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REDUCTION/SUPPRESSION OF VIV OF CIRCULAR CYLINDERS THROUGH ROUGHNESS DISTRIBUTION AT $8\times10^3 < Re < 1.5\times10^5$

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ABSTRACT

Vortex Induced Vibration (VIV) of a circular cylinder in a steady flow is reduced using distributed surface roughness. VIV reduction is needed in numerous applications where VIV is destructive. Roughness is distributed to the surface of the cylinder in the form of sandpaper strips to achieve three goals: (1) Trip separation in a controlled manner so that some uncertainties are removed and the flow becomes more predictable. (2) Reduce spanwise correlation, which is strongly linked to VIV. (3) Select roughness grit size to achieve the first goal without energizing too much the boundary layer, which would induce higher vorticity and circulation, and consequently lift. Our experiments show that it is possible to reduce VIV amplitude and synchronization range. More tests are needed to achieve full suppression. Our experiments are conducted in the TrSL2 and TrSL3 flow regimes.

I. REDUCTION/SUPPRESSION OF VIV

Control of vortex shedding behind a bluff body and control of vortex induced motion of a bluff elastic body or bluff rigid body on elastic support have been topics of research and patenting for over a hundred years (Zdravkovich 1997). In ocean engineering, suppression of vortex shedding is important because of the destructive effect of VIV on marine risers, underwater pipelines, SPAR offshore platforms, etc. In other engineering disciplines, VIV of cylindrical structures, such as tubes in heat exchangers, cooling towers, nuclear fuel rods, and smoke stacks can be destructive and must be suppressed. Control of vortex shedding for suppression of VIFM (Vortex Induced Forces and Motion) can be achieved by surface roughness control active, passive, or combination thereof of (Bernitsas and Raghavan 2007).

Suppression of vortex shedding was reviewed by Zdravkovich (1981; 1997) who broadly classified means for suppressing vortex shedding into three categories:

(a) Disturbing the spanwise correlation with devices such as helical strakes, wires, studs or spheres, and wavy body surfaces.
(b) Affecting the shear layer emanating from both sides of a bluff body with devices such as shrouds.
(c) Preventing the interaction of the entrainment layers with devices such as splitter plate and base-bleed.

A plethora of methods and devices have been developed to suppress VIFM (Zdravkovich 1997). None of those methods uses surface roughness to suppress VIFM (Bernitsas and Raghavan 2007).

Our approach to reducing/suppressing VIV is based on three underlying principles (Bernitsas and Raghavan 2007; Bernitsas et al. 2008a).

Principle #1: Trip separation of the boundary layer in a controlled and sustainable manner. Tripping the boundary layer early enough and maintaining it separated regardless of the Reynolds number regime provides a passive way of controlling the nature of the flow. This results in removing some uncertainties and making vortex shedding and VIV more predictable. It may enhance VIV as shown by Raghavan and Bernitsas (2008b). Reduction or enhancement can be achieved by properly selecting the thickness of the sandpaper base, grit size, the beginning and end of the sand paper strip along the direction of the flow and the circumference of the cylinder crosssection.

Principle #2: Decrease the correlation length. With the flow more predictable, regardless of the Reynolds number, it is possible to reduce the spanwise correlation, which is linked to VIV. Short sandpaper strips, while located and sized according to Principle #1, can minimize the spanwise correlation of the flow and reduce VIV.

Principle # 3: Minimize the additional turbulence induced by surface roughness. Surface roughness distribution can increase turbulence at the boundary layer scale. This increased turbulence feeds the shear layer, the Von Karman vortices and the wake. The increased turbulence also affects the momentum of the separating shear layer. This added turbulence must be minimized by appropriately sizing the sandpaper grit in comparison to the boundary layer thickness.

Method of Reduction/Suppression of VIV: The method developed in this research to control VIFM is based on the above three principles. Grit size and distribution must be designed based on Principles #1, #2, and #3 even though the latter may be in conflict with the first two principles.

