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CIRCULATING WATER CHANNEL FOR INVESTIGATIONS OF FLUID-STRUCTURE INTERACTIONS IN LOW REYNOLDS NUMBERS

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Abstract. *This work originally contributed with results in a Circulating Water Channel (CWC) applied to low Reynolds number investigations of the Fluid-Structure Interaction (FSI). It is important to note that, when looking for work on FSI in water flows corresponding to low Reynolds numbers, it is noted that the overwhelming majority of them are dedicated to the investigation of vortex-shedding models and their effects in terms of the efforts generated on the stationary structures. On the other hand, few results are found in the dynamic condition, i.e. the one in which the structures subject to flow are free to oscillate with at least two degrees of freedom in regimes of low Reynolds numbers, $Re < 10^3$. Although seemingly easy to conceive and understand, experiments under these circumstances are extremely demanding and challenging to perform, possibly as justification for the scarce availability in the literature. In this scenario, therefore, this work presents the CWC recently built at UFSC-Joinville, funded by CNPq with the primary objective of investigating Flow-Induced Vibrations (FIV) in cylinders and cylinder arrangements elastically supported with two degrees of freedom and subjected to water flows of low Reynolds numbers. In this regard, aspects related to the construction of models on an ultra-reduced scale are presented, as well as the precise measurement technique of dynamics via the Motion Capture System (MCS), both solutions that allowed results at the desired low Reynolds numbers. In fact, the results are quite close to those obtained from experiments in large and expensive towing tanks, which validates the CWC at low Reynolds numbers as a promising infrastructure for the investigation of FSI, faster and cheaper, particularly in research campaigns with a large number of conditions to be selected already in the initial development phase, for example, when defining the best geometry for a Floating Offshore Wind Turbine (FOWT). Undoubtedly, it is important to make clear that in the offshore industry, there are no practical cases of FIV in Reynolds numbers as low as those studied in this work. However, it is common sense that the flow models responsible for the full-scale FIV phenomena are qualitatively preserved in low Reynolds numbers which therefore allows the use of investigations in these regimes for faster and cheaper selection of promising designs, in addition to contributing to a more comprehensive and robust validation of numerical approaches via CFD.*

Keywords: *Circulating Water Channel (CWC), Low Reynolds Numbers, Reduced Models, Motion Capture System (MCS), Fluid-Structure Interactions (FSI)*

1. INTRODUCTION

Researchers and engineers usually employ small-scale tests in controlled environments to investigate complex phenomena. This approach is typically used to verify and validate numerical results and/or when experiments with real-scale prototypes are unfeasible. However, even though small-scale models are cheaper than full-scale prototypes, they can still cost tens of thousands of dollars, which is a high amount to be spent in an initial design phase or for didactic purposes. In addition to the high costs of the model, the tests themselves are carried out in specialized laboratories. In the case of experiments in an aquatic environment, water channels and towing tanks are expensive and complex equipment to operate.

Another use for a CWC, especially for low Reynolds regimes, is to sort possible solutions for Flow-Induced Vibrations (FIV) problems and validate CFD in ranges where experimental results are scarce for some phenomena, such as Vortex-Induced Vibrations (VIV). It is noteworthy that there are many low-Reynolds results for vortex shedding, in fixed

cylinders, but when dealing with VIV in systems free to oscillate at least in two directions, the number of available results is drastically reduced.

In this work, Fluid-Structure Interactions (FSI) will be on focus, especially Vortex-Induced Vibrations (VIV). The VIV phenomenon has a resonant nature and is a particular case of FIV, remembering that both are encompassed by the FSI.

The VIV is triggered by the synchronization between one of the system's natural frequencies and the frequency of vortex shedding arising from the flow in its surroundings. This results in a self-excited and self-controlled phenomenon, characterized by low-amplitude oscillations, around one diameter for circular cylinders, which can lead to fatigue failures in structures due to its oscillatory nature and, therefore, must be considered in engineering projects.

In terms of publications about FIV in circular cylinders submitted to the Low Reynolds regime, one single publication with an experimental approach was found. Blevins and Coughran (2009) evaluate the response of single elastic cylinders through experimental tests. The Reynolds interval used is between 170 and 150000. The study develops a systematic database for one- and two-dimensional responses in terms of amplitude, frequency, and drag force, varying the system's characteristics such as damping factor and mass ratios. One of the main results presented is the influence of the Reynolds number on the response amplitudes. Note that the VIV amplitude in the synchronization range decreases in lower Reynolds number ranges, which is 60% of the diameter for $Re \approx 1500$, compared to an amplitude diameter for $Re \approx 25000$.

Regarding surface roughness, the amplitude drops to half when the surface has an increasing of it. The study also concluded that with increasing damping factor, for the same mass ratio, the VIV amplitude decreases in both directions (crossflow and inline). The authors also verify the influence of the mass ratio in a system for a given damping. Increasing the mass ratio shortens the response interval in VIV and also considerably decreases the maximum VIV amplitude.

Typically, small-scale tests to investigate the VIV phenomena are carried out on towing tanks and large circulating water channels, and to perform them in a low Reynolds number with a lower budget, a small Circulating Water Channel (CWC) was designed and built for the Laboratory of Fluid-Structural Interaction (LIFE), at the Federal University of Santa Catarina (UFSC). The CWC was based on the concept built on the Núcleo de Dinâmica e Fluidos (NDF) at the Polytechnic School of the University of São Paulo (EPUSP), selected among other concepts that can be found in Saeed *et al.* (2018), Kalgutkar *et al.* (2016) and Jiang *et al.* (2018).

