are used, the dynamic behavior of the motor-godet system becomes also very important.

Small differences in the angular velocity of the feed and take-up rollers impact the tension of the yarn, but the yarn itself also affects the behavior of the godet drive, by its inherent compliance in rotation.

### 3.1.2 Models of dynamic behavior of electric motors

Electric motors are subject to non-linear dynamic behavior, and in some cases develop irregularities in torque and speed.

These characteristics affect the dynamic behavior of the load directly applied to the motor shaft and thus lead to inappropriate system operations.

Various books have been published with models and analyses of the dynamic behavior of almost all types of common electric motors. [28] [29] [30] [34] [52] [66] [67] [68] [69]

The interest for high speed motors together with the goals of removing the mechanical gears and reducing motor dimensions have induced the focus on dynamic behavior for high speed operation motors.

At the other side, in order to reduce the costs of the drive, continuous research has concentrated on the elimination of the speed sensor on the machine shaft without however deteriorating dynamic performance of the drive control system.

Induction motors, as already described, are today the most widely used A.C. machines due to the advantageous mix of cost, reliability, and performance.

Studies on the dynamic behavior started already almost 30 years ago and since then many models and publications have been produced.
Even though cage induction motors are described by fifth-order equations in transient stability studies, induction motors are normally represented either by a third-order model which neglects the stator transients, or by a first-order model which ignores both stator and rotor dynamics. [52]

In Xu [50] a singularly perturbed model of the effects of frequency changes on induction motor dynamics is presented.

Starting from fifth-order model equations of single cage induction motors, a linear system using singular perturbations is derived for both stator and rotor dynamics. Time domain simulations using the approximated model are then performed and good agreements with the full model are demonstrated. [50]

Torque control in induction motors can be achieved by various techniques ranging from the inexpensive constant voltage/frequency ratio method to the sophisticated field-oriented control (FOC).

If a precise and fast torque and flux control is required, FOC is mandatory. In fact, only by controlling both components of the stator current, in phase and in quadrature with the rotor flux, it is possible to decouple the control of torque and flux, obtaining high dynamic performance comparable with that of D.C. and brushless drives.

The operation of speed controlled A.C. drives without mechanical speed or position sensors requires thus the estimation of internal state variables of the machine. This is generally based on measured terminal voltages and currents. [28]

High performance systems rely on dynamic models for the estimation of the magnitude and spatial orientation of magnetic flux waves in the stator or in the rotor.

Speed estimation is an issue of particular interest with induction motors, where the mechanical speed of the rotor is generally different from the speed of the revolving magnetic field.

Pioneering work in sensorless vector control was contributed by Jötten [47]. His concept uses an estimated back emf vector as the key signal from which the stator voltage reference and an estimated rotor frequency signal are generated.

Robust estimation techniques and parameter identification by automatic set-up or by on-line tuning have the potential of reducing estimation errors.

In Etien [48], a non-linear control of squirrel induction motors is designed using the sliding mode theory. The developed approach leads to the design of a sliding mode controller in order to linearize the behavior of an induction motor. To take account of
parametric variations, a model-based approach is used to improve the robustness of the control algorithm despite perturbations.

In the field of A.C. drives, synchronous reluctance motors are becoming increasingly popular.

In Vagati [54] the synchronous reluctance motor drive is presented and described in detail. The obtainable performance in terms of torque-per-volume, control, and costs are then compared to that of A.C. brushless and induction motors.

In Fratta [55] an analysis on the dynamic behavior of synchronous reluctance motors is done. Particular attention is given to the problem of torque ripple and to the appropriate countermeasures. A mathematical model to predict the torque ripple behavior of a multiple-segment synchronous reluctance motor is presented. It can be seen that skewing, or using selected rotor windings can be adopted to reduce ripple, but a residual ripple still remains. The validity of the model is verified by comparing the measured behavior and the one predicted by the model.

In a further publication of Vagati [22], the suitability of synchronous reluctance motors for a sensorless control is presented. Using a flux observer, a sensorless drive was set up and tested. The results confirm the reasonably good dynamics achieved with a sensorless synchronous reluctance motor, placing it as a possible competitor of induction motors.

Due to their lower current requirement, lower losses, lower speed variation from no-load to full-load operations, permanent magnet (PM) motors are becoming more and more an attractive alternative to induction and synchronous reluctance motors.

Since PM motors are relatively young, the studies are still focused on the determination of the dynamic characteristics and on design optimization.

In Bianchi [35], a software tool for design of a high speed permanent magnet brushless motor is presented. Starting with the resolution of the Maxwell equations, an analytical approach to predict the air gap flux density is adopted. In a first approximation, neglecting saturation and slot opening, the typical sinusoidal distribution of the air gap flux density is found. Since the torque is computed as the interaction between the PM flux density and stator currents, and since the flux density is sinusoidal and the currents constant (using square wave current control), an oscillating torque occurs.

The typical current and torque behavior versus rotor angular position $\theta_m$ is shown in Fig. 42.
In a second publication of Bianchi [37], several different design solutions for PM motors are discussed, highlighting their advantages, drawbacks, and limits. An analytical approach and a finite element (FE) approach are adopted to determine the motor electromagnetic and mechanical quantities. Torque is then computed as the interaction between PM flux density and stator currents.

Different solutions considering slotted and slotless stator design and the use of soft magnetic composites (SMC) instead of silicon-iron (Si-Fe) laminated shells are considered.

Simulations of all design combinations, plotting the developed motor torque at different frequencies (up to 1 kHz) have denoted large differences in the behavior.

In general it can be said that high-energy magnets, such as sintered NdFeB, are to be preferred due to their higher remanence and coercive force. For the stator core, the SMC is favorable in comparison with the Fe-Si iron, especially for the higher frequencies.

The slotless configuration is presented as an interesting solution, mainly for high speed use. The advantages are essentially the limited effect of the current reaction, while the drawbacks are a lower no-load flux density and the more complex manufacturing process.

Torque ripple can also affect brushless motors even though different design and control solutions have already been found.
In Islam [57], various sources of torque ripple are first listed and then a model is
developed to study the saturation effect on torque linearity and verified by FE simulation.
The publication discusses the factors influencing the harmonic content of the induced
EMF waveform, effect of slot/pole combination, winding distribution, and magnetic
saturation. Design optimization is directed to minimize cogging torque and the harmonic
contents in the back EMF, thus reducing overall torque ripple.
This research demonstrates that saturation in the magnetic circuit is another major source
of producing torque ripples and torque nonlinearity, as the current increases. A model is
then presented to study the saturation effect on torque linearity and verified by FE
simulation.
In Song [56], a study on reducing commutation torque ripples generated in brushless D.C.
motor drives with only a single D.C. link current sensor is presented.
The proposed commutation compensation technique is based on the principle that the
current slope of the incoming and outgoing phases during the commutation can be
equalized by a proper duty-ratio control. The proposed algorithm effectively makes it
possible to equalize the mismatched commutation times of the two commutated phase
currents.
As it can be seen, the problem of rotational speed irregularities is well treated, and
solutions for a better control and performance are well developed.
However, it is difficult to find publications on the interaction between the mechanical
system connected to the motor shaft and the electrical parameters of the motor drive.

3.1.3 Models of torsional oscillations

Torsional interaction, i.e. the interplay between electrical and mechanical system, is a
very significant factor during steady-state operation. Small oscillations caused by
slightest changes in the operating status can be amplified by torsional interaction.
In Canay [10], a model of the torsional interaction and electrical damping of a
synchronous motor is presented.
The model is based on the definition of the additional torque that a synchronous motor
develops in response to small rotor oscillations. Using “complex torque coefficients”
(also known as “complex synchronizing coefficients”), a frequency response analysis of
the interaction between the electrical and the mechanical systems is studied.
The complex torque coefficient is defined as the constant of proportionality between rotor oscillations and the developed torque. The real part of this complex coefficient is considered to be the electrical spring constant while the imaginary part the electrical dampening constant.

It is shown that during the interaction and due to the negative damping of the generator (induction generator effect), the shaft of the generator tends to oscillate at its model frequencies if this motion is not counteracted by the mechanical damping of the shaft itself. It is demonstrated that these oscillations can be described with the complex torque coefficient.

In a further work of Canay [11], the phenomenon of oscillations is first analyzed in specific practical examples and then a theory is proposed. In this theory not only the relevant machine and network characteristics can be properly accounted for, but simultaneously also the shaft peculiarities. Using the complex torque theory, the electrical spring and dampening coefficients and the mechanical spring and dampening coefficients are expressed as functions of electrical/mechanical parameters.

3.1.4 Dynamic behavior of filament yarns

Inhomogeneous drawing under high deformation rates with temperature gradients results in poor fiber properties. However, in a manufacturing process it is important to use a draw process with high deformation rate in order to improve productivity. During the drawing process, new crystals are formed and redistribution of existing crystals occurs, changing yarn stiffness completely. The starting point of all studies performed in this field has been the assumption that the dynamic modulus of a fiber or yarn (group of fibers) should be defined as the initial slope of the stress-strain curve obtained with quasi-static testing. Fiber stiffness covers a scale from rubber-like limpness to glass-like stiffness. Stiffness is in fact one of the most important properties of a fiber. The chemical composition of the polymer chain of which the fiber is composed is of fundamental importance in determining the stiffness scale. Classical physics describes this scale in terms of Young’s modulus of elasticity, with the qualification that it applies only to perfectly elastic materials or only to the very limited
initial portion of a stress-strain curve where a material exhibits essentially elastic behavior, as opposed to plastic flow and permanent deformation.

In testing fibers on ordinary mechanical equipment currently in use, such as the *Uster Tensorapid 3* [91], it is customary to measure the initial slope of the stress-strain curve over the first percent or two of extension and to then call this slope, measured in cN/tex, the *modulus of elasticity* of the fiber.

One of the last developed apparatus for the determination of the elastic modulus in fibers, filaments, films and other similar materials, is the *Dynamic Modulus Tester* [38] [92]. This instrument measures the velocity of sonic pulses in small cross-section materials. Recurrent longitudinal mechanical pulses are transmitted through the sample at a precise rate and simultaneously a timing circuit is turned on. The pulses are converted to electrical energy by the receive transducer, amplified, and the timing circuit is turned off. These recurrent differences between “turn-on” and “turn-off” time provide continuous elapse time readings as a function of distance along the sample.

The alternative to standing-wave systems is the technique of measuring directly the velocity of a burst of waves of known frequency along the sample, which, if the wave burst is sufficiently short, indicates the velocity of a single stress pulse.

The fundamental equation connecting Young modulus with the velocity of propagation of the stress pulse in a solid body is:

\[
v = \sqrt{\frac{E}{\rho}} \tag{Eq.12}
\]

where

\[v = \text{propagation velocity of the stress pulse [m/s]};\]
\[E = \text{Young modulus [N/m}^2]\];
\[\rho = \text{density of the material [Kg/m}^3]\].

For yarns, this equation is normally written:

\[
v = \sqrt{\frac{M}{F}} \tag{Eq.13}
\]

where

\[v = \text{propagation velocity of the stress pulse [m/s]};\]
\[M [N] = \text{modulus of the yarn};\]
\[F [Kg/m] = \text{yarn fineness}.\]
The “specific dynamic modulus” $E_c$ is calculated starting from $E$ (dynamic modulus) and then dividing it by the linear density of the material considered. It can be noted that

$$E_c = \frac{E}{\rho} \quad \text{Eq. 14}$$

but since

$$E = \rho v^2 \quad \text{Eq. 15}$$

the relationship reduces to $E_c = \frac{v^2}{\rho}$, $\rho$ being the linear density of the fiber, or count of the yarn.

In conclusion, the final equation reads as follows:

$$E_c \left[ \frac{N}{tex} \right] = v^2 \left[ \frac{km^2}{s^2} \right] \quad \text{Eq. 16}$$

There are different techniques used up to now, with the frequency ranges involved in such methods, for the determination of Young’s modulus under dynamic conditions:

1-5 Hz Conventional low speed measurement of stress-strain diagram
2-40 Hz Free vibration of probe mass and yarn
1-300 Hz Forced resonant vibration of probe mass and yarn

Besides the Dynamic Modulus Tester and the Uster Tensorapid 3, a new instrument the SWaTT (Shock Wave Transmission Tester) [38] has been recently developed and used at the Institute for Manufacturing Automation of the ETH in Zurich.

The measuring method uses the principle of traveling wave and consists of impinging a yarn sample with a longitudinal excitation that causes a longitudinal strain wave to travel along the sample.

![Fig. 43: Speed measurement of the longitudinal strain wave with the SWaTT [38].](image-url)
By measuring the time between the impact on the yarn (first receiving unit) and the second point (second receiving unit) it is possible to calculate the longitudinal speed and thus using Eq.16, the specific dynamic modulus.

In Maccabruni [38], various tests were carried out with the SWaTT on different yarns, and the results have been then compared with the Uster Tensorapid and the Dynamic Modulus Tester. In same samples, good agreement was found, but in others it can be seen that the SWaTT represents more accurate measuring system.

Particularly interesting is the comparison of the dynamic modulus of the same yarn drawn at different draw ratios. It can be seen that the dynamic modulus of an FDY yarn with drawing ration of 1.8 is about 6 times greater then the same yarn in a POY state (Fig.44).

![Dynamic Modulus [cN/tex]](image)

*Fig. 44: Values of the dynamic modulus as a function of the draw ratio as calculated from SWaTT. [38]*

Salem [45] investigates the influence of uniaxial draw strain on crystallization in PET films, under both constant extension rate and constant strain rate conditions. He found that decreasing the strain rate shifts the onset of crystallization to higher draw ratios and reduces the rate at which crystallinity increases with draw ratio, an effect that becomes more pronounced as draw temperature increases.
3.2 SYSTEM ANALYSIS AND IDENTIFICATION

The study of previous works has shown that the research on the dynamics of filaments drawing was limited to the study of the slipping of a yarn being processed on rollers, using the similarity with the theory of the transmission in belt-pulley systems.

This theory is valid as far as the rotational speed of the roller can be considered constant. Since the studies on the dynamics of common electric motors show that there is always an inaccuracy in the speed control and even that some kind of electric motors develop rotational oscillations, it is important at this point to define and then to quantify the actors that contribute to the dynamics of drawing godets.

Following the theory of Canay of torsional oscillations in electrical generators (Subpar. 3.1.3), particularly attention has been put on the interaction between the electrical and the mechanical systems.

The goal of the model is first to identify the actors involved in the drawing process and then with the model to study the dynamic behavior and the stability of the speed control loop by different godets, electric motors, controllers, and yarns.

In this work the Gray Box analysis is followed. The Gray Box [71] method consists in splitting up the system into smaller interactive subsystems, and studying them either by direct physical investigation, or as a Black Box. In the Black Box proceeding, the system/subsystem behavior is identified by analyzing the output of the system in a function of inputs.

3.2.1 Model chosen as hypothesis

In order to better understand the mechatronic model, some definitions, preliminary concepts, and hypotheses are now introduced.

The drawing, as already explained in Paragraph. 2.2, occurs between two machine elements, typically rollers or godets, rotating at different speed, pulling on the yarn.

As a reference system in order to build up the model, the case of the Hotbox is taken. The same model and the same derived equations can then be applied to the other type of godets: for monofilaments and godets with transfer roll.
In the case of a machine using Hotboxes, like the FasTex.EDU (Paragraph 2.2.3), the drawing occurs between two consecutive Hotboxes. Since those Hotboxes are all identical, the system that is going to be analyzed and studied in this work is that made of a single Hotbox.

The actors of this dynamic system are as following defined.

In the stationary state there is a yarn entering the Hotbox, called *yarn in* (Fig.45), with a given speed, a given tension, a given temperature, and a given modulus (Par.3.2.2).

The yarn in its path inside the box laps for several times around the two godets, *yarn lapping*. The number of laps $N$ is given in dependence on process parameters, i.e. the yarn fineness, the yarn speed ($v$), the temperature of the Hotbox, and the draw ratio.

![Fig. 45: Schematics of the godet duos.](image)

Each godet in the Hotbox is defined by a given geometry and a given mass, resulting in a given inertia $J$.

As also described in Paragraph 2.2.4, each godet is driven by an individual electric motor. The motor, depending on its specifications, develops a given torque $M$ at a given speed $\omega$ and is characterized by a given speed accuracy and dynamic behavior. The moving part of the electric motor, called the rotor, is directly coupled with the godet shaft, so that the speed of the electric motor defines also the speed of the godet. The rotor of the motor is also defined with its inertia $J_r$.

After the yarn laps around the godets, it exits the Hotbox with a given speed, a given tension, a given temperature, and a given modulus (*yarn out*).
Fig. 46: Yarn speed behavior along its path. Before entering the Hotbox \((v_{yarn\ in})\), during the lapping around the godets \((v_{yarn\ lapping})\), where the yarn reaches the godet speed, and after leaving the Hotbox \((v_{yarn\ out})\).

A first assumption is to consider the yarn moving at the same speed as the surface of the godet, without slip. In reality, not only the yarn could slip continuously on the godet but, since the tension of the yarn is mostly irregular, the rotational speed of the godets as well, and the friction not constant (change in the yarn temperature), the so called “stick-slip” effect may also happen.

On this assumption of no slip, the tension of the part of the yarn between two consecutive godets is thus defined by the relative motion of the two godets.

The effects of the yarn coming into the box and exiting the box are considered as external factors of the system. Since the tension and the other characteristics (temperature, Young’s modulus) of the yarn in and yarn out are also impacted by other processes and components, the model in this work analyzes only the dynamics of the system restricted to two godets connecting the yarn lapping around them.