Figures 1 and 2 show examples of successful use of roughness strips for VIFM reduction. Strips are more effective than trip-wires because of the inherent oscillatory nature of the separation point (Mei, Currie 1969). The roughness strips trip separation and maintain it because their width makes it possible to accommodate the oscillatory nature of the separation points. The roughness strips are broken down into short, discontinuous, and staggered strips of variable roughness as shown in Figure 2. Reducing the spanwise correlation along the separation lines or shear layers, weakens correlated vortex shedding and the induced alternating forces. This reduction in correlation results in reduction/suppression of VIFM. To accommodate variation in direction of the relative fluid flow, roughness strips would be distributed around the body. Another variation of distribution of roughness that can reduce/suppress VIFM is shown in Figure 1.

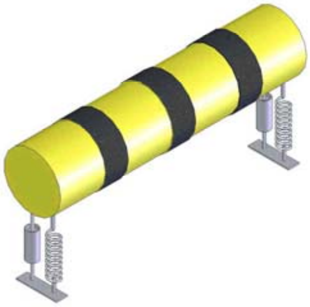

Figure 1. Example of roughness distribution to reduce/suppress VIV.

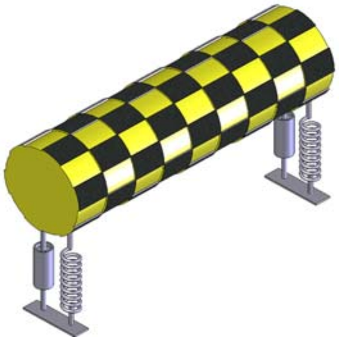

Figure 2. Example of roughness distribution to reduce/suppress VIV.

Besides reducing the correlation length, roughness controls the flow separation. A flow past a structure, typically separates at two separation points, one on each side of any cross section of the structure. Using roughness strips before the regular separation point, determines the nature of the flow downstream. The flow can be laminar, or in transition between laminar and turbulent, or turbulent. In each case, control of separation using roughness may have different effect on the flow and consequently VIFM.

The most profound effect of separation point control appears in the critical flow regime. Transition from laminar to turbulent flow can be controlled using roughness strip/s. This exploits the concept of tripping the boundary layer and energizing the boundary layer with eddies that are shed from the roughness elements on the roughness strip/s. Depending on the size, width, height of the strips and the location of the roughness strip/s, the flow can be controlled to reattach in a laminar or turbulent manner. The size of the separation bubble can be controlled changing the roughness configuration. The size of the separation bubble is linked to the pressure loss; the larger the bubble, the larger the loss of pressure, and the larger the loss in lift.

II. EXPERIMENTAL SETUP AND TEST MATRIX

Model tests are conducted in the Low Turbulence Free Surface Water Channel (LTFSW) of the Marine Renewable Energy Laboratory of the University of Michigan using smooth and rough cylinders suspended on two coil springs attached to end plates/struts. Details are provided in (Bernitsas et.al, 2006a).

Based on the discussion in Section I, it is obvious tat there is a high number of parameters involved in the design of distributed roughness to reduce/suppress VIV: beginning and end of roughness with respect to flow separation, pattern of breaking the spanwise flow correlation, thickness of sandpaper base and size of grit with respect to the boundary layer thickness, amount of vorticity added by the grit size.

It is important that the effect of each parameter is studied separately. The effect of minimizing the correlation length using different roughness patterns requires an extensive study, which is underway. Here we report only on the effect of location of the beginning and end of roughness with respect to flow separation. Accordingly, sandpaper strips are not broken into short pieces. The cases presented in this paper are tabulated below.

Case	Sandpaper	Grit size k (10^{-6} m)	Sandpaper thickness k+P (10^{-6} m)	Diameter D (inch)	k/D	k+P/D	No: of strips	Circumferential angle
1	P120	125	508	3.0	0.0016	0.0067	2	±64°- ±80°
2	P36	538	1651	5.0	0.0042	0.0130	2	±80°- ±103°
3	P80	201	711	5.0	0.0016	0.0056	2	±80°- ±103°
4	P80	201	711	5.0	0.0016	0.0056	4	±80°- ±103°, ±117°- ±140°

III. EXPERIMENTAL RESULTS

The following observations can be made on the amplitude of VIV, the range of synchronization, and the frequency of oscillation. Reference should be made to Raghavan and Bernitsas (2007), where grit size effect and critical Reynolds number are studied.

