August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering
ICWE 16

Identifying dominant flow field features in an isolated street canyon: a data-driven analysis procedure

Xisheng Lin [1], Yunfei Fu [2], Cruz Y. Li [3], Tim K.T. Tse [4]

[1]*The Hong Kong University of Science and Technology, Hong Kong, China, xlinbl@connect.ust.hk*
[2]*The Hong Kong University of Science and Technology, Hong Kong, China, yfuar@connect.ust.hk*
[3]*The Hong Kong University of Science and Technology, Hong Kong, China, yliht@connect.ust.hk*
[4]*The Hong Kong University of Science and Technology, Hong Kong, China, timkttse@ust.hk*

SUMMARY: (10 pt)
This work develops a data analysis procedure, namely Proper Orthogonal Decomposition (POD)-Dynamic Mode Decomposition (DMD) augmented analysis, to isolate the energy- and evolution-wise dominant features of flow field in a street canyon. Demonstrated via a generic street canyon flow simulated through large-eddy simulation (LES), this systematic procedure identified three types of flow field modes according to energetic and dynamic significance, providing useful guidance for pollutant dispersion phenomenon analysis.

Keywords: Large-eddy simulation, Proper orthogonal decomposition, Dynamic mode decomposition

1. INTRODUCTION

Reduced-Order Models (ROMs) are suggested as an efficient solution to isolating spatial features and dynamical properties from the complex high-dimensional flow field. Among the present ROMs, Proper Orthogonal Decomposition (POD) is one popular scheme that has been widely employed to investigate pollutant dispersion and wake dynamics around buildings and moving vehicles (Wang et al., 2020). The limitations of POD lie in its modes mixed in frequency and its neglecting some low-energy modes that impose significant dynamical effects on the flow field. This leads to difficulty in identifying flow patterns corresponding to each dominant frequency and poor low-dimensional reconstruction models (Rowley and Dawson, 2017).

DMD is another purely data-driven ROM where each mode contains a unique frequency, providing great convenience in identifying specific dynamic features (Schimid, 2010). Additionally, the mode selection criterions applied in DMD such as the α-criterion (Kutz et al., 2016) efficiently evaluate DMD modes' dynamical influence. However, DMD is weak in determining the highly physically relevant modes due to lacking an approach to ranking eigenvalue significance. Due to the two schemes' limitations, this paper develops a POD-DMD augmented analysis procedure to isolate dominant features of fluid-driven pollutant dispersion in a street canyon from the perspectives of both energetic and dynamic significance. The dominant flow field structure patterns and their contribution to pollutant dispersion are identified and concluded.

2. METHODOLOGY

2.1. POD-DMD augmented analysis procedure

The POD-DMD augmented analysis procedure can be formulated as four steps, as shown in Fig.1: Firstly, conduct POD and DMD to the raw flow field data. Secondly, find the dominant frequencies of the first POD mode through Fast Fourier Transform (FFT) analysis, after which classify the DMD modes into three types based on the dominant frequencies of the first POD mode: (1) type 1: energetically & dynamically significant mode; (2) type 2: energetically significant & dynamically insignificant mode; (3) type 3: energetically insignificant & dynamically significant mode. Thirdly, analyze the mode contribution based on the mode patterns of each mode type. Fourthly, conduct superposition to the three types of modes to have a comprehensive judgement of the dominant flow structures each mode type contributes to from energy and dynamical perspectives.

