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Application of a force partitioning method for vortex-induced vibrations in a cylindrical wind turbine tower

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ABSTRACT

The abstract will be included at the very end. After the complete research project is finished and the article is finalised, I will write this part of the text.

1. INTRODUCTION

When a circular cylinder is immersed in a fluid, the flow around it already becomes unstable at very low Reynolds numbers ($Re > 47$). This results in alternating vorticity in the wake of the cylinder, known as a Kármán vortex street. The instability also causes the side regions of the object to experience periodically changing pressures and velocities and as such unsteady lift and drag forces (Mittal & Singh, 2005). If the cylinder is elastically supported, it will start oscillating, which in turn strongly influences the behaviour of the flow. This interaction between the oscillating body and the surrounding flow becomes most significant if an eigenfrequency of the body approaches the frequency of vortex-shedding. This frequency f_{St} is usually found using the Strouhal number St, defined as

$$St = \frac{f_{St} D}{U}, \tag{1}$$

where U is the flow velocity and D the cylinder diameter. In such case where f_{St} is close to a natural frequency of the elastic system, the frequencies tend to *synchronise*. This phenomenon, which is also called *lock-in*, was first described by Bishop & Hassan (1964) and Feng (1968). It may cause significant additional fatigue loads and lead to early failure.

One specific application where these vortex-induced vibrations (VIV) are increasingly important is the design of wind turbine towers. These are particularly susceptible to VIV when they are (i) standing on the quayside, (ii) being transported on a ship or (iii) placed on their foundation, prior to the installation of the rotor-nacelle assembly (Livanos, 2018; Viré et al., 2020)[1].

It has been concluded over the last decades that the behaviour of VIVs has a complex dependence (i) on structural properties like mass damping and the mass ratio - that is, the structural mass divided by the mass of moved fluid (Khalak & Williamson, 1999; Govardhan & Williamson, 2000) and (ii) on fluid dynamics parameters such as Reynolds number (Anagnostopoulos & Bearman, 1992; Meneghini & Bearman, 1995). This complicates the matter since it implies that subcritical results may not simply be used to draw conclusions for the transitional ($1.5 \times 10^5 \leq Re \leq 3.5 \times 10^6$) or fully turbulent ($Re \geq 3.6 \times 10^6$) regimes, which are relevant for most realistic applications. Both experimental research and numerical simulations have been performed within these flow conditions (Achenbach, 1968; Lehmkuhl et al., 2014)[2], however, these regimes impose challenges: To create such Reynolds

[1] I have seen almost this exact construction in several articles. Should I best use quotes in this case? And how can I know who first determined these load cases?

[2] I found a number of other articles about this but am not shure how many to include since I did not read them all

numbers in an experimental setup, very high velocities are required in very large wind tunnels. This makes the process expensive and influences the accuracy of the outcome, so that different setups have resulted in inconsistent measurements for the various force coefficients (Schewe, 1983). For computational models, the difficulty of setting up realistic and accurate wall conditions comes into play. However, in some cases, the numerical results have been convincingly similar to the experimental data (Singh & Mittal, 2005).
[3]

One aspect of VIVs that has not been very rigorously researched is the contribution of various force generating mechanisms to drive these oscillations. Menon & Mittal (2020) recently proposed a mathematical force-partitioning method to isolate and quantify the contributions of the added mass, the vorticity-induced and viscous shear force on the oscillating body. Moreover, their approach separates spacial regions, in order to include the effects from various flow structures (e.g. the vortex wake) on the forcing behaviour.

Other partitioning methods had already been used, including one where the force is separated into a component in phase with velocity and another in phase with acceleration. For instance, Sarpkaya et al. (1978) demonstrated that the in-line force increases with the ratio of amplitude to cylinder diameter, whereas the transverse force seriously varies close to the Strouhal frequency f_{St} (1).

However, this last method does not isolate different physical mechanisms and neither does it take into account the spacial location of the flow structures. That is where the technique of Menon & Mittal (2020) mostly proves its worth. It combines the fundamental work of Quartapelle & Napolitano (1983) about conveniently rewriting forces and moments on a body by projecting the Navier-Stokes equations (see section 2) with the observation by Chang (1992), who recognised the partitioning into vorticity-induced, added mass and shear forces.

Notice that breaking down the force components does not yet indicate to what extent they contribute to or counteract the oscillation. One way to do just that, is to determine the energy extracted from the surrounding flow by the elastic system of the cylinder under forced vibrations. As shown by the work of Morse & Williamson (2009), there exists a close relationship between extracted energy in forced oscillations and amplitude response in free oscillations. Therefore, measuring the work done by each of the forcing mechanisms on the cylinder will quantify their respective influence on the vibration. This method has shown all the more useful, because of the highly nonlinear responses that characterise this type of system (Williamson & Govardhan, 2004).

Using this combined approach of force partitioning and energy mapping, Menon & Mittal (2020) concluded that the most important factor in the sustenance of VIVs is the vorticity-induced force, rather than the vortices in the wake behind the cylinder. It was found that the wake vortex shedding only contributes temporarily at the onset of the oscillations, whereas growth of the vibrations is very much determined by vorticity in the shear layer. In that phase, the wake vortices extract energy from the oscillations rather than adding to it.

It must be noted that these simulations were performed at very low Reynolds numbers ($Re = 100$), which avoids most of the complex dependencies described before. This regime is of course completely unrealistic for actual wind turbine applications, or any real applications for that matter.

The purpose of this paper is hence to apply the method of Menon & Mittal (2020) to a more realistic Re regime, in order to identify the influence of various force creating mechanisms on the severity of VIVs. To this effect, an Unsteady Reynolds-Averaged Navier Stokes (URANS) simulation based on the setup created by Viré et al. (2020) will be analysed[4].

The article starts by describing both the modelling approach, following the work of Viré et al. (2020) and the force-partitioning method as proposed by Menon & Mittal (2020) in section 2. After that, section 3 presents the results (**I will be more specific later**) and finally, these are discussed in further detail in section 4.

[3] Is this transition too abrupt? Should there be something extra here?

[4] I am not certain if this has already been done. I was not able to find a paper describing this method for high Re.

2. METHODOLOGY

Work in progress. I will leave this part out for now since it is far from finished. I will send you an update when a first draft is written.

2.1 Modeling Approach

How extensively should I explain the model, since much of it will be exactly the same as described in your article (Viré et al., 2020)?

2.2 Force-Partitioning Method

I am currently working on this.

2.3 Energy Method

I will get started on this when the force-partitioning method is completed.

3. RESULTS

I have not documented real results so far.

4. DISCUSSION

This will come later.

5. CONCLUSION

I am not sure if I should combine discussion and conclusion or keep them separated. In any case, I will write the conclusion at the end.

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