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Surrogate-based aerodynamic shape optimization to enhance wind-induced vibrations of bluff bodies for energy harvesting

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ABSTRACT

Wind energy harvesting based on wind-induced vibrations of bluff bodies has attracted substantial attentions in the past few years due to its potential to be a power source for wireless sensors and portable devices. A number of studies endeavored to improve the efficiency of wind energy harvesters from different aspects, including customized electric circuitry, coupling of different vibrations, and aerodynamic shape modifications. In this paper, the potential of a surrogate-based optimization approach for determining the optimal shape with the largest crosswind vibrations of bluff bodies is discussed. An optimization framework is proposed and the application on a square prism with corner fins is outlined.

1. Introduction

Bluff bodies with a wind-sensitive shape often undergo severe wind-induced vibration such as galloping, vortex-induced vibration (VIV) and fluttering. Wind and aerospace engineers have made substantial efforts to mitigate these types of undesirable vibrations in large scale systems such as tall buildings, chimneys, long-span bridges, aircraft wings and transmission lines to prevent damages or failures. In contrast, a wind energy harvester is immersed in wind flow to be excited and undergoes large vibration that can be converted to electricity via piezoelectric and/or electromagnetic transducers.

During the last decade, many studies have been focused on harvesting energy from wind-induced vibrations. One possible source of wind-induced vibration is the aeroelastic phenomenon associated with the transverse galloping of prismatic bodies studied and explained for the first time by Den Hartog (1932). Barrero-Gil et al. (2010) first analytically explored the potential use of transverse galloping to obtain energy. From then on, a number of studies have been devoted to develop galloping-based wind energy harvesting technique. For example, Abdelkefi et al. (2012a) investigated the concept of exploiting galloping of square prisms to harvest energy. They focused on the effects of the Reynolds number on the aerodynamic force, the onset speed of galloping, and the level of the harvested power. Yang et al. (2013) experimentally investigated the influence of the cross-section geometry on the performance of a galloping-based energy harvester. Their experimental results show the superiority of square cross-section geometry compared to other considered cross-section geometries (triangles, D-section, rectangle). Recently, the energy harvesting from the galloping oscillations of rigid prisms was tested in a wind tunnel by Hémon et al. (2017).

Another widely studied aeroelastic phenomenon for energy harvesting is vortex-induced vibration (VIV). For the concept of harvesting energy from VIV of a rigid circular cylinder, Abdelkefi et al. (2012b) proposed a phenomenological model that couples the fluctuating lift, the cylinder's oscillation, and the generated voltage. Mehmood et al. (2013) performed numerical simulations to analyze the problem of piezoelectric energy harvesting from VIV of a circular cylinder. An optimal electrical load resistance was found for which the harvested power is maximized for different Reynolds numbers. Dai et al. (2014a) developed a nonlinear distributed-parameter model based on the Euler–Lagrange principle of a VIV-based energy harvester. Using their validated nonlinear distributed-parameter model, the concept of piezoelectric energy harvester to concurrently harness energy from base excitations and vortex-induced vibrations was also investigated (Dai et al., 2014b). Recently, an operable strategy to enhance the output power of piezoelectric energy harvesting from vortex-induced vibration (VIV) using nonlinear magnetic forces is proposed for the first time by Zhang et al. (2017). The proposed energy harvester displays a softening behavior, which greatly increases the performance of the VIV-based energy harvesting system, showing a wider synchronization region and a higher level of the harvested power by 138% and 29%, respectively, compared to the classical configuration.

