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One-way and two-way couplings of CFD and structural models and application to the wake-body interaction

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ABSTRACT

The current study focuses on the wake-body interaction of a circular cylinder, whose transverse free vibration is modeled by a mass-spring-damper system coupled to a computational fluid dynamics (CFD) model for the flow and wake. We first simulate the free vibration of the elastically-mounted cylinder and the wake, and analyze the transverse load it exerts on the cylinder and its phase with the vibration. We vary the damping by three orders of magnitude and examine the difference in the wake-body interaction for slightly-damped and highly-damped systems. We then use the spectral properties of the free vibration and use them to construct two different types of forced vibrations: one consists only of the fundamental component of the free vibration, and the other accounts for all spectral properties of it. We compare the wake load for each type to that corresponding to the free vibration. The forced vibrations correspond to a one-way coupling and the information is communicated from the CFD model to the structural model, whereas the free vibration corresponds to a two-way coupling of the models. By comparing the spectral properties of the wake load, including the phase relation of its components with the vibration, which we obtained for the free vibration and for the equivalent forced vibration, we identify the effects of the wake feedback. The findings show that a forced vibration does not reproduce exactly the wake load at small and intermediate levels of structural damping. As the damping increases, the vibration changes from being in-phase with the wake load to being 90° out-of-phase with it, corresponding to two different wake states, and the forced vibration gives wake load that is very close to the one occurring in the case of full wake-body interaction.

1. Introduction

A fluid stream over a streamlined body generates a wake region with periodic variations in the fluid motion and pressure field. This quasi-steady state induces alternating loads on the body, causing it to vibrate if it is elastically mounted. This vibration, in turn, affects the wake dynamics and re-shapes the wake loads. This wake-body interaction is a complex problem where the body dynamics and wake dynamics instantaneously interact with each other. A circular cylinder is special case of streamlined bodies because of its simple geometry, described by a single parameter, namely the diameter, thereby eliminating necessary parametric studies on the individual effects of multiple geometric variables. The galloping phenomenon does not occur for a circular cylinder [1,2], unlike square and semicircular cylinders. Therefore, we can focus on one mode of linear vibration, which is not interfered with other vibration modes. In addition, cylinder-like elements are used in many engineering applications, such as offshore structures and flue stack gases. For these reasons, we will consider an infinitely-long

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circular cylinder as the body which is interacting with its wake, undergoing a transverse free vibration in the direction orthogonal to both the free-stream and the span, as illustrated in Fig. 1. To model and simulate this problem, one needs to couple a fluid model to a structural model and allow two-way communication between them through appropriate mathematical formulation and numerical implementation so that the free vibration of the cylinder affects the flow field through the boundary conditions at the moving interface in addition to updating the grid details, and also the instantaneous wake load on the cylinder is applied in the structural model. On the other hand, if the vibration is forced and prescribed in an explicit manner, such as being controlled by an external mechanism, this vibration is not affected by the wake load on it, but the fluid model is still influenced by this forced vibration. Thus, the two-way coupling is reduced to a one-way coupling.

The two problems, free and forced vibrations of a circular cylinder placed in a free-stream, were studied computationally and experimentally at different conditions of the free-stream and the elastically-mounted cylinder or the forced vibration. When the forced vibration is considered, it is usually described as a simple sine function. Thus, it is described by a single amplitude and a single frequency [3–10]. On the other hand, the elastically-mounted cylinder is attached, either physically in experimental studies or virtually in computational ones, to a spring and a damper [11–16], and the free vibration is determined by the wake-body interaction. The mass, damping coefficient, and spring constant are the parameters of the structural system to govern the free vibration, either in a dimensional or a non-dimensional form.

The majority of these studies focus on either a forced vibration or a free one. There are few studies that analyzed both problems, but in an isolated manner, without attempting to establish a relation between them. For example, the authors in Ref. [16], who simulated both problems in their study of transverse vibration, refer to each group of simulations as a 'batch', reflecting the lack of systematically linking the results of the two problems. The authors commented on a difference between the two problems, which is that the free vibration is not always purely sinusoidal, whereas the forced one is. Also, they indicated the existence of lock-in zone in the frequency of the forced vibration and a lock-in zone in the spring of the elastically-mounted cylinder. However, this was conducted in a qualitative manner, and the relation between the two zones was not studied.

An improved better step was taken by the authors in Ref. [17], who also studied computationally both free and forced vibrations of a cylinder, because they considered a case of free vibration and applied a similar forced vibration and compared the wake loads in the time domain for both problems. The loads 'looked' similar based on their figures. The drawback of this analysis is that the time domain is not an efficient tool to analyze the similarities or differences in the wake loads, and one needs to perform this analysis in the spectral domain because many differences in the spectral properties between two sets of wake loads can be concealed in the time domain. Other than commenting that two sets of wake loads are similar, the authors did not examine the level of similarity between them, by computing and comparing the frequency or the standard deviations for example. In addition, the authors followed this procedure for a single case of free vibration and it is not clear how the damping affects this 'time domain' similarity.

The computational brief study in Ref. [18] is even a better step toward analyzing the difference between free and forced vibrations, in terms of the influence on the wake. In addition to constructing the forced vibration as a simple sine wave, which was referred to as 'pure-tone', that is similar to the free vibration, the authors considered a multi-frequency forced vibration that consists of a primary component added to one or two smaller components at other frequencies. Their objective was to generate a transverse wake load that is similar to the one obtained in their simulation for a free vibration. The damping of the elastically-mounted cylinder was constant, but was not specified. The capability of the pure-tone forced vibration to reproduce a similar wake to the one for the free vibration was judged based on a single variable only, which is the phase-shift between the fundamental components in the wake load and the displacement of the moving cylinder. This is a serious limitation in this study because it ignored many properties of the wake load, such as its magnitude and frequency. The pure-

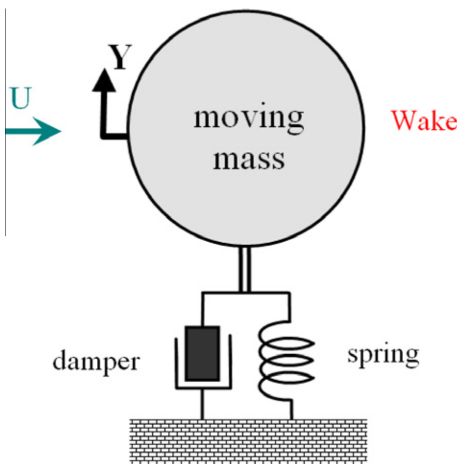

Fig. 1. The mass-spring-damper system.