It is worth mentioning that the structure built at LIFE-UFSC is notably cheaper than a typical CWC, not an easy task for a piece of equipment that, in order to be improved, needs to meet different demands simultaneously. Being smaller, less complex to use, and cheaper to operate, the CWC at LIFE-UFSC can be used as a didactic tool in classes and also as a means of training human resources in the design and execution of experiments with scientific rigor, as well as in the theoretical study of the phenomena of FSI itself. That is, to run a batch of experiments in the CWC, the operator must both understand the operation of the equipment and also understand the phenomenon to be able to point out any unexpected behavior in the system, formulate hypotheses for this occurrence, and create ways to mitigate them.

Performing small-scale experiments in circulating water channels with low Reynolds numbers contains an important aspect for the study of VIV, as it allows the first analysis of ocean systems to be performed. Assays with high and low Reynolds number present a similarity between the results found among those found in the Assays for the study of the phenomenon of vortex-induced vibrations.

In this context, from this similarity it is possible to reduce the matrix of tests performed for channels with high Reynolds number, and it is possible to verify which are the critical cases of the models tested during tests with low Reynolds number. In addition, assays with a higher number of Reynolds are more expensive systems to operate, as well as more difficult to assemble and operate and with longer operating time, as well as easier training of the technical team specialized in performing the experiments.

Since VIV results in low Reynolds regimes are scarce, this work will discuss not only some of the characteristics of the CWC and the data acquisition system used in tests of this nature but also the tests carried out in the CWC as a way to verify its operation and obtain results comparable with those from the literature on the VIV phenomenon. Additionally, these results in terms of amplitude and frequency can be a source of data for validating numerical simulations, since they are consistent with the literature.

The FIV investigations presented in this work were carried out with cylinders with circular and square sections, elastically supported with two degrees of freedom and with low values of the mass ratio (m^*), damping coefficient (ζ) and aspect ratio (AR).

2. METHODOLOGY

The structure of CWC, as shown in Figure 1, can be divided into five main parts: upstream tank (1), contraction section (2), test section (3), downstream tank (4), and pump (5). The upstream tank, the contraction, and the downstream tank were fabricated in polypropylene. The framework that supports the test section has the function of providing structural stability and rigidity to the CWC and was made of steel and painted to avoid corrosion.

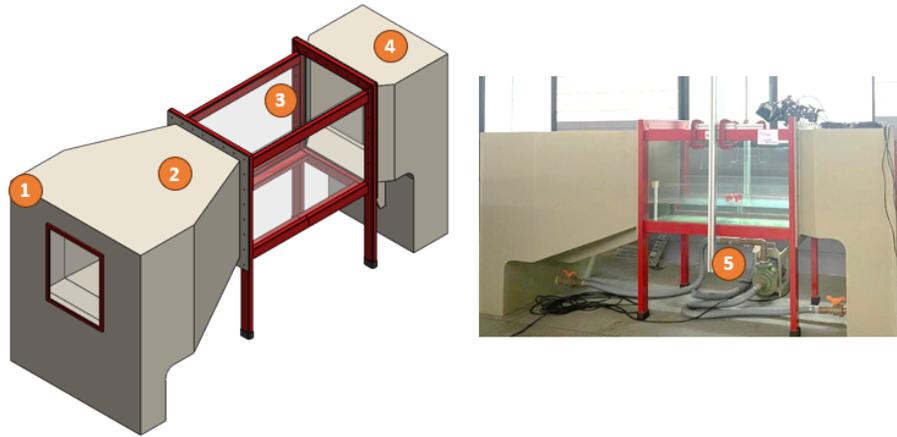


Figure 1. Circulating Water Channel in LIFE-UFSC-Joinville and its main parts: (1) upstream tank; (2) contraction section; (3) test section; (4) downstream tank; and (5) pump.

To reduce turbulence in the test section, a flow distributor consisting of a spool with multiple holes was installed at the bottom of the upstream tank. This arrangement helps evenly distribute the fluid flow. Additionally, a flow straightener was placed at the beginning of the contraction section to minimize vorticity, comprising a thin mesh within a frame. The primary function of the contraction section is to accelerate the fluid flow, dissipating any remaining vorticity before it enters the test section.

The test section comprises three thick glass sheets and measures 1200mm in length, 550mm in width, and 750mm in height. This section is where all experimental tests take place, requiring a rigid steel frame to ensure structural stability during experiments. The frame also serves as a support for assembling models and instrumentation, such as accelerometers, load cells, strain gauges, and/or microphones. The transparent glass was chosen for the test section to allow visual monitoring of the height markings of the water column and to ensure that the water level remains appropriate for the desired flow rate throughout the experiments.

For water circulation in the CWC, a 1hp centrifugal pump was selected. Rubber hoses of 2 inches in diameter were used instead of regular PVC pipes and connections to minimize the transmission of vibrations to other components. A T-termination was used at the pump outlet to facilitate tank drainage. In the absence of electronic velocity control, valves were placed in both the upstream and downstream tanks to regulate the flow rate if necessary. Achieving low Reynolds numbers requires maintaining the velocity as low as possible while still exciting the VIV phenomena in the system.

The CWC serves as the controlled environment for placing and testing the systems, allowing the use of various data acquisition systems, such as accelerometers, load cells, and Motion Capture Systems (MCS), depending on the desired results. For the tests carried out herein, the commercial Optitrack MCS was used. This system offers advantages in terms of low marker mass and high-precision data acquisition, which is crucial when dealing with small-scale models.