Although a number of studies have been devoted to advance the wind energy harvesting technique from various aspects such as Reynolds number effect, cross-section geometry of bluff body, energy transferring mechanism, and effect of electrical load resistance, only few attempts have been made to aerodynamically optimize bluff body shapes to enhance wind-induced vibration and hence to improve the efficiency of wind energy harvesting. For example, Hu et al. (2016b) studied a circular cylinder VIV-based wind energy harvester with two small-diameter cylindrical rods attached on both sides of the cylinder parallel to the cylinder axis and symmetrical about the stagnation line at a series of circumferential locations ϑ. It was found that two rods at locations ϑ = 45° to 60° significantly expands the aeroelastic unstable range beyond the lock-in wind speed range to sustain energy harvesting over a broader range of wind speeds, as shown in Fig. 1. In a separate study, a splitter plate was placed in the lee of a plain circular cylinder (Song et al., 2017) to achieve similar results to those for two strategically located small cylindrical rods and expands remarkably the aeroelastic unstable range. Hu et al. (2016a) also studied a square prism galloping-based piezoelectric wind energy harvester fitted with corner fins and found that leading-edge fins with an optimal length 1/6 of the prism width improve output power by up to 150%. These studies are pioneer studies which utilized aerodynamic optimization as an effective approach to enhance the performance of bluff body-based wind energy harvesters. Furthermore, these studies were conducted using wind tunnel model tests to experimentally determine the optimal shape for square prism and circular cylinder. The wind tunnel test approach is reliable but can only compare a limited number of simple shapes, in addition to being costly for repetitive testing. Consequently, a large portion of the search space for an optimal shape remains unexplored, limited by the shapes tested. It is important to find an alternative approach to identify more efficiently optimal shapes with less costly effort. In this paper, a framework of adopting a surrogate-based optimization approach to determine the optimal bluff body shape with the largest crosswind vibration for a square prism with corner fins is proposed.

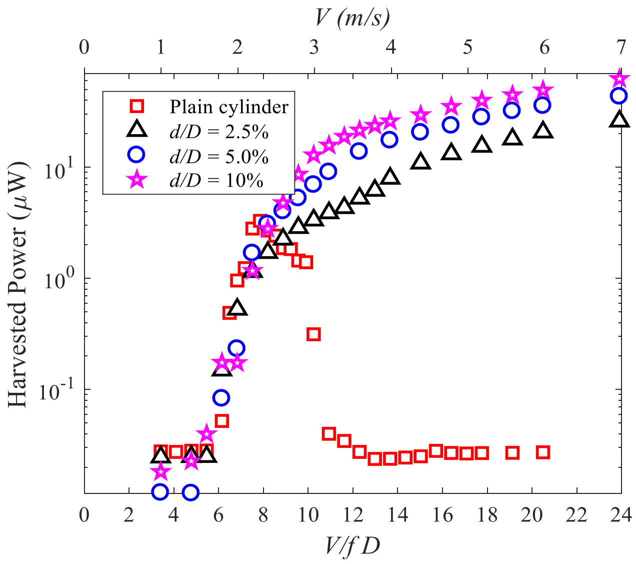

Fig. 1 Harvested power of a circular cylinder based wind energy harvester with and without attaching rods at $\vartheta = 60°$ (Hu et al., 2016b).

2. Framework of adopting surrogate-based optimization approach to optimize bluff body shape to enhance crosswind vibration

The framework for surrogate-based optimization (SBO) as shown in Fig. 2 starts by defining the objective function, which is the crosswind response targeted to be maximized; and then design variables, which are the geometric parameters controlling the shape of bluff bodies. Upper and lower bounds are usually defined for the design variables based on the existing knowledge to shrink the search space. Random combinations of the design variables (i.e. training samples) are generated via design of experiment (DoE) approach. The corresponding objective function is evaluated via computational fluid dynamic (CFD) simulations for each training sample to form a training database for the artificial neural network (ANN) model. The training ANN process will continue by increasing the number of training samples until satisfactory accuracy for estimating the objective function is achieved. After that, the optimization algorithm (e.g. genetic algorithm) is utilized to find the optimal shape that optimize the objective function. The optimization process requires multiple evaluations of the objective function that are conducted using the computationally affordable ANN model. The optimal shape is obtained when no further

