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Application of Proper Orthogonal Decomposition to physically simulated downburst wind loads

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SUMMARY:
Proper Orthogonal Decomposition (POD) is a means of decomposing a set of time-series (e.g. the fluctuating pressures at multiple positions spanning a building envelope) into a set of modes and corresponding, time-varying mode coefficients. The POD method presents these modes in order of descending "energy" of the original signal they contain, giving a means of approximating the original signal by inclusion of a reduced number of modes. In this paper, POD is applied to velocity and pressure data measured during a set of pulsed impinging jet physical simulations of thunderstorm downburst-like flows.

The analysis demonstrates the run-to-run consistency of the simulations for both the generated velocity field and the pressure field it generates on a portal-framed building model. The overwhelming majority (>85%) of the velocity and pressure field fluctuations are captured in the first two POD modes, and the mode shapes elucidated for each run fall within a narrow range of the across-run mean mode shape.

Keywords: Downbursts, POD, Wind loading

1. INTRODUCTION

It is acknowledged that small-scale (non-synoptic), extreme wind events associated with convective storms, such as downbursts, are the design-load case for structures in many parts of the world (e.g. Chay and Letchford, 2002). The differences between a downburst flow field and that of standard atmospheric boundary layer (ABL) are well-recognised, with studies ranging from the early work of Fujita (1985), Hjelmfelt (1988) and others, through to the more recent work of Lombardo (2018), showing important features such as the nose-shaped wind speed profile, with a maximum near the ground. The importance of these events in design is evidenced by the number of studies aimed at physically simulating downburst wind fields in order to quantify their loading (e.g. Chay and Letchford, 2002; Jesson et al., 2015b, 2015a; Junayed et al., 2019; Kim et al., 2007; Lin and Savory, 2010).

In the analysis of wind loading, Proper Orthogonal Decomposition (POD) is often applied to reduce the dimensionality of the system, particularly for modelling of structural dynamic response. In the study of downbursts, POD has been applied to the wind field in the development of models of downburst flows (e.g. Chen and Letchford, 2005), while more generally POD is receiving renewed attention due to the potential for application in machine learning for wind engineering (e.g. Diop et al., 2022). In the current paper, POD is applied to both velocity and pressure fields time-series data recorded at multiple spatial locations (specifically sets of velocity data measured at multiple heights above ground, and sets of pressure data measured at points spanning a rectangular grid) for which data are recorded at regular time intervals.

In POD analysis If there are N measurement points and data are recorded N_t times, once every Δt seconds, then the data may be written as $\boldsymbol{X}(t) = \{x_1(t), \dots, x_N(t)\}$ $(t = \Delta t, 2\Delta t, \dots, N_t\Delta t)$, a time-varying vector in N-dimensional space. Each $x_i(t)$ is the time-series recorded at the i^{th} measurement point, and is the time-varying co-ordinate of the i^{th} standard basis vector for $\mathbb{R}^N$. The purpose of POD is to find an alternative orthonormal vector basis, specifically that which best correlates with the recorded data. Due to space constraints, full details of POD are not given in this extended abstract, but the reader is directed to Tamura et al. (1999), Baker (2000) and Chen and Letchford (2005) for details and discussion of its application in wind engineering.

2. METHOD AND DATA

This paper uses data recorded during a set of novel experiments to quantify downburst wind loading on buildings. The experiments were conducted in the University of Birmingham Transient Wind Simulator (TWS), a $D = 1m$ diameter, pulsed impinging jet simulator fully described by Jesson et al. (2015b, 2015a), which has been shown to produce a 1:1600 scale simulated wind field of an isolated, microburst flow. Velocity data were recorded at 25 vertical positions using multi-hole velocity probes at rate of 10kHz, with pressure data recorded using a bespoke 64-channel digital pressure measurement system at a rate of 500Hz. A limitation of the experimental setup was the need to record velocity and pressure data separately. Due to the known run-to-run variation of such simulators, 10 experimental runs were performed for each set of measurements and an ensemble-mean approach used to allow generalisable conclusions to be drawn.

The velocity data presented here were recorded at the radial position, x, where the peak maximum velocity occurred, i.e. $x/D = 1.5$. Pressures were measure at tappings on the windward half of the roof of a $42 \times 240 \times 130mm$ (eaves height × ridge length × width), $53mm$ ridge height, portal-framed building model in a 9×5 grid – more details are available in Jesson et al. (2015b, 2015a). All data shown in this extended abstract are for the $0°$ yaw case, with the radial outflow perpendicular to the ridge line.

It is typical in the study of transient wind events to decompose the velocity time-series into a time-varying mean component and a zero-mean, fluctuating component. This approach has been followed in this work, using wavelet decomposition via a coupled discrete wavelet transform and inverse wavelet transform, with the inverse using only those coefficients corresponding to low-frequency levels. The choice of cut-off is not clearly defined, with the exception that the zero-mean quality of the residual high-frequency component must be ensured. The decomposition was performed using the wavedec and waverec functions of the Matlab Wavelet Analysis Toolpak, with 15 and 12 levels for the velocity and pressure data respectively (determined by the length of the time-series, $32768 = 2^{15}$, $4096 = 2^{12}$) in total and the first 6 and 7 levels respectively used for the low-frequency reconstruction. This paper uses the POD code developed for Matlab by Zigunov (2019).