The OptiTrack MCS is operated using Motive software. The process begins with the wand procedure, where the capture volume is set to correctly track reflective markers strategically placed on the objects of interest. These markers reflect infrared light emitted by the OptiTrack cameras, allowing for precise tracking of their positions and orientations. The cameras, positioned throughout the capture area, record the movement of these markers in real time.

Motive software processes the captured data and offers various functionalities for analysis. One of its key features is the “rigid body” option. By attaching three or more markers to an object, Motive can create a virtual rigid body representation of that object. The software triangulates the positions of the markers and establishes the centroid, orientation, and overall motion. This option is particularly beneficial for capturing rotation in the system. To ensure the accurate synchronization and alignment of data from multiple cameras, an eSync device is utilized. The eSync device sends synchronization signals to all connected cameras, allowing them to capture data simultaneously. This synchronization guarantees precise temporal alignment of the recorded data from each camera.

The combined operation of the OptiTrack MCS, Motive software, wand procedure, and the availability of the rigid body option allows accurate recording, analysis, and interpretation of motion data. The system provides the ability to precisely track the movements and interactions of objects, facilitating detailed investigations and valuable insights into various phenomena and processes. The temporal records captured by Motive can be exported to “CSV files” for further analysis. The sampling rate employed was 100Hz, surpassing the anticipated frequencies of approximately 0.5Hz.

Three cameras were used in the tests, as shown in Figure 2, on the left. Two cameras were dedicated to motion capture, while the third camera was used for filming the tests, serving as a means of observing any possible anomalies in the results, such as eventual marker loss, external interference, or model-related problems. To facilitate the data acquisition process, reflective markers were utilized and to minimize external reflections, black fabric was placed along the sides of the test section. The exposure and lens focus of the cameras were adjusted to enhance marker tracking.

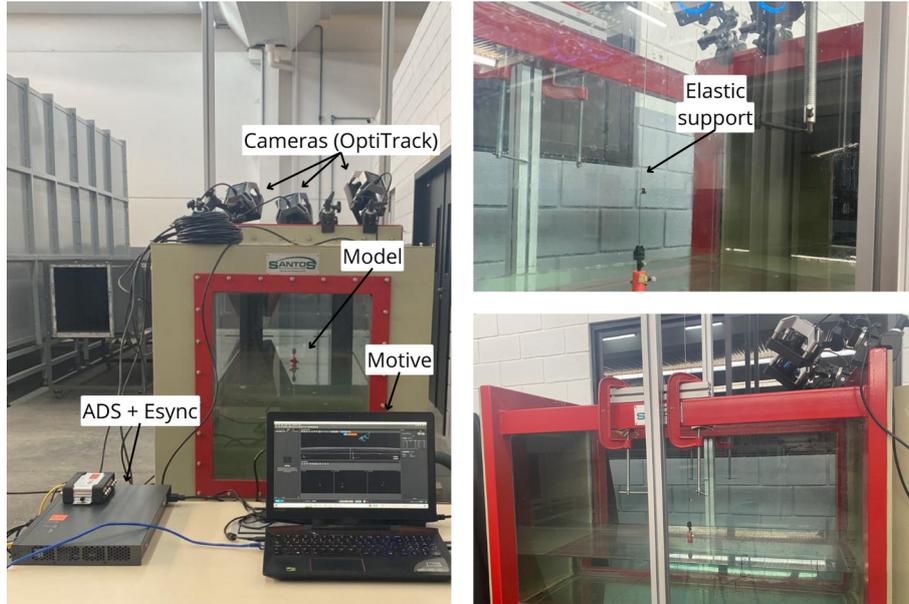


Figure 2. Experimental setup at the CWC in LIFE-UFSC-Joinville.

The models were 3D printed using PLA filament, as shown in Figs. 3 (a) and (b). The circular cylinder had a diameter of 20mm , while the square cylinder had a side length of 20mm . These dimensions are denoted as D in Figure 3 (c). Both models had a submerged length of 40mm , resulting in an aspect ratio $AR = 2$. Ballast was added to the cylinders, which yielded a mass ratio of $m^* = 1.83$. This study investigates two different cross-sectional shapes: circular and square. The circular cross section represents the conventional shape, while the square section introduces geometric variations to examine their impact on flow behavior. As mentioned, the characteristic dimensions of these model cross sections are denoted by D , considered both in Reynolds number and in reduced velocity.

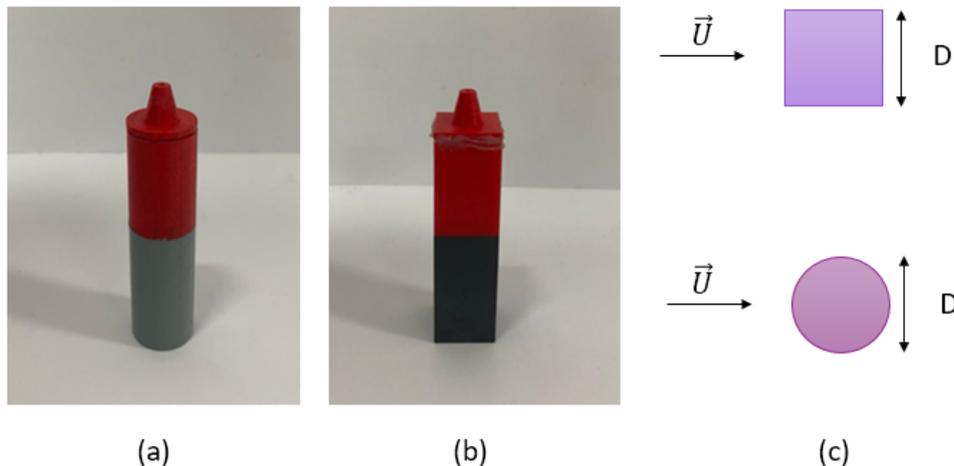


Figure 3. Details of the models: (a) circular cylinder, (b) square cylinder, (c) cylinder sections submitted to fluid flow.