The alternative design of drawing godet made of a driven godet and a transfer roll is a very similar case of that of a Hotbox. There is a yarn coming into the system, lapping around the godet and the transfer roll. The difference is in the transfer roll that is not driven, and that does not supply any torque, and in the diameters of the godet and the transfer roll being different.
The case of two sequential godets for monofilament plants (Subpar. 2.2.1) is also very similar to the Hotbox. In monofilament extrusion lines, all the godets are individually driven and thus supplying torque. There is a multitude of monofilaments being processed in parallel on the same godets, and each monofilament is lapping for less than one turn around each godet. So that, instead of having a yarn lapping several times around the godets (case of the Hotbox and godet with transfer roll), there is a multitude of yarns in parallel, lapping for less than one turn on each roll.
3.2.2 Yarn as an elastic coupling element

The term “elasticity” is normally used to refer to the properties of a material to return spontaneously to its former size, shape, or form, after being strained; whereas “resilience” connotes the amount of mechanical energy stored in a stressed system. In the case of material that is not ideally elastic, as in the case of a yarn, there are three components of deformation: the immediate elastic deformation, primary creep, and secondary creep. The function of stress versus strain is the sum of these three components. The strain is not constant with time. In this case, there exists an initial elastic strain proportional to the load, followed by a delayed creep at a decreasing rate with time. The recovery is not complete and the material does not return to its original unloaded length. This failure to return is a function of the magnitude of secondary creep manifested by the material. [17]

The stress-strain diagram is not linear since the delayed components affect its shape; hence it is important to consider the shape of the diagram in determining the behavior of non-linear materials such as textile fibers and other textile structures.

The typical stress-strain curves obtained experimentally from textile fibers and structures show the superposition of the effects of all three strain components (Fig.49).

![Fig.49: Typical stress-strain curve of POY polyester multifilament yarn. [17]](image)

However, if the linear initial part of a stress-strain curve is regarded, the material exhibits essentially an elastic behavior.

A Young’s modulus of elasticity can be defined for this part, which in textile is expressed in cN/tex, related to the mass per length of the fiber.

In the Hotbox, the two godets are supposed to rotate at the same nominal speed.
In the hypothesis of no slip on the godets, the part of the yarn lapping, which is strained between the two godets, is strained only in the case of a different rotational speed of the two godets. Since the difference of the rotational speeds is limited to some percent it follows that also the strain is in this range.

The part of the yarn strained between the two godets can thus be considered to have an elastic behavior with a given modulus of elasticity.

As a belt used in a mechanical transmission, the yarn represents here a coupling element between the two godets.

3.2.3 Moment of inertia of the rotating parts

Inertia relates to the conservation of linear momentum or the conservation of angular momentum of a rotating object and describes how much force or torque is needed to accelerate the object at a given rate.

In general, an object's moment of inertia depends on its shape and the distribution of mass within that shape: the greater the concentration of material away from the object's centroid, the larger the moment of inertia. It also varies depending upon the axis of rotation.

In the Hotbox, but also in all the individually driven godets, the rotating elements are the godets and the rotors of the motors.

The shape and the mass of the godet together with those of the rotor define the moment of inertia of the rotating parts.

As described in subparagraph 2.2.1, there is a range of sizes of godets available on the market; each of them is characterized then by a moment of inertia.

The formula to calculate the moment of inertia of a continuous mass distribution requires an infinite sum over all the point mass moments which make up the whole. This is accomplished by integrating all the masses $dm$ over all three-dimensional space involved.

$$J = \int \! dm \, dV$$  \hspace{1cm} \text{Eq.17}

where

$J =$ inertia

$dm =$ mass element

$dV =$ volume element
The inertia of complicate shapes is calculated by splitting it into standard shapes and summing up the inertia of the known standard shapes.

With some approximations, the moment of inertia of the godet-rotor can be calculated as a sum of the moment of inertia of a full cylinder (the rotor of the motor), a thick cylinder with open ends (the godet) and a thin disk (the godet cover).

\[
J_{\text{godet-rotor}} = J_{\text{cylinder}} + J_{\text{thick-cylinder}} + J_{\text{disk}} \quad \text{Eq. 18}
\]

where:

\[
J_{\text{cylinder}} = \frac{1}{2}Mr^2 \quad \text{Eq. 19}
\]

\[
J_{\text{thick-cylinder}} = \frac{1}{2}M(r_1^2 + r_2^2) \quad \text{Eq. 20}
\]

\[
J_{\text{disk}} = \frac{1}{2}Mr^2 \quad \text{Eq. 21}
\]

where:

- \( r \) = radius of the cylinder or of the disk.
- \( r_1, r_2 \) = internal and external radius of the thick cylinder with open ends.
- \( M \) = mass.

Standard godets due to their internal heating are much bigger than the godets used in the Hotbox. Furthermore, standard godets are made of tempered steel while the godet of the Hotbox is made of aluminum.

Using small and light godets, with a lower inertia, gives the chance to use smaller and thus cheaper drivers. On the other hand, a lower mass system is much more sensitive to external forces.

It becomes so more and more important to study the effect of the yarn on the godet-drive system.

<table>
<thead>
<tr>
<th>Diameter [mm]</th>
<th>Inertia [Kgmm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Godet</td>
<td>60</td>
</tr>
<tr>
<td>Small heated godet</td>
<td>100</td>
</tr>
<tr>
<td>Big heated godet</td>
<td>230</td>
</tr>
</tbody>
</table>

Table 2: Calculated inertia for three different designs of individually driven godets. The shown values include the inertia of the motors.
3.2.4 Mass-spring-damper analysis

The model used in this work is a stationary representation of a godet drive. All the actors of the system are dynamically modeled and then analyzed by using mass-spring-dampering elements. The analysis technique is restricted to the stationary case of individually driven godets and, with some adjustments; it can be applied to the godet-transfer roll system. The yarn lapping around two godets, the two godet rotors, the electric motors, and the motor drives are the elements that constitute the model. With the proper transformations of all the parameters, the model can be made either in a linear motion representation or in a rotational motion representation.

As stated in Subpar. 3.2.2, the yarn between the godets is considered a fully elastic element with a given dynamic modulus $K_{\text{yarn}}$. The dynamic function of the yarn is to couple the movements of the two godet rotors.

The godet rotor mass is calculated as a single rotating element with its inertia $J_{\text{godet rotor}}$. In a stationary analysis (Par. 2.3.6), electric motors can be considered as spring-damper with the spring constant $K_{\text{motor}}$ and the dampening constant $D_{\text{motor}}$. The voltage controller, characterized by a much lower time constant than the mechanical element dynamics, is also considered as a spring-damper element but with a negligible mass.

It follows that the complete system is characterized by the following subsystems:

- The yarn as a spring (defined by the dynamic modulus).
- The rotor-godet as a rotating mass (defined by the moment of inertia).
- The spring-dampening of the electric motor (defined by the stationary behavior).
- The spring-dampening of the drive of the electric motor (defined by the control set up).
The electromagnetic interaction between the stator and the rotor magnetic fields is a subsystem in the definition of the dynamic behavior of the rotor-godets. An observer rotating at the speed of the magnetic field of the stator of a motor would see, on an asynchronous motor, the rotor rotating with a given slip, without oscillations. On a synchronous motor, the observer would see essentially stationary rotor with oscillations. In fact, the real behavior of the synchronous rotor is characterized by the typical rotor angle movement around the mean value $\theta_0$ between $\theta_0-\epsilon$ and $\theta_0+\epsilon$ with relative frequency $\lambda$.

The spring-damper model proposed in this work corresponds to the relative behavior and interaction between stator and rotor in a stationary state. With the use of spring-damper elements, the oscillations of the synchronous motors are first measured and analyzed, and then used to simulate such motors godet for the Hotbox.
4. EXPERIMENTS: STATIC AND FREE OSCILLATION TESTS

This chapter deals with the description of the experiments performed on different type of motors and godet systems with the aim of finding out the important parameters of their dynamic behavior.

The first paragraph describes the motors chosen for the experiments, the innovative measuring techniques adopted, and the stationary stator magnetic field. A differentiation of the experiment proceeding has been necessary for the synchronous and asynchronous motors developed for the Hotbox.

In paragraph 4.2 the spring and dampening behavior of these motors is quantified with calculations using the results of the experiments.

In the end of the chapter, paragraph 4.3 shows the summary of the results obtained from the experiments discussing the synchronous and the asynchronous behavior of the analyzed motors.

4.1 SET-UP OF THE EXPERIMENTS

One of the targets of the experiments is to confirm the theoretical analysis of spring damper behavior of motors and to define the spring and the dampening constant.

Four different types of experiments with four different measuring processes and two different measuring principles characterize the experiment campaign.

- static torque measurements on permanent magnet synchronous motors, to calculate the spring constants;
- measurements of free torsional oscillations on permanent magnet synchronous motors, to calculate dampening constants;
- measurements of rotor speed under constant load on asynchronous motors, to calculate the dampening constant on asynchronous motors;
The analysis is done on motors principally developed for the drive of the Hotbox. The static conditions are created with a static stator magnetic field. Such magnetic field is generated by supplying D.C. current to one of the three phases of the stator. The speed of the rotor is then measured with a tacho generator directly coupled to the rotor shaft.

4.1.1 Objects of the investigation

Dynamic properties of different synchronous and asynchronous motor designs are investigated.

Two permanent magnet synchronous motors and an induction asynchronous motor are investigated.

While the permanent magnet synchronous motors have been developed at the ETH, the asynchronous is taken from an existing machine.

A three phase ABB/Hitachi slotted stator, originally made for an induction (squirrel cage) rotor, is further used with 2 different designs of permanent magnet rotors.

The original asynchronous motor is a prototype of the drive of individually driven spindles of a ring-spinning machine. Its nominal power at 25000 rpm is about 200 W.

Each of the three stator phases is made of 183 windings of 0.335 mm diameter (section 0.87 mm²) and is connected to the others by a Y (star) connection.

![Windings Slots Slots teeth Stator windings Stator laminations](image_url)

*Fig. 51: The stator chosen for the experiments: Asea Brown Boveri ZS/MAS TYP 368 SER.-NR. 8809211070.*
By changing the mechanical design, the rotor of this motor is adjusted to be used with a godet of the Hotbox. The induction asynchronous rotor is a typical squirrel cage rotor used in the ABB/Hitachi original motor but with a new shaft in order to fix the godet.

![Diagram of rotor and godet](image)

**Fig. 52: The design and the construction of the induction asynchronous rotor.**

The two permanent magnet rotors, used for the construction of the further two motors, have been developed and constructed in different Semester and Diploma works done at the ETH. [59] [60] [61]

The first of these two rotors is a 2 pole permanent magnet rotor, and the second is very similar to the first but with an additional damper winding. The magnets used, are standard parallelepiped NdFeB magnets, distributed by the company Maurer Magnetic AG (Maurer Magnetic AG, Industriestrasse 8, CH-8627 Grüningen).

The design of the second rotor includes a copper wire with a diameter of 1 mm between each set of magnets. These wires are shorted together by two rings (Fig. 53).
Fig. 53: Design and construction of the permanent magnet rotor with damper winding.

The differences of the dynamic parameters (spring and dampening) between the asynchronous motor, the synchronous permanent magnet motor, and the synchronous permanent magnet motor with damper winding, are tested with a stationary stator supply. Each of the three designs of rotors, the synchronous P.M. rotors with and without damper winding, and the asynchronous induction rotor are separately mounted with two ball bearings into the three phase ABB/Hitachi slotted stator of Figure 51. The whole motor is then fixed on the frame of the FasTex.EDU in its operating position.

Fig. 54: The mounting of the stator and rotor on the Hotbox plate.
4.1.2 Tacho speed measurement

For the first type of experiments, a new method using a motor as a tacho generator is developed and used.

A small Maxon DC motor with precious metal brushes (Maxon RE 6, 0.3 Watt) is directly clamped to the rotor shafts of the motors (Fig. 55) [82]. This motor is then used as a generator supplying a voltage proportional to the rotor speed. The rotor of the tacho with a diameter $\Phi = 3\text{mm}$ is assumed not to influence the dynamic of the rotor.

![Diagram of tacho speed measurement](image)

*Fig. 55: Permanent magnet rotor connected to the rotor of the Maxon RE 6 motor used as a generator.*

The generated voltage, proportional to the rotor speed, is then amplified and used for the rotor position measurements.

4.1.3 Signal conditioning

The analog signal generated by the tacho, proportional to the rotational speed of the rotor, is then filtered, amplified, and transformed by a circuit board. The generated voltage by the tacho is proportional to the rotating speed and follows the Faraday’s Law:

$$U = (v \times B) \cdot l$$

Eq.22
where

\[ U = \text{generated voltage} \]
\[ V = \text{rotor rotational speed} \]
\[ B = \text{permanent magnet field of the tacho} \]
\[ l = \text{length of the wire moving in the magnetic field}. \]

For a better read out of the voltage, this is filtered and amplified by a circuit board and in order to have a measurement of the rotor position, the speed signal is integrated over the time.

![Fig. 56: Picture of the circuit board for the tacho signal conditioning.](image)

A signal buffering is used as low pass filter of 1 ms, to clear the signal from noise at higher frequencies.

After the filter, the signal is amplified by an operational amplifier and used as speed measurements.

![Fig. 57: Schematic diagram of the signal conditioning board.](image)
For the speed measuring, the output of the tacho is filtered and amplified by the conditioning board with a resulting output of 0.018455 V s/rad.

For the position measuring, after the filtering and the integration of the tacho signal, the output is 0.03 V/° (1.7186 V/rad).

![Circuit diagram of the signal conditioning board.](image)

In the circuit board, a high gain operational amplifier of the series LM 324 is used. The board is built with connectors to facilitate the voltage supply and the read out.

The output signals of speed and position are individually displayed by dedicated channels of a digital oscilloscope.

The calibration of the speed signal has been made with an inverter. By supplying the synchronous motor with a voltage at known frequencies, the output signal referring to the rotor speed is measured. Doing this for different frequencies, the calibration curve is found.

The calibration of the signal referring to the position is made with a scale drawn in CAD and applied on the front of the godet. On the machine frame, where the godet with the motor are mounted for the test, a horizontal line as a reference point is drawn. Without supplying any voltage to the motor, the godet is rotated by an angle that is read out from the scale.
4.1.4 Power supply for stationary tests

By supplying D.C. current to one phase of the stator of the motor, the stationary behavior of the motor is investigated.

A D.C. stator supply creates a magnetic field with a rotational frequency of 0 Hz.

![Diagram of D.C. stator supply](image)

*Fig. 59: The D.C. stator supply.*

By a non-moving rotor, this is considered a still image of a steady-state. From this state, each rotor movement is assumed as displacement from the steady-state. These displacements are in position and speed. The movements are in general defined as super or sub-synchronous oscillations.

The amplitude of the current supplied to the phase of the stator is supposed to be that at steady-state. Even though the insulation class of this motor is a class F, it is typical to use this motor as a class B motor.

The value of the steady state current is thus established following the standard EN61558-1 for winding insulation of class B. The standard for this insulation states a temperature limit of 90°C. [95] From this maximum temperature \(\theta=90°C\), the maximum resistance is calculated as following:

\[
R_{90} = R_{20} \left[1 + \alpha_{20}(\theta - 20^\circ)\right] \quad \text{Eq.23}
\]

with \(\alpha_{20} = 0.004\) and \(R_{20}=32.54 \Omega\) (resistance measured at 20°C), the maximum resistance is:

\[
R_{90} = 41.65 \Omega.
\]
Different measurements of the phase resistance rise (Annex 1) have shown that with a current of 0.65A the resistance grows to a maximum of about 41.5 Ω (Fig. 60).

![Fig. 60: Diagram of the measured stator resistance with a phase current of 0.65 A (the table of the measured values is in Annex 1).](image)

The test should reproduce the static (not rotating stator magnetic field) steady state condition.

For both tests, one of the three phases of the stator is then connected to a DC power supply with direct current of 0.65 A, as illustrated in Fig. 61.

![Fig. 61: Three phase connection and D.C. supply during the experiments.](image)
4.2 RESULTS OF THE EXPERIMENTS

4.2.1 Static torque measurement on permanent magnet synchronous motors

With these tests, the spring constant of the synchronous motor is calculated from the diagram of the torque versus rotor position. The position measurements are made with the amplified and integrated signal of the D.C. tacho.

By supplying D.C. current to one phase of the stator windings, the rotor rotates to a position where it performs no torque. For all the tests, this point is taken for zero angle reference.

By hanging a given weight \( P \) through a rope glued on the surface of the godet, a known loading torque \( T \), proportional to the weight, is applied to the rotor shaft.

\[ T = P \cdot r \]  

Eq.24

where \( r \) is the godet radius.

The torque \( T \) moves the rotor that opposes an electromechanical torque. The torque supplied by the motor increases as the rotor angle increases. At a certain point the motor torque counterbalances the loading torque. By measuring the rotation at the point of balance, a first point of the diagram torque versus rotor rotation is found.

Changing the weight applied to the godet, new balances at different rotor rotations are found. The diagram of all measured points is displaced in figure 62.
Table 3: Measured balanced points between an external load (applied weight) and the generated torque of motor 1 (function of the relative rotor rotation $\Delta \theta$. The applied weight [g] is also expressed in torque [Nm].

<table>
<thead>
<tr>
<th>Measured Points</th>
<th>Measured rotor relative position $\Delta \theta$ [°]</th>
<th>Applied weight [g]</th>
<th>Applied torque [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>5.666661</td>
<td>150</td>
<td>0.044145</td>
</tr>
<tr>
<td>2</td>
<td>7.999989</td>
<td>210</td>
<td>0.061803</td>
</tr>
<tr>
<td>3</td>
<td>9.333322</td>
<td>270</td>
<td>0.079461</td>
</tr>
<tr>
<td>4</td>
<td>11.4999875</td>
<td>130</td>
<td>0.038259</td>
</tr>
<tr>
<td>5</td>
<td>11.83332</td>
<td>165</td>
<td>0.048559</td>
</tr>
<tr>
<td>6</td>
<td>12.033316</td>
<td>120</td>
<td>0.035316</td>
</tr>
<tr>
<td>7</td>
<td>12.666646</td>
<td>155</td>
<td>0.0456165</td>
</tr>
<tr>
<td>8</td>
<td>19.099968</td>
<td>265</td>
<td>0.0779895</td>
</tr>
<tr>
<td>9</td>
<td>19.6333</td>
<td>290</td>
<td>0.085347</td>
</tr>
<tr>
<td>10</td>
<td>20.799965</td>
<td>270</td>
<td>0.079461</td>
</tr>
<tr>
<td>11</td>
<td>32.999945</td>
<td>265</td>
<td>0.0779895</td>
</tr>
<tr>
<td>12</td>
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<tr>
<td>13</td>
<td>36.66656</td>
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<td>0.11772</td>
</tr>
<tr>
<td>14</td>
<td>58.66655</td>
<td>470</td>
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<td>15</td>
<td>88.33321</td>
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<tr>
<td>16</td>
<td>107.999875</td>
<td>405</td>
<td>0.1191915</td>
</tr>
</tbody>
</table>

Fig.62: The motor torque versus relative rotor angle ($\Delta \theta$ is the rotor relative rotation related to the 0 angle position).
In certain points, the balance between the external torque and the motor torque is almost impossible to find. As it can be seen in the following diagram, there are some ranges where no balance is found.