3. RESULTS AND DISCUSSION

Key findings from the initial POD analysis are given in this extended abstract - additional results will be presented at the conference and, if applicable, the full-length paper. For individual runs, Mode 1 contributes approximately 85% of the velocity time-series fluctuations around the mean (Figure 1, left), with Mode 2 contributing approximately 3% and subsequent modes contributing ~2% or less. In the case of the ensemble-mean run, the contribution of Mode 1 increases to 95%. This increase can be explained by the smoothing effect of the across-run averaging process used to calculate the ensemble-mean, and the consequent reduction in the high-frequency fluctuations. Similarly, Mode 1 dominates the pressure field decomposition, encapsulating 90% of the fluctuations for the raw pressure data (Figure 1, middle) and ~98% for the low-frequency decomposition pressure data (Figure 1, right). In the latter case, Mode 1 is of approximately the same weighting in both the individual run and ensemble-mean cases, consistent with both being an indirect form of low-pass filter themselves.

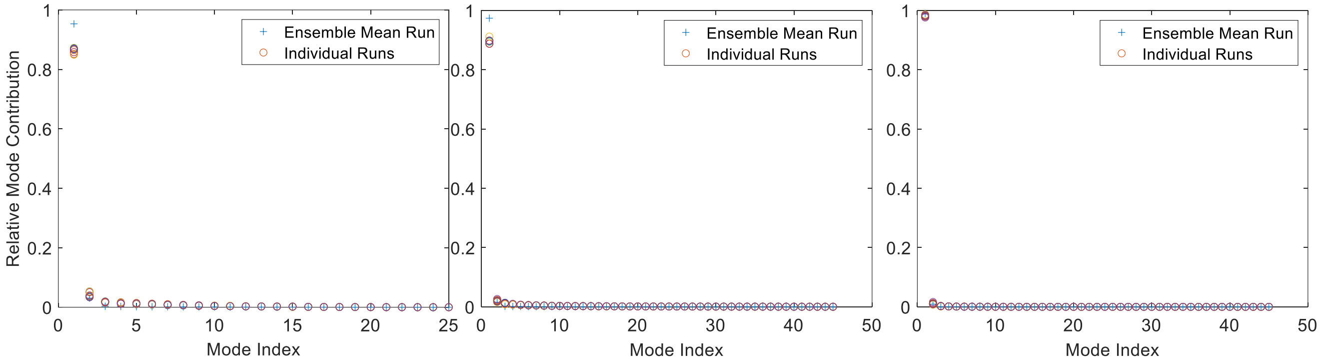

Figure 1. Relative contribution of each mode to the velocity (left), raw pressure (middle) and low-frequency pressure component (right) time-series for the ensemble-mean run and the individual runs.

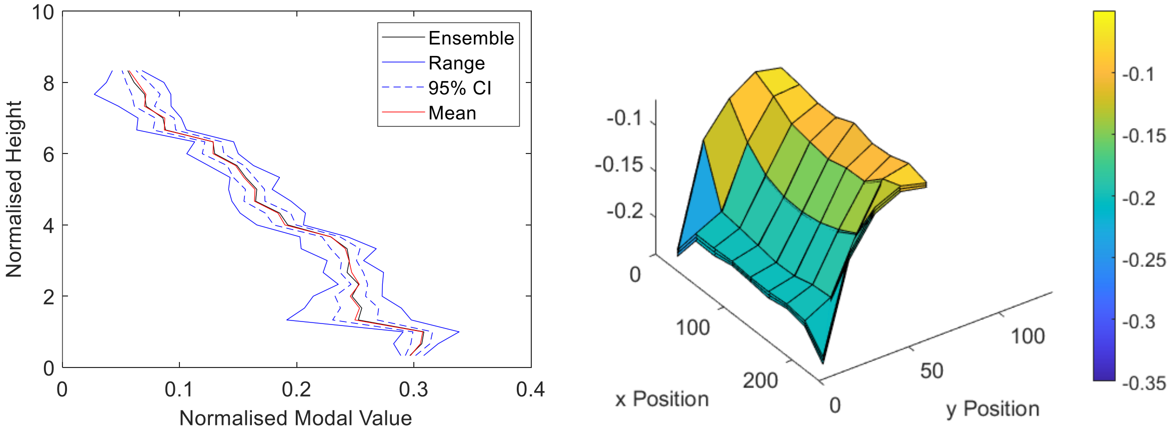

Figure 2. Mode 1 Shapes for velocity 1 (left) and roof pressure (right). Confidence interval (CI) based on the across-run standard deviation for each point; upper and lower surfaces in right-hand figure indicate 95% CI

Mode 1 (Figure 2, left) is of a similar shape to the peak-maximum velocity profile produced by the TWS (see Jesson et al., 2015b). The mode shape for the ensemble-mean run follows the shape of the mean of the mode shapes for the individual runs (the "across-run mean"). The individual run mode shapes all follow the same pattern, with a narrow 95% confidence interval

(CI). As will be discussed in the presentations, more run-to-run variation is seen for Mode 2 with the range showing both positive and negative values at each height and deviation of the ensemble-mean run and the across-run mean shapes. Similar run-to-run consistency is seen for the 2-D pressure field Modes 1 (Figure 2, right). These findings indicate that POD may be suitable for reducing the dimensionality of velocity and pressure models, with possible application to machine-learning approaches to model downburst wind loading.

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