CONTROLLING THE FLOW-INDUCED VIBRATION OF A CIRCULAR CYLINDER VIA A SINGLE SPANWISE TRIPWIRE

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ABSTRACT
This study investigates experimentally the effects of a single spanwise tripwire on the vortex-induced vibrations (VIVs) and flow structure of a circular cylinder that is free to oscillate in the cross-flow direction. Oscillatory motion of the cylinder and the near-wake flow field are linked through the synchronized use of a high-resolution laser distance sensor and a high-image-density Particle Image Velocimetry (PIV) system. Various tripwire locations are considered from $\theta = 0^\circ$ to $180^\circ$ with $1^\circ$ and $5^\circ$ increments with respect to the most upstream point of the cylinder. As a breakthrough, the present study identified a range of tripwire locations (specifically $105^\circ \leq \theta \leq 108^\circ$) for which the amplitude of the free transverse oscillations of the cylinder is reduced by more than 90%. The presented results focus on this specific range of tripwire locations and address the flow characteristics induced through the tripwire control. It is shown that the tripwire alters the vortex shedding mechanism significantly. Specifically, for the range of tripwire locations where significant reduction in oscillation amplitude is observed, the vortex shedding pattern is found to randomly switch between two distinct vortex shedding modes.

NOMENCLATURE
- $\zeta$ Damping ratio
- $\theta$ Angular position of the tripwire
- $A'$ Nondimensional amplitude of oscillation based on $D$ (i.e., amplitude/cylinder diameter)
- $d$ Tripwire diameter
- $D$ Cylinder diameter
- $f_n$ Natural frequency of the system in still water
- $f_a$ Oscillation frequency of cylinder
- $f_u$ Frequency of streamwise velocity component
- $f^*$ Frequency ratio based on $f_n$
- $L$ Cylinder length
- $m^*$ Mass ratio
- $St$ Strouhal number, i.e., nondimensional vortex shedding frequency
- $S_u$ Autospectral density of the streamwise velocity component
- $U$ Free stream flow velocity
- $U^*$ Reduced velocity
- $x$ Streamwise direction
- $y$ Transverse direction

INTRODUCTION
Vortex-induced vibration (VIV) is a significant phenomenon affecting elastically-mounted structures in fluid flow. In engineering applications, a practical method is needed for controlling the oscillation of structures undergoing VIV. Avoidance of VIV in civil engineering structures can be achieved through structural modifications that change the natural frequencies of the structure or the use of vibration dampers; however, these methods are very expensive and sometimes impractical. Instead, more practical, and thus most widely used, approach to suppress or at least subdue the intensity of vibrations is the use of methods that can energize the boundary layer or disrupt the vortex shedding process. One such method is the application of a surface protrusion, such as helical wires and strakes, staggered separation wires, fairings, etc.

The simplest protrusion that can be applied to the surface of a cylinder is a spanwise tripwire. The effects of spanwise tripwires on the flow and loading characteristics have been studied extensively in the literature for stationary cylinders. For a stationary cylinder fitted with a single spanwise tripwire, Nebres and Batill [1] have discussed the variation of the non-dimensional vortex shedding frequency ($St$) by considering the effects of the tripwire size $d$, tripwire angular position $\theta$, and
Reynolds number. Based on this variation, they defined several critical tripwire locations where the Strouhal number $S_t$ undergoes significant changes. In addition, Ekmekci and Rockwell [2] have elaborated on the variations of the near-wake and shear-layer flow structures through detailed examination of PIV data of a cylinder fitted with a single spanwise tripwire. They demonstrated that a single spanwise tripwire that is larger than the boundary layer thickness can attenuate the Karman vortex shedding when placed at certain angular positions on the cylinder surface, while the same tripwire can be used to intensify the Karman vortex shedding when placed at other critical positions.

