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VIV RESPONSE AND DRAG MEASUREMENTS OF CIRCULAR CYLINDERS FITTED WITH PERMEABLE MESHES

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ABSTRACT

Experiments have been carried out on models of rigid circular cylinders fitted with three different types of permeable meshes to investigate their effectiveness in the suppression of vortex-induced vibrations (VIV). Measurements of amplitude of vibration and drag force are presented for models with low mass and damping which are free to respond in the cross-flow direction. Results for two meshes made of ropes and cylindrical tubes are compared with the VIV response of a bare cylinder and that of a known suppressor called the "ventilated trousers" (VT). All three meshes achieved an average 50% reduction of the peak response when compared with that of the bare cylinder. The sparse mesh configuration presented a similar behaviour to the VT, while the dense mesh produced considerable VIV response for an indefinitely long range of reduced velocity. All the three meshes have increased drag when compared with that of the bare cylinder. Reynolds number ranged from 5,000 to 25,000 and reduced velocity was varied between 2 and 15.

Keywords: *circular cylinder, vortex-induced vibration, suppression, permeable meshes, ventilated trousers VT.*

NOMENCLATURE

$\overline{C}_D$ Mean drag coefficient
d Bobbin reference diameter
D Cylinder external diameter
m^* Mass ratio
f_0 Natural frequency in air
f_N Natural frequency in water
U Flow speed
U/Df_N Reduced velocity
$\hat{y}/D$ Cross-flow amplitude of vibration
ζ Structural damping ratio
Re Reynolds number
St Strouhal number

INTRODUCTION

The development of new suppressors of vortex-induced vibration (VIV) of offshore risers still is a challenging topic for technological research. Offshore operations in ultra-deep waters require both risk and drilling time to be reduced. Harsh environmental conditions may limit the operational window or even interrupt drilling operations altogether. Therefore, drilling companies are constantly seeking new solutions that are not only efficient in suppressing VIV with minimal drag penalty, but also that can be transported, stored, assembled, installed and removed in the fastest and simplest manners [1, 2]. Effective suppressors must also be reliable and resistant to severe conditions at sea.

Recently, a type of VIV suppressor reappeared in the scientific-technological scene with novel geometric modifications. Patented by Brown in 2010 [3] it has since been called *ventilated trousers*, or simply VT. Essentially, the VT is a development of the idea of wrapping the drilling riser in a type of flexible cover able to deform with the flow and mitigate the body response to hydrodynamic loads. The VT could be thought of as a combination of or inspired by previous solutions as rope nets, canvas sleeves and perforated shrouds, some of which have

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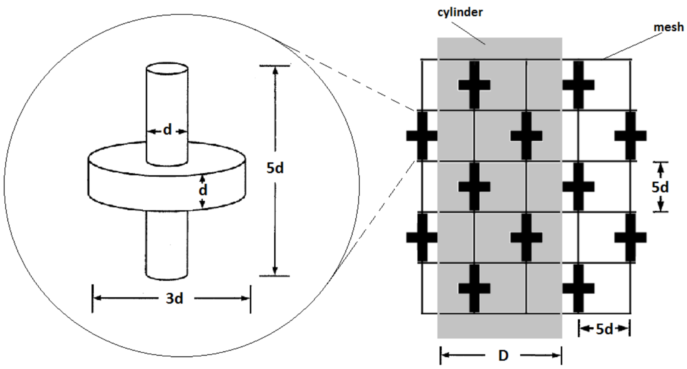

FIGURE 1. Bobbin geometry and distribution of the VT mesh based on [3].

been developed in the 1960s [4,5]. In the words of the inventors, "the VT suppressor is a loose fitting sleeve in the form of a light flexible net with integral bobbins in a special arrangement. It is omni-directional, rugged, and made from materials compatible with the offshore environment" [6].

