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On the identification of a wake-oscillator model from forced-motion wind tunnel experiments

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ABSTRACT:
Bluff bodies in a smooth flow experience vortex-induced vibrations: a type of fluid-structure interaction involving the alternating shedding of vortices from the body. Different models have been proposed to represent such a system; arguably the wake-oscillator models are the most appropriate to capture the salient features of nonlinear characteristics (which include entrainment, frequency lock-in, and resonance). The present article addresses the parameter identification of a wake-oscillator model based on forced-motion wind tunnel experiments.

Keywords: vortex-induced vibration, wake-oscillator model, parameter identification from wind tunnel tests

1. INTRODUCTION

Experimental studies of Vortex-Induced Vibration (VIV) often involve a standardized bluff body (a circular cylinder) that is either rigid or elastic (Blevins, 2001). When the body is rigid, either it is elastically mounted or its motion is imposed. Such experiments are identified as free-vibration or forced-vibration experiments respectively. Both approaches have their merits and limitations; Morse and Williamson (2009) studied how VIV responses can be predicted from controlled-motion experiments.

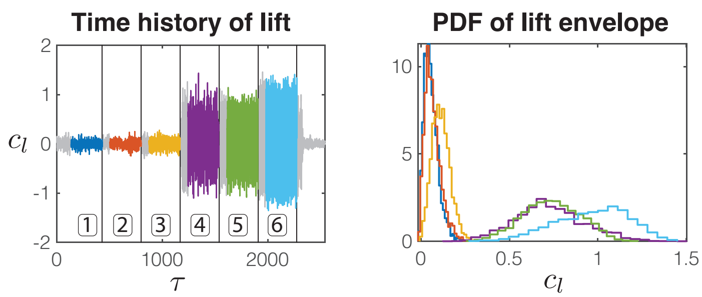
Empirical, physics-based VIV models entail a structural part and a fluids part. Arguably wake-oscillator models are the most versatile, given that only these models fully acknowledge the dynamics of the wake. It remains a challenge, though, to determine the empirical model parameters from experimental data. Recently, Rigo et al. (2022a) identified the parameters of a generalized fluids equation based on fixed cylinder experiments and showed significant difference with well established models. In the present work, we investigate whether this generalized approach can be extended to retrieve the model parameters from forced-motion experiments as well.

2. WIND-TUNNEL EXPERIMENTS

A dedicated wind-tunnel experiment has been set up in the Atmospheric Boundary Layer (ABL1) tunnel of the Vrije Universiteit Brussel. This tunnel has a test section spanning 2 m in width and 1.04 m in height. The wind speed reaches up to 20 m/s. The level of incoming turbulence intensity at 10 m/s is below 0.5 %. The bluff body under test is a custom-built lightweight circular cylinder. The cylinder diameter D is 25 cm; the span is 90 cm. Among others, the cylinder is equipped with 40 pressure taps at mid-span (resolution = 9°) which are integrated and scaled to determine the lift coefficient $c_l(t)$. The cylinder is placed upright in the test section on a crankshaft-driven mechanism to impose transverse (quasi) sinusoidal oscillations.

In the present work, three amplitude ratios $A/D \in \{0.1, 0.2, 0.4\}$, three Reynolds numbers (Re, see Figure 1 below), and six excitation frequencies $f_y \in \{1,2,3,4,5,6\}$ Hz have been tested. Each forced-motion experiment is performed at a constant wind speed and constant amplitude ratio. The frequency f_y is varied in a stepped manner.

The high subcritical flow regime, characterized by intermittent vortex shedding, is investigated. Figure 1 illustrates the lift coefficient as a function of dimensionless time $\tau = 2\pi f_{St} t$. It also shows the distribution of the lift envelope, which takes larger values, on average, when the excitation frequency f_y is closer to the shedding frequency (lock-in range).



U_∞ (m/s)	Re	f_{St} (Hz)
6	1.0×10^5	4.2
8	1.3×10^5	5.2
10	1.7×10^5	6.8

	①	②	③	④	⑤	⑥
f_y(Hz)	1	2	3	4	5	6

Figure 1. Time history of the lift coefficient and corresponding distribution (Re = 1×10^5, $A/D = 0.1$)

