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Circular cylinders fitted with small-scale straight and helical wires: A comparative study on the wire-induced critical effects

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ABSTRACT

An experimental investigation is carried out to compare critical flow effects induced by a single straight wire and a system of three-start helical wires, protruding from the surface of a circular cylinder in uniform cross flow. The cinema technique of Particle Image Velocimetry (PIV) is employed. The Reynolds number is 10,000 and the diameter of the wires is 1.2% of the diameter of the cylinder. This size wire is a small-scale wire on the basis of a comparison with the boundary-layer thickness forming around a smooth cylinder. The cylinder fitted with the single straight wire was tested for the specific case when the wire is at $\theta = 60°$ on the cylinder surface. This is a critical location, where the spanwise wire yields: (i) the greatest extension in the time-averaged near-wake bubble, (ii) a bistable instability in the shear layer separating at the wire, and (iii) early onset of shear-layer instability on the wire-side shear layer. Spectral analysis shows that spanwise application of this wire on the cylinder at the critical location exerts no significant influence on the strength and coherence of the Karman instability. As for the cylinder-helical wire model, the three wires were arranged to pass, in the plane of visualization, from the critical angle and the base of the cylinder (i.e., $\theta = +60°$, $-60°$ and 180°). Distinct similarities are identified in the flow structure induced by the single spanwise wire and the helical wires in the plane where the wire(s) is/are at the critical location ($\theta = \pm 60°$). Similar to the same-size spanwise wire, the helical wires under consideration do not alter the coherence of the Karman instability; however, while passing from the critical angle, they induce several intriguing effects to the *shear layer* and the *overall near-wake structure*. In the plane where the helical wires pass from the critical location: (i) a bistable phenomenon develops in the shear layer, (ii) significant extension in the near-wake is accompanied by a reduction in the peak levels of Reynolds stress and rms velocity fluctuations, and (iii) the onset of shear-layer instability advances to upstream locations.

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1. Introduction

For cylindrical, or near cylindrical, structures in fluid flow, vortex-induced vibration has long been recognized as a challenging problem, still not fully resolved. Over the last three decades, means to suppress this problem have been the focus of intense research. Several methods with varying degrees of effectiveness have been proposed. Zdravkovich [1] and Naudascher and Rockwell [2] reviewed many of these methods. One widely-used approach involves the application of protrusions on the surface of the structure, for example, application of helical strakes, helical wires, staggered separation wires, rings and fairings. Among these protrusions, those with helical patterns are the most commonly employed. Disadvantages of the helical devices, however, include: substantial increase in mean drag [3], significant reduction of effectiveness in turbulent approach flow [4], and inefficiency below a certain critical value of mass-damping parameter [5]. Nevertheless, irrespective of these shortcomings, helical-type protrusions have been broadly used, for example, in industrial chimneys, tall process towers, antennas, and marine risers, owing to their effectiveness in suppressing the vortex-induced vibrations.

With helical devices, whether an effective suppression is achieved or not depends on the number, pitch, cross-sectional shape and the thickness of the protrusion. An excellent overview of the previous empirical studies, seeking the optimum configuration in helical protrusions, is given by Naudascher and Rockwell [2]. According to these investigations, for effective suppression, the number of helical wires or strakes should be 3 or 4 [6–8], and the thickness of the protrusion should be at least 10% of the diameter *D* of the structure for marine applications [9]. Interestingly, applying a large number of helical windings, for example 8 or 16, enhances the lift force, instead of suppressing it [6,10]. For helical protrusions with a rectangular cross-section, which are generally referred to as helical strakes, the optimal pitch is determined for three helixes to be between 4*D* and 5*D* [11,12], whereas for

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Nomenclature

d	diameter of the surface wire
D	diameter of the main cylinder
f_K	Karman vortex shedding frequency
L	length along the wetted span of the cylinder
p	pitch distance of helical winding
p^*	local pitch distance of helical winding
Re_D	Reynolds number based on the diameter of the main cylinder
$S_u(f_K)$	autospectral density of streamwise velocity component at Karman frequency
t_o	initial time
T_K	period of a full Karman cycle
δ	boundary layer thickness
θ	angular position of the wire from the forward stagnation point of the cylinder, in degrees
θ_{c1}	first critical angle
θ_{c2}	second critical angle
Ψ	streamlines
u	streamwise velocity component
U_o	free-stream velocity
v_{rms}	root-mean-square of transverse velocity
ω	vorticity
$\lvert\cdots\rvert$	absolute value of $\cdots$
$<\cdots>$	time averaged value of $\cdots$
Δ	difference

helical wires, which are protrusions having a circular cross-section, the most effective pitch is in the wide range of 8D to 16D [6], far away from 4D to 5D found for the helical strakes.

