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Reconstruction of wind field measurements: a machine learning approach

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SUMMARY:
Validating post-event investigations and numerical simulations is primarily done in wind tunnels, either at reduced scale or large-scale testing. A realistic solid-fluid interaction is required for wind tunnel testing to understand how a building responds to wind loads. The test chamber at the Insurance Institute for Business & Home Safety is capable of running full-scale experiments. To recreate field measurements, the test chamber uses active (vane and fan modulation) and passive (stationary spires) flow controls. With active fan modulation, traditional linear relationships between fan RPM and velocity are no longer valid. In this paper, the methodology to recreate a desired unsteady velocity time history is explained. Several years of data collected at IBHS test chambers were used to train a Lasso regression model. In this model, velocity and its derivatives (1^{st} to 30^{th}) are predictors, and RPM time history is the response. The flow characteristics in the field (mean wind speed, 3s gust, turbulent scales and intensities) were compared with those in the IBHS test chamber. This technique is able to accurately simulate wind flow in testing facilities and replicate unsteady field measurements.

Keywords: Wind tunnels, Machine Learning, Transient flow.

1. INTRODUCTION

The main way of validating hypotheses derived from post-event investigations and numerical simulations is through experiments, whether reduced scale or full scale. There are, however, limitations to experimental testing. Reduced-scale tests are governed by dimensional analysis where the Reynolds, Froude, and Rayleigh numbers remain constant between a model and its full-sized counterpart (Tieleman, 2003). Nondimensional groups often have competing interests, making it impossible to satisfy a number of them simultaneously. Furthermore, the relative interactions between wind forces and materials' resistance cannot be scaled down proportionally beyond a certain scale factor. As a result, large-scale and full-scale testing is essential.

Wind load on buildings is significantly affected by different characteristics of the flow including mean wind speed, maximum gust value, turbulent scales and intensities. It is very difficult, if not impossible, to match artificially generated wind flows to field measurements. To match flow characteristics to field measurements, roughness elements are typically used in front of a uniform flow (Farell and Iyengar, 1999; Fernández-Cabán and Masters, 2020; Tieleman, 1993, 2003). There could be tens of meters of roughness elements upwind of the test building. To overcome this problem, the wind tunnel at the Insurance Institute for Business & Home Safety uses active fan controls, spires, and vanes. In modulated fans, successive air control volumes leave the blades at different speeds. As a result of the differences in velocity between the control volumes traveling at different speeds and the distance between the fans and the specimen, some level of mixing occurs. Thus, RPM and velocity are no longer linearly related. In this paper, we describe a method for recreating a flow field with similar characteristics to field measurements. Other testing facilities interested in creating unsteady flows could benefit from this technique.

2. IBHS WIND TUNNEL AND FLOW CONTROLS

Figure 1 shows the IBHS test chamber, which is an open jet wind tunnel with 105 fans placed in 15 cells. The lower five cells each have nine fans, while the rest have six fans with a diameter of 1.7 meters and power of 261 kW at 1780 RPM. The chamber has overall dimensions of 46 m x 46.5 m and a height of 21.8 m. There are two sets of active control devices in the test chamber to control the fluctuating wind speeds: the fan RPM in each cell and 16 vertical vanes. The flow can be generated by modulating the fans between 180 and 1800 RPM at different ramping rates between 180 to 1388 and 1566 to 1800. This allows us to create large scale changes in wind speed. The vanes are designed to create lateral mixing between the cells. The chamber is also equipped with spires in the lower and middle cells. The spires are triangular with an angle of 6 degrees from the vertical.

(a)

(b)

Figure 1. IBHS (a) test chamber and (b) fans with active and passive flow controllers

3. METHODOLOGY

During the past several years, IBHS has been using different input RPMs to create a wind flow in the chamber. The use of active flow controllers (fan and vane oscillations) eliminates the need for roughness elements upwind, but the flow becomes unsteady as a result. Rapid modulation of the fans leads to sudden pressure changes in the flow during the travel time from the fans to the specimen. As a result, air molecules do not move at the same speed, devaluing the linear relation between RPM and velocity. Hence a nonlinear predictive model to control the fans is needed. To create the data set for building predictive machine learning models, IBHS old traces were run, and the flow was measured with ultrasonic anemometers (at 10 Hz) mounted on a gantry as can be seen in Figure 1b. Finally, the velocity values and their derivatives from 1^{st} to 100^{th}, as predictors, were calculated and tabulated accompanied with the associated RPM, as the response value. The size of the data set was then equal to 529496 x 102. All predictors were in the train dataset were normalized by their means and standard deviations. These means and standard deviations were saved and used for test data set transformation.