Spanwise tripwires can be used as a method for controlling the VIV of cylinders, but few studies were conducted on this topic. In this category, only a very small number of specific scenarios were investigated with only one or two tripwire locations, while a wider range of locations needs to be studied to assess the interactions between tripwire-induced flow patterns and structural vibrations. For example, Hover et al. [3] studied the vortex-induced load and vibration characteristics at $Re = 3.0 \times 10^4$ for a cylinder fitted with two spanwise tripwires ($d/D = 0.3\%$) at only one fixed angular position ($\pm 70^\circ$). They showed that their tripwires decrease the peak oscillation amplitude moderately in the reduced velocity range of $U^* = 5.1 - 6.0$; and above $U^* = 6.0$, vibrations are decreased remarkably. More recently, the fluid forces on an elastically mounted rigid cylinder with two symmetrically positioned tripwires ($d/D = 12\%$) are investigated by Quadrante and Nishi [4] for a range of Reynolds numbers from $3.45 \times 10^3$ to $2.04 \times 10^4$. They considered only four tripwire angular positions, and they suggested that the vibration is intensified with the use of the tripwires at $60^\circ$ and $75^\circ$, and is diminished at $105^\circ$ and $120^\circ$.

In the current research campaign, the effects of a tripwire in altering the VIV response is studied by measuring the oscillation motion and the near-wake velocity field simultaneously for a rigid cylinder undergoing free oscillations in the cross-flow direction. To address the shortcomings of the previous studies in this research area, a wide range of tripwire positions is considered while keeping the characteristics of the oscillation system and the flow properties constant. In the present study, the placement of the spanwise tripwire at a specific range of positions is shown to be effective in suppressing the VIV of the cylinder. Up to 97% amplitude reductions in cylinder oscillations are shown possible through the use of a single spanwise tripwire in this range.

**EXPERIMENTAL SETUP**

Experiments are conducted in a recirculating water tunnel located at the University of Toronto. All tests are conducted at a Reynolds number of $10^4$ (based on the cylinder diameter), which corresponds to a reduced velocity of $U^* = U/f_n D = 10.61$. The test model is a rigid circular cylinder with a diameter of $D = 50.8 \, mm$ and a length of $L = 534 \, mm$, and is made of polycarbonate. A clear acrylic wire is tightly stretched and glued on the surface of the cylinder, parallel to its span. From the boundary-layer thickness data provided by Aydin et al. [5], it is known that the diameter of this wire is larger than the boundary layer thickness forming around a non-tripped equivalent circular cylinder at the Reynolds number considered here ($Re = 10^4$). The tripwire was positioned at a range of angular positions from $\theta = 0^\circ$ to $180^\circ$ with respect to the most upstream point of the cylinder. The angular increment for $\theta$ was $1^\circ$ and $5^\circ$ for different test cases.

The model was mounted vertically inside the water tunnel, and an endplate was placed under the lower free end of the cylinder with a gap of $13.8\%$ of the cylinder diameter. For the free oscillation experiments, the test mechanism was designed carefully to achieve a low value of mass ratio ($m^*$), which is the ratio of the total oscillating mass (including 1/3 of the spring mass) to the mass of the displaced fluid. The mass ratio
of this system was $m^* = 2.58$. The oscillation mechanism consisted of two shafts that supported a mounting plate and a step motor as depicted in Fig. 1. The cylinder was attached to the step motor. This motor was used to rotate the cylinder around its spanwise axis so that the tripwire location can be changed for each test case. The damping ratio was calculated around its spanwise axis so that the tripwire location can be changed for each test case. The damping ratio was calculated for the spanwise axis to determine the cylinder displacement and the near-wake flow structure were measured simultaneously. To determine the cylinder displacement, a high-resolution laser distance sensor was used; and to capture the instantaneous velocity fields in the near wake, the technique of high-image-density Particle Image Velocimetry was utilized.

RESULTS

The cross-flow oscillations of the clean cylinder (the cylinder without a tripwire) showed uniform sinusoidal oscillations, non-dimensional amplitude of which was determined to be $A^* = 0.513$ at the tested reduced velocity. The response of the clean cylinder lies on the lower response branch and the detected amplitude is comparable with the results presented by Williamson and Govardhan [6] for a clean cylinder having mass and damping ratios similar to the present study.