Other suppressors of flow-induced vibrations have dealt with the idea of wrapping rope meshes and other flexible structures around bluff bodies [7, 8]. However the novel modification brought into the VT concept is the addition of characteristic volumetric bobbins to the elements of a rope mesh. Several bobbins of different proportions have been studied in model tests [9] before the final geometry illustrated in Figure 1 was patented. Recent full-scale tests on a 0.53m diameter riser in the range of $Re = 1.2 \times 10^6$ have been performed by King et al. [6] and reported a 90% reduction in peak amplitude of vibration.

The present work is part of a scientific investigation of the hydrodynamic and hydroelastic mechanisms that make this family of suppressors to effectively work. Starting from the patented geometry of the VT (figure 2(a)), two other permeable meshes were tested, as illustrated in figure 2. The new geometries had simplified bobbins made of small cylindrical tubes with diameter d, i.e. simply as if the $3d$-disc had been removed from the VT bobbin. The length of the small tubes was $5d$, equal to the length of the VT bobbin, thus covering the entire length of a cell of the mesh. Two meshes were built with different distributions of tubes. The first, called the *sparse mesh* in figure 2(b), had the same distribution of the VT with tubes in every other cell. The second, called the *dense mesh*, had tubes fitted in every cell of the mesh, as seen in figure 2(c).

EXPERIMENTAL ARRANGEMENT

Experiments have been carried out in the Circulating Water Channel of NDF (Fluids and Dynamics Research Group) at the University of São Paulo, Brazil. The NDF-USP water channel has an open test section which is 0.7m wide, 0.9m deep and

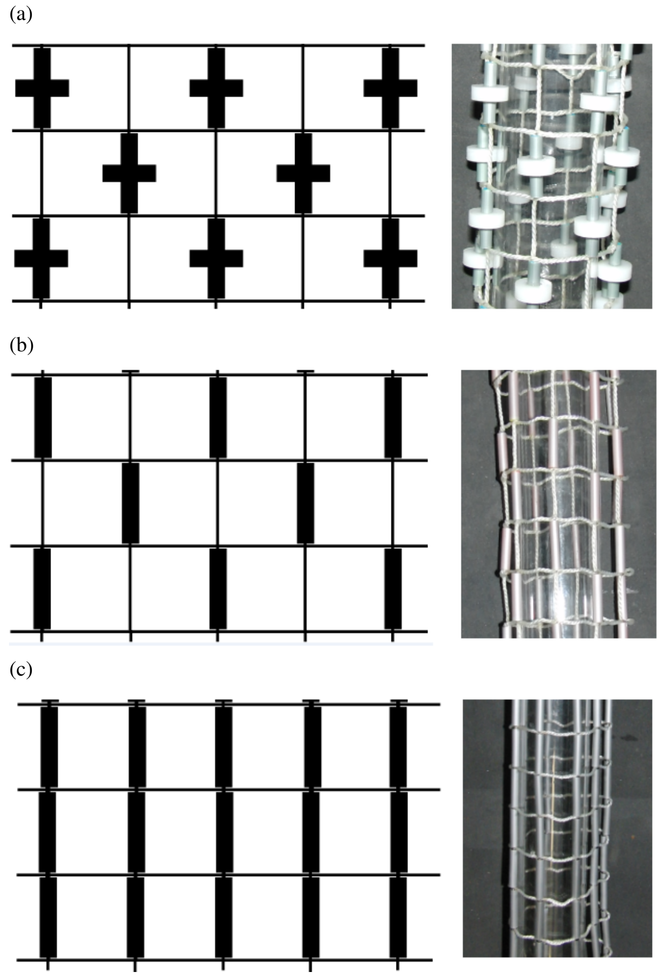

FIGURE 2. Arrangement of the (a) VT mesh, (b) sparse and (c) dense meshes with cylindrical tubes.

7.5m long. Good quality flow can be achieved up to 1.0m/s with turbulence intensity less than 3%. This laboratory has been especially designed for experiments in flow-induced vibrations; further details about the facilities are described in Assi et al. [10].