Due to this sudden change in the motor torque, the searching of the balance requires more than one minute for each different applied weight. The integrated taco signal, coming from the amplification board, is after one minute back to zero voltage. It is because of this that the right rotor position is measured by turning back the rotor from the balance to the zero angle position.

If a connecting curve of some filtered values is drawn, the sinusoidal theoretical behavior of the torque is recognized (Fig.63). However, the connecting curve differs considerably in some points from the theoretical one.

![Graph showing comparison of measured and theoretical torque](image)

*Fig.63: Comparison of the measured and theoretical torque.*

The cause of this highly non linear course (theoretically a sinus) of the torque is caused by the interaction between the permanent magnetic field of the rotor and the iron slots of the stator. These drops in the motor torque are also called torque ripples (Fig.64)
A linearly dependence of the torque on the relative position of the rotor is thus assumed only in some ranges of the diagram. If the initial part of the diagram is taken (up to $\Delta \theta = 10^\circ$), the electromechanical torque $T_s$ shows a mostly linear behavior.

$$T_s = K_s \cdot \Delta \theta$$  \hspace{1cm} Eq.25

where

$T_s =$ generated torque

$K_s =$ spring constant [Nm/rad]

$\Delta \theta =$ rotor relative rotation in [rad]

<table>
<thead>
<tr>
<th>Measured rotor relative position $\Delta \theta$ [°]</th>
<th>Measured rotor relative position $\Delta \theta$ [rad]</th>
<th>Applied torque [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5.666661</td>
<td>0.098860101</td>
<td>0.044145</td>
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<td>7.999989</td>
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</tr>
<tr>
<td>9.333322</td>
<td>0.162828367</td>
<td>0.079461</td>
</tr>
</tbody>
</table>

Table 4: Measured rotor relative position values up to $10^\circ$. The rotor relative positions are reported also in rad.
Fig. 65: Linearization of the initial part of the torque vs. relative rotor position diagram. The proportional constant between the generated torque and the rotor relative position.

The value of the calculated initial constant represents the rotational spring coefficient of this motor.

With a stator supply current of 0.65 A, the calculated value of the spring constant is then: 

$$K_s = 0.465 \text{ [Nm/rad]}.$$ 

### 4.2.2 Free oscillation tests of dampening properties

Here the dampening constants of the two different designs of synchronous motor are calculated and compared. One of the aims of these tests is to quantify the dampening effect of the damper winding, by comparing the dampening coefficients of the two motors.

The tests are based on the measurements of the decay of the free oscillations. From a given initial rotation of the rotor of 90°, the rotor is released to swing back to the zero angle position. The amplitude of the oscillations of the rotor speed around the zero angle position is measured by the tacho generator. The same experiment is also made for the motor with the dampening winding (Fig.66 and Fig.67).
Fig.66: Oscillations around the zero angle position for the synchronous motor without damper winding.

The oscillations, as they are displayed on the screen of the oscilloscope, are very similar to the free oscillations of a mass connected to a spring and a dampening. Using this similarity, the decay of the oscillations is expressed by an exponential curve. Reporting the values of the measured oscillations in Excel, the exponential curves for the two motors are so reconstructed.

Fig.67: Oscillations around the zero angle position for the synchronous motor with damper winding.
The comparison of the two exponential curves of the two designs of synchronous motors shows how the motor with dampening winding has a more than two fold exponential decay (Fig.68).

The dampening coefficients of the motors are thus calculated from the coefficient of the exponential decay of the oscillations.

The typical equation of non-forced dynamics of second order systems with one degree of freedom is:

\[ J \dddot{\theta} + D \ddot{\theta} + K \theta = 0 \rightarrow \dddot{\theta} + \frac{D}{J} \ddot{\theta} + \frac{K}{J} \theta = 0 \quad \text{Eq.26} \]

where \( J \) is the moment of inertia, \( D \) the dampening coefficient, \( K \) the spring coefficient.

Substituting \( 2A = \frac{D}{J} \) and \( \omega^2 = \frac{K}{J} \), the equation becomes:

\[ \dddot{\theta} + 2A \ddot{\theta} + \omega^2 \theta = 0 \quad \text{Eq.27} \]

The solution of this equation is exactly an exponentially damped sinusoidal:

\[ \theta = e^{-\alpha t} \cdot C \cdot \cos(\omega t + \phi) \quad \text{Eq.28} \]

From the value of the exponential constant \( (A) \) calculated in Excel, the dampening coefficient are calculated as:

\[ D = 2A \cdot J \quad \text{Eq.29} \]

Using the calculated value of the moment of inertia of the rotor-godet (Subpar. 3.2.3), the dampening coefficients of the two motors are:

motor 1: \( D = 0.000624 \) [Nmsec/rad],

\[ y = 0.0139e^{-0.0091x} \]

\[ y = 0.0247e^{-0.004x} \]
motor 2: $D = 0.001404$ [Nmsec/rad].

### 4.2.3 Dampening torque measurements on the asynchronous motor

The result of the following tests is the calculation of the dampening coefficient of the asynchronous motor.

As already stated before, the combination of the Hitachi stator and the asynchronous squirrel cage rotor was the original solution for the drive of the spindles of the prototype of ring-spinning machine of Rieter.

Because of the inherent induction principle of this kind of motor, the torque is generated by the motor only in the case of a different speed between the stator magnetic field and the rotor.

The following tests are done with a stationary stator magnetic field. As in the measurements on the synchronous motors, the stator windings are connected to the D.C. power supply with a current at 0.65 A. The relative rotation of the two magnetic fields is generated by the rotation of the rotor with a static stator field.

By applying a given weight through a rope glued on the godet, the rotor is forced by a torque to rotate.

At the very beginning, no motor torque exists, since the relative speed between stator and rotor is zero. As the rotor speed increases, the opposing torque supplied by the motor increases, until a balance with the loading torque is reached and the speed is constant (steady-state speed).
Fig.70: Stationary measured speed vs. time of the godet with the asynchronous motor under a constant load of 0.017Nm (weight 60g).

By changing the load, further measurements on the speed are done and reported in table 5 and Fig.71.

<table>
<thead>
<tr>
<th>Weight [g]</th>
<th>Torque [Nm]</th>
<th>Speed [m/s]</th>
<th>Speed [rad/sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>0</td>
<td>0</td>
</tr>
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</tr>
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<td>28.06080408</td>
</tr>
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</tr>
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<td>1.111207842</td>
<td>37.04026139</td>
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<tr>
<td>250</td>
<td>0.073575</td>
<td>1.212226736</td>
<td>40.40755788</td>
</tr>
<tr>
<td>270</td>
<td>0.079461</td>
<td>1.346918596</td>
<td>44.89728653</td>
</tr>
<tr>
<td>280</td>
<td>0.082404</td>
<td>1.431101008</td>
<td>47.70336694</td>
</tr>
<tr>
<td>300</td>
<td>0.08829</td>
<td>1.548956385</td>
<td>51.63187951</td>
</tr>
<tr>
<td>320</td>
<td>0.094176</td>
<td>1.71732121</td>
<td>57.24404032</td>
</tr>
<tr>
<td>350</td>
<td>0.103005</td>
<td>1.953031964</td>
<td>65.10106547</td>
</tr>
</tbody>
</table>

Table 5: Measured speed with different weight. The weight is also expressed in torque on the godet.
Fig. 71: Load Torque vs. relative rotational speed of the asynchronous rotor.

As stated in Subpar. 2.3.5, after any change in the load, the asynchronous motor reacts with a change in the rotor speed. To a higher load torque, the motor reacts with a higher rotor slip. A typical value of the percentage slip is in the range of some percent of the rotational speed. [70]

By filament drawing using the Hotbox, the small godets rotate, depending on the positioning in the machine (first, second or third Hotbox), at a speed between 5000 and 15000 rpm (500-1500 rad/sec). The rotor slip would then be between 5 and 15 rad/sec (typical slip value of 1%).

Doing a linearization of the curve of the load torque vs. relative rotational speed in the range of 0-10 rad/sec, the dampening coefficient is found.

The very initial value of the curve is taken as a dampening coefficient for the asynchronous motor (Fig.72).
It follows that for the asynchronous motor, the dampering constant is: $D = 0.0019$ Nmsec/rad.

### 4.3 INTERPRETATION OF THE EXPERIMENTS

A first important result of the whole experiment campaign is the quantification of the real effect of the damper winding. Its expression through the dampering coefficient makes the comparison between different motor designs possible and allows further dynamic and stability analysis.

A second result is the approximated expression and description of the sub and super-synchronous torsional oscillations, through the measured spring and dampering coefficients.

The method used for the static measurements represents a very practical and simple tool to determine the dynamic characteristics of electric motors.

The following table shows the main quantitative results of the experiments. For each motor, the spring and the dampering coefficients are shown.
<table>
<thead>
<tr>
<th>Motor type</th>
<th>Spring coefficient [Nm/rad]</th>
<th>Dampening coefficient [Nmsec/rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronous PM</td>
<td>0.4</td>
<td>0.000624</td>
</tr>
<tr>
<td>Synchronous PM with dampening winding</td>
<td>0.4</td>
<td>0.001404</td>
</tr>
<tr>
<td>Asynchronous induction</td>
<td>0</td>
<td>0.0019</td>
</tr>
</tbody>
</table>

*Tab. 7: The comparison of the spring and dampening parameters of the three motors.*

The asynchronous motor, according to its induction principle, does not express any spring behavior.

Regarding the dampening coefficients, the effect of the dampening winding can be easily recognized by comparing the values of the synchronous motors. The measured dampening value of the asynchronous motor is just a little bit higher than the dampening of the permanent magnet synchronous motor with the dampening winding. This means that with a thicker dampening winding a dampening coefficient similar to that of an asynchronous motor may be reached.

Besides the quantitative results of the experiments, like the values of the spring and the dampening constants also the qualitative analysis has brought important conclusions. In the static torque measurements of permanent magnet motors, torque ripples are found. Such ripples are caused by the interaction between the magnetic field of the rotor and the slots of the stator. This leads to very bad nonlinearities in the motor behavior. In the mass-spring-damper model proposed in Par. 3.2 and used in the following chapter for simulations, the static behavior of the electric motor is described only by the spring and dampening coefficients. The torque ripple is however considered as external disturbance with a given frequency and amplitude.

By analyzing more in detail the frequency of the free oscillations of the permanent magnet motors, two different frequencies of oscillations are found. The two frequencies are associated with two different ranges of the amplitude of the oscillations.
From the diagram of the free oscillation, the two different frequencies of oscillations are measured.

With the analogy used with second-order systems, the frequency of the free oscillation is a function of the spring and of the moment of inertia of the system. Since the moment of inertia remains the same during the experiments, a change in the spring constant of the motor is assumed.

The two different spring constants ($K_1, K_2$), corresponding to the two different frequencies, are thus calculated from the same formula used for the eigenfrequencies of the reluctance motor:

$$\omega_i = \sqrt{\frac{k_i}{J}}$$

$$k_i = \omega_i^2 * J \quad \text{Eq.31}$$

From the measured periods, the calculated frequencies of oscillation and pulsations are shown together with the calculated spring constants in table 7.
<table>
<thead>
<tr>
<th></th>
<th>Period T [ms]</th>
<th>Frequency f [Hz]</th>
<th>Pulsation [rad/sec]</th>
<th>Spring constant [Nm/rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First oscillation</strong></td>
<td>200</td>
<td>6.67</td>
<td>41.9</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Second oscillation</strong></td>
<td>90</td>
<td>11.1</td>
<td>71</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 7: The two spring constants calculated from the period of oscillation through Eq.31.

The spring constant of this motor calculated with the static torque measurement, is the same as the $K_2$ calculated from the period of the free oscillation. This is a confirmation of the approximated spring constant that this motor exhibits for small rotor oscillations.

The other calculated spring constant $K_1$ is considered the spring constant of the motor at greater rotor amplitudes. In the static torque measurements, this value is found as the angular coefficient of the linearization curve of the theoretical sinusoidal behavior.

Fig.81: Calculated value of the spring constant from the theoretical sinusoidal behavior of the permanent magnet motors.

The value, as calculated from the diagram in Fig.81 is $K = 0.028 \, [\text{Nm/}^\circ] = 0.16 \, [\text{Nm/rad}]$, very close to the value of $K_1$ calculated from the period of oscillation.
5. COMPUTER SIMULATION OF DRAWING GODETS

In this chapter, simulations of the stationary behavior of the individually driven godets are carried on. The tool used is Working Model 2D, which represents a very simple, but precise computer program, specifically made for simulating the dynamic behavior of mechanical components.

After some considerations on the elements constituting the model, already presented in the previous chapters, the limitations and the tools for the simulation program are described in paragraph 5.1.

The setup of the model and the preliminary tests of the simulations in Working Model, together with the forced oscillations and resonance analysis are dealt in the paragraph 5.2.

Paragraph 5.3 accounts the mathematical foundation of the linearized model of the drawing godets. In particular, the small displacement equations of the Hotbox are found and expressed in a state-space representation.

A frequency response analysis in MATLAB is done and described in paragraph 5.4. The Bode and the step response diagrams are shown for the system using respectively the P.M. synchronous motors with and without damper winding, and for the asynchronous induction motor.

The study of the limits of stability of the different drive solutions, and the calculation of the critical dampening value of the system, is described in Paragraph 5.5.

The chapter ends by showing the dynamic of the tension of the yarn, using the different solutions for the drive of the Hotbox. The possible external factors that may force the system to the resonance are identified and described.
5.1 IDENTIFICATION AND SPECIFICATION OF DISCRETE ELEMENTS

Working Model 2D is a computer simulating software typically used to simulate mechanical systems in 2 dimensions.

The program is based on the drawing of discrete mass elements and on the connection of these by standard mechanical components like linear spring and dampening, and rotational spring and dampening. Forces, torques and other types of actuators can be introduced.

The calculation of the dynamic behavior of the drawn system is done with a time step integration algorithm. The integration basis is accessible and can be adjusted for the simulations.

The calculated position, speed, and acceleration of the masses, and the tension of the spring elements can also be plotted in diagrams versus time.

*Fig. 82: The working space in Working Model: a typical example of the simulation of the free oscillation movement of a godet.*
The system Hotbox, proposed in Chapter 3, is here modeled in 2 dimensions by using the elements available in Working Model.
The yarn lapping for several wraps around the twin-godets is modeled with two linear springs (Subpar. 5.1.1).
The godet-rotor is modeled by a disk having a diameter equal to that of the godet and a moment of inertia equal to that calculated in Subpar. 3.2.3 (Table 2) for the godet-rotor (Subpar. 5.1.2).
The electro-magnetic behavior of the electric motors for each type of the three analyzed motors (P.M. synchronous, P.M. synchronous with damper winding, and induction asynchronous) is expressed by rotational spring and dampening elements in Subpar. 5.1.3, as measured in Chapter 4 (Table 7).

5.1.1 Spring constant of the yarn

The yarn modeled in the simulation is a typical multifilament polyester yarn for the process of drawing.
A PET Multifilament 167f34, produced by DuPont is the sample yarn chosen for the simulations.
In the case of polyester POY multifilament, the calculated elastic modulus varies considerably with the drawing-ratio (Fig. 44). Since during the process of drawing, the drawing ratio is dynamically changing, it is practically impossible for a given yarn to define a unique value of the modulus of elasticity and thus the spring constant.
It is so helpful for the simulations to consider a range of values in which the drawing ratio and thus the dynamic properties of the simulated yarn vary.
The values of the modulus of elasticity of the yarn are taken from the results of the experiments made with the SWaTT (Subpar. 3.1.4) and published in Maccabrini [38]. For this yarn different tests under various conditions and states have been made. Among all the results, the most interesting for the simulations and the studies of this work are these made on the same yarn drawn by different draw-ratios. For this yarn, the minimum and the maximum values of the calculated Modulus of elasticity are taken.
The minimum and the maximum values correspond respectively to the POY yarn and to the same yarn drawn at 1.8 drawing ratio. With these two extreme values, a range of
operating conditions is defined. The calculated modulus of elasticity is given in the following table.

<table>
<thead>
<tr>
<th>Description</th>
<th>Modulus of elasticity [cN/tex]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET POY Multifilament, 167f34, fineness 29.8tex</td>
<td>262.1</td>
</tr>
<tr>
<td>PET FDY Multifilament, 167f34, draw ratio 1.8 fineness 16.9tex</td>
<td>1375.7</td>
</tr>
<tr>
<td>PET Monofilament 17f1, Diameter 0.04mm</td>
<td>700</td>
</tr>
</tbody>
</table>

Table 8: The modulus of elasticity of a PET Multifilament 167f34 before and after being drawn, and of a PET monofilament.

As an additional information and for comparison, in the table it is also included the modulus of elasticity of a sample of polyester PET monofilament. Since its modulus is in the range defined by the other two values, for the simulations it is not considered. In order to obtain a modulus of elasticity in [N/m], as requested by the specification of a linear spring element in Working Model, the following calculation has to be done:

\[
\text{Modulus of elasticity [cN/tex]} \times \frac{\text{fineness [tex]}}{\text{yarn length [m]} \times 100} = \text{spring constant [N/m]}
\]

Eq.32

Fig. 83: A front view of the portion of the yarn connecting the two godets. The yarn is considered an elastic coupling between the axes of the two godets.
The length of the lapping yarn is considered to be only the two portions of the yarn between the two godets, named *yarn between* (Fig.83). These portions of yarn are these that couple the axis of the godets. The other portions of the yarn in contact with the surface of the godets are supposed to move rigidly with them without slip. Under this hypothesis, these portions, named *yarn in contact*, do not have any effect on the dynamic of the godets, so that they are neglected.

