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MULTIPURPOSE EXPERIMENTAL RIG FOR AEROELASTIC TESTS ON BRIDGE GIRDERS AND SLENDER BEAMS

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Abstract: *The bridges, footbridges and broadcast towers create an important subset of infrastructure subjected to dynamic loading of various origins. Especially, exposed to wind, they are susceptible to vibrations under certain circumstances due to pure load action or aero-elastic effects. This means that once an element or a structure starts to vibrate, a complex interaction between the moving boundary and the airflow takes place. Because of the complexity, the research has been in progress for several decades in both theoretical and experimental way. The article describes an original and multi-purpose experimental frame for the analysis of complex linear and non-linear aspects of aero-elastic behavior of the slender beams. The apparatus meets the rigorous theoretical assumptions and allows very precise and quick adjustment of the stiffness and mass of the structure, which is not always possible with a traditional "parallel spring-supported bridge" approach used by many researchers. The principal advantages are described together with key construction details.*

Keywords: ***Bridge aero-elasticity, wind tunnel, experimental set-up, non-linear response.***

1. Introduction

The bridges and footbridges create an important subset of the infrastructure. The spans have lengthened to a great extent over the last hundred years with limits being established constantly by civil engineers and architects. These structures typically have low natural frequencies of oscillation and low damping, which makes them sensitive to wind loading. Once such a structure starts to vibrate, a complex interaction (self-excited) between the moving boundary and the airflow may take place, which either effectively attenuate or reinforce the driving force of the wind.

The investigations showed that some of the violent oscillations couldn't be predicted by static or quasi-static analyses. Indeed, the interaction of oscillating flexible structures and the fluid flow around them can give rise to a number of different responses. For the last few decades' extensive studies were carried (Scruton, 1963; Novak & Davenport, 1970; Ricciardelli, 2003). They revealed a relatively considerable diversity of results, with subsequent understanding that the discrepancies can be caused by hidden or obvious linear treatment. Because many experimental works create their own experimental conditions in accordance with emphasis on own parameters, the results are often incompatible (O`Neil, 1996). It is uncertain which parameters are at the origin of instability and which are only for the particular technical branch.

In the context of above-mentioned references, the authors want to propagate a generalized experimental approach, which would include the analysis of non-linear post- and pre-critical system behavior in both smooth and turbulent airflow. Therefore an original and multi-purpose experimental set-up has been designed. It allows observing both the linear and non-linear aero-elastic behavior of slender beams. The apparatus meets the rigorous theoretical assumptions together with practical very precise and quick adjustment of the stiffness and mass of the structure, which is not always possible with a traditional "parallel spring supported bridge" or its modifications being used by many researchers (Hjorth Hansen, 1992). Examples of the large amplitude non-linear response are presented, to illustrate the capacity and usefulness of the stand.

The current trends of aero-elasticity are focused on the description of full three-dimensional behavior of a body, taking into account the along-body distribution of the load. In many cases, this type of

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investigation is, however, an ultimate goal with regard to the experimental time and economic requirements. Two-dimensional models are therefore prevailing in both theory and experiments and used for initial analysis starting for example with the model in Fig. 1.

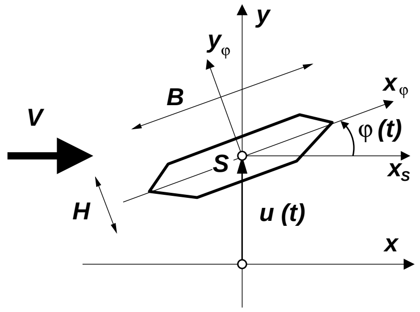

Fig. 1: Double degree of freedom model of the bridge girder. It can move only in the direction of principal response components u and φ or simultaneously.

Mathematical model for such double-degree-of-freedom (DDOF) system can be described, for instance, by a couple of differential equations related to the Fig. 1:

$$\begin{aligned} m_0\ddot{u} + b_{u0}\dot{u} + k_{u0}u &= F(\ddot{u},\dot{u},u,\ddot{\varphi},\dot{\varphi},\varphi,t) \\ I_0\ddot{\varphi} + b_{\varphi 0}\dot{\varphi} + k_{\varphi 0}\varphi &= M(\ddot{u},\dot{u},u,\ddot{\varphi},\dot{\varphi},\varphi,t) \end{aligned} \tag{1}$$

Here, $F = q_s BC_L$ is the lift force, while $M = q_s B^2 C_M$ is the moment around point *S*. These forces, or rather the lift and moment coefficients C_L and C_M are functions of explicit time and the response components $u(t)$ and $\varphi(t)$ stemming from the aerodynamic load. The coefficients m_0 and I_0 represent mass and mass moment of inertia of the cross-section with unit length. They are referred to the still air, respectively, while the effective parameters consist of these basic values and aeroelastic influences. Similarly, $b_{u0}, b_{\varphi 0}$ are the damping coefficients in the still air. Finally, k_{u0}, $k_{u\varphi}$ stand for stiffness for u and φ in the still air. Variable q_s is the stagnation pressure in the bridge height given by the Bernoulli formula $q_s = \rho/2V^2$ using a free stream wind velocity V.