Incident flows are characterized by low Reynolds numbers between 598 and 1318, equivalent to seven different flow velocities that essentially maintain the phenomenology of FIV. The chosen range was based on the VIV resonance interval documented in the literature, specifically $5 < Vr < 10$, with the behavior of a single circular cylinder serving as a reference. All depths, Reynolds numbers, and reduced velocity were listed in Tables 1 and 2.

Table 1. List of water depths, dimensional flow velocities, reduced velocities Vr , and tested Reynolds numbers Re of the circular cylinder.

Water depth (mm)	Velocity (m/s)	Reynolds Number	Reduced velocity
150	0.0527	1317.5	9.48
175	0.0445	1112.5	8.00
200	0.0374	935.0	6.73
225	0.0329	822.5	5.92
250	0.0302	755.0	5.18
275	0.0260	650.0	4.68
300	0.0239	597.5	4.30

Both models have the same Reynolds number since Reynolds (denoted by $Re = (UD)/\nu$, where U is the flow velocity, D the characteristic length, and ν is the kinematic viscosity of the flow, in this case fresh water) and a different reduced velocity Vr (denoted by $Vr = U/(f_n D)$ where f_n is the natural frequency of the cylinder). Natural frequencies for circular- and square-section cylinders are, respectively, $f_n = 0.28Hz$ and $f_n = 0.26Hz$. These values are quite similar to those obtained analytically considering added mass coefficients as proposed, for example, in Blevis and Plunkett (1979).

Since both natural frequencies have slightly different values, their reduced velocities will also be different. The natural frequency of an oscillating structure is determined primarily by its mass and stiffness properties. Although the characteristic length is the same, the distribution of the mass in a square cylinder differs slightly from that of a circular cylinder.

Table 2. List of water depths, dimensional flow velocities, reduced velocities Vr , and tested Reynolds numbers Re of the square cylinder.

Water depth (mm)	Velocity (m/s)	Reynolds Number	Reduced velocity
150	0.0527	1317.5	10.33
175	0.0445	1112.5	8.73
200	0.0374	935.0	7.33
225	0.0329	822.5	6.45
250	0.0302	755.0	5.65
275	0.0260	650.0	5.10
300	0.0239	597.5	4.69

A square cylinder has a geometry with sharp corners, which affects its overall mass contribution. The corners of the square shape introduce more additional mass, altering the dynamics of vibration, resulting in a lower natural frequency compared to a circular cylinder. The presence of corners can lead to a different pattern of vortex shedding which affects the pressure field and responses for the higher values of added mass. On the other hand, a circular cylinder exhibits a more symmetric and uniform mass distribution.

Following the Vortex-Induced Motion (VIM) test guidelines established by the International Towing Tank Conference (ITTC) and adopted in this study, a minimum of 20 complete FIV cycles must be recorded. The data acquisition frequency should be at least 10 times higher than the highest frequency of interest. To meet these requirements, each combination of arrangement, heading, spacing, and velocity will undergo three repetitions of 5-minute acquisitions. This duration allows for the registration of at least 60 cycles of the FIV phenomenon. The complete test matrix consists of a total of 326 5-minute tests, excluding the preliminary decay tests conducted to characterize natural frequencies and the corresponding damping coefficients.

The time histories collected during the tests were analyzed using computational algorithms implemented in the GNU-Octave environment. These algorithms read the data from the “CSV files” generated by the Motive program and perform the desired analyzes. The algorithm first evaluates the data and identifies the peaks (maximum values) and troughs (minimum values). It then calculates the absolute values of these extrema, sort them in descending order, and calculates the average of the highest 10% largest values. These average values represent the maximum dimensionless response amplitudes (A_x/D and A_y/D), where the diameter of a column serves as a reference. This process was repeated for each arrangement, considering the three recorded data sets.

Regarding frequency characterization, the Fast Fourier Transform (FFT) is employed. The characteristic frequency of the movements is determined by identifying the peak with the highest spectral density (PSD). To conform to the notation used in the literature, the results are presented in their dimensionless form, which is achieved by dividing the movement frequency in the considered direction (X or Y) by the cross-flow natural frequency f_n obtained in water.

3. RESULTS AND DISCUSSIONS

As described, this study focuses on exploring the VIV characteristics of two cylinder geometries: circular and square cross sections. By subjecting these cylinders to controlled fluid flow conditions, parameters such as VIV amplitudes and frequencies can be compared. The aim of this comparative analysis is to gain a deeper understanding of how the different cylinder geometries influence the behavior of VIV, especially under low Reynolds conditions. The results of this study contribute to the existing body of knowledge and provide valuable information on the design and analysis of structures vulnerable to VIV.

Figures 4 and 5 show the time history of one of the experiments carried out, namely the circular cylinder at $Vr = 4.30$ and the square cylinder at $Vr = 4.69$. The time history analysis of the circular cylinder reveals a characteristic signal typical of VIV phenomena. The recorded data show periodic oscillations with varying amplitudes and frequencies, reflecting the cyclic nature of VIV. The signal shows distinct peaks and troughs, representing the maximum and minimum displacements of the cylinder as it undergoes vibration. The time history provides valuable information on the dynamic behavior and response of the circular cylinder due to fluid flow.

