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Cross-flow vortex induced vibrations of inclined helically straked circular cylinders: An experimental study

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ABSTRACT

Effects of suppression devices on the vortex induced vibration (VIV) of inclined cylinders appear not to have received previous due attentions. The current paper reports the results of some towing tank experiments on the vortex induced cross-flow vibrations of bare and helically straked cylinders in vertical and inclined arrangements. Rigid test cylinders were mounted on a single degree of freedom elastic support. The inclination angles examined were $\theta=0^\circ$, $\pm 20^\circ$ and $\pm 45^\circ$. The Reynolds number ranged from 4000 to 45 000 and the reduced velocity from 1 to 16. With all tests the mass ratio and the mass-damping parameters were kept constant.

Test results on “inclined bare” and “inclined helically straked” cylinders showed that the peak amplitude of the cross-flow oscillations decreased as the inclination angle increased. The suppression ratio remained almost the same with the vertical and inclined cylinders. The validity of the so called “Independence Principle” (IP) was also examined against the test data obtained in the current study. The IP, to some degrees, was valid in the case of “inclined bare” cylinders. In the case of “inclined helically straked” cylinders, the IP outcomes were almost entirely inconsistent with actual test data. In addition, the up- and downstream effects on the VIV response of the inclined bare and helically straked cylinders were discussed. Hilbert Transform of the VIV responses showed that it was able to efficiently discriminate signals belonging to the lock-in, initial and lower branches of the response.

1. Introduction

Vortex-induced vibration (VIV) of tubular elements is a source of concern in many industries. Helical strakes can be placed around a tubular structure to suppress the VIV. This solution is simple, reliable and it benefits from omni-directional effectiveness and performance. The mechanism of VIV mitigation provided by the helical strakes is complex. The vortices shed from a straked cylinder are noticeably weakened. In the wake of a straked cylinder, the two shear layers do not interact with each other. The vortex formation length is increased by the strakes. The helical configuration disrupts the regular shedding of vortices along the span. The strakes also considerably reduce the correlation length along the cylinder because they disrupt the spanwise synchronisation of the flow separation (Korkischko and Meneghini, 2010).

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Nomenclature

A	RMS of the cross-flow displacement
A^*	reduced amplitude$=\frac{A}{D_o}$
a_d	analytical amplitude of the cross-flow displacement
a_F	analytical amplitude of the lift force
C_D	drag force coefficient
C_L	lift force coefficient
$C_{L,n}$	normalised lift force coefficient (using IP rules)
C_{LRMS}	RMS of the lift force coefficient
D_i	inner diameter of the cylinder
D_o	outer diameter of the cylinder
D_t	water depth of the towing tank
f	vibration frequency
f^*	reduced frequency$=\frac{f}{f_N}$
F_l	lift force
f_N	in-water natural frequency of the model
f_s	frequency of vortex formation
H	height of the strakes
$\mathbf{H}(d)$	Hilbert transform of the cross-flow displacement
$\mathbf{H}(F)$	Hilbert transform of the lift force
L_i	immersed length of the cylinder
m	structural mass
m^*	Reduced moving structural mass (mass ratio)$=\frac{m}{m_d}$
m_d	mass of the displaced water$=\pi\rho L_i D_o^2$
P	pitch of the helix
PSD	power spectral density
PSD*	normalised power spectral density
R_A	aspect ratio of the cylinder$=\frac{L_i}{D_o}$
Re	Reynolds number$=\frac{U_n D_o}{\nu}$
St	Strouhal number$=\frac{D_o f_s}{U}$
t_D	waiting time between two consecutive runs
U	free stream velocity
U^*	reduced velocity$=\frac{U}{D_o f_N}$
U_r	residual flow velocity
U_n^*	normalised reduced velocity$=\frac{U_n}{D_o f_N}$
U_n	flow velocity component normal to the cylinder axis$=U\cos\theta$
U_∞	free stream velocity
θ	inclination angle of the cylinder
ν	kinematic viscosity of the water
ξ	in-air damping ratio of the model
$\Phi(t)$	phase shift between the lift force and the cross-flow displacement
$\Phi_d(t)$	analytical phase angle of the cross-flow displacement
$\Phi_F(t)$	analytical phase angle of the lift force

Several experimental studies were already conducted on the VIV in vertical cylinders where the flow direction was normal to the cylinder axis (e.g., Bearman, 1984; Khalak and Williamson, 1996, 1997a, 1997b; Govardhan and Williamson, 2000; Branković and Bearman, 2006). However, in many engineering applications, such as cable stayed bridges, offshore mooring lines and catenary risers, the fluid flow direction is not perpendicular to the structure (Jain and Modarres-Sadeghi, 2013). Hanson (1966), Ramberg (1983), Franzini et al. (2009, 2013) and Jain and Modarres-Sadeghi (2013) conducted experimental investigations on bare cylinders with various inclination angles. Franzini et al. (2009) examined inclined low mass-damping cylinders ($m^*\xi \approx 0.0125$), in a circulating water channel in Reynolds numbers ranging from 2000 to 8000. Inclination angles of 0°, 20° and 45° were studied. The peak amplitude, reportedly, reduced as the inclination angle increased from 0° to 20°. It was observed that the peak oscillation amplitude for cylinders of 20° and 45° inclination angles remained almost the same. The onset of oscillations was delayed as the inclination angle increased. Jain and Modarres-Sadeghi (2013) conducted an experimental study in order to investigate the VIV response of the cylinders with large inclination angles ($0° < \theta < 75°$). They reported agreements between their results and findings from Franzini et al. (2009) for inclinations of 20° and 45°. With larger inclinations (i.e., 65° and 75°) the amplitude of the oscillations, intensively decreased.

An approach previously used to estimate the vortex shedding characteristics of cylinders inclined to the oncoming flow is the Independence Principle (IP). It is assumed that parameters such as force coefficients, the Strouhal number, shedding frequencies, etc. when normalised by the velocity component normal to the cylinder axis, are independent of the cylinder's inclination angle. The IP, therefore, neglects the effect of component of the free stream velocity parallel to the cylinder axis, which is legit for small angles of inclination, but not when the angle of inclination increases (Franzini et al., 2013; Jain and Modarres-Sadeghi, 2013).

Helical strakes are widely used to mitigate VIV in spar platforms, chimney stacks, towers, suspended pipes and cables, subsea tubular, risers, tendons, jumpers and pipeline spans. Experiments were also conducted by a number of researchers such as Korkischko and Meneghini (2010), Zhou et al. (2011) and Quen et al. (2014) to study the effect of helical strakes on suppression of the oscillations. Quen et al. (2014) investigated the influence of helical strakes with various pitches ($P=5$, 10, $15D_o$) and heights ($H=0.05$, 0.20, $0.15D_o$) on suppressing the VIV in vertical cylinders. In their studies, the peak amplitude of the oscillations reduced to 72% for a configuration of $P=10D_o$ and $H=0.15D_o$ and to 58% for a configuration of $P=10D_o$ and $H=0.10D_o$.

Korkischko and Meneghini (2010) conducted a series of VIV experiments on isolated and tandem circular cylinders fitted by helical strakes of different configuration. Three strake pitches and heights were tested ($P=5$, 10, $15D_o$, and $H=0.10$, 0.20, $0.25D_o$). In the case of $H=0.10D_o$, the strakes were able to reduce the response amplitude in comparison to that from the isolated bare cylinder, however the oscillations were still persistent. On the other hand, higher strakes ($H=0.20$, $0.25D_o$)