A rigid section of circular cylinder with an external diameter of $D = 50$mm was made of a perspex tube. Each mesh was fitted as a sleeve around the cylinder, as seen in figure 2. VT bobbins and cylindrical tubes were made out of plastic rods with a reference diameter of $d = 5.8$mm, yielding the ratio $d/D = 0.116$. The mesh perimeter was 232mm, corresponding to $4.64D$ (approximately $1.5\pi D$), based on the best configuration achieved by Brown & King [9]. All meshes were neutrally buoyant, and their masses were much smaller than the mass of the cylinder. Figure 2 also shows the actual meshes fitted around the perspex cylinders employed in the experiments.

Models were mounted on a low damping rig that allowed the cylinder to freely respond with one degree of freedom (1-dof)

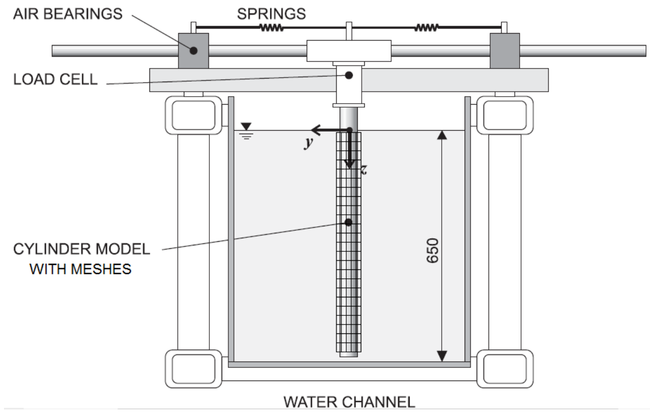

FIGURE 3. Experimental setup. Cylinder with mesh suppressor mounted on the pendulum rig in the test section of the NDF/USP water channel.

in the cross-flow direction, as seen in figure 3. The model was fixed at its upper end to an elastic mounting. Fig. 3 shows a schematic representation of the apparatus and helps in describing the operation of the system. The support system is firmly installed on the channel structure and the sliding cylindrical guides are free to move in the transverse direction, defined by the y-axis. A load cell connects the moving parts of the base to the top end of the model.

An optical sensor was employed to measure displacements in the y direction. One pair of springs was installed in the y axes to set the natural frequency of motion (f_0, measured in air) in the cross-flow direction. A specially built load cell was attached between the cylinder and the support system to deduce the hydrodynamic forces on the cylinder model in x (drag) and y (lift) directions.

Decay tests have been performed in air in order to determine f_0 as well as the level of structural damping. The apparatus turned out to present a low structural damping of $\zeta \approx 0.40\%$, measured as a fraction of the critical damping. The total oscillating mass of the system was measured in air, resulting in a non-dimensional mass parameter $m^* \approx 2.8$, defined as the ratio between the total mass and the mass of displaced fluid. Consequently, the mass-damping parameter $m^*\zeta$ of the system was kept to the lowest possible value in order to amplify the amplitude of response. Table 1 presents a summary of the structural parameter for all tested models. Notice that m^* varies slightly from model to model due to the mass variation of the installed meshes.

Preliminary tests have been performed with a plain cylinder to serve as reference for comparison. Measurements were made using a fixed set of springs and the reduced velocity range covered was up to $U/Df_N = 12$, where f_N is the natural frequency determined by decay tests in water. The only flow variable changed during the course of the experiments was the flow velocity U, which alters both the reduced velocity and the Reynolds number between 5,000 and 25,000. Throughout the present study, cylinder displacement amplitude non-dimensionalised by the cylinder diameter ($\hat{y}/D$ for cross-flow directions) was found by measuring the root-mean-square value of response and multiplying by $\sqrt{2}$.

