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DENOISING THE PRESSURE SENSITIVE PAINT MEASUREMENT OF UNSTEADY LOW-SPEED FLOW USING EXTENDED KALMAN FILTER BASED DYNAMIC MODE DECOMPOSITION

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KEYWORDS:
Main subjects: square cylinder, flow visualization
Fluid: low speed flow
Visualization method(s): Pressure Sensitive Paint
Other keywords: Dynamic Mode Decomposition, Extended Kalman Filter

ABSTRACT:
In the present study, the extended-Kalman-filter-based dynamic mode decomposition (EKFDMD) processing is applied to the unsteady pressure-sensitive-paint (PSP) data of the wake flow of the square cylinder. The wind tunnel experiment was conducted at the T-BART wind tunnel of Tohoku University. The freestream velocity was set to be 50 m/s and the 6.5 mm square cylinder mounted on a flat plate was located in the test section. The pressure fluctuation on the flat plate in the vicinity of the wake flow of the square cylinder was visualized by the PSP measurement, together with the unsteady pressure sensor measurement of a couple of points as a reference. The original PSP data accurately shows the primary peak but other peaks are hidden by the noise floor. The conventional singular value decomposition (SVD) processing is applied, but the secondary peak is not recovered, even if we carefully select the mode to reconstruct. On the other hand, EKFDMD processing gives us the secondary peak though the amplitude of the peak differs from the unsteady pressure sensor data.

1 Introduction

The pressure sensitive paint is very powerful tool to visualize and evaluate the pressure distributions on the surface of the model. Recently, a lot of efforts on developing the unsteady measurement of pressure distribution were dedicated. Especially in the low speed condition, signal-to-noise ratio becomes severe. One of the ways to improve the signal-to-noise ratio is using the signal processing techniques. Thus far, we employed the singular value decomposition (SVD)[1] which is equivalent to well-known proper orthogonal decomposition, to improve the signal-to-noise ratio. For this technique, we employed the prior knowledge that the pressure distribution owing to the fluid motion can be expressed by the finite number of the SVD modes. In other words, we use the knowledge that the data matrix of the pressure distribution of the fluid motion can be well approximated by the low-rank matrix. For further improvement of the signal-to-noise ratio, we need more of prior knowledge. Additional prior knowledge of the pressure distribution might be the temporal variation can be well approximated by the linear system expression. This idea is corresponding to the dynamic mode decomposition (DMD) approximation. Recently, one of the present authors proposed the extended Kalman filter based DMD (EKFDMD)[2] which simultaneously identify the system and denoise the data, and he demonstrated that it works well for the several test problems. In this study, EKFDMD is applied to the pressure sensitive paint measurement of unsteady low-speed flow.

2 Methods

The footprints of the unsteady wake of the square cylinder of the width of 6.5 mm are measured.[3] The freestream velocity was set to be 50 m/s. The suction type wind tunnel was employed. The polymer/ceramic sprayable pressure-sensitive paint which was developed for the unsteady measurement up to 3, 000 Hz was utilized. The high speed camera Photoron SA-X was used for taking the unsteady images. As a reference, the Kulite pressure sensor measurement was simultaneously conducted. We applied the SVD signal processing technique and the EKFDMD processing technique to the data obtained. We compare the unsteady pressure distribution and discrete-Fourier-transform results of raw data, SVD processed data, and EKFDMD processed data.

Here, the idea of the EKFDMD is shortly addressed. We assume the data has following relationship in the framework of the dynamic mode decomposition:

$$\mathbf{x}_{n+1} = \mathbf{A}\mathbf{x}_n \tag{1}$$

Here, $\mathbf{x}_n$ is state of flow fields of the nth time step, and $\mathbf{A}$ is coefficient matrix for time advancement of the system. In the extended Kalman filter, the system is written in the extended state variables including coefficient matrix in the follow equation, and those states are estimated by using the extended Kalman filter. In the EKFDMD, both $\mathbf{x}_n$ and $\mathbf{A}$ are treated as state variables and are estimated as follows.

$$\begin{aligned} \boldsymbol{\theta}_{n+1} &= \begin{bmatrix} \mathbf{x}_{n+1} \\ vec(\mathbf{A})_{n+1} \end{bmatrix} \\ &= \mathbf{f}(\boldsymbol{\theta}_n) + \mathbf{v}_n \\ &= \begin{bmatrix} \mathbf{A}_n\mathbf{x}_n \\ vec(\mathbf{A})_n \end{bmatrix} + \mathbf{v}_n \end{aligned} \tag{2}$$