So far, the reason why certain helical configurations optimize the suppression under certain conditions, while others worsen the problem has remained unresolved. At this point, without trial-and-error experiments, it is not clear whether a configuration would work better than another. Despite the huge engineering interest on helical-protrusion devices, little is understood about the controlled flow structure and the basic flow physics involved. This is mostly because the helical protrusions introduce three-dimensionality to the flow, as shown in the study of Chyu and Rockwell [13], greatly increasing the complexity of ensuing flow fields. In search of a physical understanding, a number of investigators have turned their attention to relatively simpler, two-dimensional models, where the surface protrusion took the form of a straight wire attached to the outer surface of the cylinder, parallel to its spanwise axis.

Regarding the cylinders fitted with spanwise wires, many of the previous investigations have focused on the shedding frequency and the mean loading characteristics. The wire size, the wire location on the cylinder surface, and the Reynolds number were found to significantly affect the shedding frequency, and the mean drag and lift loads [14–18,22,23,25]. By convention, the wire location is defined, in all these works, as the angular position θ on the cylinder surface, with $\theta = 0°$ being the forward stagnation point. In the case of a single spanwise wire, the frequency of shedding was found to vary considerably from its characteristic value only when the surface wire is located within a certain range of θ [16,17]. On the basis of this variation, Nebres [16] and Nebres and Batill [17] identified a number of fundamental wire locations. A large number of equally-spaced spanwise wires along the surface of the cylinder were also shown to induce considerable changes in the shedding frequency and the drag coefficient [19].

On cylinders fitted with spanwise wires, there are also investigations where the flow patterns were pursued. The works of Igarashi [20], Fujita et al. [21], Nebres [16], and Nebres and Batill [17] classified the flow patterns at subcritical Reynolds numbers into distinct regimes based on the transition and separation characteristics of the boundary layer. In the order of increasing θ, the following regimes were noted to appear by these investigators: The first regime involves a reattachment bubble beyond the wire; downstream of this reattachment, a laminar boundary layer forms and separates from the cylinder surface. The second regime also shows a reattachment bubble after the separation at the wire; however, in this case, a turbulent boundary layer forms downstream of the wire, and the final separation angle from the cylinder surface is larger than that of a bare cylinder. In the third regime, the flow completely separates at the wire with no reattachment to the cylinder surface. In the forth regime, the wire is in the base of the cylinder and has no significant effect on the flow.

Further to the abovementioned flow regimes, more recently, Ekmekci [22] and Ekmekci and Rockwell [23,24] identified a bistable regime for a cylinder fitted with a single spanwise wire. During this regime, the shear layer, separating at the wire, goes between the state of reattachment and the state of complete separation (no reattachment). This bistable situation occurs only when the spanwise wire is placed at a certain angular position on the cylinder surface. This critical wire location (designated as θ_{c1}) also marks the border between the abovementioned second regime involving stable reattachment of the shear layer and the third regime associated with stable no-reattachment state. Another recent, independent study conducted by Alam et al. [25] also observed the appearance of this bistable phenomenon, involving the shear-layer reattachment and early separation from the wire, for a circular cylinder fitted with a pair of symmetrically-placed spanwise wires.

As a further distinguishing characteristic for the critical location θ_{c1}, Ekmekci [22] and Ekmekci and Rockwell [23,24] revealed that a single spanwise wire at this critical location yields the greatest extension in the streamwise length of the near-wake bubble. About 10 or so degrees after this first critical angle θ_{c1}, they also determined a second critical location (designated as θ_{c2}), where implementation of a spanwise wire induces significant contraction in the near-wake bubble. These critical locations were shown to change with the size of the wire (larger the wire, smaller the critical angles) [24].

Moreover, Ekmekci [22] and Ekmekci and Rockwell [23] showed that the spectral amplitudes associated with the velocity fluctuations at Karman frequency significantly mitigate when a large-scale spanwise wire is placed at the first critical angle θ_{c1} (which is the location where the abovementioned bistable instability and near-wake extension occur). On the other hand, the same wire intensifies the spectral amplitudes associated with the Karman instability when attached at the second critical angle θ_{c2}. These findings mark a major breakthrough in flow-control research, as it unveiled the conditions that attenuates and exacerbates the coherence and strength of the Karman vortex shedding by use of a single spanwise wire. A small-scale wire, however, was found to have insignificant effect on the strength and hence the coherence of the Karman vortex shedding at θ_{c1} [24]. Here, the scale of the wire, i.e., large- or small-scale, is defined relative to the boundary-layer thickness forming around a smooth cylinder, and the large-scale wire, which was shown to induce significant impacts on the Karman instability at critical locations, was indeed quite small in size (although being larger than the boundary layer

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