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Transverse galloping of circular cylinders fitted with solid and slotted splitter plates

Gustavo R.S. Assi [a,*], Peter W. Bearman [b]

[a] Dept. of Naval Arch. & Ocean Eng., University of São Paulo, São Paulo, Brazil
[b] Department of Aeronautics, Imperial College, London, UK

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ABSTRACT

The galloping response of a circular cylinder fitted with three different splitter plates and free to oscillate transverse to a free stream has been investigated considering variations in plate length and plate porosity. Models were mounted in a low mass and damping elastic system and experiments have been carried out in a recirculating water channel in the Reynolds number range of 1500 to 16 000. Solid splitter plates of 0.5 and 1.0 diameter in length are shown to produce severe galloping responses, reaching displacements of 1.8 diameters in amplitude at a reduced velocity of around 8. Fitting a slotted plate with a porosity ratio of 30% also caused considerable vibration, but with a reduced rate of increase with flow speed. All results are compared with the typical vortex-induced vibration response of a plain cylinder. Force decomposition in relation to the body velocity and acceleration indicates that a galloping mechanism is responsible for extracting energy from the flow and driving the oscillations. Visualisation of the flow field around the devices performed with PIV reveal that the reattachment of the free shear layers on the tip of the plates is the hydrodynamic mechanism driving the excitation.

1. Introduction

The study of bluff bodies fitted directly with splitter plates or in the presence of splitter plates is not new. Experiments performed by Roshko (1954), Bearman (1965) and Gerrard (1966) with a variety of bluff bodies report significant changes in base pressure, vortex formation length and Strouhal number depending on the length of a splitter plate and the distance it is positioned downstream of the body. From the attenuation of vibration of offshore risers to the reduction of noise from an aeroplane's landing gear, previous studies are mainly concerned with the suppression of vortex shedding.

The present investigation was motivated by the use of a splitter plate as a means to suppress vortex-induced vibration (VIV) of offshore risers, which are characterised by highly flexible pipes with relatively low mass and damping susceptible to excitation by ocean currents. In contrast, if the purpose is to enhance vibrations of a low mass-damping system (Chang et al., 2011, for example), the addition of splitter plates may produce considerable improvement in the response for the same range of flow speeds. Cylinders with splitter plates or fitted with other devices prone to galloping may be useful if employed to harvest energy from the flow.

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[*] Correspondence to: NDF Research Group – Dept. Eng. Naval e Oceânica, Escola Politécnica da Universidade de São Paulo, Av. Prof Mello Moraes 2231, 05508-030, São Paulo - SP, Brazil.

E-mail address: g.assi@usp.br (G.R.S. Assi).
URL: http://www.ndf.poli.usp.br (G.R.S. Assi).

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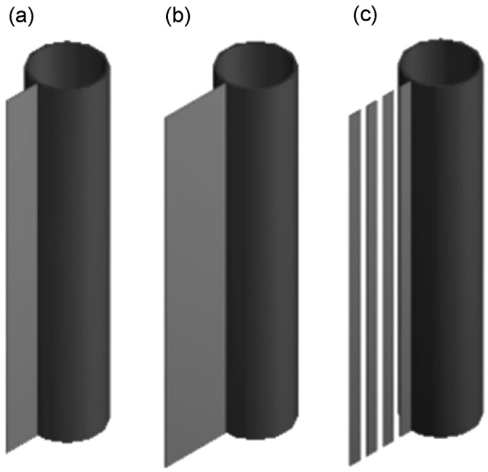

Fig. 1. Representation of tested devices: (a) solid splitter plate $L/D=0.5$, (b) solid splitter plate $L/D=1.0$ and (c) slotted splitter plate $L/D=1.0$.

It is known that if vortex shedding from a fixed cylinder is eliminated, say by the use of a long splitter plate (Cimbala and Garg, 1991), then drag is reduced. Hence conceptually an effective VIV suppression device should be able to reduce drag rather than increase it. Assi et al. (2009) have shown that suppression of cross-flow and streamwise VIV of a circular cylinder, with resulting drag coefficients less than that for a fixed plain cylinder, can be achieved using two-dimensional control plates in low mass-damping systems. A free-to-rotate splitter plate was found to suppress VIV, but instead of remaining aligned with the flow on the centreline of the wake the plate adopted a stable but deflected position when it was released. Cimbala and Garg (1991) had also observed such a bi-stable behaviour of the plate for a free-to-rotate cylinder fitted with a splitter plate.

Successful VIV suppression has been achieved with splitter plates for systems with one and two degrees of freedom as reported by Assi et al. (2009, 2010a). In their experiments the plate was free to rotate to allow for the device to realign itself with the incoming flow, thus producing a omni-directional suppressor. However, when non-rotating splitter plates (among other devices) were investigated it was found that they induced the system into severe galloping-type responses instead of suppressing VIV. Although a failure in VIV suppression, we find such behaviour very interesting and worthy of a detailed investigation.

Therefore, the present study will focus on the comparison between the flow-induced vibration (FIV) of a plain circular cylinder and a cylinder fitted with non-rotating splitter plates with different lengths and porosities, as illustrated in Fig. 1.

1.1. Classical galloping of non-circular cross sections

The term *galloping* has been generally employed to describe a specific type of FIV mechanism that occurs for bodies moving in one degree of freedom (1-dof) with non-circular cross sections. Comprehensive reviews of the classical theory of galloping have been written by Parkinson (1971, 1989), Blevins (1990), Naudascher and Rockwell (1994) and Paidoussis et al. (2011). Classical galloping of non-circular cylinders (the square section being the classic example) is caused by a fluid-dynamic instability of the cross section of the body such that the motion of the structure generates forces which increase the amplitude of vibration (Bearman et al., 1987).

We will argue that a galloping mechanism similar to that occurring in a square cross-section takes place when an elastically mounted cylinder with a non-rotating splitter plate is placed in an oncoming flow.

If a perturbation displaces the body from rest the relative velocity of the flow will be the vectorial sum of the oncoming flow speed, U, and the body's velocity, $\dot{y}$, defining an angle of incidence, α, in relation to the free stream. As depicted in Fig. 2, the upper shear layer approaches the body surface whereas the lower shear layer moves away. Depending on plate length and the body's movement, the separated shear layers will tend to reattach to the tip of the plates as the cylinder oscillates. This generates a decrease in pressure on the upper surface and an increase on the lower surface leading to a transverse fluid force, F_y, acting in the same direction as the motion and causing an increase in the displacement. The stiffness of the spring will eventually act to restore the body back to its original position. When the body reaches its maximum displacement and $\dot{y}$ then changes direction the process is inverted, though with F_y still acting in the same direction as $\dot{y}$. Therefore, in the classical galloping mechanism the cross-flow fluid force is *in phase* with the body's velocity, acting as a negative damping term in the equation of motion, hence classical galloping is classified as a damping-controlled fluid-elastic mechanism. The magnitude of F_y increases with α, which itself increases with $\dot{y}$, resulting in a continuous increase in the steady state amplitude of vibration with increasing flow speed.

"For while VIV is typically limited to amplitudes less than $1D$, galloping amplitudes can be many times D" (Parkinson, 1971). Of course a vortex wake will develop further downstream of a square section or a cylinder with splitter plate as in any