Analyzing these time histories provides valuable information about the vibration amplitudes, frequencies, and phase relationships associated with the VIV phenomenon. The findings contribute to the understanding of VIV behavior and can aid in the design and optimization of structures exposed to similar low flow velocity conditions, ensuring their structural integrity and performance.

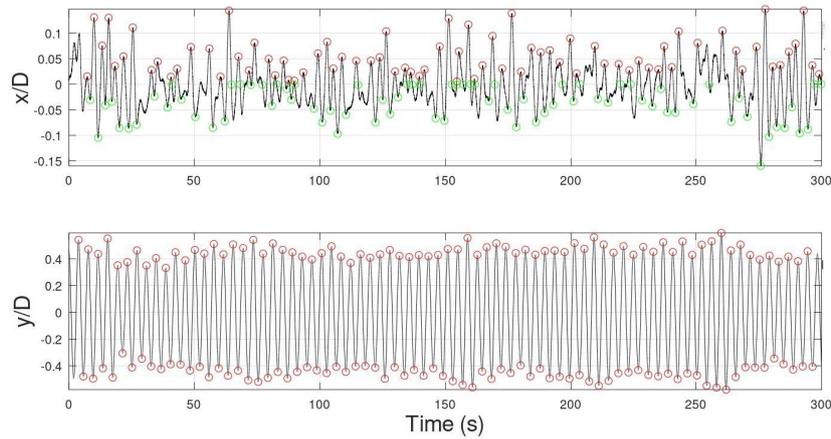


Figure 4. Time-histories of circular cylinder displacement in $Vr = 4.30$: inline x/D and cross-flow y/D .

It should be noted that although both recordings were made at a depth of 300mm , the “regularity” of the signals was different. It is believed that this difference is due to the FSI, given the fact that, because they are different sections, the pressure fields and vortex shedding modes are different, which results in the difference between the dynamic responses, cross-flow, and inline amplitudes when the values obtained for each section are compared.

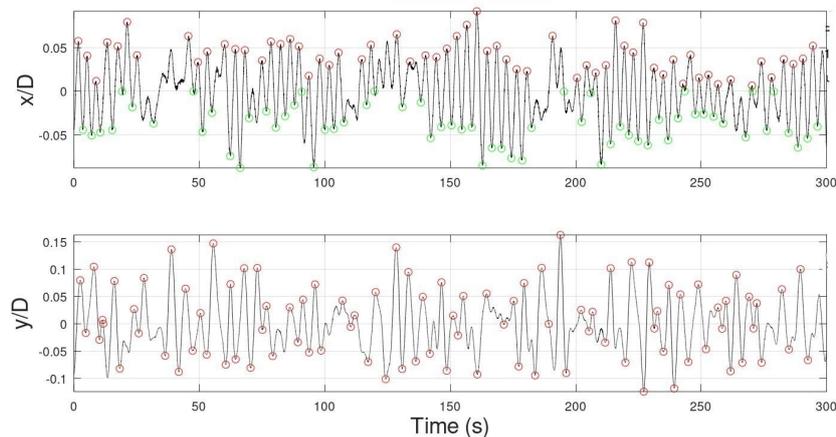


Figure 5. Time-histories of square cylinder displacement in $Vr = 4.69$: inline x/D and cross-flow y/D .

Figure 6 presents the vibration amplitude based on the average value of 10% of the largest peaks in the cross-flow direction using the reduced velocity variation to characterize the VIV phenomenon. The vertical axis denotes the dimensionless amplitude based on the ratio between the mean value and the characteristic dimension D of the system.

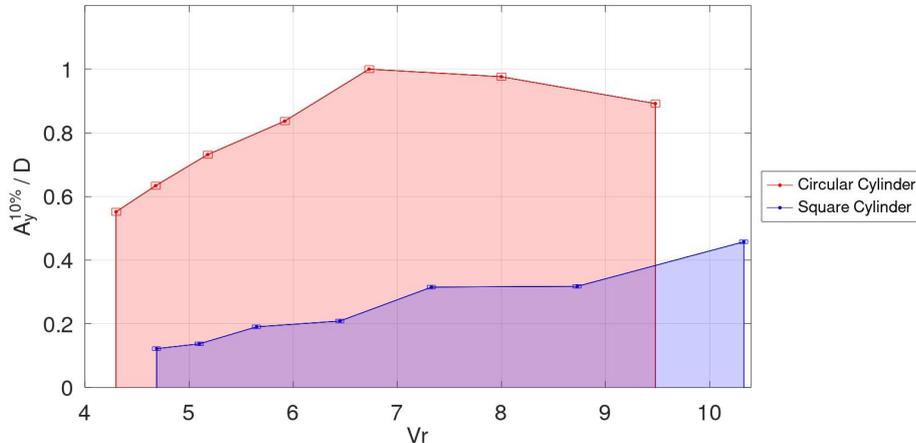


Figure 6. Mean values of the ten-percent-largest dimensionless amplitudes in cross-flow direction, $A_y^{10\%}/D$, as a function of the reduced velocities, Vr .

Furthermore, Figure 6 allows comparing the maximum values of peaks between circular and square sections, configuring which presents higher response values when excited in the same velocity range. It is possible to observe that, for the circular section, the cross-flow amplitudes increase as they increase up to $Vr \approx 7$. It is observed that after this reduced velocity the amplitudes present a decrease in their values, which characterizes a curve of the VIV phenomenon similar to the ones observed in the literature for circular cylinders. However, for the square cylinder, the response signal for the cross-flow amplitude does not show this characteristic, as the notable peak was characterized for the critical channel velocity. It is important to emphasize that studies for the characterization of the square section curve will be carried out further to better investigate where the maximum response amplitude occurs.