TABLE 1. Structural properties.

	f_0 (Hz)	f_N (Hz)	m^*	ζ	$m^*\zeta$
Bare cylinder	0.680	0.584	2.80	0.34%	0.009
VT mesh	0.662	0.562	2.92	0.36%	0.010
Sparse mesh	0.671	0.573	2.85	0.42%	0.012
Dense mesh	0.665	0.571	2.88	0.36%	0.010

RESULTS AND DISCUSSION

A preliminary VIV experiment was performed with a bare cylinder in order to validate the set-up and methods. Figure 4 compares the reference cross-flow response obtained for the bare cylinder with those obtained for each suppression device. The observed peak amplitude of $\hat{y}/D = 0.8$ around $U/Df_0 = 4.0$ for the bare cylinder is in good agreement with other results presented in the literature [10,12,14]. For $U/Df_N > 9.0$ random vibrations reaching $\hat{y}/D \approx 0.2$ might be associated with turbulence buffeting. The frequency response in figure 4 also shows the synchronisation mechanism typical of VIV. The inclined dashed line is a reference to the typical frequency of vortex shedding for a static cylinder with $St = 0.2$. the mean drag coefficient shown in Fig 5 is also in good agreement with results presented in the literature [15, 16]. In $U/Df_N \approx 5$, maximum amplitudes occurs and $\overline{C}_D \approx 3$. The mean drag decreases up to $\overline{C}_D \approx 1$ when the amplitudes are very small, for $U/Df_N > 11$.

In general, all suppressor meshes in figure 4 showed a reduction of the peak response of almost 50% at $U/Df_0 \approx 4.0$ when compared with response of the bare cylinder. The VT mesh was able to reduce peak response down to $\hat{y}/D = 0.38$ as well as shorten the VIV synchronization range to the limits of $U/Df_0 = 3$ and 8. It was also able to reduce the level of residual vibration attributed to turbulence buffeting observed for higher reduced velocities beyond the synchronisation range. The performance of the VT in the present work was not as successful as that presented in Brown & King [9], where they found a maximum peak response of only $\hat{y}/D = 0.14$ for their best VT configuration. This difference could be related to the fact that not only their experiments presented a bobbin