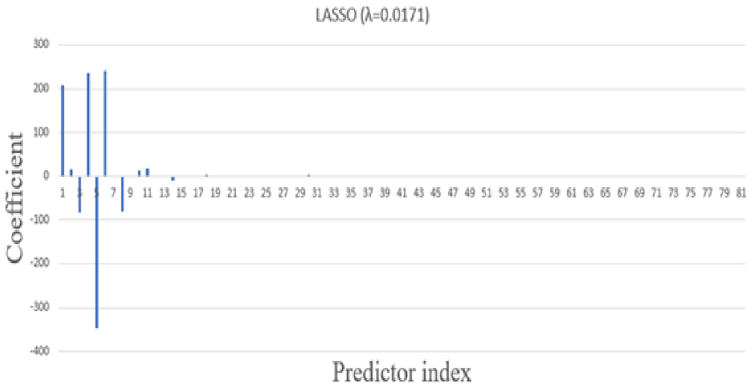


Figure 2. The value of predictor coefficients for λ=0.0171

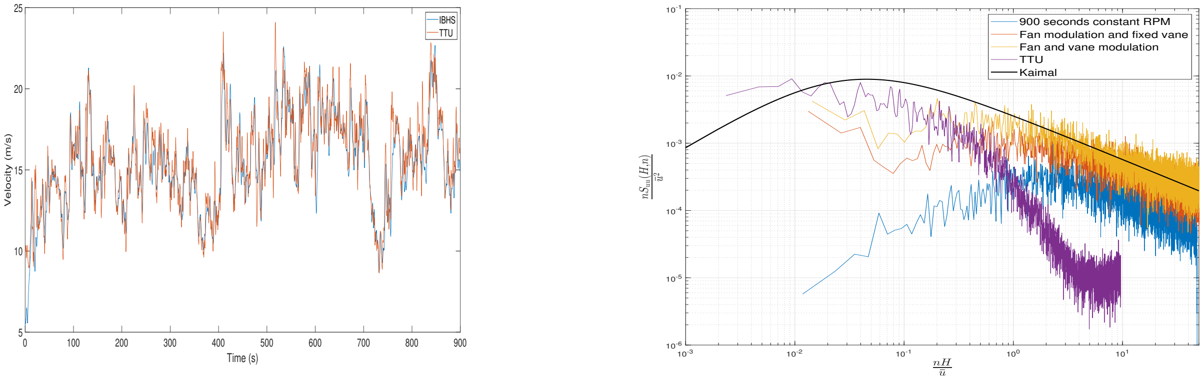
For assessing the model's performance, cross-validation and external validation were considered. Fivefold cross validation was used to develop the calibration model and select latent variables, shrinking parameters, or penalty coefficients. Model predictions were evaluated based on the root mean square error of calibration (RSMEC), root mean square error of prediction (RMSEP), calibration coefficients (R_c^2, R_p^2), and residual performance deviations (RPD).

The Lasso regression technique reduces the number of predictors, eliminates multicollinearity, and avoids overfitting. This technique adds the absolute value of coefficient magnitude to the penalty and results in sparse models (model shrinkage). As a result, accuracy can be enhanced and significant predictors can be found. To determine the influential features, 5-fold cross validation was used with Lasso (Homrighausen and McDonald, 2013; Obuchi and Kabashima, 2016). Larger values of shrinking parameter (λ) lead to a smaller number of predictors which would be used for model explanations. Figure 2 shows the optimum shrinkage parameter and significant predictors. The performance indicators obtained at λ=0.0171 were R_c^2 =0.976, RMSEC=32.40, R_p^2=0.892 and RMSEP=32.519. The high values of R_c^2 and R_p^2 as well as the negligible difference between RMSEC and RMSEP signify the accuracy and robustness of the predictive model.

The response, RPM, and weights of predictors, velocity, and their derivatives, can be seen under a linear relationship in Figure 2. This graph does not consider the interactions between the predictors. The mutual interaction between the first 30 terms of predictors were added to the model, and step wise linear regression were used to determine their effect on response. While the accuracy of the predictive model was slightly enhanced, because of the additional computational time, the mutual interaction of the predictors was not considered in this model.

4. RESULTS

The flow field created at IBHS and the one reported by Texas Tech University are compared in Figure 3 and Table 1. The effects of fan and vane modulation on the energy spectra of the flow field at IBHS test chamber is also presented in Figure 3b.



(a) **(b)**

Figure 3. Comparison between IBHS and Texas Tech (a) measurements (1s moving mean) and (b) logitudinal velocity spectra normalized by the mean streamwise velocity squared.

Table 1. Comparing mean, 3s gust, turbulent intensity between TTU and IBHS.

Flow parameters	TTU	IBHS	Error
$\bar{u}$(m/s)	15.6	15.2	-3%
G_{3s} (-)	1.46	1.58	8%
I_u (%)	18.2	16.7	-8%
u_{max} (m/s)	25.3	26.1	3%
u_{min} (m/s)	7.9	7.3	-7%
RMS	15.9	15.4	-3%

The results demonstrate that in order to reconstruct a flow regime, modulating fans and vanes can be substituted for upwind roughness elements. There are some physical limitations such as the horsepower of the fans and the dimensions of the facility. These limitations limit the ability to match all peaks and valleys to recreate the desired time history. The majority of the authors' efforts have been dedicated to fans' modulations, and only recently have we begun to investigate how the vanes affect the energy spectra. All testing facilities could benefit from further research and development into this method for recreating desired transient flow time histories.

REFERENCES

Farell, C. and Iyengar, A. K., 1999. Experiments on the wind tunnel simulation of atmospheric boundary layers. en. Journal of Wind Engineering and Industrial Aerodynamics 79, 11–35.

Fernández-Cabán, P. L. and Masters, F. J., 2020. Experiments in a large boundary layer wind tunnel: upstream terrain effects on surface pressures acting on a low-rise structure. EN. Journal of Structural Engineering 146, 04720002.

Homrighausen, D. and McDonald, D., 17–19 Jun 2013. The lasso, persistence, and cross-validation. Proceedings of Proceedings of the 30th International Conference on Machine Learning. Ed. by S. Dasgupta and D. McAllester. Vol. 28. Proceedings of Machine Learning Research. PMLR, Atlanta, Georgia, USA, 1031–1039.

Obuchi, T. and Kabashima, Y., 2016. Cross validation in LASSO and its acceleration. Journal of Statistical Mechanics: Theory and Experiment 2016, 053304.

Tieleman, H. W., 1993. Pressures on surface-mounted prisms: The effects of incident turbulence. en. Journal of Wind Engineering and Industrial Aerodynamics 49, 289–299.

— 2003. Wind tunnel simulation of wind loading on low-rise structures: a review. en. Journal of Wind Engineering and Industrial Aerodynamics 91, 1627–1649.