The behavior of a cylinder subjected to VIV in the low Reynolds regime is characterized by distinct dynamics influenced by the fluid flow conditions. In this regime, characterized by a low Reynolds number, the flow around the cylinder is typically laminar with smooth and predictable streamlines. The fluid forces acting on the cylinder are significantly reduced compared to higher Reynolds number regimes, resulting in a subdued VIV response. The vibrations observed in this regime are characterized by low amplitudes and low frequencies. The reduced fluid forces limit the energy transfer from the fluid flow to the cylinder, leading to modest vibration amplitudes. Low-frequency oscillations occur at a slower rate than higher Reynolds numbers, indicating longer periods between consecutive vortex-shedding events.

The predictable flow patterns in the laminar regime result in fewer interactions between the cylinder and the vortices, leading to longer intervals between shedding. In the low Reynolds regime, the damping effects, such as fluid damping, become more pronounced. The viscosity of the fluid contributes to the dissipation of energy, reducing the amplitude of the cylinder's vibrations. However, the relatively low fluid forces in this regime can limit the effectiveness of damping, resulting in longer vibration decay times. It is important to note that even in the low Reynolds regime, the cumulative effects of repeated low-amplitude vibrations can still lead to fatigue and potential structural issues. Understanding the behavior of a cylinder in the low Reynolds regime is crucial for designing structures that can withstand VIV effects and ensuring their long-term structural integrity and operational safety.

Usually, the phenomenon responds with amplitudes of one diameter, a value consolidated for Reynolds numbers of the order of 10^5 , as described by Blevins and Coughran (2009). This reference also shows that the Reynolds number influences the response of the system, resulting in a reduction in the peak amplitude when this parameter is on the order of 10^3 . Although the system in the present work has different damping characteristics and mass ratios compared to those presented by Stappenbelt *et al.* (2007) and Blevins and Coughran (2009), qualitatively, both studies can be compared since the low damping somewhat counteracts the effect of the mass ratio. In other words, the peak amplitude response is less than one, which is consistent with what is presented in the literature, given the low Reynolds number, high mass ratio, and low damping.

In the range of speeds experienced, the square cylinder showed significantly smaller response amplitudes than the circular cylinder. Generally, square cylinders respond with smaller amplitudes due to a number of factors. First, the square shape of the cylinder introduces additional flow separation and vortex interactions at the corners and edges. These flow phenomena can disrupt the development and shedding of the vortex, leading to a reduction in the amplitude of the resulting fluid forces acting on the cylinder. The disrupted vortices and flow separation create a more stable and

controlled flow regime around the square cylinder, resulting in lower vibration amplitudes. Second, the shedding of vortices from the corners and edges of a square cylinder occurs at multiple frequencies, including higher-order modes. These additional modes can partially counteract each other, resulting in a more distributed and lower amplitude vibration response compared to cylinders with simpler shedding patterns. Furthermore, the square shape also affects the natural frequency of the cylinder. The presence of corners and edges alters the structural characteristics, leading to a wider range of natural frequencies compared to cylinders with smoother shapes. This wider range of natural frequencies can help avoid resonance conditions, which can result in excessive vibration amplitudes.

It is important to note that in the low Reynolds regime, although the vibrations in the inline direction are subdued, they can still have an impact on the structural integrity of the cylinder. Even small-amplitude vibrations over a prolonged period can contribute to fatigue and potential damage. The response amplitudes of a cylinder in the inline direction are generally lower than in the cross-flow direction due to several factors.

First, in the inline direction, the fluid flow encounters the frontal area of the cylinder, resulting in a more streamlined and less turbulent flow pattern. This smoother flow reduces the impact and interaction of vortices with the cylinder, leading to lower fluid forces acting on the cylinder. As a result, the amplitude of vibrations in the inline direction tends to be smaller. Second, the shedding of vortices occurs primarily in the inline direction. These vortices are formed as a result of the unsteady separation of the boundary layer from the cylinder's surface. The shedding process induces alternating lift and drag forces on the cylinder, leading to significant vibrations in the cross-flow direction. On the contrary, the inline direction experiences less influence from the vortex shedding process, resulting in lower response amplitudes.

In addition, the structural characteristics of the cylinder play a role in determining the response amplitudes. The natural frequency of the cylinder in the cross-flow direction is typically closer to the shedding frequency of vortices, leading to resonance and higher response amplitudes. On the other hand, the natural frequency in the inline direction may be further from the shedding frequency, reducing the amplification of vibrations. Furthermore, the presence of flow-induced damping can also contribute to the lower response amplitudes in the inline direction. The damping effect caused by the fluid flow can dissipate energy and reduce the amplitude of vibrations, particularly in the smoother inline direction.

Figure 7 shows the amplitude responses in the inline direction for both geometries. It can be seen that the curves are similar in shape and magnitude, but are shifted in Vr . Both amplitudes are lower than one, and it is characteristic of VIV behavior, where while the cross-flow amplitudes are about one diameter, the inline amplitudes keep being significantly small. Since square shapes have higher drag coefficients when compared to circular cylinders with the same frontal area, the response amplitude is slightly lower. This small difference can be justified by the low Reynolds regime to which the models were subjected.