For the Hotbox, the portion of the yarn between the two godets is 0.15 m, so that the spring coefficient is calculated as in Table 9.

<table>
<thead>
<tr>
<th>Type of yarn</th>
<th>Spring constant [N/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET POY Multifilament, 167f34, fineness 29.8tex</td>
<td>520.7</td>
</tr>
<tr>
<td>PET FDY Multifilament, 167f34, draw ratio 1.8 fineness 16.9tex</td>
<td>1550</td>
</tr>
</tbody>
</table>

Table 9: *Spring constant of a PET POY Multifilament 167f34 and of a PET FDY Multifilament, 167f34, calculated with the Eq.32.*

For a typical drawing process of a PET multifilament yarn with a fineness of 167dtex the number of wraps around the two godets vary between 2 and a maximum of 7 wraps. The exact value is defined only empirically after tests on the quality of the final yarn. Tests done on production plants have shown that this is a function of the yarn denier, of the process speed, of the temperature of the godet or of the heating box, and of the draw-ratio. [75] The higher the number of wraps the lower is also the risk that the yarn slips on the surface of the godet, and thus irregularities in the tension of the yarn.

The representation of the Hotbox by Working Model is in 2 dimensions. The Hotbox is represented in its top and front view, as drawn in Fig. 84. The N wraps of yarn coupling the godets are seen as a pair (upper and lower part) of N yarns that connect the axis of the two godets in parallel (Fig. 84). Even though in order to do more wraps, the axis of one of the two godets is slanted towards the other (Subpar.2.2.1 and 2.2.4), for the simulations and for the analytical model the two axis are considered parallel.
Fig. 84: Example of the parallel wraps of the yarn around two godets (top and front view).

These N parts of the yarn (upper and lower) are modeled as a single spring having a spring constant equal to the sum of N wraps.

The temperature and the tension of the yarn is not the same for each wrap. As described in Subpar. 3.1.4, this affects the dynamic modulus. However, since in the simulation in Working Model a range of values of the modulus of elasticity is considered, it is supposed that the yarn has in its entire path around the godets the average value.

The N wraps of the yarn in Working Model are represented by two linear spring elements, one for the $N$ upper parts and one for the $N$ lower parts of the yarn. The value of the constant of each linear spring element is calculated as following:

$$K_{spring \ upper/lower} = N_{wraps} \ast K_{spring}$$  \hspace{1cm} \text{Eq.33}

$N_{wraps} = \text{sum of the upper or lower } N \text{ wraps of yarn}$

$K_{spring} = \text{average spring constant of the yarn}$
Fig. 85: The 2-dimensional representation in Working Model of the two springs representing the 2 parts of the N wraps of yarn lapping around the two godets.

With a range of spring constant of each part of the yarn comprised between 520 N/m and 1550 N/m and a range of numbers of wraps around the godets between 1 and 7, the range of values of the spring constants of each of the 2-dimensional springs is calculated as in Table 10.

<table>
<thead>
<tr>
<th>Yarn type</th>
<th>Spring constant $K_s$ [N/m]</th>
<th>Number of wraps $N$</th>
<th>2-dimensional spring constant $N*K_s$ [N/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET POY Multifilament, 167f34, fineness 29.8tex</td>
<td>520.7</td>
<td>1</td>
<td>520.7</td>
</tr>
<tr>
<td>PET FDY Multifilament, 167f34, draw ratio 1.8 fineness 16.9tex</td>
<td>1550</td>
<td>7</td>
<td>10850</td>
</tr>
</tbody>
</table>

Table 10: The range of the 2-dimensional spring constant values, defined as 1 wrap of POY yarn, and 7 wraps of FDY yarn.

5.1.2 Representation of the godet-rotor

In the 2-dimensional representation of Working Model, plain mass elements with different geometry are drawn. For each mass element different properties can then be defined: initial position, initial speed, mass, static friction, dynamic friction, elasticity, electric charge, density and moment of inertia.
Each rotor-godet is modeled in Working Model by a disk with inertia equal to that calculated in Subpar. 3.2.3 of about 80 kgmm² (Table 2).

The radius of the disk is that of the godet, and the distance between the axes of the disks is 0.15 m, as in the real Hotbox.

Following the assumption of no slip between the yarn and the godets (Subpar.3.2.1), the discs representing the godets and the springs representing the yarn are connected in Working Model to each other with the use of joint elements.

The disks are fixed in the center and they are free to rotate around their center.

The springs representing the two parts (upper and lower) of the yarn between the godets are fixed on the circumference of the disks at opposite positions (Fig.86).

![Diagram of disks modeling the godets and fixing points with the springs, representing the yarn lapping.](image)

Fig. 86: The disks modeling the godets and the fixing points with the springs, representing the yarn lapping.

The linear springs are so fixed with the disks that their extension or compression is given only by a relative rotation of the two disks. While the upper spring is compressed the lower is stretched and vice versa.

### 5.1.3 Spring and dampening coefficients of the electric motors

Among all the elements available in Working Model the rotational spring and the rotational dampers are the most suitable to model the static behavior of the different motors for the Hotbox.

The rotational springs and dampers representing the different motors are fixed in the center of the rotating disks representing the godet-rotor. The values of their coefficients
are directly taken from the results of the experiments (Chapter 4) and transformed in the unit of measurements used in Working Model.

The values used in the simulations are these reported in the following table.

<table>
<thead>
<tr>
<th>Motor Type</th>
<th>Rotational spring constant [Nm/rad]</th>
<th>Rotational dampening constant [Nm/sec/rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor 1: P.M. Synchronous</td>
<td>0.4</td>
<td>0.000624</td>
</tr>
<tr>
<td>Motor 2: P.M. Synchronous with damper winding</td>
<td>0.4</td>
<td>0.001404</td>
</tr>
<tr>
<td>Motor 3: induction asynchronous</td>
<td>0</td>
<td>0.0019</td>
</tr>
</tbody>
</table>

*Table 11: The measured values of the rotational spring and dampening coefficient for the three motors.*

### 5.2 DISCRETE ELEMENT MODEL

The simulations described in this paragraph are done with the model in Working Model using the elements described in the previous paragraph.

All the simulations are stationary analysis of the behavior of the three different motors operating with different yarns. The results reported in this paragraph refer only to the operation with two different combinations of yarns and number of wraps, corresponding to the 2 opposite limits of the range of values of modulus of elasticity and number of wraps, as defined in Subpar. 5.1.1. However, other experiments with other values of the modulus of elasticity and number of wraps have been done and are reported in the Annex 3.

After the element recognition and the specification of the different coefficients and masses, two different sets of simulation have been done. The first set of simulations concerns a single motor-godet without the yarn. The aim of these simulations is to reproduce the results that have been found in the experiments.

The second set of simulations aims to find out the range of frequencies of resonance of the entire system, made of the two motor-godets coupled by different yarns and yarn wraps.
5.2.1 The stationary simulation of a single motor-godet

Two different kinds of experiments have been done for synchronous and asynchronous motors (Chapter 4), in order to measure and then to calculate the spring and the dampening coefficients. These tests are reproduced as simulations in Working Model, in order to compare the values and to verify the correctness of the simulation model.

The object of these simulations is a godet with its inertia, modeled in Working Model by the disk, connected to the motor, which is modeled by the rotational spring and the rotational damper.

Simulations of the free oscillations for the synchronous motors are done, while constant load simulations are done for the asynchronous motors.

Like for the free oscillations experiments (Subpar. 4.1.6), the rotational spring is preloaded by giving an initial rotor rotation of 90°. From this point the rotor is free to swing back to its initial position. The rotational speed of the godet (in the simulation represented by the disk) is plotted (Fig.87).

![Fig.87: Simulated free oscillations of the P.M. synchronous motor without dampening winding.](image)

The oscillations plotted in Working Model reflect perfectly the typical dynamic behavior of dampened oscillations of second order systems.

The same simulations have been done for the synchronous motor with damper winding (Fig.88).
The comparison of the two figures (Fig.87 and Fig.88) shows the effect of oscillation dampening of the damper winding.
For both synchronous motors, with and without the damper winding, the frequency of oscillations calculated from the period of the simulated oscillations (T=100 ms) is 10 Hz. This value of the frequency of the simulated free oscillation of the synchronous motor is compared to that calculated from the results of the experiments.
The experiments have shown two different behaviors, a lower spring behavior at high oscillation amplitude and a higher spring behavior at low oscillation amplitude (Subpar. 4.3.2). Considering the behavior at low oscillation amplitude, it can be noticed from Table 7 a period of oscillation of T= 90ms corresponding to a frequency of 11.1 Hz.
For the asynchronous motor, constant load simulations of the behavior of a single godet are done. Setting the value of the spring constant to zero and that of the dampening constant to 0.0019 Nmsec/rad, a constant torque is applied to the godet shaft.
Fig. 89: The simulated dynamic behavior of the induction asynchronous motor under a constant torque of 0.06 Nm.

Fig. 89 shows the typical exponential curve of systems of the second order with a supercritical damper.

Other simulations with different values of the constant load have been done and are shown in Annex 3.

Also for the asynchronous motor, the simulations reflect the results found in the experiments. In fact, from Fig. 71 (Chapter 4) for a load of 0.06 Nm a godet steady state speed of about 30 rad/sec is measured.

Generally, it can be stated that both type of motors are modeled with a good approximation with a second order system, made of mass, springs and dampers.

5.2.2 Forced oscillations and resonance of the closely coupled godets

The aim of these simulations is to find the critical frequencies, at which the two godets connected by the yarn are in resonance.

These frequencies are known under the name of Eigen frequencies. If a system is excited by an external impact at these frequencies, it shows the maximum amplitude of oscillations.

As described in Subpar. 5.1.1, the yarn lapping is modeled by a couple of springs, having a coefficient that counts the N wraps of yarn around the two godets. The resulting spring constants for the two limits used to fit the model are: 520 N/m and 10850 N/m.
The values of the spring and dampening constant of the three simulated motors are these included in the table 7.

It follows that with the 2 extreme conditions of the yarn and the 3 types of motors, 6 different states are defined. For each of these states, the value of the Eigen frequency is found by trying different values of the exciting torque. By the measurement of the tension of one of the two springs representing the yarn lapping, the amplitude of the oscillations is shown. The frequency, at which the amplitude of the oscillations is the greatest, is the Eigen frequency, i.e. the frequency of resonance.

![Diagram](image-url)

Fig.90: Correlation between the elements of the Hotbox and the components used in Working Model.
<table>
<thead>
<tr>
<th></th>
<th>Value in Working Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertia of godet 1 and of godet 2 [Kgmm²]</td>
<td>80</td>
</tr>
<tr>
<td>2-dimensional spring constant of POY yarn $N*K_s$ [N/m] $N=1$</td>
<td>520.7</td>
</tr>
<tr>
<td>2-dimensional spring constant of FDY yarn $N*K_s$ [N/m], $N=7$</td>
<td>10850</td>
</tr>
<tr>
<td>Rotational spring constant of synchronous permanent magnet motor with and without damper winding [Nm/rad]</td>
<td>0.4</td>
</tr>
<tr>
<td>Rotational dampening constant of synchronous permanent magnet motor without damper winding [Nmsec/rad]</td>
<td>0.000624</td>
</tr>
<tr>
<td>Rotational dampening constant of synchronous permanent magnet motor with damper winding [Nmsec/rad]</td>
<td>0.001404</td>
</tr>
<tr>
<td>Rotational dampening constant of asynchronous induction motor [Nmsec/rad]</td>
<td>0.0019</td>
</tr>
</tbody>
</table>

*Table 12: List of the elements and parameters used in working model to model the Hotbox.*

Simulations of forced oscillations on the Hotbox are done with a sinusoidal load torque $\tau$ at different frequencies. The torque is applied directly at the godet shaft of one of the two godets. By varying the frequency $\omega$ of this sinusoidal torque, a frequency response analysis is done.

The torque defined in Working Model using the function called Motor is:

$$\tau = 0.1 \sin (\omega t) \text{ [Nm]} \quad \text{Eq.34}$$
Fig. 91: The tension of one of the two linear springs, under an exciting torque of 43Hz. This simulation refers to the synchronous motor without damper winding and to a POY yarn lapping for 1 wrap around the godets.

For each of the three types of motors, simulations on the behavior of the 2 different yarn conditions, given by the type of the yarn and the number of wraps, are done. The following table summarizes all the simulations and shows the frequency at which the greatest oscillations take place.

From the table it can be seen that the stiffer the yarn, the greater the oscillations are. It can be also noticed that the yarn tension oscillations with the motor with damper winding are much lower than the motor without damper winding. This states again the good stabilizing effect of the damper windings.

For the asynchronous motor, where no spring elements of the motor are present, the yarn tension oscillations are practically negligible.
Fig. 92: Simulation of the forced oscillations of the permanent magnet synchronous motor without damper winding and one wrap of POY yarn.

Fig. 93: Simulation of the forced oscillations of the permanent magnet synchronous motor without damper winding and seven wrap of FDY yarn.
Fig. 94: Simulation of the forced oscillations of the permanent magnet synchronous motor with damper winding and one wrap of POY yarn.

Fig. 95: Simulation of the forced oscillations of the permanent magnet synchronous motor without damper winding and seven wraps of FDY yarn.
Fig. 96: Simulation of the forced oscillations of the asynchronous induction motor and one wrap of POY yarn.

Fig. 97: Simulation of the forced oscillations of asynchronous induction motor and seven wraps of FDY yarn.
<table>
<thead>
<tr>
<th></th>
<th>POY with 1 wrap</th>
<th>FDY with 7 wrap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronous permanent magnet motor without damper winding</td>
<td>≈30 Hz</td>
<td>≈110 Hz</td>
</tr>
<tr>
<td>Synchronous permanent magnet motor with damper winding</td>
<td>≈30 Hz</td>
<td>≈110 Hz</td>
</tr>
<tr>
<td>Asynchronous induction motor</td>
<td>≈30 Hz</td>
<td>≈110 Hz</td>
</tr>
</tbody>
</table>

Table 13: The resonance frequencies of the HotBox with the three different types of motors and the two limit conditions of the yarn lapping (POY with 1 wrap and FDY with 7 wrap).

5.3  ANALYTICAL MODEL

5.3.1 Small displacement behavior

The most convenient method to study the dynamic stability is to consider the system changing linearly around the operating point. This representation can be obtained by considering deviations in the time dependent variables from their steady-state values. The hypothesis of a spring-dampening stationary behavior of the electric motors and of the yarn is an assumption of the linearization of the system around a specified operating point. It is known that electric motor behavior is indeed not linear. However, at small disturbance and displacement, it can be approximated with a linear system. The disturbances are considered sufficiently small for linearization of system equations to be permissible for purposes of stability analysis. Small-signal (or small-disturbance) stability is a requirement of the system to maintain synchronism under small disturbances. Instability may result in two forms: steady increase in rotor angle due to lack of sufficient synchronizing torque, or rotor oscillations of increasing amplitude due to lack of sufficient dampening torque.
5.3.2 Hypothesis and formulation

The method used to study the stability follows the theory of Lyapunov’s linearization. [96]

If the linearized system is strictly stable, i.e. all Eigenvalues of the matrix A are strictly in the left-half-complex-plane, then the equilibrium point is asymptotically stable for the actual nonlinear system. If the linearized system is unstable, then the equilibrium point is unstable for the actual nonlinear system.

In order to treat the system of the Hotbox with the lapping yarn as a linear system, the following assumptions are made:

- No slipping of the yarn on the surface of the godets is considered.
- Infinitely rigid connection between the motor and the godet shaft.
- The air resistance is neglected.
- The yarn being processed is assumed elastic.
- All the processes and changes are assumed isothermal.
- The tensions of the yarn coming into the Hotbox and leaving it are assumed to be external factors acting as disturbances.
- The torques of the two motors are assumed to be the sum of 3 terms: a constant term (nominal torque at that operating point); a term depending on the variation of speed (“damper”/induction torque); and a term depending on the variation of position (“spring”). The variation of speed and position is considered as the difference between the stationary speed/position of the stator magnetic field and the actual speed/position of the rotor magnetic field.

5.3.3 State-space representation of the linearized model

The dynamic of a system can be conveniently expressed through the state space representation. With the use of the following schematics, the equations of the conservation of angular momentum are written for each of the two godets.
Fig. 98: The Hotbox at steady-state: the conservation of the angular momentum of the two godets.

Using as variables the rotor angular positions $\theta_1$ and $\theta_2$, the equations of the conservation of angular momentum are written as following:

for godet 1: \[ J_1 \ddot{\theta}_1 = M_1 + 2 \cdot N_{\text{laps}} \cdot K_{\text{Yarn}} \cdot r^2 \cdot (\theta_2 - \theta_1), \quad \text{Eq. 35} \]

for godet 2: \[ J_2 \ddot{\theta}_2 = M_2 - 2 \cdot N_{\text{laps}} \cdot K_{\text{Yarn}} \cdot r^2 \cdot (\theta_2 - \theta_1), \quad \text{Eq. 36} \]

where:

$N_{\text{laps}}$ = number of wraps of yarn around the two godets,

$K_{\text{Yarn}}$ = spring constant of the yarn.

$r$ = radius of the godet.

The terms $T_1*r$ and $T_2*r$ are external disturbances and they thus not enter the eq.1 and eq.2.

The motor torque $M_i$ of each motor is considered as the sum of three terms:

\[ M_i = \overline{M_i} + K_m \cdot (\theta_{si} - \theta_{ri}) + D_m \cdot (\dot{\theta}_{si} - \dot{\theta}_{ri}) \quad \text{Eq. 37} \]

where:

$K_m$ = spring constant of the motor,

$\theta_{si}, \theta_{ri}$ = angular position and velocity of the stator magnetic field,

$\dot{\theta}_{si}, \dot{\theta}_{ri}$ = angular position and velocity of the rotor magnetic field.
The first term \((\overline{M}_f)\) is the constant torque necessary to keep the steady-state, while the other two terms are the “spring” and the “damper” behavior of the specific electric motors, as reaction of the small displacements. The nominal torque is the torque constant as specified by the motor supplier.