The most fundamental task of experimental aero-elasticity lies in the formulation of the self-excited forces *F* and *M* (the wind load caused by the movement of the structure interaction) and in the determination of the critical state (Jain et al., 1996).

2. Novel experimental approach

Despite some disadvantages, structures are most commonly analyzed experimentally using section models. The model is mounted on a set of springs, which are tuned to produce an appropriate relation of the modal stiffness. The flow of the wind along such model results in the model movement with possible two components; in a vertical (u) and pitch (φ) directions. Such approach with the set of springs of stiffness k_i is depicted in Fig. 2 left. Aerodynamic properties of the cross section can be determined by either pressure measurements along the perimeter or by a force balance on the whole model. The behavior of a static, harmonically forced or freely vibrating deck can thus be studied.

Although the method is used predominantly these days, it is rather slow and costs much experimental time, because every change of the parameters is related to the change of the springs or other important parts, which makes it inefficient. With usage of the proposed experimental rig, this aspect is negligible. It is constructed to allow very quick manipulation before measurement itself. The second important issue stems from the theoretical aspect and actual trend, i.e. the need of the measurement of both linear and non-linear aero-elastic complex behavior.

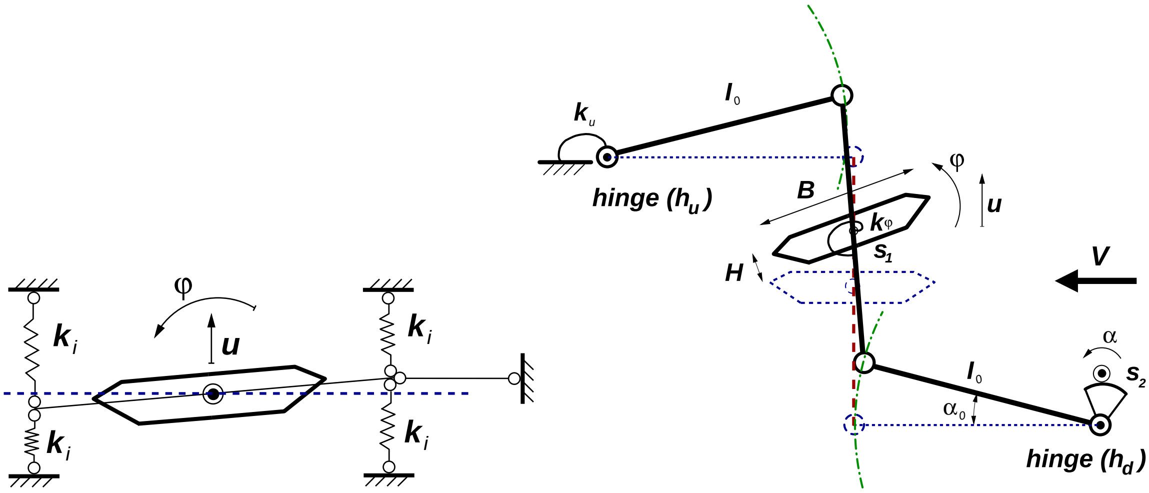

Fig. 2: The common concept of mounting of the section models using spring-supported body (left); Working principles of original multi-purpose stand (right).

In Fig. 2 right, the principal idea of the new type of model attachment is illustrated. The framework of moveable parts was designed to be as light as possible. It is made of fiber composite bars linked to each other with joints. Special gadgets are able to simulate the elastic properties inherent to the structure. Two levers with the length l_0 are supported by hinges h_u and h_d. The stiffness k_u can be adjusted by means of gadget depicted in Fig. 3 left, while the stiffness k_φ uses the system from the Fig. 3 right.

