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Wind tunnel experiments on unstable self-excited vibration of sectional girders

Radomil Král*, Stanislav Pospíšil, Jiří Náprstek

Institute of Theoretical and Applied Mechanics, Prosecká 76, 190 00 Prague, Czech Republic

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ABSTRACT

In this paper, a wind tunnel analysis of two degrees-of-freedom system represented by sectional girders is carried out. Besides an evaluation of the aeroelastic coefficients, the analysis is focused on the influence of the natural frequency ratio on the initiation of unstable vibration, which can be of practical interest. On the phenomenological level, the paper also discusses experimentally ascertained response regimes, with an emphasis on their stability character. The attention is paid to the memory effect in the response described by the hysteresis loop together with the separation curves determining the stability boundaries. The influence of initial disturbance on the stability is examined. Two types of cross-sections were investigated: (i) rectangular one with the aspect ratio 1:5, and (ii) bridge-like cross-section with comparable principal dimensions. For both types of cross-sections, the limits of the stability are significantly affected by an intentionally introduced initial disturbance. This holds especially with regard to the rectangular profile where the separation curves create very narrow sub-domains between a stable and an unstable response, while the bridge-like cross-section demonstrates much stable behaviour.

1. Introduction

Stability of bridges and other line-like engineering structures is an important part of their overall design. It is also still of great interest nowadays due to a higher demand on increasing the span while maintaining an economical cost and service. Indeed, the spans have been lengthened considerably over the last one hundred years. Now plans exist for suspended bridges having spans of more than 3000 m as it is the one across the Messina Strait in Italy. Also cable-stayed bridges are about 1000 m long, such as the Normandy Bridge in France or the Suton Bridge in the United Kingdom. This industrial expansion stimulates the progress of theory and computational resources resulting in more precise numerical analyses as well as development of the experimental techniques. Moreover, this crates a space to apply new methods and extension of phenomenological knowledge.

During the previous decades sophisticated methods for the aeroelastic instability prediction have evolved and successfully applied to the real structures and many questions have been adequately answered. The majority of the methods is based on the knowledge of the aeroelastic coefficients (flutter derivatives), see e.g., Larose and Livesey (1997), Ma and Chen (2007), Matsumoto et al. (1996), Caracoglia et al. (2009) and Sarkar et al. (2009) representing frequency dependent self-excited damping and stiffness forces induced by wind–structure interaction. Other complementary (time

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* Corresponding author. Tel.: +420 286 882 121; fax: +420 286 884 634.
E-mail address: kral@itam.cas.cz (R. Král).

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domain) approaches using indicial functions are employed as an alternative, see e.g., Caracoglia and Jones (2003) or Costa et al. (2007).

It has been noticed, however, that the approach based on the flutter derivatives is developed for linear self-excited forces and it becomes considerably problematic as soon as the response is characterized by the large amplitudes or by the loss of the character of linear harmonic movement with clearly expressed frequency. The question is how to work with such experimental results in theoretical models. The paper by Noda et al. (2003) demonstrates the effects of oscillating amplitude on the instability of rectangular cross-sections and shows that different cases of the torsional amplitude cause different courses of the flutter derivatives.

Also natural frequencies of the structure play a significant role in terms of stability. During the process it may well happen that certain cross-sections with stable response in the linear range (small oscillating amplitudes) become unstable for large oscillations. Another possibility emerges when a stable cross-section being in the vicinity of stationary point may become unstable introducing a small disturbance or increase of the initial amplitude. The torsional flutter oscillations of a 4:1 rectangular cylinder around its pitching axis is investigated in Andrianne and Dimitriadis (2009) both experimentally in wind tunnel and numerically. The responses of the rectangle to different initial conditions and turbulence excitations at various wind tunnel airspeeds are examined. The effect of an initial conditions on the final response of a bridge deck section is studied in Manzoor et al. (2011). The authors combined two different methods consisting in the initial mechanical excitation and in the excitation by an upstream single gust. For three cases with different frequency ratios the amplification rate of total mechanical energy is extracted from the transient response. One of the key points of that work is the determination of the critical wind velocity as a function of the pitch to heave frequency ratio. Effect of the frequency tuning on the critical velocity has been studied earlier by the present authors including also non-linear aspects, see Král et al. (2009).

The effect of the non-linearity for bridges with increasing spans and aerodynamic characteristics sensitive to the effective angle of incidence is discussed in Chen et al. (2000). There, a non-linear aerodynamic force model and associated time domain analysis framework for predicting the aeroelastic response of bridges under turbulent winds is presented. The response comparison between linear and non-linear approaches considering the level of angle of incidence has been explained. The mechanism of the flutter onset, the role of flutter derivatives and the coupling effects on the buffeting response due to self-excited forces are set forth. The dependency of flutter derivatives upon the angle of attack is shown in the contributions by Mannini and Bartoli (2008) and Diana et al. (2005). In both papers, the importance of an accurate measurement in the wind tunnel is emphasized. The paper by Matsumoto et al. (2002) puts forward the geometrical shape of the bridge cross-section on the flutter types. It clarifies the flutter mechanism as it relates to frequency characteristics.

The problem of flutter instability is not just a matter of the profile and the aerodynamic forces. Effective suppression of this phenomenon can be inherently included beforehand in the structural design of a bridge. One of the basic ideas avoiding two degrees-of-freedom (dof) flutter consists in decreasing the ratio of basic vertical bending and the torsional natural frequencies of basic modes with similar shapes below one. A feasibility of such arrangement was numerically studied on the Messina Strait Bridge by Bartoli et al. (2008). The authors of the paper concluded that this arrangement, if it was compatible with other constraints, can generate such a regime of fluid–structure interaction where the danger of coupled modes is reduced or even prevented due to their separation into isolated single modes.

In this paper, the self-excited oscillation of two cross-sections is analyzed experimentally: (i) rectangular prism with the aspect ratio 1:5, and (ii) bridge-like prism (Great Belt bridge) with comparable principal dimensions. Initially in Section 2 before experiments in the wind tunnel have been started, a detailed testing of the kinematic, dynamic and elastic linearity is executed in a wide range of working parameters, in order to avoid any non-linear processes influencing the experiments due to the set-up itself. Furthermore, flutter derivatives identification by means of the adapted Unified Least-Square technique (ULS), see Gu et al. (2000), is carried out. This method is modified and offers more robust initial parameter estimation, necessary for the start of the full ULS iterative procedure. An experimental analysis of the influence of natural frequencies on the stability of the tested prisms is carried out and described later in Section 4. The phase shift between response components, flutter frequency and the range of the critical velocity with respect to the frequency (or frequency ratio) is determined.

In Section 5, special attention is paid to the response of the cross-sections at the margins of the critical state when wind speed is increased or decreased. This is demonstrated by the memory effects described by the hysteresis loops together with the separation curves determining the stability boundaries.

For both types of profiles, the limits of the stability are significantly affected by an initial disturbance. This holds especially with regard to the rectangular one where the separation curves create narrow sub-domains between a stable and an unstable response, while the bridge-like cross-section demonstrates much stable behaviour. Using the step-by-step initial disturbance method, separative curves are obtained. They can be compared to the separatrices (known from the theory of dynamical non-linear systems) that divide the phase space into distinct stability areas. Some recommendations for practical design are given.

2. Analysis of testing facilities for large amplitude oscillations

2.1. Experimental set-up description

The tested models with a span of $L=60$ cm were examined in the wind tunnel and exhibited in a practically smooth flow. They were mounted in an experimental set-up specially designed to allow very large deflections with a linear behaviour in