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Analysis of dynamic instabilities in bridges under wind action through a simple friction-based mechanical model

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Abstract

In the field of stability of structures under nonconservative loads, the concept of follower force has long been debated by scientists due to the lack of actual experimental evidence. Bigoni and Noselli's work [2] aimed to investigate flutter and divergence instability phenomena through a purely mechanical model with Coulomb friction represents a praiseworthy attempt to shed light on this issue. A two-degree-of-freedom (DOF) system, conceived as a variant of the Ziegler column, was set up experimentally. The follower load was induced by a frictional force acting on a wheel mounted at the column end, so that the rolling friction vanishes and the sliding frictional force keeps always coaxial to the column, thus representing a tangential follower force. Along this research line, in this contribution a model is elaborated that stems from the analysis of an elastically supported rigid plate that represents the behaviour of a bridge deck suspended on springs and subjected to a wind-induced force. The wind force has been simulated by a Coulomb friction force acting on a wheel mounted on the plate aerodynamic centre, so that the sliding friction force keeps perpendicular to the plate axis throughout the system motion, thus representing a follower force. To properly reproduce the wind force, the friction force is applied to the wheel by a lever mechanism wherein one of the two lever arms involves the plate rotation via a particular circular guide. The corresponding equations of motion of the bridge deck are derived in a completely dimensionless form. Depending on the mechanical characteristics of the plate and the magnitude of the friction force, stability, flutter or divergence phenomena may occur. The occurrence of these phenomena is numerically investigated by integration of the equations of motion. The development of an experimental framework of the model to corroborate these intuitions is the object of an ongoing research.

Keywords: Flutter instability; divergence instability; follower force; Coulomb friction.

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1. Introduction

In the field of stability of structures under nonconservative loads, the concept of *follower force* has long been debated by scientists, and the lack of actual experimental evidence has given rise to a controversy about the real existence of such follower force [1]. By this term we denote a force that is not derivable from a potential and which depends on the instantaneous position of the system, i.e., a configuration-dependent force. The water jet observed at the nozzle of a fluid-conveying pipe or the rocket thrust of a flexible missile are just a few real-world examples of follower forces. Other physical phenomena involving follower forces are related to the so-called "aeroelastic flutter", i.e., the

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dynamic instability that may occur in bridges when self-excited oscillations driven by wind increase in amplitude as if the system had an effective negative damping. Many scientists and researchers believe such aeroelastic fluttering triggered the never-before-seen twisting mode of vibration of the Tacoma Bridge in 1940, led to an exponentially growing response and eventually caused the well-known catastrophic collapse of the bridge.

Investigating follower forces from a numerical and, above all, an experimental point of view is rather intricate as they involve either complex fluid-structure interactions or extremely-short-duration effects. Bigoni and Noselli's work [2] aimed to investigate flutter and divergence phenomena through a purely mechanical model with Coulomb friction represents a praiseworthy attempt to shed light on this issue. They demonstrated, by a two-DOF system designed as a variant of the Ziegler column, the existence of the follower force on an experimental basis.

Along this research line, in this contribution a mechanical model is elaborated that stems from the analysis of a horizontal elastically supported rigid plate under aerodynamic forces [3]. This schematic model aims at reproducing the behaviour of a bridge deck suspended on springs and subjected to a wind-induced force. The effects of the wind (follower) forces are simulated by a Coulomb-type friction force. Indeed, we introduce a wheel mounted on a point identifying the aerodynamic centre of the bridge and having axis perpendicular to the longitudinal direction, so that the rolling friction cancels out and the sliding friction force keeps perpendicular to the plate axis throughout the system motion. The friction force accordingly represents a follower force for the system. Similar to the experiment in [2], the vertical reaction entering the Coulomb friction law is applied to the wheel by a lever mechanism. The equations of motion of this simple two-DOF system representing the bridge deck are derived and expressed in a completely dimensionless form. Depending on the magnitude of the friction force and the mechanical characteristics of the plate, stability, flutter or divergence phenomena are observed in the model (which reflects the bridge behaviour for increasing value of the associated wind velocity). The development of an experimental framework of the model to corroborate these intuitions is the object of an ongoing research.

2. Bridge aerodynamics, associated mechanical model and governing equations

The description of the mechanical behaviour of bridges under wind action is a challenging field that has attracted a plethora of researchers [4]. Strictly speaking, highly fluctuating pressure fields arise from the turbulent nature of wind flow, thus resulting in a so-called "aerodynamic load". Additionally, the bridge oscillates according to its vibrational natural characteristics, which gives rise to "aeroelastic" phenomena involving complex fluid-structure interaction. Consequently, resonance-type or instability phenomena may occur depending on the geometry and mechanical properties of the bridge, as well as the main features of the turbulent flow such as its mean velocity.

The above complex phenomena are here simplified in order to investigate the main qualitative aspects of the problem. Let us consider a bridge of length L sketched by a rigid plate (representing the section of the roadway) of unit width and specific mass m per unit length, suspended on springs of stiffness k_1 and k_2 (the stiffness coefficients depend on the actual bridge suspension cables). The system has two DOFs: the rotation θ about the z-axis (i.e., the counterclockwise angle between the horizontal plane and the bridge section in the deformed state), which is depicted as a red arrow in the 3D isometric view, and the vertical motion w of the plate midpoint (or centre of gravity) G. The plate is loaded by wind of velocity v. Under the simplifying hypothesis of slow steady oscillations, as those of very long span suspended bridges, the fluid-structure interaction may be neglected and the wind action can be represented by the wind force resultant $P_w = kv^2 \sin\theta$ acting on the so-called aerodynamic centre of the bridge C, where k is a constant and the location of C does not depend on the angle θ. For two-dimensional incompressible flow C is located at a distance $a = L/4$ relative to the centre of gravity G, on the windward side.

The simplified aerodynamic problem of the bridge discussed above can be reproduced by the schematic mechanical model sketched in Fig. 1: the wind action is replaced by a Coulomb-type friction force exerted by a perfect (massless and fully free of rotating) wheel. The wheel, rigidly connected to the plate of length L identifying the bridge cross-section, slides with pure Coulomb friction on an underlying rigid plane. This plane is ideally touched at a specific point, the aforementioned aerodynamic centre C, and is moved at the speed $-v_p\mathbf{e}_1$, with $\mathbf{e}_1$ indicating the unit vector corresponding to the horizontal direction. For convenience, in Fig. 1 besides the fixed reference system $\mathbf{e}_1 - \mathbf{e}_2$ we introduce a moving system $\mathbf{e}_\mathrm{r} - \mathbf{e}_\mathrm{s}$. The wheel axis is perpendicular to the longitudinal direction, i.e., it is directed along $\mathbf{e}_\mathrm{s}$ (with $\mathbf{e}_\mathrm{s} = -\sin\theta\,\mathbf{e}_1 + \cos\theta\,\mathbf{e}_2$), therefore the rolling friction (along $\mathbf{e}_\mathrm{r}$) cancels out and the sliding friction force keeps perpendicular to the plate axis throughout the system motion. Consequently, the resulting sliding friction