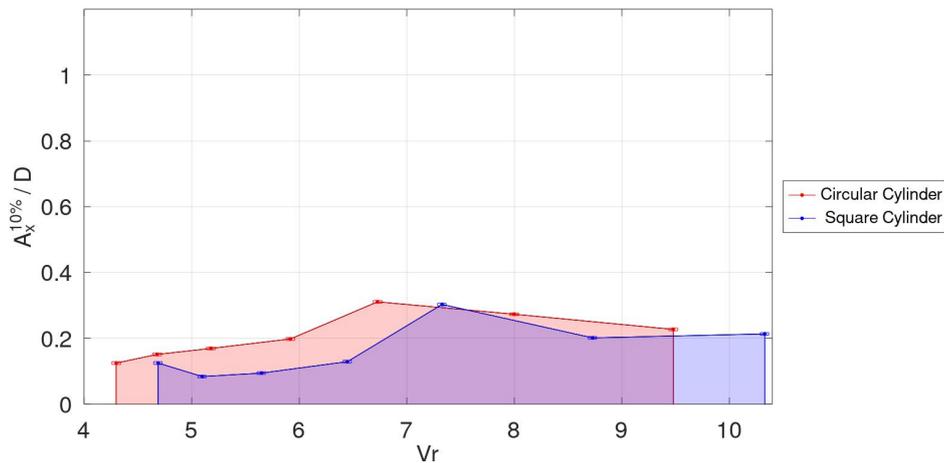


Figure 7. Mean values of the ten-percent-largest dimensionless amplitudes in inline direction, $A_x^{10\%}/D$, as a function of the reduced velocities, Vr .

Regarding frequencies, the frequency ratio parameter will be presented in the results. It is denoted by $f_x^* = f_x/f_n$ and $f_y^* = f_y/f_n$, where f_x is the frequency in the inline direction, f_y is the frequency in the cross-flow direction, and f_n is the natural frequency of the structure. These results can be seen in Figs. 8 and 9. The shape of the cylinder's cross section does not show much influence on the frequency parameter of the system for both directions. In the cross-flow direction, the circular cylinder shows a frequency ratio equal to one at the reduced velocity, where the peak of amplitude occurs, characteristic of the VIV behavior.

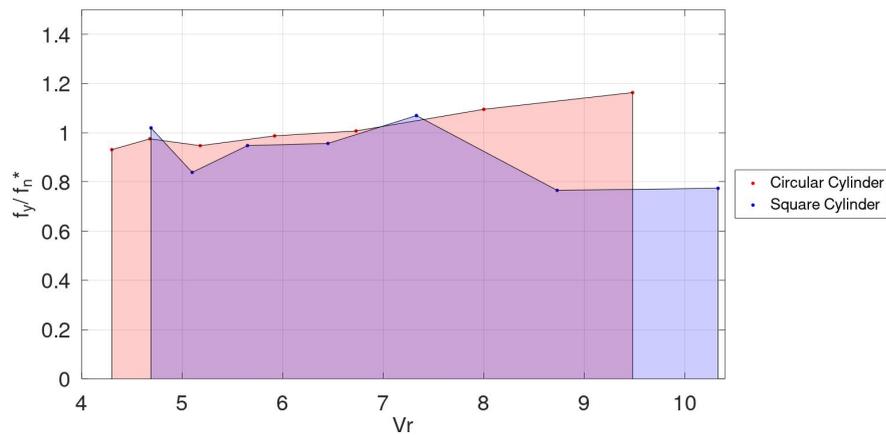


Figure 8. Dimensionless frequencies in cross-flow direction, f_y/f_n^* , as a function of the reduced velocities, V_r .

For the square cylinder, a desynchronization can be seen in the last two reduced velocities tested. This dynamic behavior can lead to a decrease in the vibration amplitude and a shift in the dominant frequency of the response, which explains the decrease in the frequency ratio. The consequences of desynchronization in VIV depend on the specific circumstances and characteristics of the system. It can result in a reduced overall vibration response, and can be seen in Figure 6. This aspect may be desirable in terms of mitigating fatigue and structural damage. However, desynchronization can also lead to changes in the distribution of forces and vibrations along the structure, potentially causing localized stress concentrations or uneven wear.

Figure 9 shows the frequency ratio parameter f_x^* . Again, the geometry of the cross section does not significantly affect the response in this direction. It can be noted that there is again a desynchronization of the higher reduced velocity for the square-section cylinder. In turn, a circular-section cylinder exhibits behavior parallel to the characteristic flow of a cylinder subjected to the VIV phenomenon.

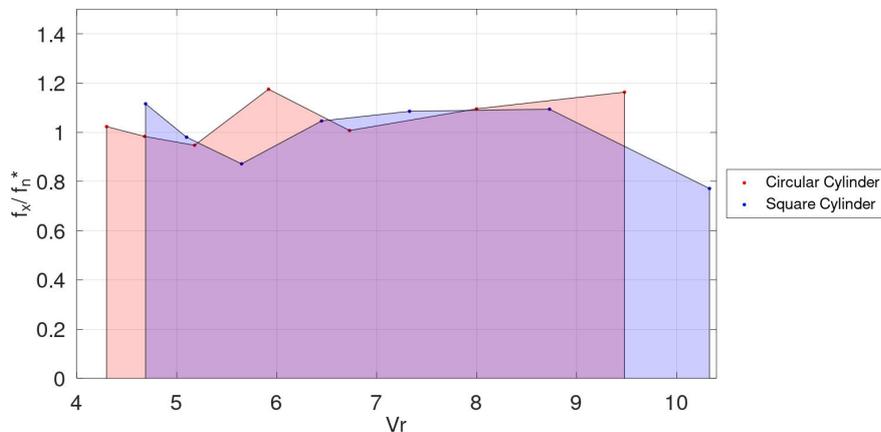


Figure 9. Dimensionless frequencies in inline direction, f_x/f_n^* , as a function of the reduced velocities, V_r .