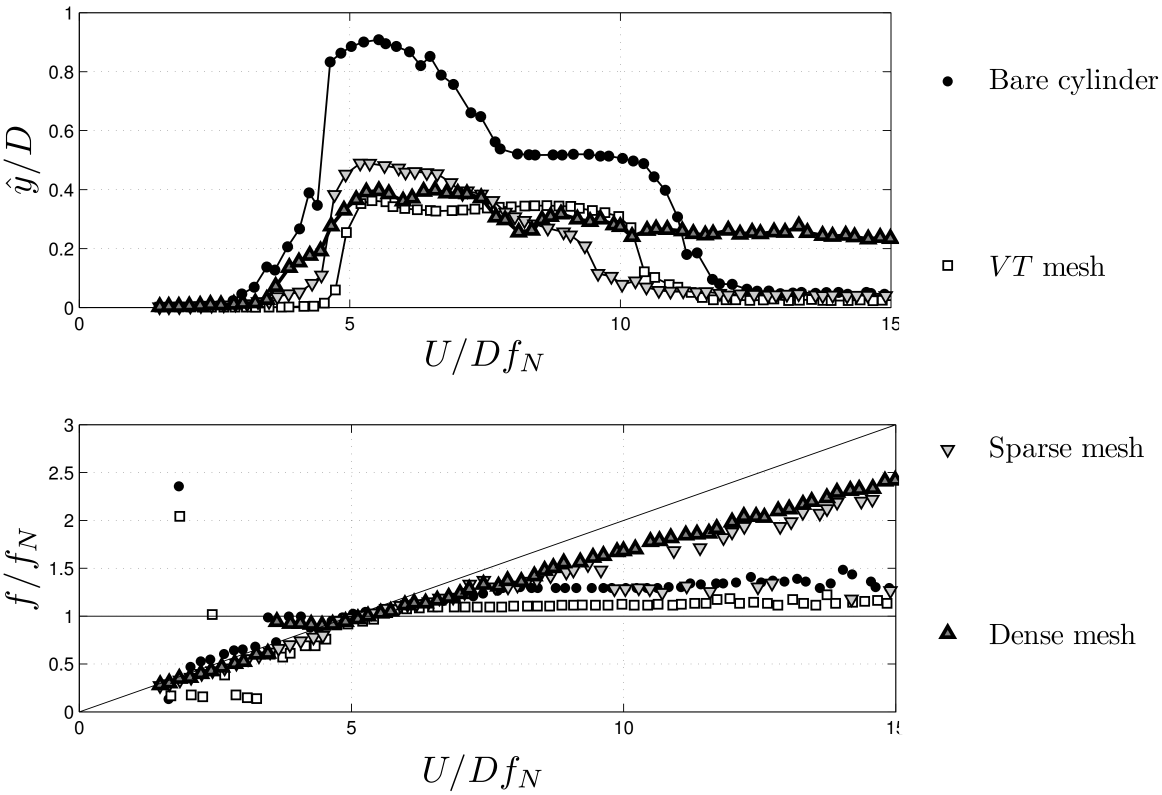

FIGURE 4. VIV response of a bare cylinder and cylinder with suppressors. (a) Cross-flow amplitude of vibration ($\hat{y}/D$) and (b) dominant frequency (f/f_N) versus reduced velocity.

ration d/D that was almost half of that of the present work, but also they employed a flexible cable with higher values of structural damping ($\zeta = 1.37\%$) at Reynolds numbers one order of magnitude higher.

The VT response frequency presented in figure 4-b shows a behavior similar to that of the bare cylinder, with dominant frequencies of vibration following the shedding frequency during the upper branch of VIV and remaining close to f_N for the rest of the response. Note that dominant frequencies are not as representative of the VIV response for reduced velocities beyond the synchronization range due to random vibrations caused by turbulence buffeting. The Figure 5 shows that VT reduces drag forces for $4 < U/Df_N < 7$, which is the same range where maximum amplitudes occurs. For higher values of U/Df_N the VT mesh increase the mean drag coefficient in about 20% when the amplitudes of vibration are small.

The response of the sparse mesh in figure 4 shows a slightly different behavior when compared with the performance of the VT. The maximum peak response was also reduced down to $\hat{y}/D = 0.4$, but the VIV synchronization range was extended when compared with the previous case. The frequency response in figure 4-b, however, is not very different from the other previous cases, showing the same type of VIV excitation mechanism. The mean drag coefficient shows a similar behavior to that of the VT mesh. Compared to the bare cylinder, the sparse mesh reduces $\overline{C}_D$ in the range of maximum amplitudes of vibration and increase it 20% in average.

The response of the dense mesh, on the other hand, was found to be quite interesting and rather different from the others, as seen in figure 4. Vibrations of $\hat{y}/D = 0.3$ started to develop at $U/Df_N = 4$, but a single branch of response kept increasing in amplitude until $\hat{y}/D = 0.45$ was reached at $U/Df_N = 15$. In other words, the VIV synchronization range appeared not to have finished for a much higher reduced velocity, when compared with the other cases.

The frequency results in figure 4-b show that during this indefinitely long branch of response the cylinder with dense mesh is vibrating at the frequency of vortex shedding, very close to the line of $St = 0.2$. Somehow the dense mesh appears to be able to capture the excitation from the vortex shedding mechanism for a large range of reduced velocity, thus producing a very different response. One cannot tell if this branch of