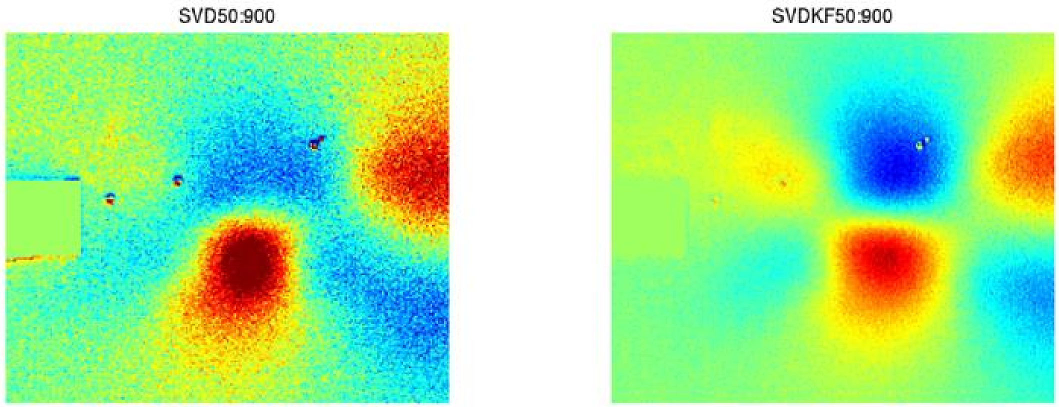
$$\begin{aligned} \mathbf{y}_{n+1} &= \begin{bmatrix} \mathbf{I} & \mathbf{0} \end{bmatrix} \boldsymbol{\theta}_{n+1} + \mathbf{w}_n \\ &= \begin{bmatrix} \mathbf{I} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{x}_{n+1} \\ vec(\mathbf{A})_{n+1} \end{bmatrix} + \mathbf{w}_n \end{aligned} \tag{3}$$

Here, $\boldsymbol{\theta}_n$ is state variables for the extended Kalman filter and $\mathbf{f}$ is the nonlinear function for the time advancement of state variables. $\mathbf{v}_n$ and $\mathbf{w}_n$ are system and observation noises, respectively. It should be noted that an assumed system is linear but the considered extended system is nonlinear and the extended Kalman filter should be used for represent the system.

The system described above is estimated by the extended Kalman filter. The dynamic mode can be computed by analyzing A after the filtering. In the present experiment, the EKFDMD is applied to the time history of the SVD modes because the EKFDMD for many-degrees-of-freedom require huge computational costs. See reference[2] for more details.

3 Results

Figure 1 shows SVD and EKFDMD processed data. The noise of the EKFDMD results seems to be reduced much. The temporal spectra compared with the Kulite sensor were shown in Fig. 2. The results show that the raw data only shows the first peak because of the very high noise floor level cover the second peak. The SVD results show that the noise floor can be reduced 10 times lower. However, the second peak was not observed well. On the other hand, EKFDMD results show that the first and second peaks are clearly captured while the other part of spectra were too much reduced even compared with the Kulite sensor output. This leads to difficulty in the quantitative evaluation of the pressure distribution, while EKFDMD can be used for the qualitative discussion because it captures the very small second peak.



(a) 50 mode SVD results (b) EKFDMD for 50 SVD modes

Fig. 1 Results of original PSP and EKFDMD processed one.

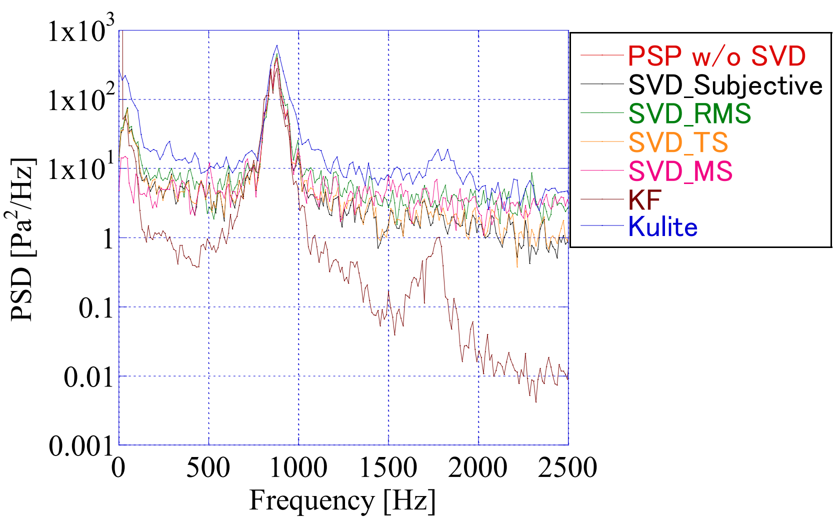


Fig. 2 Spectra obtained by manually-selected-SVD-processed data and EKFDMD data.

4 Conclusions

In this study, EKFDMD was applied to the pressure sensitive paint measurement of unsteady low-speed flow. EKFDMD utilize the prior knowledge that the pressure distribution can be approximated by the linear system. The results show that the EKFDMD captures the very small pressure peak in the spectrum and it can be used for the qualitative discussion of the unsteady pressure measurement.

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