III.1. Amplitude of oscillation and synchronization range: Results are presented based on two extreme locations of the sandpaper strips. In the first configuration, the sandpaper strips cover the entire range of oscillation of the separation point (Bernitsas et.al. 2008a). In the second configuration, the sandpaper strips are placed right after the end of the separation zone. In the present experiments the maximum amplitude of oscillation for smooth cylinder seems unusually high, that is A/D >1.6. This high amplitude of oscillation is attributed to the high Reynolds number regime (TrSL3) at which the experiments were conducted (Raghavan 2007).

The downstream edge of the roughness strip at 80°: Figure 3 shows the results for Case 1 (3.0″ cylinder). The amplitude of oscillation and range of synchronization reduce dramatically. At reduced velocity greater than 6.75, VIV is nearly suppressed reducing from A/D of 1.6 to 0.2. This can be attributed to the critical Reynolds number that must be reached before the roughness strips start increasing the amplitude and preserve VIV (Bernitsas et.al. 2007b). Recall that the correlation length has been maintained to be equal to the entire cylinder length.

The upstream edge of the roughness strip at 80°: In this case, the roughness strips do not interact with the zone of flow separation. Instead, they interact with the shear layer separated from the cylinder. The results are shown in Figures 4 and 5. The amplitude of oscillation reduces but the synchronization range extends more than in the smooth cylinder VIV. The third and fourth strips, for Case 4, are placed further downstream of the cylinder between angles of 117°-140°. In Case 4, roughness covered nearly 25% of the cylinder surface. In comparison to the two-strip cases the four-strip cases affects the amplitude in the reduced velocity range of 4 to 6. Elsewhere it has minimal effect. The response character didn't change as the area of coverage of roughness increased from 12.5% (two strips) to 25% (four strips) confirming that strategically located roughness can be very effective in achieving the desired result.

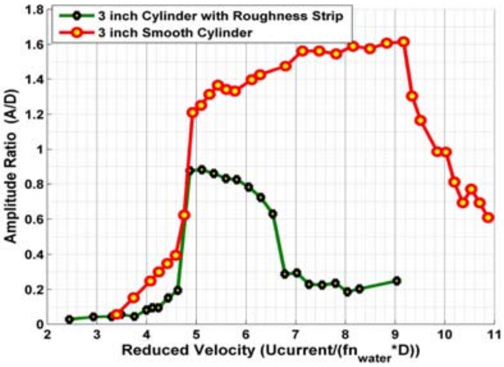

Figure 3. A/D and range of synchronization of a 3.0″ cylinder with roughness strips (Case1) and without roughness strips .

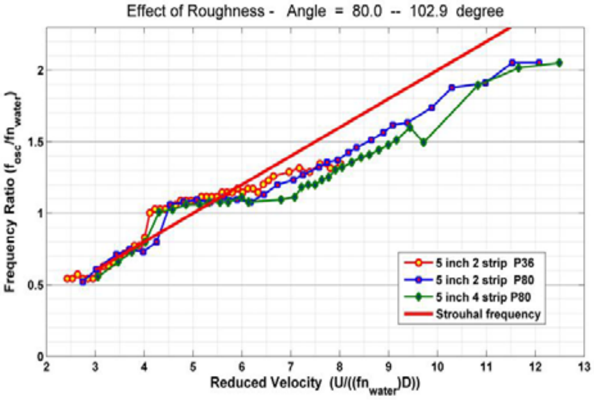

Figure 4. Frequency ratio ($f^* = f_{osc}/f_{n,water}$) vs. reduced velocity. Two-strip cases: P36 and P80 roughness strips placed at 80°– 102.9° symmetrically Four-strip cases for 5″ cylinder: two more strips placed symmetrically at 117°-140°.