The following schematic shows all mechatronic system actors: from the dynamic of the yarn (elements of Eq.35 and Eq.36), through the stationary electro-mechanical power conversion, made with the “spring” and with the “damper” of the motor, up to the electric power supply to the three phases of each motor.

The schematic shows that not only the Yarn lapping represents a coupling of the two godets, but also at the other side, that the electric power supply represents in some cases a coupling as well. In Chapter 6, where the different motor controllers are analyzed, it is also explained how this coupling occurs and in which cases there is the risk of resonance.

It follows that, since the rotor is directly coupled to the godet shaft:

\[
\dot{\theta}_r = \dot{\theta}_l \quad \text{Eq.38}
\]

By grouping the terms depending on the same variables, and by substituting Eq.3 into Eq.1 and Eq.2, it leads to:

\[
\frac{d}{dt}\begin{bmatrix}
\dot{\theta}_1 \\
\dot{\theta}_2 \\
\dot{\theta}_3 \\
\dot{\theta}_4 
\end{bmatrix} = \frac{1}{J} \begin{bmatrix}
-(K_m + 2*N_{laps}*K_{Yarn}*r^2)*\dot{\theta}_1 + 2*N_{laps}*K_{Yarn}*r^2*\dot{\theta}_2 - D_m*\ddot{\theta}_1 + 2*M + K_m*\dot{\theta}_3 + D_m*\dot{\theta}_4 \\
2*N_{laps}*K_{Yarn}*r^2*\dot{\theta}_1 - (K_m + 2*N_{laps}*K_{Yarn}*r^2)*\dot{\theta}_2 - D_m*\ddot{\theta}_2 + M + K_m*\dot{\theta}_3 + D_m*\dot{\theta}_4
\end{bmatrix} \quad \text{Eq. 39}
\]

\[
\frac{d}{dt}\begin{bmatrix}
\dot{\theta}_3 \\
\dot{\theta}_4 
\end{bmatrix} = \frac{1}{J} \begin{bmatrix}
-(K_m + 2*N_{laps}*K_{Yarn}*r^2)*\dot{\theta}_3 + 2*N_{laps}*K_{Yarn}*r^2*\dot{\theta}_4 - D_m*\ddot{\theta}_3 + 2*M + K_m*\dot{\theta}_1 + D_m*\dot{\theta}_2 \\
2*N_{laps}*K_{Yarn}*r^2*\dot{\theta}_3 - (K_m + 2*N_{laps}*K_{Yarn}*r^2)*\dot{\theta}_4 - D_m*\ddot{\theta}_4 + M + K_m*\dot{\theta}_1 + D_m*\dot{\theta}_2
\end{bmatrix} \quad \text{Eq. 40}
\]

It is now possible to recognize the typical state space representation of a MIMO (Multiple inputs, multiple outputs) system, where the angular position and velocity of the two rotor-godets represent the state variables \((\theta_1, \dot{\theta}_1, \theta_2, \dot{\theta}_2)\) and the stator magnetic field velocities \(\dot{\theta}_{s1}, \dot{\theta}_{s2}\) represent the inputs of the system. [65] The system is thus a double input-double output system.
Considering the system at the stationary state, $\theta_{s1}$ and $\theta_{s2}$ are considered equal to zero and the typical state space matrixes (A, B, C, and D) can be written as follows:

$$A = \begin{bmatrix}
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
-\frac{1}{J}(K_m + 2N_{laps} * K_{yarn} * r^2) & \frac{1}{J}2N_{laps} * K_{yarn} * r^2 & -\frac{1}{J}D_m & 0 \\
\frac{1}{J}2N_{laps} * K_{yarn} * r^2 & -\frac{1}{J}(K_m + 2N_{laps} * K_{yarn} * r^2) & 0 & -\frac{1}{J}D_m
\end{bmatrix}$$

$$B = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}$$

$$C = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0
\end{bmatrix}$$

$$D = \begin{bmatrix}
0 & 0 \\
0 & 0
\end{bmatrix}$$

Using the following data of the motors and of the yarn, shown in Chapter 3 and 4, the matrixes for the three analyzed motors are calculated for the two opposite cases of a POY yarn and of an FDY.

The parameters of the system using the three different motors are reported respectively for POY and FDY yarn in table 14 and table 15.

<table>
<thead>
<tr>
<th></th>
<th>Permanent magnet motor without damper winding</th>
<th>Permanent magnet motor with damper winding</th>
<th>Asynchronous induction motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_m$ [Nm/rad]</td>
<td>0.4</td>
<td>0.4</td>
<td>0</td>
</tr>
<tr>
<td>$D_m$ [Nmsec/rad]</td>
<td>0.000624</td>
<td>0.001404</td>
<td>0.0019</td>
</tr>
<tr>
<td>$J$ [Kg m²]</td>
<td>0.000078</td>
<td>0.000078</td>
<td>0.000078</td>
</tr>
<tr>
<td>$K_{yarn}$ [N/m]</td>
<td>520</td>
<td>520</td>
<td>520</td>
</tr>
<tr>
<td>$N_{laps}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$r$ [m]</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

*Table 14: The parameters of the system in case of POY yarn processing.*
<table>
<thead>
<tr>
<th></th>
<th>Permanent magnet motor without damper winding</th>
<th>Permanent magnet motor with damper winding</th>
<th>Asynchronous induction motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_m$ [Nm/rad]</td>
<td>0.4</td>
<td>0.4</td>
<td>0</td>
</tr>
<tr>
<td>$D_m$ [Nmsec/rad]</td>
<td>0.000624</td>
<td>0.001404</td>
<td>0.0019</td>
</tr>
<tr>
<td>$J$ [Kg m$^2$]</td>
<td>0.000078</td>
<td>0.000078</td>
<td>0.000078</td>
</tr>
<tr>
<td>$K_{Yarn}$ [N/m]</td>
<td>1550</td>
<td>1550</td>
<td>1550</td>
</tr>
<tr>
<td>$N_{laps}$</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>$r$ [m]</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

*Table 15: The parameters of the system in case of FDY yarn processing.*

It is so possible to calculate the matrixes of the system, for each type of motor and for the two different cases of POY and FDY yarns.

<table>
<thead>
<tr>
<th></th>
<th>$A$</th>
<th>$B$</th>
<th>$C$</th>
<th>$D$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motor 1: P.M.</strong></td>
<td>$\begin{bmatrix} 0 &amp; 0 &amp; 1 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 1 \ -17714 &amp; 12000 &amp; -8 &amp; 0 \ 12000 &amp; -17714 &amp; 0 &amp; -8 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 0 \ 0 \ 8 \ 0 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 1 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 1 &amp; 0 &amp; 0 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 0 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td><strong>Synchronous</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Motor 2: P.M.</strong></td>
<td>$\begin{bmatrix} 0 &amp; 0 &amp; 1 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 1 \ -17714 &amp; 12000 &amp; -18 &amp; 0 \ 12000 &amp; -17714 &amp; 0 &amp; -18 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 0 \ 0 \ 18 \ 0 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 1 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 1 &amp; 0 &amp; 0 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 0 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td><strong>Synchronous with damp. winding</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Motor 3:</strong></td>
<td>$\begin{bmatrix} 0 &amp; 0 &amp; 1 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 1 \ -12000 &amp; 12000 &amp; -243 &amp; 0 \ 12000 &amp; -12000 &amp; 0 &amp; -243 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 0 \ 0 \ 24.3 \ 0 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 1 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 1 &amp; 0 &amp; 0 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 0 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td><strong>Asynchronous induction</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 16: Comparison of the state space matrixes for the three motors with a POY yarn with 1 wrap.*
<table>
<thead>
<tr>
<th></th>
<th>$A$</th>
<th>$B$</th>
<th>$C$</th>
<th>$D$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motor 1: P.M.</strong></td>
<td>$\begin{bmatrix} 0 &amp; 0 &amp; 1 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 1 \ -235714 &amp; 230000 &amp; -8 &amp; 0 \ 230000 &amp; -235714 &amp; 0 &amp; -8 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 0 &amp; 0 \ 0 &amp; 0 \ 8 &amp; 0 \ 0 &amp; 8 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 1 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 1 &amp; 0 &amp; 0 \ 0 &amp; 0 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 0 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td><strong>Synchronous</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Motor 2: P.M.</strong></td>
<td>$\begin{bmatrix} 0 &amp; 0 &amp; 1 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 1 \ -235714 &amp; 230000 &amp; -18 &amp; 0 \ 230000 &amp; -235714 &amp; 0 &amp; -18 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 0 &amp; 0 \ 0 &amp; 0 \ 18 &amp; 0 \ 0 &amp; 18 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 1 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 1 &amp; 0 &amp; 0 \ 0 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td><strong>Synchronous</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>with damp.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>winding</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Motor 3: Asynchronous</strong></td>
<td>$\begin{bmatrix} 0 &amp; 0 &amp; 1 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 1 \ -230000 &amp; 230000 &amp; -24.3 &amp; 0 \ 230000 &amp; -230000 &amp; 0 &amp; -24.3 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 0 &amp; 0 \ 0 &amp; 0 \ 24.3 &amp; 0 \ 0 &amp; 24.3 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 1 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 1 &amp; 0 &amp; 0 \ 0 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td><strong>induction</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 17: Comparison of the state space matrixes for the three motors with a FDY yarn with 7 wraps.**

The so calculated A, B, C, D matrixes are used in the following Paragraphs to calculate the dynamic behavior of the Hotbox in its different configurations.
5.4 FREQUENCY AND STEP RESPONSE ANALYSIS

The time response of a control system is usually divided into two parts: the transient and the steady-state response. Transient response is defined as the part of the time response that goes to zero as time becomes very large. The steady-state is simply the part of the total response that remains after the transient has died out.

The study of a control system in the time domain essentially involves the evaluation of the transient and the steady-state response of the system.

In this work, for the stability analysis of the Hotbox both a time domain and a frequency domain analysis are used. The methods are the plot of the Bode diagrams for the frequency response and the step response diagrams for the time domain.

5.4.1 The Bode diagrams

The Bode diagrams compute the magnitude (in dB) and phase of the frequency response of linear models.

The following figures represent the plot of the Bode diagram of the Hotbox in Matlab for the three different motor drives and the two different yarn/yarn wraps combinations:

- permanent magnet, permanent magnet with damper winding and induction motors;
- POY with one wrap and FDY with 7 wraps.
Fig. 99: Bode diagram of Motor 1 (P.M. Sync.) with POY yarn and 1 wrap.
Fig. 100: Bode diagram of Motor 2 (P.M. Sync. with damper winding) with POY yarn and 1 wrap.
Fig. 101: Bode diagram of Motor 3 (Asynchronous induction) with POY yarn and 1 wrap.
Fig. 102: Bode diagram of Motor 1 (P.M. Sync.) with FDY yarn and 7 wraps.
Fig. 103: Bode diagram of Motor 2 (P.M. Sync. with damper winding) with FDY yarn and 7 wraps.
Fig. 104: Bode diagram of Motor 3 (asynchronous induction) with FDY yarn and 7 wraps.

From the previous figures it is possible to calculate the resonance peak for input 1-output 1. The resulting values are shown and summed up in the following table.
<table>
<thead>
<tr>
<th></th>
<th>Resonance peak [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor 1, POY with 1 wrap</td>
<td>27.4 Hz</td>
</tr>
<tr>
<td>Motor 2, POY with 1 wrap</td>
<td>27.6 Hz</td>
</tr>
<tr>
<td>Motor 3, POY with 1 wrap</td>
<td>25.3 Hz</td>
</tr>
<tr>
<td>Motor 1, FDY with 7 wrap</td>
<td>109 Hz</td>
</tr>
<tr>
<td>Motor 2, FDY with 7 wrap</td>
<td>109 Hz</td>
</tr>
<tr>
<td>Motor 3, FDY with 7 wrap</td>
<td>108 Hz</td>
</tr>
</tbody>
</table>

Table 18: Comparison of the peak resonance frequencies for input 1-output 1 represented in the Bode diagrams.

It is interesting to compare these values of resonance frequencies with those found in Working Model (Table 13). A very good correlation of the results in terms of resonance frequencies is recognized. The resonance frequency of the system with POY yarn with 1 wrap is in Working Model ca.30 Hz, while in Matlab ca.27 Hz. For the case of FDY with 7 wraps, in Working Model is found to be ca.110 Hz while in Matlab ca.109 Hz. It can be stated that the mathematical foundation and the integration in Matlab reflects with a good approximation the model and the simulations in Working Model. Both calculation methods give very similar results, confirming the goodness of each integration method.

5.4.2 The step response

With the reference to the unit-step response, performance criteria are usually measured to characterize the system, such as:

- the maximum overshoot, amplitude of the response over the unit-step input;
- the delay time, the time required to reach the 50% of its final value;
- the rise time, the time required to rise from 10 to 90% of the final value;
- the settling time, the time required to reach a value within 5% of its final value;
- and the steady-state error.
Using the matrixes A, B, C, D, the step response analysis is done in MATLAB for the Hotbox.

In the following 2 figures, the step response plots of the three motor drives with the two different yarn combinations are shown. The third figure is a focus of the first figure for Input 1 Output 1 and is used to compare the different behaviors.

Fig. 105: Step response diagram of Motor 1 (blue), Motor 2 (green), and Motor 3 (red) with a POY yarn and 1 wrap.
Fig. 106: Step response diagram of Motor 1 (blue), Motor 2 (green), and Motor 3 (red) with a FDY yarn and 7 wraps.
Fig. 107: Comparison of the step responses for the three motor drives (permanent magnet motor without damper winding, permanent magnet with damper winding, and asynchronous induction motor) for the Hotbox with seven wraps of FDY yarn (Input 1 -> Output 1).

From the two previous figures, the different behavior between the asynchronous (red lines) and the synchronous motors (blue and green) is evident. In particular, the
asynchronous motor does not show any oscillations, and no overshoot, while the synchronous motors show a dampened oscillatory response.

A detailed analysis and calculation of the three motors for the case of seven wraps of FDY yarn gives the step response performances shown in Table 19.

Also in this case it has been chosen to analyze the input 1- output 1 response.

<table>
<thead>
<tr>
<th></th>
<th>Overshoot (%)</th>
<th>Settling time [s]</th>
<th>Rise time [s]</th>
<th>Steady-state (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motor 1 (PM)</strong></td>
<td>84.6 %</td>
<td>0.963 s</td>
<td>0.0148 s</td>
<td>50 %</td>
</tr>
<tr>
<td><strong>Motor 2 (PM + Damp. wind.)</strong></td>
<td>68.5 %</td>
<td>0.425 s</td>
<td>0.0155 s</td>
<td>50 %</td>
</tr>
<tr>
<td><strong>Motor 3 (Async.)</strong></td>
<td>0 %</td>
<td>3.84 s</td>
<td>2.13 s</td>
<td>50 %</td>
</tr>
</tbody>
</table>

*Table 19: Comparison of the step response performance of the three motors with 7 wraps of FDY yarn.*

No overshoot is present by any of the analyzed drives. The settling time of the synchronous motor with damper winding is less than the half than that of the synchronous motor without damper winding, stating the value and the effect of the damper winding. The very bad performances of the asynchronous motor, such as very long settling and rise time, are to be found in the dynamic characteristics of the asynchronous motor, i.e. a lower starting torque.
5.5 LIMITS OF STABILITY

Once the system is found to be stable, it is of interest to determine how stable it is, and this degree of stability is a measure of relative stability.

In the frequency domain, the resonance peak is used to indicate relative stability. Another way of measuring relative stability in frequency domain is by how close the Nyquist plot of the system is to the (-1, j0) point.

Gain margin is one of the frequently used criteria for measuring relative stability of control systems. In the frequency domain, gain margin is used to indicate the closeness of the intersection of the negative real axis made by the Nyquist plot to the (-1, j0) point. [65]

The gain margin is defined as following:

\[ \text{Gain margin is the amount of gain in decibels (dB) that can be added to the loop before the closed-loop system becomes unstable.} \]

The gain margin is only a one-dimensional representation of the relative stability of a closed-loop system. In order to have a better understanding of a system, a phase margin criteria is also needed.

The phase margin is defined as following:

\[ \text{Phase margin is defined as the amount of phase at the gain crossover.} \]

Gain crossover is indicated by the point of the plot at which the magnitude of the plot is equal to 1.

- The gain margin is positive and the system is stable if the magnitude at the phase crossover is negative. That is, the gain margin is measured below the 0dB axis. If the gain margin is measured above the 0dB axis, the gain margin is negative, and the system is unstable.

- The phase margin is positive and the system is stable if the phase is greater than -180° at the gain crossover. That is, the phase margin is measured above the -180° axis. If the phase margin is measured below the -180° axis, the phase margin is negative, and the system is unstable.

In order to compare the relative stability of the three different drive solution for the Hotbox, the Bode plots and the step response are shown and compared in the figure 108, even though, it is evident that all the three plots follow to the same conclusion.
Fig. 108: Correlations among step responses and Bode plots for the three different drives of the Hotbox operating with 7 wraps of FDY yarn (Output 2 of the three motors are shown).

In the step response plot, it can be seen that the system with motor 1 is not well dampened and the oscillations are prolonged. In fact, for motor 2 the oscillations are totally died out after about 0.5s, while for motor 1 they are still present after about 1.2s.
For motor 3 no oscillations are present, revealing that the system is well dampened or even over-dampened.

As stated in the previous chapter, the Bode diagrams show the resonance peak, at which the system exhibits high oscillations. The resonance frequency is more or less the same for all the three drive solutions. From the Bode plots it can also be stated that for all the three drive solutions both the gain and the phase margin are positive, thus the system is stable.