The effect of the tripwire angular position on the amplitude of oscillations is shown in Fig. 2. From an overall look into the $A^* - \theta$ variation, one can partition the plot into different segments based on the trend observed in the amplitude. The polynomial curves in this figure show the overall change in each segment of the plot. The amplitude of oscillations is defined as half of the distance the cylinder sweeps between the upper and lower limits of oscillation motion, and it is non-dimensionalized based on the cylinder diameter. The horizontal dashed line in Fig. 2 depicts the oscillation amplitude of the clean cylinder. It is apparent from Fig. 2 that, depending on the location of the tripwire, the oscillation amplitude can be increased or decreased effectively via the single tripwire. What is particularly interesting for the VIV suppression is that the oscillation amplitude drops more than 90% of the amplitude of a clean cylinder when the tripwire is placed at a location in the range of $\theta = 105^\circ$ to $108^\circ$. In this range, the maximum amplitude reduction occurs at $\theta = 107^\circ$, for which the reduction reaches the 97% of the oscillation amplitude of the clean cylinder counterpart. These observations are significant and suggest that something as simple as a single spanwise tripwire can be used to suppress VIV.

The oscillation patterns for the clean cylinder and the cylinder fitted with the spanwise tripwire at $\theta = 107^\circ$ are shown in Fig. 3. The clean cylinder has a uniform sinusoidal oscillation as expected. However, when the tripwire was placed in the range of $\theta$ between $105^\circ$ to $108^\circ$, the sinusoidal oscillation motion ceased. The cylinder stayed in its mid-position with very-small-amplitude vibrations. Although this behavior is shown only for the tripwire angular position of $\theta = 107^\circ$ in Fig. 3 (as this case achieved the maximum reduction in oscillation amplitude), similar very-small-amplitude vibrations took place for all $\theta$ in the range of $\theta = 105^\circ$ to $108^\circ$.

Contour patterns of normalized instantaneous vorticity ($\omega D/U$) are shown in Fig. 4(a) and Fig. 4(b) for the clean cylinder and in Fig. 4(c) and Fig. 4(d) for the cylinder that is fitted with the tripwire at $\theta = 107^\circ$. For the clean cylinder in Fig. 4(a), a coherent vortex $V_1$ and then another vortex $V_2$ have already formed when the cylinder starts to move downward. The same vortices are marked in Fig. 4(b) at the instant when the cylinder starts to move upward. The vortices seen earlier in Fig. 4(a) are now stretched and convected downstream in Fig. 4(b).

The tripwire can effectively alter the vortex shedding mechanism. When fitted with the spanwise tripwire at $\theta = 105^\circ$ to $108^\circ$, it was seen from Fig. 3 that the cylinder does not have a regular oscillation motion and it stays in its mid-position with very-small-amplitude vibrations. For these $\theta$, two different vortex shedding modes are revealed. Fig. 4 (c) depicts a representative snapshot from one of the modes, named in this
paper as Mode A. In this mode, vortices are shed alternately into the wake at a frequency similar to that observed in the station ary clean cylinder case. On the contrary to the oscillating clean cylinder case, however, the vortices in this mode do not move away from the cylinder centerline as they convect downstream. A second mode, Mode B, is depicted with a representative snapshot in Fig. 4(d). In this mode, two vortices form (marked as $V'_1$ and $V'_2$). After circulating in their position for a brief while, they shed downstream in the form of small-scale vortices. In this mode, these small-scale vortices travel along the centerline of the cylinder as well. Long-time cinematographic PIV records of the near wake show that the vortex shedding pattern switches randomly between these two vortex shedding modes (Mode A and Mode B). Although, in Fig. 4, the modes are depicted only for the $\theta = 107^\circ$ case, these modes were equally observed for all $\theta$ in the range of $\theta = 105^\circ$ to $108^\circ$.