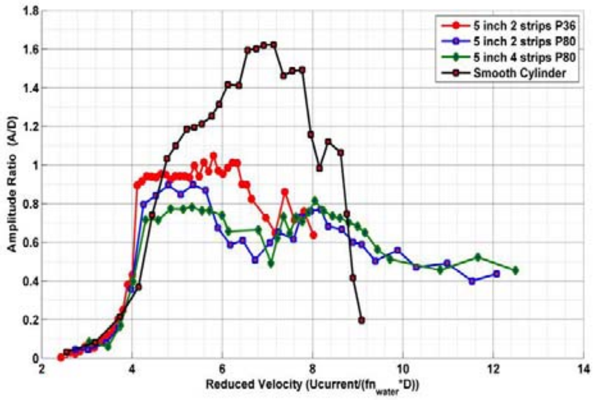

Figure 5. Amplitude ratio (A/D) vs. reduced velocity. Two-strip cases: P36 and P80 roughness strips placed at 80°– 102.9° symmetrically Four-strip cases for 5″ cylinder: two more strips placed symmetrically at 117°-140°.

III.2. Frequency of oscillation: The ratio of frequency of oscillation with respect to the natural frequency of the system in water ($f^{*}= f_{osc}/f_{n,water}$) is shown in Figure 4. In the three cases shown in this figure, roughness strips were placed after the zone of separation point if the flow is assumed to be in the laminar regime. On the other hand if the flow has been energized to the point being effectively in the TrBL regime then the roughness strips is located right before the turbulent separation.

The upstream edge of the roughness strip at 80°: In this case, the thickness of the roughness strips and the size of the grit elements affect the added turbulence which in turn interacts with the shear layer. Further, the frequency of oscillation follows parallel to the Strouhal line $\left(\frac{0.2*U}{f_{n,water}D}\right)$ as shown in Figure 4. That is, the frequency of oscillation in the synchronization range is locked on to the frequency of shedding rather than the natural frequency in water. In Case 3 (5″ cylinder with two P80 strips), vortex shedding behaves as in the case of a steady flow past a stationary cylinder with the Strouhal number of 0.185 instead of 0.2 $f_{osc} = f_{vs} = \frac{0.185*U}{D}$. This phenomenon continues upto $f_{osc}/f_{n,water} = 2$. At that point it appears that lock-on to 2 times $f_{osc}/f_{n,water}$ occurs.

IV. MAIN FINDINGS

Surface roughness has been used to reduce/suppress VIV of a circular cylinder in the TrSL3 regime. The basic principles for this methodology have been explained. The number of parameters involved in designing the roughness distribution is high and the tests presented in this paper are limited to studying the location of roughness in the form of sandpaper strips only. The sandpaper strips spanned the entire cylinder length in our tests. Breaking the strips into short ones would break the correlation length and obscure the effect of location of sand-strips with respect to the flow separation zone.

The results of the cylinder with roughness strips, undergoing vortex induced vibration in the TrSL3 regime are summarized as follows:

1. Reduction of VIV can be achieved by arranging roughness strips in multiple configurations where the spanwise correlation of flow separation is disrupted resulting in reduction of the correlation length.
2. Short roughness strips break the spanwise flow correlation and assist in reducing/suppressing VIV.
3. Roughness, when distributed properly, can reduce/suppress VIV.
4. Roughness can decrease the range of synchronization.
5. When the roughness strips were attached to the cylinder aft of the flow separation zone (aft of an angle of 80°), the amplitude ratio (A/D) of the VIV response decreased but the range of synchronization was increased.
6. When the roughness strips were attached to the cylinder aft of the flow separation zone, the frequency character of VIV for a cylinder with roughness strips was similar to the case with roughness strips placed between 57°-80° in the beginning of the synchronization. For higher reduced velocity f* follows the Strouhal line (Figure 4).

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