A detailed analysis of the gain and phase margin for the Hotbox with the drive made with motor 1, motor 2 and motor 3, follows. From all the combinations of inputs and outputs, only the case of the output 2 (acceleration of the motor of godet 2) with the input 1 (speed of the magnetic field of the motor of godet 1), are shown.

![Fig.109: Calculation of the gain margin for the drive solution with motor 1.](image)
Fig. 110: Calculation of the phase margin for the drive solution with motor 1.

Phase at magnitude 0dB

Fig. 111: Calculation of the gain margin for the drive solution with motor 2.

Magnitude at phase -180°

Fig. 112: Calculation of the phase margin for the drive solution with motor 2.
The calculated gain and phase margin of the three different drive solutions are summed up in the following table.

<table>
<thead>
<tr>
<th></th>
<th>Motor 1</th>
<th>Motor 2</th>
<th>Motor 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain margin (dB)</td>
<td>32</td>
<td>32</td>
<td>79.5</td>
</tr>
<tr>
<td>Phase margin (°)</td>
<td>15</td>
<td>35</td>
<td>∞</td>
</tr>
</tbody>
</table>

*Table 20: Comparison of the gain and phase margins for the different drive solutions with motor 1, motor 2, and motor 3.*

The relative stability analysis confirms the stability of all the three systems and it also shows the increasing stability margin from motor 1, to motor 2 and to motor 3.
This different stability margin is to be found mostly in the phase margin; in fact the phase margin for the asynchronous drive solutions is even infinite.

In contrast to the gain margin, which is determined by loop gain, phase margin indicates the effect on system stability due to changes in system parameters, which theoretically alter the phase by an equal amount at all frequencies. Phase margin is the amount of pure phase delay that can be added to the loop before the closed loop system becomes unstable. In other words the phase margin includes the effect of phase shifting.

Gain margin is the amount of gain in decibels that can be added to the loop before the closed-loop system becomes unstable. It can be seen that also this value is much higher for the asynchronous drive, while it is the same for the motor 1 and motor 2.

5.6 RESULTS OF THE SIMULATIONS AND CONCLUSIONS

Since the oscillations in all the simulations have revealed limited amplitude, the whole system is considered in all analyzed cases stable.

As a conclusion, a possible Hotbox with asynchronous motors performs less torsional oscillations than the same Hotbox with synchronous motors. In fact, due to its inherent magnetic dampening behavior, the asynchronous induction motor dampens the yarn tension oscillations or any other external disturbances better.

The range of critical frequencies is found to be between 30 Hz (case of 1 wrap of POY yarn) and 110 Hz (case of 7 wraps of FDY). This means that any kind of external disturbances in this range of frequencies causes great yarn tension variations and thus bad quality in the final drawn yarn.

External disturbances are to be found in the electrical energy supply, i.e. voltage oscillations. The frequency of this kind of disturbance is normally not known.

Another source of disturbance is the torque ripple, given by an imprecise design and assembling of the motor. The frequency of these disturbances is normally proportional to the rotational frequency.

In the experiments it has been stated that the measured torque behavior (Fig.63) does not match the sinusoidal theoretical behavior of synchronous motors; drops in the motor torque are in fact visible. The frequency of the disturbances caused by these torque ripples is multiple of the rotational speed, and it depends on the motor poles.
The unbalance of the godets, sum of that of the rotor, of that of the godet itself and above all of that given by the coupling between the godet and the rotor, is also a source of disturbances. The frequency of these disturbances is the rotational frequency.

Another source of disturbances in the range of 30 until 110 Hz, which may cause oscillations of the system, is to be found in the yarn itself. The tensions of the yarn coming into the Hotbox and exiting the Hotbox, which are considered to be external elements to the system, disturb the behavior of the godets. The frequency of the oscillation of the yarn tensions depends on the yarn processes. The unwinding of the yarn from the bobbin is affected by the so called “balloon” [72]. The traverse movement in the winding of the yarn causes a sinusoidal oscillation of the yarn tension on the bobbin [73]. The yarn texturing and interlacing causes as well yarn tension oscillations. In all these processes, the frequency of the yarn tension oscillation depends on the yarn speed, on the yarn fineness, and on the nominal yarn tension.

The frequency of all these disturbances may be in the range of 30-110 Hz and may then cause yarn tension oscillations and thus rotational oscillations of the godets.

As already stated in the experiments, the use of a damper winding in the permanent magnet synchronous motors reduces significantly the amplitude of these oscillations. The negligible amplitude of the oscillations by the asynchronous motor reveals that the asynchronous motor is a very stable system.

The model presented in this chapter allows finding the yarn tension behavior for different yarns, for different godet designs and under different dynamic conditions.

By changing the spring constant of the yarn lapping, it is accounted the processing of another type of yarn and/or another amount of yarn lapping around the two godets.

By changing the radius and the inertia of the godets, other designs of godets are simulated. By changing the rotational damper and spring, other stationary characteristics of the motors are modeled and simulated.

6. EXISTING INDUSTRIAL PROBLEMS AND INVESTIGATION TOOLS

Observations and calculations on video recordings of the dynamics of standard godets for the drawing of monofilaments, are illustrated in paragraph 6.1. The torsional oscillations, shown in subparagraph 6.1.2, confirm the results of the experiments made in the laboratory.

The paragraph 6.2 deals with the possible methods that can be used to design and model electric motors for individually driven drawing godets. In subparagraph 6.2.1, the value of the critical dampening is calculated and compared with the damper values of the analyzed motors. An idea about a future use of the damper constant as a parameter for the study and the design of electric motors is presented. In subparagraph 6.2.2, the block diagram representation of the two godets coupled by the yarn is shown. Its possible implementation in MATLAB Simulink is also shown.

6.1 EVIDENCE OF TORSIONAL OSCILLATIONS IN CONVENTIONAL GODETS FOR MONOFILAMENT EXTRUSION LINES

For some specific technical applications, the yarn fineness regularity represents the most important parameter to define the quality of the yarn and then of the final fabric. Therefore, in monofilament plants, very high precision of the components is required. During the drawing, any irregularity in the yarn tension causes irregularities in the fineness of the final yarn.

The production of the monofilaments is still made on old machines at very low speed (200 m/min). There are, however, some pilot machines working at higher speed, but they still do not deliver the requested yarn regularity.

The difference between old production machines and new pilot machines is in the drive system.

As described in Par. 2.2, the drawing of monofilaments is done between different sets of godets. In each set, the number of godets varies typically between 3 and 7. The use of this
multitude of godets at the same speed is adopted in order to have bigger contact surface and thus to have less slipping and a better control on the tension of the yarn.

Standard production machines use for all the godets in each set a single motor with transmission belts. At the other side, experimental machines use individually driven godets.

Differences among these experimental machines are to be found in the motor controllers. The motors of each group of godets are either driven by a common inverter or by individual inverters. The use of a common inverter is cost efficient, but it may result critical in the dynamics.

Therefore the experiments have been done on a prototype production machine using a common inverter for the godets of the same set.

This type of plant was accessible in Italy at Siderarc, a monofilament supplier for technical textiles (Siderarc S.p.A., Via G. Galilei 45, IT-20010 Cornaredo (MI), Italy). In this monofilament production mill, almost all types of the mentioned machines are in use. Four lines, made of a melt spinning head and godets driven by chains, are still the production plants for high quality monofilaments. Two different sample lines are used for tests and small productions.

One of these lines uses individually driven godets with individual inverters, the other uses individually driven godets, with a common inverter.

Tests done with an Uster Tester 3 on the fineness regularity of the yarn produced on this second pilot machine have confirmed the presence of irregularities in the process.

The dynamic behavior of the godets of this second machine is investigated.

The godets installed in this machine are supplied by the company Retech (Retech AG, Lindenmattstrasse 16 CH-5616 Meisterschwanden, Switzerland). [Annex 4]

The motor of those godets is a 4 poles synchronous reluctance motor with damper winding, produced by Thien (Thien E Motoren GmbH, Rankweil, Austria).

For each set of godets, a common Siemens inverter is installed.
Fig. 73: Elements of a typical monofilament production machine, similar to the machine at Siderarc. [94]

The whole machine is made of the following components:

- one melt spinning head, comprising 16 spinnerets;
- 3 groups of drawing godets,
- 2 heating zones,
- and 16 winders (one for each monofilament).

The three groups of godets with the two heating zones are the elements that simultaneously draw the sixteen yarns. The process of drawing is made in two steps, corresponding to the two heating zones. Between the first group of godets, made of seven godets, and the second, made of three godets, the first draw is imposed. Between the second group and the third group, made of five godets the second draw is made. The sixteen drawn yarns are then individually wound on sixteen bobbins by precision winders.
6.1.1 Concept of the measurements

The target of these experiments is to analyze the dynamic behavior of the godets installed in this sample plant.
Since the godets installed in the machine could be neither dismounted nor modified, a special measuring process is used.
A video recording is done of two consecutive rotating godets.
The front surface of each godet is covered by a print representing three 120° angles with three different colors.
While the godets rotate, a short torque impulse is applied manually to one of the two godets.

![Fig.74: The two godets with the front surfaces covered by the drawings.](image)

From the theory of mechanical oscillations, it is known that by exciting a system with an impulse (Dirac impulse), the system reacts oscillating at its eigenfrequency.
After applying a torque impulse by hand to one of the rotating godets, this starts to oscillate around the steady state angle of rotation. Since both godets are driven by the same inverter, the position of the second godet is taken as reference position. The oscillations are then quantified as the difference of the position between the two godets.
The camera used for the experiments is a LG KB-G3138 black/white CCD camera, with a resolution of 291000 Pixels and a capturing frequency of 50 Hz.
The video output signal of the camera is sent to a PC through a Terratec Cameo Grabster AV 250. The Grabster is a video digitizer that is connected to a PC by a USB 2.0 serial cable, allowing a fast video streaming.

The video is analyzed with the video editing software Ulead Video Studio 7.0 (Ulead Systems Inc.). Each full frame is visible separately at 50 Hz. It is then imported as JPEG into AUTOCAD, and the phase difference between the two godets is measured on each picture.

**Fig. 76: Measuring the phase difference between two godets (Measured angle=31°).**
6.1.2 Results of the experiments

The video recordings have been done with rotating godets at a speed of 50 Hz, directly set at the inverter. A sequence of pictures is taken and represented in Fig.77. The phase difference is then calculated in CAD and shown in table 6.

![Fig. 77: The sequence of the first 8 frames of the oscillation. The measured angle in CAD, shown in each frame, is used to calculate the phase difference (180°-γ). Points 3, 6, 9, 12 are not shown. Other frames are in the Annex 2.](image-url)
<table>
<thead>
<tr>
<th>Measured points</th>
<th>Time [s]</th>
<th>Measured angle in CAD</th>
<th>180°- measured angle</th>
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<tbody>
<tr>
<td>1</td>
<td>0.04</td>
<td>31</td>
<td>149</td>
</tr>
<tr>
<td>2</td>
<td>0.08</td>
<td>21</td>
<td>159</td>
</tr>
<tr>
<td>3</td>
<td>0.12</td>
<td>36</td>
<td>144</td>
</tr>
<tr>
<td>4</td>
<td>0.16</td>
<td>19</td>
<td>161</td>
</tr>
<tr>
<td>5</td>
<td>0.2</td>
<td>18</td>
<td>162</td>
</tr>
<tr>
<td>6</td>
<td>0.24</td>
<td>44</td>
<td>136</td>
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<td>7</td>
<td>0.28</td>
<td>31</td>
<td>149</td>
</tr>
<tr>
<td>8</td>
<td>0.32</td>
<td>37</td>
<td>143</td>
</tr>
<tr>
<td>9</td>
<td>0.36</td>
<td>64</td>
<td>116</td>
</tr>
<tr>
<td>10</td>
<td>0.4</td>
<td>39</td>
<td>141</td>
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<td>146</td>
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<td>12</td>
<td>0.48</td>
<td>50</td>
<td>130</td>
</tr>
<tr>
<td>13</td>
<td>0.52</td>
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<td>14</td>
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<td>0.6</td>
<td>50</td>
<td>130</td>
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<td>0.64</td>
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</tr>
<tr>
<td>42</td>
<td>1.68</td>
<td>57</td>
<td>123</td>
</tr>
</tbody>
</table>

*Table 6: Measured points with the calculated angles in CAD.*
Fig. 78: Diagram of the measured angles (difference between 180° and the calculated angles in CAD) vs. time.

Since the godets are rotating synchronously with the stator magnetic field, the measured angle differences is assumed to be the phase differences between the rotor of the godet with brake pulse impact and the stator magnetic field. The pictures of the points 3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 33, 36, 39, 42 may result in errors in the measurements in CAD (measured points are about 20° over the other measurements), so that they are not considered for the following analysis. A diagram over the time of the filtered values shows very similar oscillations to those measured by permanent magnet motors (Fig.79).

Fig. 79: Relative rotor oscillations of godets driven by a common inverter.
As it is done for the free oscillation tests on the permanent magnet motors, the dampening coefficient \((D)\) is calculated from the exponential decay of the amplitude of the oscillations \((A)\) with Eq.29.

Where \(J\) is the moment of inertia of this type of internally heated godets, as calculated in Subpar. 3.2.3 with the equation 10:
\[
J = 0.12 \text{ Kgm}^2.
\]
The calculated value for the dampening is: \(D=0.014016 \text{ Nmsec/rad.}\)

From the analysis of the frequency of the oscillations, the spring constant can also be calculated from the formula of the eigenpulsation:
\[
\omega = \sqrt{\frac{K}{J}} \tag{Eq.30}
\]
with a period of oscillations of 0.33 sec, the pulsation results \(\omega = 19.03 \text{ rad/sec}\) and the spring constant \(K= 42.7 \text{ Nm/rad.}\)

### 6.1.3 Interpretation of the dynamic behavior of standard godets

The analogy in the magnetic principle of this synchronous reluctance motor with dampening winding with permanent magnet motors is confirmed by the observations. The expected spring-dampening behavior is captured by the video recordings and quantified by the spring and dampening coefficients. Because of the inherent magnetic principle of the reluctance motor and because of the integrated dampening winding, a higher dampening coefficient than the permanent magnet is found.

However, rotational oscillations confirm also for synchronous reluctance motor the spring behavior.

The video recordings and the diagram of the rotor oscillations show that at steady-state there is still an oscillation between the two rotors. In the diagram of Fig.79, this is recognized in the last part of the curve of the oscillations where the calculated phase difference is never constant; it always remains a certain rotor oscillation.

The consequences of these rotational oscillations during the drawing of the filament yarns are irregularities in yarn tension and finally in yarn fineness regularity.

The specific case of the monofilament production represents the most critical application, since the yarn in process has to meet high tolerances.
In the investigated line, the yarn produced is specified at a fineness of 25 dtex (diameter of about 0.05 mm) and a tenacity of about 5 cN/tex.

For each yarn, a difference in the drawing force of 0.125 N causes an elongation of around 1%, and thus a corresponding change in the fineness.

From the diagram of Fig. 79, the phase difference between the rotors is estimated of 5°. Depending on the process parameter (drawing force, drawing ratio, distance between the godets, and temperature of the godets) this phase difference causes inevitably a difference in the yarn tension and in yarn elongation.

It follows that the problems of yarn fineness irregularity, discovered by internal tests done on an Uster tester in Siderarc [93], are mainly caused by these measured torsional oscillations.

On the other hand, the comparison of the spring coefficient of the synchronous permanent magnet motors and of the reluctance motor shows a big difference. This is a natural consequence of the difference of the size of the two motors. While the permanent magnet motors supplies a nominal power of about 200 W, the synchronous reluctance supplies 2 kW. Theoretically, since the permanent magnet motors have a higher power density, at comparable nominal power, they might express a higher spring coefficient.

### 6.2 METHODS FOR STUDYING, MODELING, AND DESIGNING INDIVIDUALLY DRIVEN DRAWING GODETS

#### 6.2.1 The critical dampening

In the experiments shown in Chapter 4, the value of the damper constant is calculated from the decrement of the oscillations that have been measured after a step impulse.

In the case of synchronous motors, the oscillations are these typical of a system with an “under-critical” damper constant.

For a second order equation system, it is possible to calculate and define a value of the damper constant called critical dampening. If the damper constant of a system is over or under the critical value, its dynamic behavior is totally different.

The typical homogeneous equation of a second order system is the following:

$$ J \ddot{\theta} + D \dot{\theta} + K \theta = 0 $$

Eq. 41
Substituting now

\[ 2A = D/J \]  
Eq.42

and

\[ \omega^2 = K/J, \]  
Eq.29

the following equation is obtained:

\[ \ddot{\theta} + 2A \dot{\theta} + \omega^2 \theta = 0 \]  
Eq.43

The solutions thereof are of the type

\[ \theta = e^{zt} \]  
Eq.44

where

\[ z_{1,2} = -A \pm \sqrt{A^2 - \omega^2} \]  
Eq.45

Depending on the sign of the term \( A^2 - \omega^2 \), different solutions of the differential equation are found.

The value of the dampening to which \( A^2 - \omega^2 = 0 \), is the critical dampening:

\[ D_c = 2J\omega \]  
Eq.46

If the dampening value \( D \) is smaller than the critical dampening \( D_c \), the solutions of Eq.43 are complex:

\[ \theta = \theta_0 e^{-zt} \cos(\omega t + \varphi) \]  
Eq.47

If the dampening value \( D \) is greater or equal to the critical dampening \( D_c \), the solutions of Eq.43 are:

\[ \theta = \theta_0 e^{-zt} \]  
Eq.48

where \( z_{1,2} = -A \pm \sqrt{A^2 - \omega^2} \)

As already demonstrated in the experiments, synchronous motors show rotational oscillation typical of an under-critical dampened system (Fig.66), while the asynchronous motor shows an overcritical dampened behavior (Fig.71).

It is convenient to calculate the value of the critical dampening in order to compare the actual values of the two analyzed synchronous motors (Synchronous permanent magnet motor without and with damper winding).

Starting from Eq.46 and substituting \( \omega = \sqrt{\frac{k}{J}} \),

it follows:
\[ D_c = 2 J \sqrt{\frac{k}{J}} \]

Using the values of Table 12, the value of the critical dampening is found:
\[ D_c = 0.0113 \text{ [Nm/sec/rad]} \]

Table 21 compares the calculated critical dampening with the measured values of the damper constant, showing the ratio between the measured dampening constant and the critical dampening value (D/Dc).

