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Aeroelastic effects in a traffic sign panel induced by a passing vehicle

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ABSTRACT

Here, a simple theoretical model of the vehicle induced flow and its effects on traffic sign panels is presented. The model is a continuation of a previous one by Sanz-Andrés and coworkers, now including the flexibility of the panel (and, therefore, the flow effects associated to the motion of the panel). Through the paper an aeroelastic one-degree-of-freedom model is developed and the flow effects are computed from unsteady potential theory. The influence of panel's mechanical properties (mass, damping ratio, and stiffness) in the motion induced forces are numerically analyzed.

1. Introduction

Among the structures susceptible to the action of flow are the traffic signs panels. Regular load due to the air movement of passing vehicles can result in fatigue failures as has been reported in Cali and Covert (2000). Accordingly, as aerodynamic loads eventually emerge as a significant design parameter, it is necessary to develop tools enabling the designer to estimate the effects of the moving vehicles on the signal. Unfortunately, the description of the unsteady aerodynamic forces induced by a passing vehicle is a very difficult task. Because of the size of the problem and the level of complexity, simplified mathematical models can help as a tool of modeling and prediction. In a recent article by Sanz-Andrés et al. (2004), a simple model to determine the transient aerodynamic forces induced in a traffic signal panel by the passage of a vehicle is presented. In the above mentioned model some simplifications are employed: (i) the airflow generated by the vehicle is considered incompressible and potential, where the vehicle is replaced by a source that moves at the speed of the vehicle, (ii) the characteristic timescale associated with the vehicle pass is small compared to the characteristic timescale needed to develop a boundary layer, that would lead to the buildup of a wake behind the sign, so that the model only takes into account the aerodynamic forces of non-circulatory origin, (iii) it is assumed that the vehicle is far enough from the panel, and therefore the influence of the panel on the flow around the vehicle can be neglected, and (iv) the panel is infinitely stiff. Despite its simplicity, the model provides some fairly good results when they are compared with the experimental results presented in Quinn et al. (2001), and allows to determine the role of the different geometric and kinematic variables with respect to the transient aerodynamic force on the panel (size and speed of the vehicle, vehicle distance to the signal, size and orientation of the signal). However, there are situations where the flexibility of the structure cannot be ignored without compromising the reliability of results. It seems reasonable that the next level of consideration is to take into account the flexibility of the panel and include the effect of the motion induced forces on it during the vehicle pass.

The flexibility of the cantilevered sign and signal support structures and the span of the mast arm have increased over the years (Johns and Dexter, 1998). This flexibility, combined with its inherent low mass and low damping (typically $<1\%$ of the critical damping), makes that the passage of the vehicle (either a car, a truck or a train) can induce in the sign panel (and related supports) oscillations leading to fatigue problems at the joints of the support structures. Therefore, one must take into account the aeroelastic effects in the design of the supports (or at least, one should have a reasonable theoretical background in order to asses wether such effects are negligible). The aim of this article is to include the flexibility of the panel in the model of Sanz-Andrés et al. (2004). The most important motivation is certainly of the practical consideration: from the standpoint of structural design of the panel support, one should avoid against fatigue failures, but also excessive oscillations of the panel in order to allow that the information contained in the panel be clearly displayed. Through the article we will discuss the influence of mechanical parameters (mass, damping, and stiffness) at the aerodynamics and aeroelastic forces.

The organization of the article is as follows: Section 2 presents the mathematical model and the simplifications and assumptions

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on which is based. A numerical and parametric study of the relevance of the structural mass, damping, and stiffness in the aeroelastic effect is presented in Section 3. Finally, in Section 4 some conclusions that can be obtained from the model are discussed.

2. Mathematical model

To describe the interaction of a flexible structure with a flow one needs to model both the structure and the flow.

2.1. Dynamics of the panel

Here, we consider a one-degree-of-freedom approximation for the structure's dynamics, taking into account only the first deformation mode, because typically the panel is supported by a single vertical support. Thus, at a first approximation the dynamics of the panel can be considered similar to that of a slender beam (see Fig. 1). Its stiffness is represented by a linear spring, and presents a viscous linear damping. The motion of the panel is then defined by a frequency of free oscillations ω_h, a modal mass per unit length m, a dimensionless coefficient of damping ζ_h. Therefore, the displacement, h, of the panel satisfies a linear (small displacements) oscillator equation,

$$m(\ddot{h} + 2\zeta_h\omega_h\dot{h} + \omega_h^2 h) = N_h(t) + N_v(t), \quad (1)$$

where $N_h(t)$ is the aeroelastic force, per unit length, due to the bending motion (h), and $N_v(t)$ stands for the aerodynamic force due to the passing vehicle; the dot symbol stands for differentiation with respect to time t. Before the vehicle pass the panel is at rest.

