SELBSTINDUZIERTE SCHWINGUNGEN ZWEI- UND DREI-DIMENSIONALER STRUKTUREN IN TURBULENTEN STRÖMUNGEN

SELF-EXCITED OSCILLATIONS OF TWO AND THREE-DIMENSIONAL FLEXIBLE STRUCTURES IN TURBULENT FLOWS

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Fluid-structure interaction; self-excited oscillation; PIV; turbulent flow

Abstract

The swiveling motion of a structure immersed on a flow can become self-excited as a result of different fluid-structure interaction mechanisms, e. g. movement-induced excitation (MIE) and instability-induced excitation (IIE) [Naudasher (1980)]. The present contribution aimed to analyse the resulting periodic swiveling motion of flexible structure models in turbulent flows up to 2 m/s. The coupled fluid and structure movement was characterized using a particle image velocimetry (PIV) system complemented by a time-phase detector to obtain accurate time-phase resolved measurements of both the flow velocity field and also the structure deflection over an entire period of motion. The experimental tests proved that the self-exciting mechanisms that sustain the coupled fluid and structure movement are strongly dependent on the approaching flow velocity. Because the Strouhal number is not so sensitive to the Reynolds number in the range of 140 to 15000, it was observed great similarities between the IIE mechanisms registered in turbulent and laminar flows. In this contribution, the results for a specific 2-D structure configuration are presented.

Introduction

The present contribution is an extension of the study on fluid-structure interaction (FSI) presented in previous editions of the GALA conference. Gomes and Lienhart (2005) described the application of laser measurement techniques to perform accurate time-resolved measurements in quasi-periodic FSI problems. In 2007, the same authors reported results of selected FSI test cases in laminar flows. Those tests, using Polyglycol syrups as working liquid, were performed for a Reynolds up to 270 [Gomes and Lienhart (2007)].
The present study extended the investigation to turbulent flows. First, it aimed to characterize the different fluid-structure interaction self-exciting mechanisms and to understand the influence of the physical parameters on the limit cycle oscillation of flexible structures in water flows for a Reynolds number up to 50000.
Second, the experimental investigation addressed the need for experimental data on reference test cases. It provided a reliable data base on specific, well-defined reference test

cases to be used as a diagnostic and validation tool for numerical models for fluid-structure interaction simulations. The data base created from these reference test cases included the time-phase resolved characterization of the flow velocity field and the structure movement, such as angle of the front body, structure deformation shape, coordinates of the structure trailing edge and frequency.
The present contribution reports the results of the experimental investigation performed on a specific two-dimensional structure model in uniform turbulent flows up to 2 m/s.

Experiment definition

The results reported in this contribution refer to the two-dimensional structure model that consisted of a 0,04 mm thick stainless steel sheet attached to an 22 mm diameter aluminium cylindrical front body. At the trailing edge of the membrane a 10 mm × 4 mm rectangular stainless steel mass was located. All the structure was free to rotate around an axle located in the central point of the front cylinder (z-axle of Fig.1). Both the front cylinder and the rear mass were considered rigid. The flexible section of the structure has proven to have a linear mechanical behaviour within the range of forces acting on it during the tests and the Young modulus was measured to be 200 kN/mm^2. The overall span-wise dimension of the structure was 177 mm. In addition to well defined linear mechanical properties, this model has proved to satisfy the requirements for periodicity and reproducibility of the resulting movement.

The tests were conducted in water at 22°C in a vertical closed loop tunnel. The test section has an overall length of 338 mm and a cross section area equal to 180 mm x 240 mm. The structure was mounted 55 mm downstream of the inlet plane of the test section on ball bearings, therefore, the rotational degree of freedom of the front cylinder could be considered to be free of friction. The experiment domain of the tests is represented in Fig. 1.

Experimental procedure

The task of measuring the two-dimensional flow field around the model was performed using a PIV system that consisted of two 1280 pixel × 1024 pixel synchronized cameras and double head pulsed Nd:YAG lasers with a wave length of 532 nm. Opting for the solution of two parallel cameras it was possible to cover an extended 272 mm × 170 mm flow field area while keeping the spatial resolution as low as 133 µm × 133 µm per CCD pixel. The measurements location was set to the central-plane of the test section (z=0 mm, see Figure 2).
Two laser sources were used to illuminate the flow. This solution was adopted because the flexible structure was an opaque body which creates an unsteady dark shadow region when illuminated by just one light source. Using one laser source to illuminate each side of the structure, the dark region behind the structure was extinguished and all the flow surrounding the structure was accessible to PIV measurements.
As seeding particles, 10 µm mean diameter hollow glass spheres were chosen to be used in water. They provided a good match of density and enough scattering signal over the all the measuring area.
To determine the position of the structure, the PIV system was modified to provide it with structure deflection analysis capabilities. The idea behind this set-up was to use the PIV system to acquire images from the swiveling structure and to use an especially developed software to analyse and reconstruct the time dependent deflection of the structure. The major advantage of this approach was that the same measuring system used for the velocity field measurements could be employed. The cameras were now located in such a way to acquire images the flexible structure illuminated by the laser sheet from each side of the model. No seeding was used during these tests. The quantitative analysis was performed after images acquisition in Matlab workspace by a script developed for the specific task.