<table>
<thead>
<tr>
<th>Motor</th>
<th>Rotational dampening constant [Nm/sec/rad]</th>
<th>Ratio D/Dc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor 1: P.M. Synchronous</td>
<td>0.000624</td>
<td>0.055</td>
</tr>
<tr>
<td>Motor 2: P.M. Synchronous with damper winding</td>
<td>0.001404</td>
<td>0.124</td>
</tr>
<tr>
<td>Motor 3: induction asynchronous</td>
<td>0.0019</td>
<td>0.17</td>
</tr>
</tbody>
</table>

*Table 21: The values of the measured dampening constant compared with the critical dampening \( D_c = 0.0113 \text{ [Nm/sec/rad]} \).*

For all three motors the value of dampening is at least ten times smaller than the critical dampening. It is also evident how the motor with the damper winding has a more than doubled ratio than the motor without damper winding.

The wires used for the damper winding in the rotor of the PM motor have a section of 0.75 mm². Testing different damper windings with different sections of the wires could help to find a correlation between the wire section and the resulting damper constant. A table with the dampening constant values for different damper winding wires could be found. With the model presented in this work, it is then possible to find out the correct wire section from the dynamic behavior of the system.

For any specific application, the best damper coefficient could be chosen. Depending, for example, on the accepted amplitude of oscillations, the dampening winding section may be calculated from the table and applied in the rotor.

The effects of different designs and construction of damper windings can also be evaluated through the experiments proposed in chapter 4. The results of the experiments can then be compared with the values of the dampening constant of Motor 2 (table 21), which corresponds to the solution of damper windings using copper wires.
The section of the wires determines also the amount of current that flows in it. Since the damper windings are in the rotor, and more precisely between the permanent magnets, it is important to pay attention to the temperature of the rotor. NdFeB magnets, typically used for rotor construction, maintain their magnetic field until 150°C, above they loose it very quickly.

The amount of current that flows in the damper windings depends also on the operating conditions of the motor. By non stationary conditions, the damper windings dampen the rotor oscillations as demonstrated by the experiments. Since these are short-term effects, they do not have any influence on the heating of the rotor.

By stationary conditions, the current that flows in the damper windings is a function of the harmonic waves of the field that is not synchronous with the rotor speed. Because of this current, losses and heats arise, even though in limited amplitude.

In the design of high power permanent magnet motors with damper winding, in order to avoid too high current in the damper windings and thus too high temperature in the rotor, it might be useful to do some experiments on the rotor temperature. This may represent a future research or engineering work.
6.2.2 Block diagrams of the linearized model

Using the similarity to the equation of conservation of angular momentum of a second order system, and following Eq.35 and Eq.36, the block diagram for each godet is drawn as follows:

\[ \theta_i = \text{speed of the stator magnetic field} \]
\[ \theta_i, \theta_{i*} = \text{rotor position and speed} \]
\[ V_i = \text{voltage supply} \]
\[ f = \text{friction coefficient} \]
\[ M_i = \text{torque of the motor} \]
\[ J_i = \text{inertia} \]
\[ M_{ext.} = \text{external torque acting on the godet shaft} \]

Fig.115: Block diagram of a single Godet.

In case of two godets, coupled by the yarn, the equations of the conservation of angular momentum correspond to the following block diagram.

Fig.116: Block diagram of the two godets coupled by the yarn.

The yarn acts with its elastic behavior directly on the equilibrium of the angular momentum on each godet shaft, as already stated in eq.35 and 36.
The external torque \( (M_{\text{ext}}) \) represents the sum of the external elements that also act on the godet shafts, like for example the tension of the incoming/outgoing yarn, and the torque ripple of the motor.

Eq.37 can be used, as it has been done in the previous paragraph, to split the torque of the motor into the three terms.

The two blocks called “Electro-mechanical conversion”, representing the motor, are then exploded as follows.

The variables \( \dot{\theta}_s \) (angular velocity of the stator magnetic field), \( \theta_s \) (angular position of the stator magnetic field), and \( V_i \) (voltage of the stator magnetic field) are not only directly dependent on the output of the motor controller, but rather on the dynamic characteristics given by the design and construction of the stator.

The two main parameters describing the dynamics of the stator magnetic field are summed up in the inductance and the resistance of the stator windings.

The stator voltage supply with its characteristics and dynamics may also affect the voltage at the stator windings and thus the dynamic behavior of the motor.
The block diagrams of the system, as sketched in Fig.116, are implemented in MATLAB Simulink. Simulink is a MATLAB platform designed for simulating dynamic systems through detailed block diagrams.

![Diagram](image)

**Fig.118: Stationary representation in Simulink of the system with a possible drive controller for each godet and a sinusoidal disturbance for each godet.**

The dynamic analysis of the stationary system is done by using different inputs and by measuring the outputs with virtual scopes. In the case represented in Fig.118, a step set speed response is shown. Following the signal flow from the left to the right, there is the “Step, Setpoint Speed”, which is the input for the two separate drives of the two godets: Driver 1 and Driver 2. The output of the driver, in this case only voltage ($U_i$) and frequency ($f_i$), since at stationary conditions the current is considered to be constant, are the input of the two blocks called “Electric motors”. With these blocks, the electro-mechanical conversion is modeled through the three elements of the stationary torque conversion: the stationary electro-mechanical conversion, the stationary spring behavior, and stationary dampening behavior.

Following the block diagrams of Fig.115, the output of the motor is the torque applied on the godet shaft. The part of the yarn lapping around the two godets applies also a torque on the two godet shafts, thus the two sum blocks after the blocks “Electric Motor 1” and “Electric Motor 2”.

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In the block diagrams the function of the yarn lapping is evident. It couples the rotation of the two godets.

With this block diagram, it is possible to sketch and test different open and closed loop drive solutions. The parameters of the possible drive controller, such as, for example, the proportional constant ($K_p$), the integral constant ($K_i$) and the differential constant ($K_d$) of a typical PID controller are optimized, according to the output behavior of the motors and of the processed yarn.

In a further work, different drive and drive methods for the different motor designs might be implemented and tested.
7. CONCLUSIONS FOR FUTURE DEVELOPMENTS

The chapter 7 is the final chapter of this work.

Paragraph 7.1 compares possible drive solutions for the Hotbox pointing out all the advantages and the drawbacks for each solution.

After answering the research questions in paragraph 7.2, the thesis ends with some hints for future works and developments on individually driven drawing godets.

7.1 COMPARISON AND EVALUATION OF THE DRIVE SOLUTIONS

The experiments done at Siderarc, explained in Paragraph 6.1, have confirmed the risk of high rotational oscillations. The resulting bad quality of the yarn produced on these synchronous reluctance godets has shown that the combination of the motor with the drive is very important.

Inverters and frequency converters are nowadays used in many applications, and they are becoming also very wide spread in textile.

Most inverters have the possibility to control both synchronous and asynchronous motors in open and also in closed-loop control.

As in the case of the godets used at Siderarc, a single inverter is used to drive more than one motor.

Because of the different dynamic behavior of the motor itself, a distinction should be done between the case of the synchronous motor without damper winding, the case of the synchronous with damper winding, the case of synchronous reluctance and the case of the asynchronous motor.
7.1.1 Permanent magnet synchronous motor without damper windings

The synchronous motor without damper windings, from the dynamic point of view, is the most critical drive. With the advantage of very little energy losses, it is very sensitive and critical to control.

The experiments and the simulations on this motor have confirmed high rotational oscillations and poor dampening properties. Since these oscillations are not acceptable for the quality of the drawn yarn, an improvement in the dynamic performance is absolutely needed.

In an application like the Hotbox, where the rotational speed reaches 15000 rpm and very high disturbances are present, like for example the torque ripple and the tension of the yarn, the motor oscillations are controlled up to the limit of response of the controller. In such a critical situation with high rotational speed, high precision and high torque irregularities, both on speed and torque a closed loop control is needed. A typical current transducer like one of the catalog of LEM has a response time of about 10µs. In case of torque ripple with a disturbance of four times a lap at a speed of 10000 rpm, the response time of the controller should be 1.5ms. Any delay in the controller and in the reaction of the motor means a phase shift, and since the phase margin, as calculated in Chapter 5 (Table 20), is only 15°, there is a high risk of instability in the closed loop control.

It is evident that the drive solution with synchronous motors without damper winding finds its main drawback in the risk of instability at high speed and high torque ripple. Another drawback of this kind of motor is the cost of the rotor, and, in the case of closed loop control, the cost of the sensors and of the control board. Besides these drawbacks, the big advantages are the very high efficiency and the high torque density, typical of all permanent magnets motors.

7.1.2 Permanent magnet synchronous motor with damper windings

In case of the synchronous motor with damper winding, since the oscillations in open loop control are much smaller, it could be possible to use these motors even in open loop control. The risk of high rotational oscillations with the consequence of bad quality of the produced yarn might be overcome either by a thicker dampening winding, by the use of godets with higher inertia, or by the use of closed loop control.
However, the use of this type of motor for the production of very sensitive and precise yarns, like for example the monofilaments for technical textiles, has to be done carefully. In the monofilament drawing, very small torsional oscillations of the rotor of one godet cause yarn tension irregularities and thus yarn fineness irregularities. In the case of lower quality yarns, the big advantage of this motor would be the use of a very efficient permanent magnet rotor, in open loop control, thus without extra costs for the sensor and for the control board. The use of this motor in open loop control would show the same drawbacks of the permanent magnet motors without damper winding, but since the phase margin is more than double (35°), this might be sufficient to keep the system stable. A big drawback of this solution is the very expensive construction of the rotor. Not only the magnets have to be fixed manually on the rotor, as on the permanent magnet motor, but the wires of the damper winding have also to be fixed manually on the rotor.

7.1.3 Synchronous reluctance motor with damper windings

The synchronous reluctance motors, state of the art in the drive of internally heated godets, have a dynamic behavior that has been demonstrated to be very similar to the permanent magnet motor. For this motor, as well as for permanent magnet motors there is the risk of instability. However, the big inertia given by the heating windings and the additional damper windings reduce the sensitiveness to external disturbances and oscillations. On the other hand, the big inertia requires bigger motor size, resulting in a more expensive solution. The use of a single inverter for a multitude of godets, as the drive solution adopted for monofilaments plants and analyzed in chapter 4, is a very cost efficient solution, but it does not give any chance of control on the dynamic behavior of each godet. It follows that, as it has been demonstrated in Paragraph 4.2.2, any oscillation of the godet is either absorbed by the damper winding, or it causes rotor oscillations and thus yarn tension oscillation. The use of these internally heated godets, driven by a dedicated drive with closed loop control might be a stable solution and could give good results in yarn quality. The cost of such a solution, using internally heated godets, is already very high. The use of reluctance motor with damper winding and even sensors for closed loop control might result in a too expensive solution.
7.1.4 Asynchronous induction motor

In case of the asynchronous motor, it has been stated that the oscillations are much lower thanks to the inherent dampening behavior of the motor. Such a motor would give a chance to be used in open loop control, i.e. without position or speed sensor and without any controller. In order to keep the draw ratio constant, the speed has to be kept constant. Since the asynchronous motor changes its speed with the load, a speed closed loop control is needed.

The advantages of this system are indeed the costs of the motor, the simplicity of the settings and the robustness of the drive. The drawbacks are the energy consumption, due to the rotor losses (higher than a permanent magnet motor), the very low torque density, and the bad dynamic speed accuracy. However, since the relative slip decreases with the increase of the speed, the rotor losses at high rotational speed would decrease their importance. The asynchronous motor is so a very suitable drive for the godets of the Hotbox, offering a very cost efficient, simple and stable solution.

7.2 ANSWERS TO THE RESEARCH QUESTIONS

The answer to the first research question is in chapter 2, 3 and 4:

due to the development of new drive methods for the thermoplastic filament yarn drawing, as individually driven godets, which may be the consequences in quality of the yarn?

The development of new drive systems may cause an irregularity in the dynamic of the drawing godets that would cause irregularities of the yarn fineness and furthermore the irregularities of the yarn and fiber mechanical properties, such as stress-strain diagram. These irregularities turn then into irregularities of the color of the yarn after dying and thus bad quality of the final yarn.

The tests on standard godets using individual synchronous reluctance motors with damper winding confirm that the cause of quality problems in monofilament fineness regularity is the rotational oscillations of the godets.
The experiments of chapter 4 on permanent magnet motors show by these motors even higher rotational oscillations, leading to higher risks of yarn fineness irregularities and irregularities in the mechanical properties.

Since in individually driven godets the godet is directly clamped on the motor shaft, each rotational oscillations of the motor turns into irregularities in the yarn tension.

The rotational oscillation, due to the dynamic behavior of the motor, is not previous knowledge and was not suspected as a reason of irregularities of the yarn properties.

To the second research question:

*what theoretical model is available to explain these stability problems?*

the answer is in chapter 3.

Existing models, such as the model of the stretching and slipping of belts and fibers on pulleys, on the dynamic characteristics of electric motors, and the models of torsional oscillations of synchronous motors, turned out not to be applicable for modeling individually driven drawing godets. These models do not take into account two non linear effects: the non linear mechanical coupling of the thermoplastic filament yarn between two consecutive godets, and the non linear dynamic behavior of the electric motors. Another effect that has never been taken into account and analyzed is the effect of the damper winding on the dynamic behavior of small motors.

The yarn coupling the two godets is evaluated and linearized around its operating point (part of the answer to the third research question). The non linear behavior of the motors is linearized by establishing the operating point with test in the operating area.

Apart for big generators, almost no literature is available on damper windings. Experiments made on different designs of motors (chapter 4) show the effect of the damper windings. With the results of the experiments, a quantification of the effect of the damper winding in term of dampening constant is done.

The model proposed in this work is able to determine the dynamic behavior and the limits of stability of the system made of two godets with a lapping yarn. The elements of the system are modeled by mass-spring-dampening elements. The values of the spring and dampening coefficients are introduced from the experiments into the model.

The correct function of the model is checked by the comparison with the experiments. The final confirmation of the correctness of the model comes from a third observation in practice on full size machinery.

The third question:

*which is the interaction between the yarn and the drive?*
is answered with the results of the simulations in chapter 5 and in chapter 6.
The yarn with its modulus of elasticity is considered an elastic element. Theoretically, without any slip on the surface of the godets, the yarn couples mechanically the rotations of two consecutive godets.
The main effect of this elastic coupling is the amplification of the rotational oscillation of each godet. Simulations with different yarns having different modulus of elasticity, and with different motors, show the effect of the elastic coupling of the yarn. The eigenfrequencies of two consecutive godets with the lapping yarn are found to be between 30 and 110 Hz, depending on the type of the yarn. In this range of frequencies, disturbances like yarn tension oscillations due to other processes, torque ripple, and the out of balance of the godets, take place, and the oscillations are amplified.
The amplitude of the simulated oscillations is limited and the limit of stability of the system is calculated in Matlab. The risk of instability is confirmed by the low value of the phase margin, above all by the permanent magnet motor without damper windings.

What kind of drive is able to overcome these stability problems?
A bigger damper winding can provide a higher dampening coefficient and can reduce the risk of oscillations and instability.
The use of asynchronous motors with their inherent dampening behavior represents a very stable and cost efficient solution.
The use of a P.I.D. (proportional, integral, derivative) position controller with its additional dampening can also help to keep the oscillations limited, but it means high cost of the sensors and of the conditioning of the feedback signal.

Which could be the most suitable drive in terms of stability, efficiency, assembling costs, manufacturing costs, maintenance costs, energy costs, and cost of the control, for an application like the individually driven drawing godets?
For an application like the Hotbox, the asynchronous induction motor in closed loop control represents a very suitable drive in terms of stability, assembling costs, manufacturing costs, and maintenance costs. The use of the closed loop control is due to the need to control the slip of the motor, in order to keep the draw ratio constant.
For the efficiency and the energy cost, the most suitable drive is the permanent magnet motor with damper winding. The use of the open or the closed loop control depends on the precision required by the produced yarn and thus on the need of additional dampening.
For an application like the monofilament production line, a very suitable solution would be the permanent magnet motor with damper winding in open loop control. Due to their inherent magnetic principle, the speed of the multitude of godets in parallel feed is identical. The use of the damper winding reduces the oscillations in the dynamic state due to external disturbances, and helps to start up the motor to the operation speed. The value of the damper winding should be sufficient to dampen the oscillations. If the value of the oscillations can not be kept under a given range, defined by the yarn quality requirements, closed loop control should be used.

The following table sums up the major parameters for a decision on the different drives.

<table>
<thead>
<tr>
<th>Motor Type</th>
<th>Parallel feed</th>
<th>Static speed accuracy</th>
<th>Dynamic speed accuracy</th>
<th>Cost of assembling</th>
<th>Energy efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asynchronous induction motor, open loop control</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Asynchronous induction motor, closed loop control</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Hi</td>
<td>Low</td>
</tr>
<tr>
<td>Synch. Reluctance motor, open loop</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Hi</td>
<td>Average</td>
</tr>
<tr>
<td>Synch. Reluctance motor, closed loop</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Hi</td>
<td>Average</td>
</tr>
<tr>
<td>Synch. Permanent magnet, open loop</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Low</td>
<td>Hi</td>
</tr>
<tr>
<td>Synch. Permanent magnet, closed loop</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Hi</td>
<td>Hi</td>
</tr>
<tr>
<td>Synch. Permanent magnet with damper winding, open loop</td>
<td>Possible within limits</td>
<td>Yes</td>
<td>Possible within limits</td>
<td>Hi</td>
<td>Hi</td>
</tr>
<tr>
<td>Synch. Permanent magnet with damper winding, open loop</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Hi</td>
<td>Hi</td>
</tr>
</tbody>
</table>

Table 22: Parameters to choose the suitable motor and drive for individually driven drawing godets.