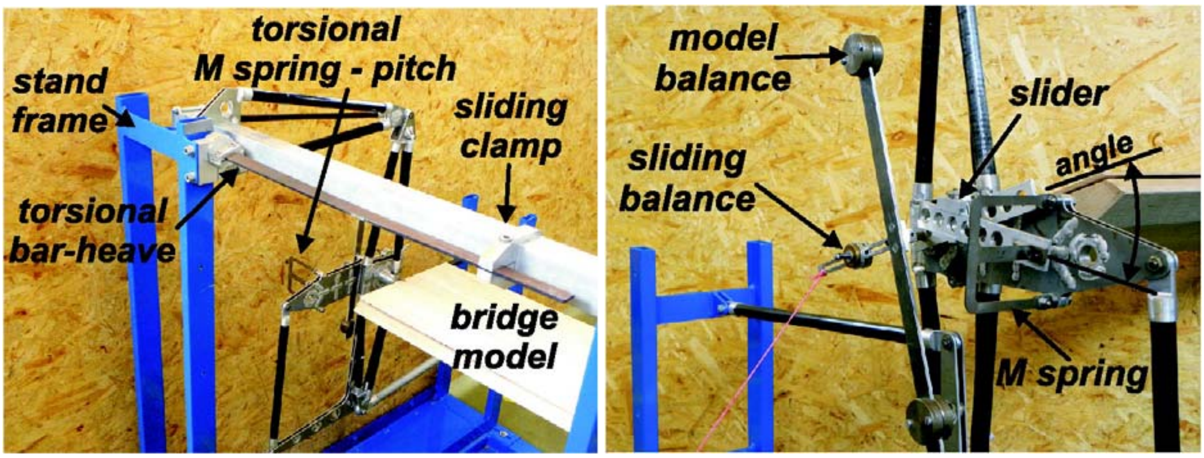

Fig. 3: The overall view at the stand with important mechanical details. System for the change of heave (left) and torsional (right) stiffness.

The centroid of the girder moves along the dotted horizontal (red) line independently of the pitch. The oscillations in both degrees of freedom (response components) can have large amplitudes. Due to movable fixation, the frequency tuning is fast and precise. The mechanical damping of the model at the stand itself is very low, the logarithmic decrement around $\delta = 0.05$. The two sides of the frame can be adjusted to fit the model size as well as the wind tunnel cross dimension.

3. Example of model response

The responses of several cross-sections with the span of $L = 60\ cm$ were measured in a wind tunnel. One example is given here. Special attention has been devoted to the response of the girder at and after the critical state. The deck is of a bridge-like shape with a height-to-width ratio $H / B = 0.2$. The deck motion measurement was ensured by means of rotary magnetic transducers and accelerometers. Tab. 1 gives basic information about the characteristics and the frequency tuning range of the selected model.

Tab. 1: Aerodynamic characteristics of experimentally analyzed girders.

section	H (m)	B (m)	m (kg)	I (kgm^2)	f_φ (Hz)	f_u (Hz)
	0.05	0.03	3.74	0.016	2-6	2.5-7

The wind speed has been increasing continuously during the wind tunnel experiments. Excessive responses occurred when the flow speed in the wind tunnel was near, or identical to the critical velocity and afterwards. Periodic limit cycle oscillations occurred in the coupled mode shape consisting of both heave and torsional components. Amplitudes of torsional motion of the deck were small until it reached the critical, in mathematical parlance, bifurcation point. The sudden growth of the experimental vibration amplitudes of bridge-like girder is depicted in Fig. 4. This time history shows also large amplitudes of vibration, especially in the torsion branch.

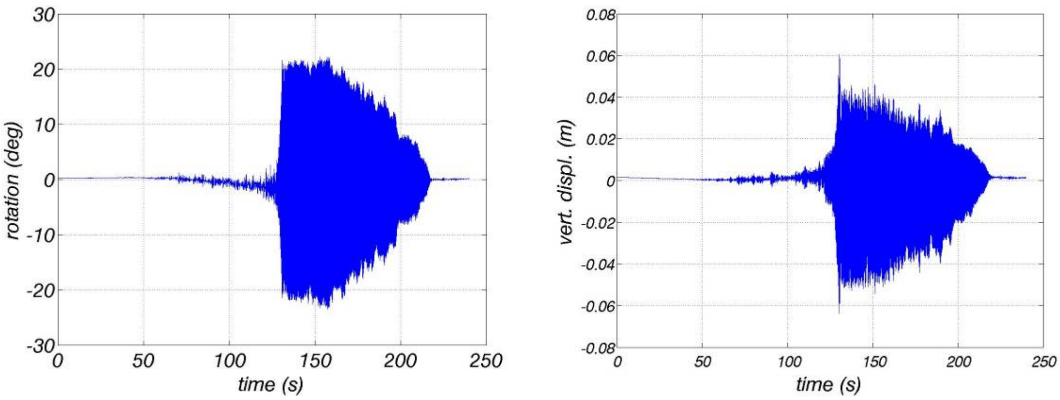

Fig. 4: Time histories of pitch (left) and heave (right) motion of bridge-like girder during continuous increase and decrease of wind speed in the wind tunnel.

4. Conclusions

The article describes an original and multi-purpose experimental set-up for the analyzing of linear and also non-linear aspects of aero-elastic behavior of the slender beams. The apparatus meets the rigorous theoretical assumptions and allows very precise and quick adjustment of the stiffness and mass of the structure, which is not always possible with a traditional "parallel spring-supported bridge" approach used by many researchers. It has been used in practical applications for the real bridge measurements (Rhine Bridge near Wessel in Germany, Sava River in Belgrade, River Vltava pedestrian bridge in Prague). The principal advantages are described together with key construction details.

Acknowledgement

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