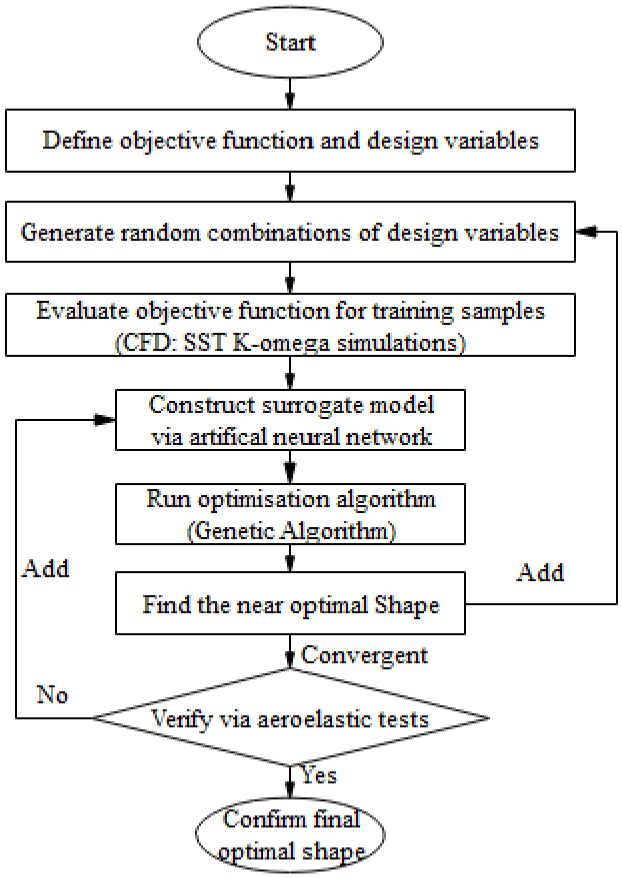

Fig. 2 Flowchart of surrogate-based shape optimization procedure.

improvement in the objective function is achieved by increasing the number of optimization iterations (i.e. generations). Finally, the identified optimal shape will be verified in the wind tunnel by using aeroelastic tests. If the verification fails, the aeroelastic test results will be added to the surrogate model to repeat the optimization process. These steps will be repeated until the verification by using aeroelastic tests is successful.

3. Application of surrogate-based optimization approach to optimize a square prism

Hu et al. (2016a) have found that fitting fins at the two leading corners of a square prism (see Fig. 3) is able to significantly increase its crosswind vibration and thus enhances the performance of a square prism-based wind energy harvester. However, the tests were conducted for only one fin angle ϑ of 45° relative to the incident wind direction and only a few fin lengths. This study aims to determine the optimal combination of fin installation angle and fin length to achieve maximum crosswind vibration.

The objective function of the optimization process is defined as:

$$\text{Maximize } \sigma_d = f(\vartheta, l), \text{ subject to } 0° < \vartheta < 150°;\ 1/10 < l < 1/3$$

where σ_d (=σ_y/D) is normalized standard deviation crosswind vibration displacement; σ_y is standard deviation crosswind vibration displacement y; D is width of square prism; ϑ is angle between fin and incident wind direction; l (=L/D) is normalized fin length; L is fin length, as shown in Fig. 3. After defining the objective function and the lower and upper bounds of these geometric parameters, the Latin hypercube sampling will be adopted to generate samples. The samples will spread uniformly within the constraint boundaries to capture global trends in the design space.

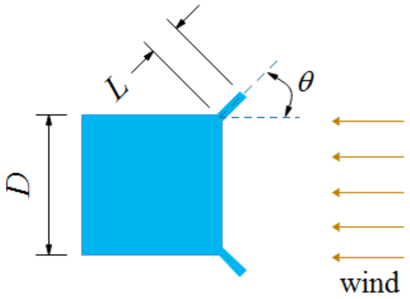

Fig. 3 Square prism with fins at two leading corners.

The corresponding objective function values of the samples will be evaluated through CFD simulations coupling fluid-structure interactions (FSI). The prism will be treated as a one-degree-of-freedom dynamic system with only crosswind vibration.

The ANN model will be selected in this study as a surrogate model for evaluating the objective function due to its proven accuracy in capturing complex function that has multiple local peaks if it is properly trained (Elshaer et al., 2017). The ANN model will be trained by using the above CFD generated crosswind response data. Genetic Algorithm (GA) will be adopted for the optimization process. The optimization procedure will be iterated several times to guarantee that the optimal solution converges, thus avoiding being trapped in a local minimum. The square prism with identified optimal configuration of fin installation angle and fin length will then be verified by using aeroelastic model tests in the wind tunnel. If the verification satisfies the pre-defined criteria, the optimization process is completed, and the optimal shape is determined. Otherwise, the aeroelastic test results will be added to the surrogate model to repeat the optimization process. These procedures will be repeated until the verification process is satisfactorily met.

4. Conclusions

This paper introduces an advanced optimization approach which integrates wind tunnel tests and surrogate-based optimization approach. This combination is able to determine a much more precise optimal shape than the commonly adopted trial-and-error approach solely based on wind tunnel tests. The optimal shape with the maximum crosswind response can be used for the purpose of wind energy harvesting based on wind-induced vibrations.

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