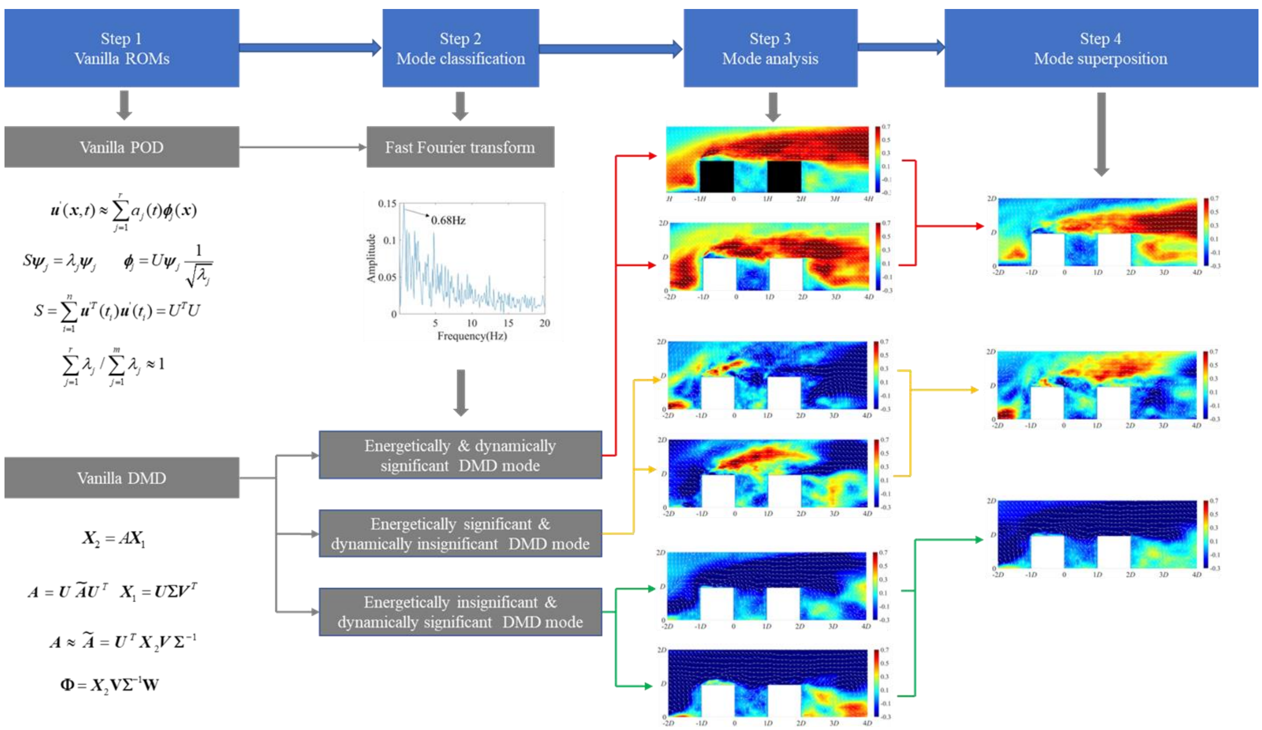

Figure 1. A conceptual rundown of the POD-DMD augmented analysis procedure.

2.2. Test Subject

Fig.2 shows the configuration of the computational domain and the building model. The street canyon model was composed of two parallel buildings with width (streamwise-*z*) × height (vertical-*y*) × length (spanwise-*x*) = $H \times H \times 10H$ (H = 120mm). The tracing gas sulfur hexafluoride (SF_6) was emitted from four line sources situated at the bottom of the model. The street canyon model was located in a computational domain with dimensions of $16.6H \times 28H \times 8.3H$ ($x \times z \times y$). Two subdomains, an inner domain Ω_1 and an outer domain Ω_2, were created to form the complete domain. In subdomain Ω_1, cubic cells with edges length equal to *H/40* were used. Hexahedral cells with a stretching ratio of 1.05 were applied for subdomain Ω_2. There were 11.9 million cells in all.

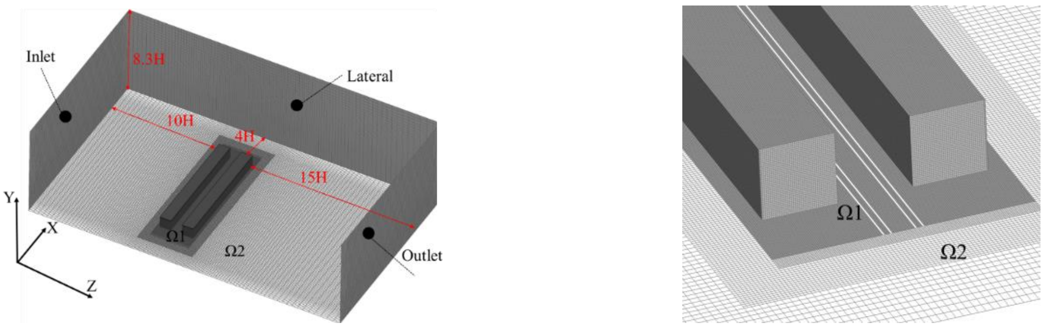

Figure 2. The dimensions of the street canyon model and the computational domain

3. RESULTS AND DISCUSSION

3.1. Mode classification

The unique frequency of each DMD mode can be found in one of the dominant frequencies of either a high-ranking or low-ranking POD mode. The high-ranking POD modes provide the greatest energy contribution to the whole flow field, while the high-ranking DMD modes bear a higher dynamical influence. Therefore, the modes' contribution to the flow field can be evaluated from both energetic and dynamic perspectives by combining the two techniques. In detail, three types of DMD modes can be isolated based on the dominant frequencies of POD modes (see Table 1.).