Further insight into the effects of the tripwire on the unsteady flow characteristics can be obtained by studying the velocity spectra. The contours in Fig. 5(a) and Fig. 5(b) show the amplitude of streamwise velocity spectra $S_u$ at the predominant frequency of streamwise velocity fluctuations for the clean cylinder and for the cylinder fitted with the tripwire at $\theta = 107^\circ$, respectively. These global spectra results have been constructed from the whole-field velocity data acquired via PIV. Note that, to ease the interpretation of the effect of the oscillation motion on the spectral results, the mid-position and the range of oscillation motion are marked on the cylinder boundary in Fig. 5. For the clean cylinder (Fig. 5(a)), the existence of high-amplitude spectral peaks is an indicator of the presence of a coherent vortex shedding process at a predominant frequency, which happens to coincide, for the case under consideration, with the frequency of cylinder oscillations (i.e., $f_d^* = f_u^* = 1.31$). Note that the plot in Fig. 5(a) is the spectral amplitude corresponding to this predominant frequency. For the $\theta = 107^\circ$ case (Fig. 5(b)), the presence of very-low spectral amplitudes is due to the less coherent shedding of vortices, which are now known to switch randomly between Mode A and Mode B from the discussions of Fig. 4(c) and (d). Note that Mode A involves shedding of vortices at a frequency identical to the vortex shedding frequency of a stationary clean cylinder at $Re = 10^4$ ($f_u^* = 2.14$, or in other words, $St = 0.21$), while Mode B involves shedding of vortices with no predominant frequency. Although being significantly lower than the clean cylinder case, the spectral peaks for the $\theta = 107^\circ$ case appear at $f_u^* = 2.14$, and hence, the spectra plot given in Fig. 5(b) shows the spectral amplitudes at this frequency. It can be concluded that in the range of $\theta = 105^\circ$ to $108^\circ$, by altering the shedding mode of vortices, the tripwire achieves attenuation in the VIV response of the cylinder.

**FIGURE 4:** CONTOUR PATTERNS OF NORMALIZED INSTANTANEOUS VORTICITY ($\omega_D/\bar{U}$) FOR: (a), (b) THE CLEAN CYLINDER, AND (c), (d) THE CYLINDER WITH TRIPWISE AT ANGULAR POSITION OF $\theta = 107^\circ$. THE CONTOURS OF NORMALIZED VORTICITY ARE SHOWN WITH AN INCREMENTAL VALUE OF $\Delta(\omega_D/\bar{U}) = 1.15$. THE SIZE OF THE TRIPWIRE SEEN AT THE UPPER SIDE OF THE CYLINDER SURFACE IS TO SCALE.

**FIGURE 5:** AUTOSPECTRAL DENSITY $S_u$ CONTOURS CORRESPONDING TO THE STREAMWISE VELOCITY COMPONENT AT A SPECIFIC FREQUENCY FOR (A) THE CLEAN CYLINDER AND (B) THE CYLINDNER WITH TRIPWIRE AT $\theta = 107^\circ$. THE MID-POSITION OF THE CYLINDER AND THE RANGE OF ITS OSCILLATION MOTION ARE ALSO DEPICTED AT THE CENTER OF THE CYLINDER BOUNDY. THE INCREMENTAL VALUE OF THE CONTOURS IS $\Delta S_u = 2.5$ mm/s.
CONCLUSIONS

The control induced by a single spanwise tripwire on the free oscillation motion of a cylinder in cross-flow direction is investigated experimentally. Tripwire locations over the full 180° angular range on one side of the cylinder were investigated. This paper showed that, the tripwire deployed over a specific angular range from $\theta = 105^\circ$ to $108^\circ$ achieves more than 90% reduction in oscillation amplitude at the considered flow conditions compared to the clean cylinder counterpart. It is observed that the tripwire in this range of angular positions suppresses the oscillation motion of the cylinder by imposing a new vortex shedding mechanism that features random switching between two modes. The presented data is for the reduced velocity of 10.61, which corresponds to a Reynolds number of $10^5$. Further study is undergoing to investigate the effects of the tripwire on the VIV of a cylinder at different flow conditions.

REFERENCES