3. CONSIDERED MODEL AND PARAMETER IDENTIFICATION

By extension of the works by Rigo et al. (2022b), It is assumed that the wake equation takes the form

$$\ddot{c}_l + \omega_{St}^2 \left[c_l + \frac{\dot{c}_l}{\omega_{St}} \left(a_{01} + a_{21} c_l^2 + a_{03} \frac{\dot{c}_l^2}{\omega_{St}^2} \right) \right] = f_{ext}\left(\frac{y}{D}, \frac{\dot{y}}{D} \right) + \nu \qquad (1)$$

so that it exhibits oscillations at shedding frequency $f_{St} = \mathrm{St}\frac{U_\infty}{D} = \frac{\omega_{St}}{2\pi}$ in the absence of external forcing and when model parameters governing the topology of the limit cycle are such that $\{a_{01}, a_{21} a_{03}\} \ll 1$. It is also essential that $a_{01} < 0$ and $(a_{21} > 0 \,\text{or}\, a_{03} > 0)$ so that the system exhibits a limit cycle. This model extends the generalized model proposed in Rigo et al. (2022b) by adding the external forcing resulting from the cylinder motion, which is considered to be

$$f_{ext}\left(\frac{y}{D}, \frac{\dot{y}}{D} \right) = \omega_{St}^2 \left(b_{10} \frac{y}{D} + b_{01} \frac{\dot{y}}{\omega_{St} D} \right), \qquad (2)$$

where b_{10} and b_{01} are two additional model parameters affecting the magnitude of the Power Spectral Density (PSD) of the lift in the neighborhood of f_y. To ease comparison with literature results, a dimensionless time $\tau = \omega_{St} t$ and a dimensionless body motion $Y(\tau) = y[t(\tau)]/D$ are defined. The lift coefficient is rewritten $q(\tau) = c_l[t(\tau)]$, so that the considered wake equation becomes

$$q'' + q + q'\left(a_{01} + a_{21}q^2 + a_{03}q'^2\right) = b_{10}Y + b_{01}Y' + \eta. \tag{3}$$

Last but not least, to capture the randomness of vortex ejection, due to the turbulent nature of the flow field, the model is equipped with an additive zero-mean white noise $\eta(\tau) = \nu[\tau/\omega_{St}]/\omega_{St}^2$, with PSD intensity s_η.

Equation (3) describes the considered model, which is composed of 7 parameters : a_{01}, a_{21}, a_{03}, b_{10}, b_{01}, s_η, as well as ω_{St} which is required to construct the dimensionless time, but is easily observable from wake data. Apart from this one, the other six parameters are identified in such a way to fit (i) the probability density function (PDF) of the lift coefficient, (ii) its PSD, and (iii) the PDF of the lift envelope. A metric was constructed from these three indicators, combining them with equal weights. The identification technique was developed in two steps : first, a nonlinear least square fitting provided a suitable starting guess from which, second, a Bayesian inference approach (based on a Monte Carlo Markov Chain) was used to determine the distributions of the model parameters conditioned upon the observed quantities. In this short abstract, results of the first step identification only are discussed.

4. RESULTS AND DISCUSSION

In order to appreciate the good agreement between the experiment and the model predictions, Figure 2 shows the time series of the lift coefficient collected in the experiments (for $U = 6\,\mathrm{m/s}$, $A/D = 0.1$ and $f_y = 6\,\mathrm{Hz}$), together with the model prediction (in blue), after identification. While the time series is seen to mimic the features of the recorded data, the PDFs of the lift and its envelope are in very good agreement. Also predictions of trajectories in the $(c_l, \dot{c}_l)-$plane are very realistic, even though they have not been used for the fitting. Once the model is fitted, it is possible to simulate alternative scenarii; for instance, the same model can be run while discarding the imposed motion of the cylinder ($b_{01} = b_{10} = 0$) or even by also discarding the added noise. These results are shown in orange/yellow. They are significantly different from the results simulated with the full model, which indicates that the motion induced forces and the body-induced turbulence play a major role in the balance of forces. At least, their signature on the PDFs of the lift and its envelope are clearly noticeable.

Identified model parameters are given in Table 1; a_{03} is significantly smaller than a_{01} and a_{21}; this is consistent with the observations on the fixed cylinder and seems to confirm again that experimental data better correlates with Tamura's model than others. The values identified for the coefficients a_{ij} are different in the three tested configurations $A/D \in \{0.1, 0.2, 0.4\}$. This hints that a simple model with constant coefficients might not be the best option to account for the motion of the cylinder. The use of b_{ij} coefficients is central in the model (see yellow/orange lines) and, interestingly, could be considered insensitive to A/D. Conversely, the magnitude of the noise $\eta(t)$ grows with A/D.