The answer to the last research question is in Chapter 6:

*In the design and construction of a motor for individually driven godets, and also for similar applications, which are the parameters and the tools that might be used?*
With the model in Working Model, the dynamic behavior of different design of godets and different type of yarns is simulated. The type of motor is thus determined according to the requests on the precision of the drive and on the energy consumption.

In case of permanent magnet motor with damper windings, the section of the damper winding is determined by the value of the required dampening constant. This is determined by the value of the oscillations that are accepted by the production of the yarn.

With the analytical model in Matlab, the limits of stability and the step response analysis is calculated and simulated.

In case of closed loop control, the block diagrams model in Simulink helps finding the optimization of the controller.

7.3 FURTHER RESEARCH ON INDIVIDUALLY DRIVEN DRAWING GODETS

The development of the controllers with the definition of the dynamic parameters (depending on the motor) for the closed loop control, such as the speed accuracy and the dampening is a future topic of research. With the use of the model in Simulink (Chapter 6), the concept of the closed loop control and the optimization for the different motors is done.

During the first phase of this project, because no permanent magnet motor with the required cost, power, and size was offered on the market, the focus was to develop a permanent magnet synchronous motor to satisfy the request of the godets of the Hotbox. In this phase a lot of ideas of possible innovative constructions of the permanent magnet rotor and also of the stator appeared and some of them were developed by students during their Semester and Diplom project works. [59] [60] [61] [74]

New designs of the rotor may also yield better dynamic properties of the motor, i.e. a higher damper constant. A study on the effect of different design of synchronous permanent magnet motors with damper winding on the dynamic of individually driven godets is a topic of a possible future work. Better dynamic speed accuracy together with a reduced cost of the assembling could be obtained.
The study of the design of the electronic commutated Maxon motors and their special windings gives new ideas for a slottless and fully automated construction of the stator. The absence of the slots has a big advantage reducing the torque ripple. A study of the amount of the torque ripple, of the dynamic characteristic of such a motor, and of the possibility of a fully automation of the assembling of the winding of the stator is the matters of future engineering works.

In this work, the dynamic properties of the yarn are taken independent on temperature. Tests on the stress-strain behavior under different temperatures should be done in order to better model and analyze the yarn dynamic in the Hotbox and generally in the drawing process.

During the filament yarn drawing, because of changes in the yarn properties and also because of rotational oscillations of the driving elements, the processed yarn may slip irregularly on the surface of the godets. This sticking and slipping of the yarn lead to an irregular tension and then to a poor yarn quality. The study of the causes and of the effects of this stick-slip phenomenon represents an interesting topic for future developments of godets. The temperature, the roughness of the surface, the geometry of the godets and the distance between the godets, may have a big impact on the yarn tension. A possible future work on the influences of these geometric parameters with attention to the angle between the two axes of the godets of a Hotbox may also help to understand the dynamic behavior of the yarn on the surface of the godets.

In this work, the dynamic behavior of the yarn in a godet duos (Hotbox) is shown and analyzed. A possible future work could be the analysis of the dynamic behavior of the yarn in the drawing zone, i.e. between two consecutive Hotboxes. In this case, the yarn is not lapping around two elements, and it does not represent an elastic coupling between them. However, the tension and the temperature are the two most important parameters that determine the yarn properties. The study and the control in the drawing zone are decisive for a good quality of the yarn and may represent a topic for a future engineer project.

Sensorless control of synchronous reluctance motors has made a lot of progress during the last years. This offers new points of discussions and studies.

The S.S.P. (Sensorless Speed and Position) reluctance motor, presented by REEL S.r.l. can be controlled in sensorless until a certain torque load. It assures performance in speed and position control comparable to a closed loop drive. The big advantage of such a solution is the very simple and cost convenient construction and the very low inertia of
the rotor. With a common three phase wound stator and a rotor made of a steel lamination package similar to the squirrel cage asynchronous rotor, it might be a very interesting solution for a drive of the Hotbox. Since it is a very new solution with a new dedicated drive, the dynamic behavior is still unknown and depends directly on the rotor construction and on the drive. Detailed studies on the dynamic behavior of the godets with this type of motor and drive may show chances and drawbacks of this drive solution.

In De Crescenzo [75], a feasible new development of a drawing box was presented. A drawing box is a completely new system made of two special conical godets, enclosed in a heating box. The two conical godets are so designed that they have levels where the lapping yarn lays on. Due to the increasing diameter of the levels of the conical godets (Fig.119), the yarn speed increases at each wrap around the godets. The yarn is by this continuously stretched at each wrap, with a drawing ratio proportional to the differences of the diameter of the levels. A lot of space, a lot of driven elements, and a lot of energy may thus be saved.

Studies and experiments on the feasibility of such godet design together with an analysis of the resulting yarn properties may represent a very interesting basis for a further development of individually driven drawing godets.

The precision requested by such a drive is very high and no torsional oscillations are accepted.
In filament drawing and filament draw-texturing, over the past 20 years almost no developments and innovations have been introduced into production machines. The consequence is the limitation in speed accuracy and thus the limitation in process speed. Sensors for yarn quality measurements and for process control, like sensors for measuring the tension of the processing yarn, sensors for measuring the speed of the turning parts, and sensor to measure the speed of the yarn, are tools that help to study, to control and to improve the process. None of such sensors are in common use in the production plants.

New technologies in drive system, electronics, and in sensors leave a lot of chances of possible developments for energy saving, for yarn quality improvement and for higher production speed; as it is shown with the project “FasTex”.

Fig.119: Yarn stretching with a drawing box. [75]
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ANNEX 1: RESULTS OF EXPERIMENTS

Measured values of the stator resistance with a phase current of 0.65 A

<table>
<thead>
<tr>
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<th></th>
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<tbody>
<tr>
<td>0</td>
<td>32.54</td>
<td>595</td>
<td>39.5</td>
</tr>
<tr>
<td>50</td>
<td>35.125</td>
<td>635</td>
<td>39.625</td>
</tr>
<tr>
<td>100</td>
<td>36.5</td>
<td>680</td>
<td>39.75</td>
</tr>
<tr>
<td>135</td>
<td>36.875</td>
<td>732</td>
<td>39.875</td>
</tr>
<tr>
<td>160</td>
<td>37.125</td>
<td>785</td>
<td>40</td>
</tr>
<tr>
<td>180</td>
<td>37.375</td>
<td>835</td>
<td>40.125</td>
</tr>
<tr>
<td>220</td>
<td>37.75</td>
<td>892</td>
<td>40.25</td>
</tr>
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<td>280</td>
<td>38.125</td>
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<td>40.375</td>
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<td>41.125</td>
</tr>
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<td>39.25</td>
<td>1727</td>
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<td>39.375</td>
<td>1910</td>
<td>41.25</td>
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Diagram of the measured stator resistance with a phase current of 0.5 A
Diagram of the measured stator resistance with a phase current of 0.8 A

Stationary torque measurements on permanent magnet synchronous motor, positions of balance (Motor1):

<table>
<thead>
<tr>
<th>Position. [°]</th>
<th>Weight [N]</th>
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<tbody>
<tr>
<td>1.1999988</td>
<td>0.981</td>
</tr>
<tr>
<td>1.333332</td>
<td>1.1772</td>
</tr>
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<td>1.4666652</td>
<td>1.2753</td>
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<td>1.999998</td>
<td>1.6677</td>
</tr>
<tr>
<td>2.666664</td>
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<td>2.999997</td>
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</tr>
<tr>
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<td>83.33325</td>
<td>5.886</td>
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</table>
Rotational oscillation of synchronous reluctance motors: the sequence of the frames of the oscillation and the calculated angle (Chapter 4):
ANNEX 2: RESULTS OF SIMULATIONS

Dynamic elastic modulus of the yarn as calculated with the results of SWaTT, for different wraps around the godets (Chapter 5):

<table>
<thead>
<tr>
<th>Wraps</th>
<th>POY [N/m]</th>
<th>FDY drawn [N/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca. 1 wrap</td>
<td>520</td>
<td>1500</td>
</tr>
<tr>
<td>Ca. 2 wraps</td>
<td>1000</td>
<td>x</td>
</tr>
<tr>
<td>Ca. 4 wraps</td>
<td>x</td>
<td>6000</td>
</tr>
<tr>
<td>Ca. 6 wraps</td>
<td>6000</td>
<td>9300</td>
</tr>
<tr>
<td>Ca. 7 wraps</td>
<td>x</td>
<td>10850</td>
</tr>
</tbody>
</table>

Results of constant load simulations on asynchronous motor:

With a load of 0.02 Nm:

![Graph](image-url)
With a load of 0.08 Nm:

With a load of 0.1 Nm:
ANNEX 3: DIFFERENT DESIGNS OF GODETS

Godet DIENES (Figure and properties):

- **Godet Diameter**: 220 mm.
- **Lengths**: 310-370-450 mm.
- **Speed**: Up to 8000 rpm
- **Drive**: Inverter up to 20 kVA
- **Maximum force**: 140 N
- **Motor power**: 5 kW
- **Maximum temperature**: 400°C
- **Uniformity of temperature**: +/- 1.5°C
- **Temperature sensor**: Rotating Pt100 - 1 x zona
- **N. heating zones**: Up to 5
- **Heating Power**: kW 15

Small Godet DIENES (Figure and properties):

- **Diameter**: 80/100/120 mm
- **Lengths**: 75/90/100/121/150 mm
- **Speed**: 600/1,200/2,500 rpm
- **Drive**: Direct electric motor or belt drive
- **Maximum force**: 10/15/25/40 N
- **Maximum temperature**: 150°C-250°C
- **Uniformity of temperature**: +/- 1.5°C
- **Temperature sensor**: Pt100
Godet RETECH (Figure and properties):

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Godet Diameter</td>
<td>100 – 300 mm</td>
</tr>
<tr>
<td>Lengths</td>
<td>100 – 700 mm</td>
</tr>
<tr>
<td>Speed</td>
<td>≥6000 rpm</td>
</tr>
<tr>
<td>Drive</td>
<td>Induction motor with inverter</td>
</tr>
<tr>
<td>Maximum force</td>
<td>160 N</td>
</tr>
<tr>
<td>Maximum temperature</td>
<td>Induction: up to 250 °C, Infrared: up to 300 °C</td>
</tr>
<tr>
<td>Uniformity of temperature</td>
<td>± 2°C</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>Rotating or fixed Pt100</td>
</tr>
<tr>
<td>N. heating zones</td>
<td>≥ 3</td>
</tr>
</tbody>
</table>

Small Godet RETECH (Figure and properties):

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>60 - 130 mm.</td>
</tr>
<tr>
<td>Lengths</td>
<td>44 - 100 mm.</td>
</tr>
<tr>
<td>Speed</td>
<td>1.200 rpm</td>
</tr>
<tr>
<td>Drive</td>
<td>Direct electric motor or belt drive</td>
</tr>
<tr>
<td>Maximum force</td>
<td>40 N</td>
</tr>
<tr>
<td>Maximum temperature</td>
<td>Resistance: 180 °C, Induction: 250 °C</td>
</tr>
<tr>
<td>Uniformity of temperature</td>
<td>Not specified</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>Pt100</td>
</tr>
</tbody>
</table>
Godet Barmag (Figure and properties):

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>100 - 250 mm.</td>
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<tr>
<td>Lengths</td>
<td>80 - 535 mm.</td>
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<tr>
<td>Speed</td>
<td>8000 m/min</td>
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<tr>
<td>Drive</td>
<td>Inverter up to 20 kVA</td>
</tr>
<tr>
<td>Maximum force</td>
<td>160 N</td>
</tr>
<tr>
<td>Maximum temperature</td>
<td>250 °C</td>
</tr>
<tr>
<td>Uniformity of temperature</td>
<td>+- 1.5°C</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>Rotating Pt100</td>
</tr>
</tbody>
</table>
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ANNEX 6: CURRICULUM VITAE

MATTEO CASTIGLIONI
Im Isisbüel 4
8800 Thalwil (CH) Switzerland
Mobile: +41(0) 78 819 05 93
Office: +41 (0) 55 250 27 30
e-mail: mcastiglioni@ethz.ch

Civil status: married

PROFESSIONAL EXPERIENCE

2006-present
Sultex AG Rüti (ZH), CH

• 2006: In the quality assurance department as responsible for the outsourcing of the assembly and manufacturing of the Sultex rapier weaving machine. Definition of the processes and improvements in the quality of the delivery (technical and commercial specifications, completeness).

• 2006-2007: In the supply chain management as the responsible and the coordinator of the Sultex rapier weaving machine besides being a supply chain manager by two main Italian suppliers. Followed as supply chain manager the development of the terry version of the rapier machine, of an active rapier and of a reinforced rapier machine. Projects ended with the successful presentation at the ITMA ’07 in Munich.

• 2007-2008: Project leader of relocation/merging project from Rüti (CH) to Colzate (IT). Change and merge of informatic tools and transfer of activities related to bill of material, commercial configurator, technical documentations (3D models, drawings, assembly proceedings, etc.), and modification management. Merging two organizations while redefining the order fulfillment process, the supply chain management, the product care, and the quality management. Definition of all connected processes, interfaces, and responsibilities together with a new intercompany contract.

• 2008-present: Product manager of Sultex rapier machine (40 Mio. EU turn over). Managing customer commitments, development projects, and product care tasks with a team of 10 persons (software, electronic, and mechanical engineer, textile experts, designers). Budgeting personnel, investments and projects. Coordination with other departments: spare parts, service, sales, innovation, supply chain management, production, and general management.

2001-2006
ETH Swiss Federal Institute of Technology Zurich, CH

Assistant and researcher at the Institute of Manufacturing Automation under Prof. Dr. Urs Meyer

• 2001: Hilfassistent during the Exchange period at the ETH. Measurements using Piezoresistive sensor and finite elements simulation in Working Model. Subject: tension irregularities of a polyester yarn in the taking-up zone.

• 2001-2003: Responsible of the information technology: budgeting, managing, and maintenance of 50 WINPC connected through a LAN.

• 2002-2003: Responsible of the development and inventor of a new draw-texturing machine. First phase of feasibility study followed by the design, the mechanical and electrical planning, the construction and the textile tests. Presented at the ITMA in October 2003 under the name FasTex.EDU, it is patented by Rieter A.G. (WO2005038107).


• 2002-present: Supervisor and tutor of several semester and diploma works of students of the ETH Zurich, Politecnico di Milano (I), Università di Bergamo (I). Main subjects: machine control systems, drive technologies, mechatronics, textile measuring, logistics, and process analysis and optimization using POA (Process Oriented Analysis).
EDUCATION

2003-Present  ETH Swiss Federal Institute of Technology Zurich, CH
Ph.D. work at the Department of Management, Technology and Economics (D-MTEC) with the title: “Control and Stability in Velocity of individually driven drawing Godets for thermoplastic filament Yarn”.

1997-2002  Politecnico di Milano Milan, IT
Master Degree in “Management and Production Engineering” with focus on production processes.
Graduated 97/100, ranked top 2%. Different project works on risk analysis, logistics, ergonomics, business plan, and budgeting.

2001-2002  ETH Swiss Federal Institute of Technology Zurich, CH
Exchange student in the Erasmus program for the master degree thesis with the title “High Speed Texturing, a new concept of texturing Unit”. The thesis received the best mark possible and is a claim of the patent WO2005038107.

2000-2001  ETH Swiss Federal Institute of Technology Zurich, CH
Exchange student in the Erasmus program. Taken 6 exams (20 ECTS) in German language. Average mark: 5.25 (max. mark 6).

Sep 1997  Liceo Scientifico “M. Curie” Tradate (VA), IT
Secondary school degree in scientific subjects with the evaluation of 54/60. Merit award for a work on the studies of particles physics at the CERN in Geneva.

PERSONAL EXPERIENCE

2002-present  ETH-Università degli Studi di Bergamo
Organizator and guide of excursions for students of the ETH, HGK (Luzern), and Università di Bergamo to the most important Italian and Swiss textile companies (about 30 companies).

2004-2005  Facoltà di Ingegneria Tessile, Università degli studi di Bergamo Dalmine, IT
Giving classes on Textile Measuring Technology and Quality Control (about 30 students).

Oct 2003  ITMA International Textile Machinery Exhibition Birmingham, UK
Responsible of the installation of the stand and exhibitor during the exposition.

LANGUAGES

Italian (Mother tongue); German (fluent); English (fluent); Swiss German (good); French (basic).

PUBLICATIONS

Dec.2005  Neujahrsblatt aus dem Institut für Automatisierte Produktion der ETH Zürich, 2005

May 2005  The Fiber Society Spring Conference St. Gallen, CH
Paper with oral presentation: “Modeling of individually driven drafting Godets”.

Mar 2005  A.N.A.E. Azionamenti elettrici XVI Seminario interattivo Bressanone (BZ), IT
Paper with oral presentation: “Modellizzazione dinamica di godet di stiro usate nella lavorazione di fili sintetici”.

Nov 2004  Convegno per gli 80 anni dell’Università di Firenze Prato, IT
Forum: Università, Impresa, Società: Tra radicamento locale e competizione globale.
Paper with oral presentation: “Trasferimento tecnologico tra Università ed industria”.

Oct 2004  Fall annual meeting and technical conference, Fiber Society Ithaca (NY), US
Poster: “Dynamic modelling of driven drawing godets”.

Paper: “Modern drive technology, the key for high production in draw-texturing”.

Aug 2004  Man-Made Fiber Year Book 2004
Paper: “Modern drive technology, the key for high production in draw-texturing”.

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Gen 2004  
**Annual meeting: Synthetic fibers processing**  Dalmine (BG), IT
Oral presentation: “FasTex.EDU: testurizzazione ad alta velocità, sviluppo di un prototipo accademico”.

Oct 2003  
**FasTex.EDU, Ing. Matteo Castiglioni, Prof. Dr. Urs Meyer**
Patent WO2005038107. Claims: layout of the machine, cooling system, texturing unit and HotBox.

Gen 2003  
**Annual meeting at Rieter A.G.**  Winthertur, CH
Oral presentation: “Hochgeschwindigkeits-texturieren: Neuentwicklung eines Drallaggregates”.

SOFTWARE KNOWLEDGES


INTERESTS

Automobiles, travelling, physics, and tennis.