In general, the results obtained, supported by the classic literature about the phenomena of vibration induced by the flow, demonstrate that the Circulating Water Channel, built at LIFE-UFSC, is a more economical alternative to other typical structures and can be used for experiments that involve phenomena subjected to slow flows and that result in low Reynolds numbers for the system. More investigations must be carried out, increasing the velocity range investigated, mainly for the square cylinder, which has more complex dynamics.

4. CONCLUSIONS

The primary objective of the Circulating Water Channel (CWC) built at UFSC-Joinville, funded by CNPq, is to investigate the vortex-induced effects in cylinders and cylinder arrangements elastically supported with two degrees of freedom and subjected to water flows of low Reynolds numbers. The CWC is used to investigate fluid-structure interactions in low Reynolds-number flows. The CWC is notably cheaper, smaller, and less complex than a typical CWC, making it a useful didactic tool in classes and a means of training human resources in the design and execution of experiments with scientific rigor.

The CWC is used to investigate the VIV phenomenon in cylinders and cylinder arrangements elastically supported with two degrees of freedom and subjected to water flows of low Reynolds numbers. Compared to other investigations of Fluid-Structure Interactions (FSI) in low Reynolds numbers, which are mostly dedicated to vortex-shedding models and their effects on stationary structures, this study focuses on the dynamic condition in which structures subject to flow are free to oscillate with at least two degrees of freedom in regimes of low Reynolds numbers. The study also evaluates the response of single cylinders with two different cross sections, circular and square, through experimental tests, developing a systematic database for one- and two-dimensional responses in terms of amplitude and frequency for seven different flow velocities.

The study found that the square cylinder showed significantly smaller response amplitudes than the circular cylinder in the range of speeds experienced. The square shape of the cylinder introduces additional flow separation and vortex interactions at the corners and edges, which can disrupt the development of vortex shedding, leading to a reduction in the amplitude of the resulting fluid forces acting on the cylinder. The disrupted vortices and flow separation create a more stable and controlled flow regime around the square cylinder, resulting in lower vibration amplitudes. Additionally, the shedding of vortices from the corners and edges of a square cylinder occurs at multiple frequencies, including higher-order modes, which can partially counteract each other, resulting in a more distributed and lower-amplitude vibration response compared to cylinders with simpler shedding patterns. However, a circular cylinder exhibits a more symmetric and uniform mass distribution, resulting in a more evenly distributed mass and stiffness. This configuration allows for a lower natural frequency compared to that of a square cylinder. The study also found that the square cylinder has a higher drag coefficient than the circular cylinder.

The lower response amplitudes observed in the square and circular cylinders can be attributed to the low Reynolds regime in which the experiments were conducted. In low Reynolds flow conditions, the fluid flow around the cylinders is relatively smooth and laminar, resulting in reduced levels of turbulence and vorticity. As a result, the magnitude of the fluid forces acting on the cylinders, including the drag and lift forces, is comparatively lower. In VIV, the response amplitudes of the cylinders are influenced by the interaction between the shedding of vortices and the natural frequency of the structure. In the low Reynolds regime, the shedding of vortices is less pronounced and occurs at lower frequencies compared to higher Reynolds flow regimes. This reduced shedding frequency and the corresponding excitation of the cylinder's natural frequency contribute to the lower response amplitudes observed. Additionally, the low Reynolds regime in this study is provided by low flow velocities, which further contribute to the lower response amplitudes. Lower flow velocities lead to a reduction in the dynamic forces acting on the cylinders, resulting in a decrease in vibration amplitudes.

It is important to note that the lower response amplitudes observed in the square and circular cylinders under low Reynolds flow conditions are specific to the experimental setup and the range of parameters considered. Different flow conditions, Reynolds numbers, or geometric variations may lead to different response amplitudes. Therefore, understanding the influence of Reynolds number and flow regime on VIV response is crucial for accurate design and analysis of structures subjected to fluid-induced vibrations.

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6. REFERENCES

- Blevins, R. and Coughran, C., 2009. "Experimental investigation of vortex-induced vibration in one and two dimensions with variable mass, damping, and Reynolds number". *Journal of Fluids Engineering*, Vol. 131, No. 10. doi: 10.1115/1.3222904.
- Blevins, R.D. and Plunkett, R., 1979. *Formulas for natural frequency and mode shape*. Krieger Publishing Company, 1st edition.
- Jiang, Y., Gao, C., Geng, Z. and Chen, C., 2018. "The hydrodynamic design and critical techniques for 1m×1m water tunnel". In *AIP Conference Proceedings*. Author(s). doi:10.1063/1.5033637.
- Kalgutkar, S., Meshram, A., C., S., Masurkar, K., Tople, V., Sawant, S., Wasnik, S., Khobragade, S. and Mhatre, M., 2016. "Low speed water tunnels. design, fabrication and analysis". Report by GRIN Verlag.
- Saeed, M., Uddin, E., Mubashar, A., Zahir, S.U. and Zaidi, A.A., 2018. "Design and development of low-speed water tunnel". In *2018 15th International Bhurban Conference on Applied Sciences and Technology (IBCAST)*. IEEE. doi: 10.1109/ibcast.2018.8312288.
- Stappenbelt, T., Lalji, F. and Tan, G., 2007. "Low mass ratio vortex-induced motion". *Proceedings of the 16th Australasian Fluid Mechanics Conference, 16AFMC*, p. 13.

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