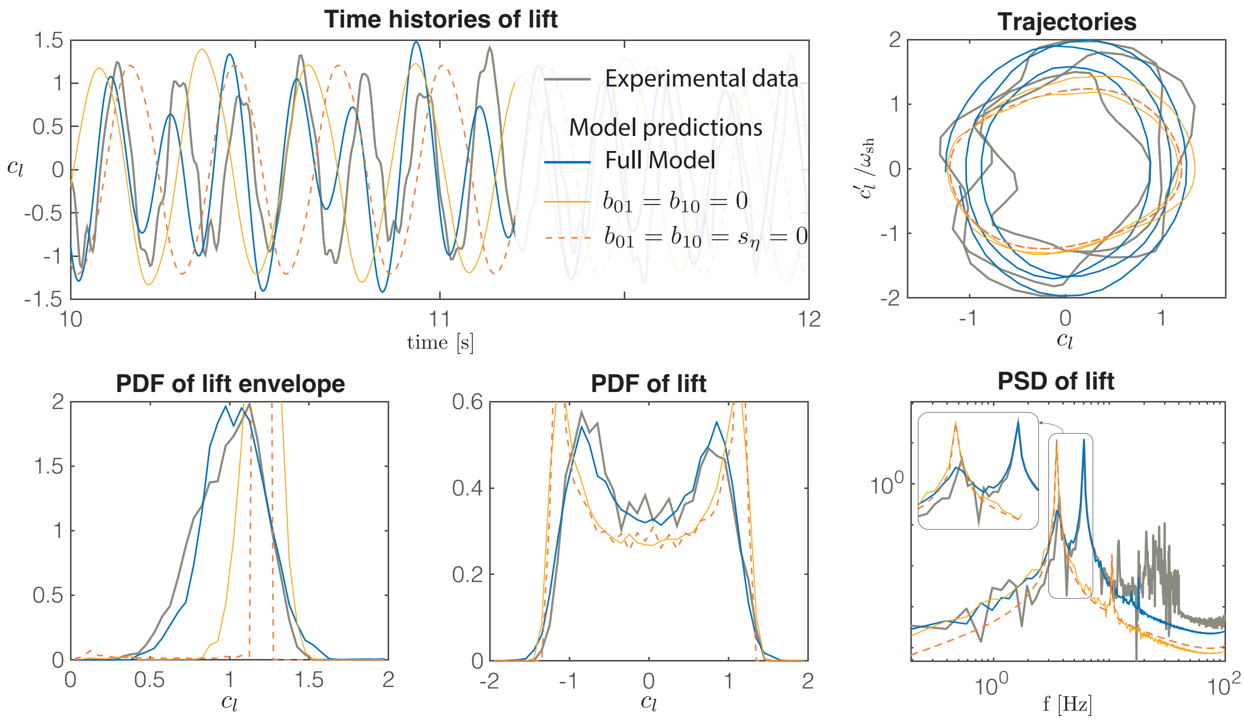


Figure 2. Comparison of model predictions and measured quantities. Re = 1×10^5, $A/D = 0.1$, $f_y = 6\,\text{Hz}$.

A/D	ω_{St} [rad/s]	a_{01}	a_{21}	a_{03}	b_{10}	b_{01}	s_η
0 (Rigo et al., 2022a)	-	-0.063	0.09	-0.009	-	-	-
0.1	22.3	-0.23	0.62	0.0008	16.0	7.0	0.030
0.2	22.3	-0.39	0.19	0.0008	16.0	7.1	0.100
0.4	21.4	-0.60	0.06	0.0035	16.0	7.2	0.142

Table 1. Identified model parameters (Re = 10^5, $f_y = 6\,\text{Hz}$) for $A/D \in \{0.1, 0.2, 0.4\}$ and $A/D = 0$ (from literature).

5. CONCLUSIONS

The parameters of a generalized wake equation under forced cylinder motion have been identified. The model appears to be versatile enough to capture the main statistics of the lift (amplitude, envelope and frequency content). Yet, no unique set of parameters has been obtained, which indicates that the proposed model cannot be considered as universal.

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REFERENCES

Blevins, R. D., 2001. Flow-induced vibration. Krieger.

Morse, T. and Williamson, C. H., 2009. Prediction of vortex-induced vibration response by employing controlled motion. Journal of Fluid Mechanics 634, 5–39.

Rigo, F., Andrianne, T., and Denoël, V., 2022a. Generalized lift force model under vortex shedding. Journal of Fluids and Structures 115, 103758.

Rigo, F., Andrianne, T., and Denoël, V., 2022b. Parameter identification of wake-oscillator from wind tunnel data. Journal of Fluids and Structures 109.