Table 1. POD mode's dominant frequencies and DMD mode classification

POD	Freq.	DMD	Rank	Freq.	Mode type
Mode 1	0.68	Mode 1-2	High	0.68	Energetically & dynamically significant mode
	1.07	Mode 3-4		2.13	
	1.36	Mode 5-6		0.77	Energetically insignificant & dynamically significant mode
	2.15	Mode 7-8		0.78	
	2.34	Mode 157-158	Low	1.07	Energetically significant & dynamically insignificant mode
	2.63	Mode 277-278		2.34	

3.2. Mode analysis

Fig. 3 illustrates the normalized velocity vectors on the *y-z* plane at $x/H = 0$ of DMD mode 1-2, which belongs to mode type 1: energetically & dynamically significant mode. It delineates typical flow structures which can be observed in the mean flow field, including flow separating and reattachment. Nonetheless, this is not to say that the mode resembles mean flow field. Instead, this mode is supposed to work as the primary energy contributor, which transports energy to the mean flow field continuously. This stable and continuous contribution makes the mean flow field form such a distribution pattern.

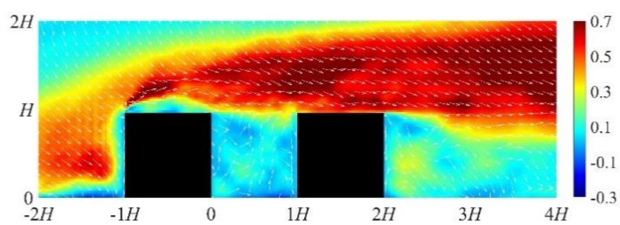

Figure 3. Normalized velocity vectors on the *y-z* plane at $x/H = 0$ of DMD mode 1-2

3.3. Mode superposition

The mode superposition step adds up the modes within one type to have further investigation to the mode's contribution to the flow field. Fig. 4 shows the normalized vectors of Mode type Ⅲ: energetically insignificant & dynamically significant mode. This mode type contributes to the long-term reversed flow structures, occurring near the stagnation point, inside the street canyon, and in the wake region. The velocity of these structures is slow, accounting for their low energy contribution to the flow field. These modes are a practical street-canyon illustration of the low-energy but highly dynamic modes found by Noack et al (2008). Lacking considering these modes may lead the flow reconstruction inaccuracy.

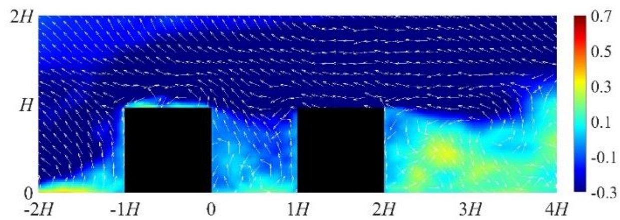

Figure 4. Normalized velocity vectors on the *y-z* plane at *x/H* = 0 of Mode type III

4. CONCLUSIONS

A mode analysis method combing POD and DMD techniques successfully extract modes imposing critical influence on the flow field from both energetic and dynamical perspectives. According to the dominant frequencies of the first POD mode, the extracted modes are classified as three types. Results show that mode type 1 contributes to the mainstream and the main vortex structures, which occur near the stagnation point, the separating point, and the fluid reattachment area; Mode type 2 throws light on where the turbulent kinetic energy is the largest, leading to periodically sudden pollutants increase on the building roofs and in the wake region. Mode type 3 contributes to the long-term reversed flow structures, occurring near the stagnation point, inside the street canyon, and in the wake region. These findings help to better understand the flow field in complex urban environments, and might have potential applications in the future, such as pollutant dispersion issues on a city scale.

ACKNOWLEDGEMENTS

We thank the IT Office of the Department of Civil and Environmental Engineering at the Hong Kong University of Science and Technology for its support in installing, testing, and maintaining our high-performance servers.

REFERENCES

Wang, F., Liu, C. H., and Xie, J., 2021. Wake dynamics and pollutant dispersion behind a light-duty lorry. Physics of Fluids 33(9), 095-127.

Rowley, C. W. and Dawson, S. T. M., 2017. Model reduction for flow analysis and control. Annual Review of Fluid Mechanics 49(1), 387-418.

Schmid, P. J., 2010. Dynamic mode decomposition of numerical and experimental data. Journal of Fluid Mechanics 656, 5–28.

Kutz, J. M., Brunton, S. L., Brunton, B. W., and Proctor, J. L., 2016. Dynamic mode decomposition: data-driven modeling of complex systems. Society for Industrial and Applied Mathematics, PA, USA.

Noack, B. R., Schlegel, M., Ahlborn, B., Mutschke, G., Morzynski, M., Comte, P., and Tadmor, G., 2008. A finite-time thermodynamics of unsteady fluid flows. Journal of Non-Equilibrium Thermodynamics 33(2), 103-148.