2.2. Aerodynamic force induced by the vehicle passing

Here, we follow the model introduced by Sanz-Andrés et al. (2004). Let us make a brief summary. In order to develop a simple theoretical model the following assumptions are considered:

(1) The flow generated by the vehicle motion is incompressible, potential, and it is represented by a moving two-dimensional source (with the same velocity as the vehicle) whose intensity is not affected by the presence of the panel.

(2) No circulation is produced around the panel. The characteristic timescale of the vehicle pass is of order $t_p = L/U_\infty$ (L is the characteristic length of the panel ($2B$ in Fig. 1) and U_∞ is the vehicle speed) and the characteristic timescale for the development of a boundary layer on the panel is of order $t_v = L^2/\nu$ (being ν the kinematic viscosity). Therefore, $t_p/t_v \sim \mathrm{Re}^{-1}$ (where $Re = U_\infty L/\nu \gg 1$ for the problem under consideration). As there is no boundary layer, circulation around the panel does not appear.

(3) The geometry of the panel is considered equivalent to a flat plate and slender enough to consider bidimensional flow around the panel (neglecting the end effects). It constitutes a barrier to the flow, so that the perpendicular component of the fluid velocity should be matched to the plate's motion.

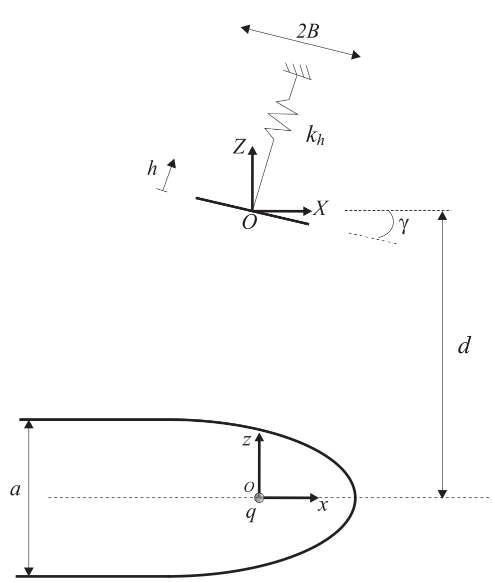

Fig. 1. Sketch of the flow around the vehicle (source) and references frames used in the analysis.

Under these assumptions it is straightforward to obtain the aerodynamic force. Using the notation defined in Fig. 1, the velocity field (u, w) in the (x, z) reference frame, fixed to the vehicle (source), is given by

$$u(x,z,t) = -U_\infty + \frac{qx}{2\pi(x^2+z^2)}, \quad w(x,z,t) = \frac{qz}{2\pi(x^2+z^2)}, \quad (2)$$

with a stagnation point located at $(q/2\pi U_\infty, 0)$. The intensity of the source is determined by the characteristic dimension of the vehicle, a, $(q = U_\infty a)$.

The velocity field (U, W) on the panel can be expressed in the panel reference frame (X, W) by using the coordinate change $X = x + U_\infty t$, $Z = z + d$ [here, d is the distance in the z direction between x and X axis (distance from the center of the vehicle to the panel's center)] and the velocity composition $U = u + U_\infty$,

$$U(X,Z,t) = \frac{U_\infty a}{2\pi}\frac{X - U_\infty t}{(X-U_\infty t)^2 + (d+Z)^2}, W(X,Z,t) = \frac{U_\infty a}{2\pi}\frac{Z+d}{(X-U_\infty t)^2 + (d+Z)^2}. \quad (3)$$

Once the velocity field is known, the aerodynamic force from non-circulatory origin (normal to the plate) is equal to the apparent mass times the acceleration of the fluid (normal to the plate) evaluated at the center of the flat plate (Fung, 1955; Lighthill, 1986). For the flat plate, the apparent mass is equal to $\pi\rho B^2$ (ρ is the fluid density and B is the half-chord of the panel). Therefore, the aerodynamic force (normal to the panel) induced by the vehicle passing is given by

$$N_v(t) = \rho\pi B^2 \frac{\mathrm{d}V_N}{\mathrm{d}t}, \quad (4)$$

where V_N is the velocity (normal to the panel) evaluated at the center:

$$V_N = W(0,0,t)\cos\gamma + U(0,0,t)\sin\gamma, \quad (5)$$

where γ is the orientation of the panel with respect to the vehicle direction (see Fig. 1).

Evaluating $W(0,0,t)$ and $U(0,0,t)$, differentiating and introducing the dimensionless time $T = U_\infty t/d$ one arrives at the following expression for N_v:

$$N_v(T) = \rho B U_\infty^2 C_G\left(-\frac{T}{(T^2+1)^2}\cos\gamma + \frac{1}{2}\frac{T^2-1}{(T^2+1)^2}\sin\gamma\right), \quad (6)$$

where $C_G = Ba/d^2$ is a geometric factor. From Eq. (6) we can draw some conclusions: (i) the higher speed of the vehicle, the higher aerodynamically induced force at the panel and (ii) the induced aerodynamic force is proportional to the size of the vehicle, a, to the square of panel size, B, and inversely proportional to the