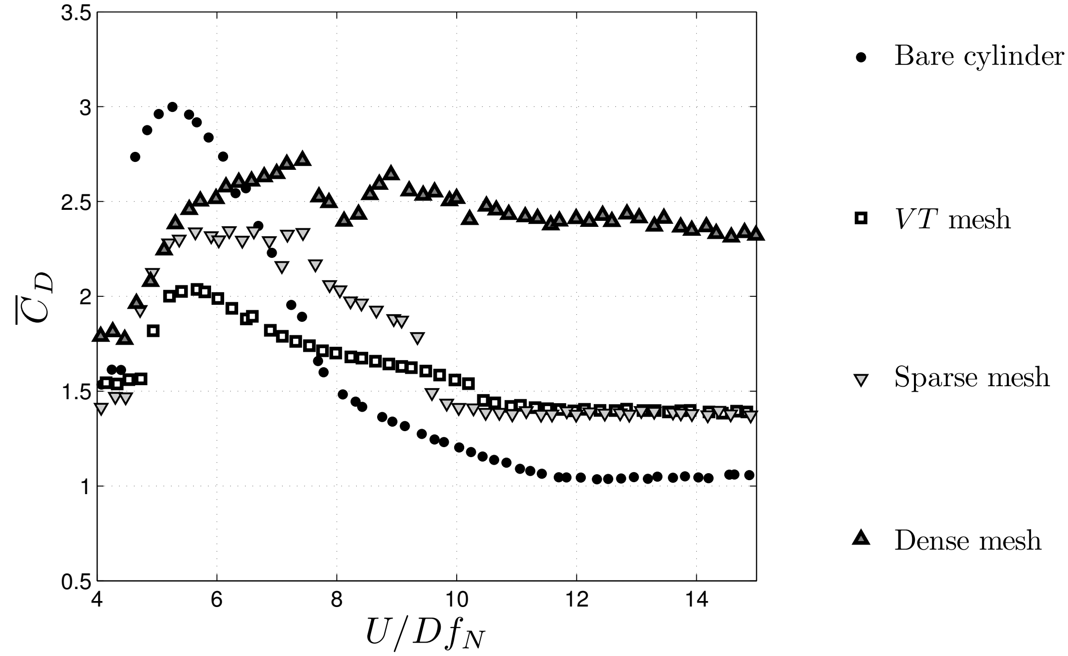

FIGURE 5. Mean drag coefficient for cylinders with suppressors.

response would be sustained for much higher reduced velocities. Future experiments with higher flow speeds must be employed to verify that. Brown & King [9] reported a similar behaviour to be occurring with VT meshes of perimeter greater than $1.5\pi D$. The mean drag coefficient for the dense mesh is higher than that of other meshes, reaching $\overline{C}_D \approx 2.5$ in the range $4 < U/Df_N < 15$.

A comparable behaviour has been observed by Govardhan & Williamson [17] to be occurring in the VIV response of a very light cylinder with mass ratio below a certain critical value of $m^* = 0.54$. They called this phenomenon "resonance forever" meaning that the response of the cylinder would be driven by the frequency of vortex shedding for an infinitely long range of synchronisation. In the present work, the system is clearly heavier than the critical mass ratio reported by Govardhan & Williamson but the presence of the mesh might be acting in a way to capture the wake excitation and reproduce this mechanism. Further investigation is surely needed to clarify this hypothesis.

CONCLUSION

In the present work we have investigated the VIV response of a circular cylinder fitted with three suppressors of the permeable mesh type. Suppression of about 60% of the peak response was achieved by the VT mesh proposed by Brown [3] and 50% for a simpler mesh made of cylindrical tubes instead of bobbins. When the dense mesh was tested, response was fundamentally different and vibrations at the frequency of vortex shedding were sustained for much higher reduced velocities.

The VT mesh reduces the mean drag coefficient on the range of reduced velocity in which the maximum amplitude occurs, but for ranges where there are small vibration drag force is increased in about 20%. Similar behavior occurs for the simple mesh. The dense mesh showed the highest drag force and amplitude of vibrations. We conclude that drag force is decreased due to VIV suppression.

We conclude that bobbin distribution might have a considerable effect on the effectiveness of the suppressor, since the sparse mesh and the VT achieved similar levels of suppression having the same distribution yet with different bobbin geometries. This could point towards significant three-dimensional flow structures induced by the helical distribution of the bobbins.

The fact that the VT was able to suppress turbulence buffeting may point to it producing higher hydrodynamic damping than the other meshes. The sparse mesh with the same bobbin distribution was not as successful in suppressing random vibrations at higher reduced velocities, proving that this configuration may present lower hydrodynamic damping than the VT, which is rather intuitive given their distinct geometries. In fact, decay testes performed in still water showed that the hydrodynamic damping associated with the VT mesh is indeed higher than that of the sparse mesh, yet both are lower than that measured for the dense mesh.

Future investigations should concentrate on the PIV (particle-image velocimetry) measurements of the wake, measurements of lift forces as well as experiments at higher reduced velocities.

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