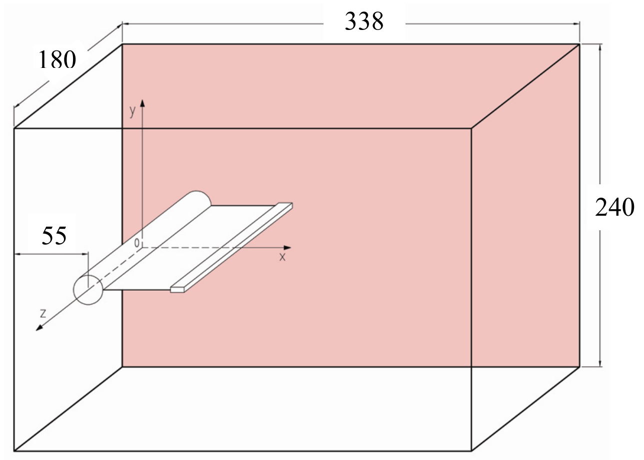

Fig. 1: Experiment geometrical definition (dimensions in mm).

The software analysed and compared the PIV images of both sides of the model and reconstructed the time dependent image of the light sheet reflected by the structure. To achieve that purpose it mapped the pixel value in the gray-scale of the entire image and detected the line resulting from the intersection of the laser sheet and the structure as well as the edges of the rear mass. With the information of the position of the membrane all relevant data of the structure could be computed.
To resolve the measurements in the time-phase space, an in-house designed time-phase detector was implemented to obtain accurate time-phase resolved measurements. The idea was to operate the PIV system at constant acquisition rate and both events, the acquisition of a measurement and the start of a new movement cycle, recorded based upon an absolute clock. Using this time information, the data was reorganized in a post-processing program to provide the time-phase resolved data. The measurements were resolved in the time-phase space with a resolution of 2,5° associated to an uncertainty of 0,5°. More detailed description of the measurement techniques are given in Gomes and Lienhart (2005; 2006).

Results

The structure model was tested at different incoming velocities up to 2 m/s. Fig. 2 presents the dynamic response of the structure versus the incoming water flow velocity. The Reynolds number, based on the diameter of the front cylinder, reached the maximum value of 44000 at 2m/s. As shown in the figure, the structure was excited to a periodic swiveling motion at very low flow velocities. Visualizations has shown that this first excited mode corresponded to the rigid body motion mode, i.e. the structure swiveled in the fluid around its free rotating axel without changing its original and straight shape. Because it corresponded to the rigid body motion, this mode was assumed to be the zero swiveling mode. As an example of this zero mode, Fig. 3 shows the structure behaviour at approximately 0,19 m/s.
A swiveling mode transition was registered for a flow velocity close to 0,4 m/s. The transition between modes is abrupt and it was not possible to observe any evolution of the structure motion during the transition. No hysteretic behavior as observed as well. In the new swiveling mode, the structure deflection was dominated by the first bending mode of the membrane.

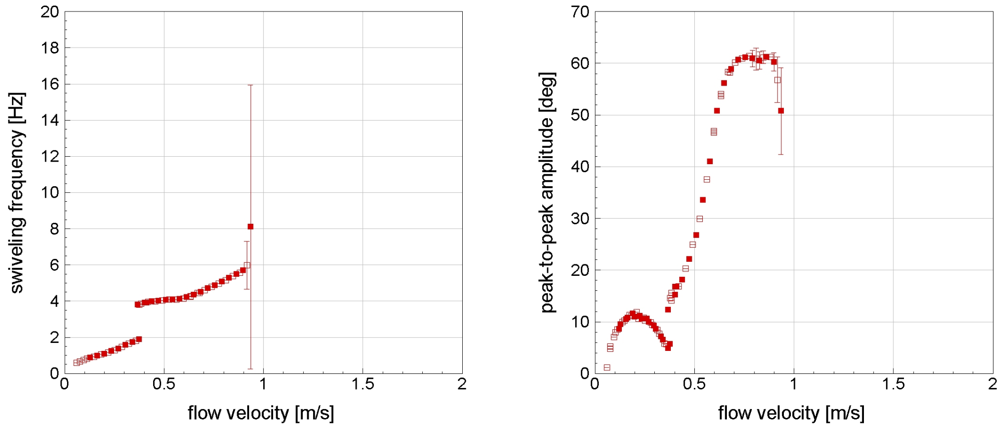

Fig. 2: Structure swivelling frequency, left, and structure frond body peak-to-peak amplitude, right, versus incoming flow velocity up to 2 m/s.

Further increasing the incoming flow velocity an unusual behaviour was observed. As soon as the amplitude of the structure started to decrease, after reaching the local maximum, the motion characteristics degraded very fast. This effect was supported by the RMS value presented in Fig. 2. The coupled movement became non-periodic and non-symmetric and led the structure to a fast destruction. Therefore no measurements could be obtained for flow velocities higher than 0,9 m/s.

In the range in which the structure movement is periodic and reproducible, up to 0,9 m/s, the RMS value of the cycle-to-cycle motion period stayed lower than 1%.

Detailed investigations were performed at 0,68 m/s, which corresponds to a Reynolds number close to 15000. This particular velocity was chosen as representative of the first swivelling mode for being close to the velocity of maximum structure amplitude excitation (Fig. 2, right). Under such conditions, the structure exhibited periodic swiveling motion with the rear mass delayed, in time-phase angle, 95° in relation to the front body. The last parameter was measured comparing the time-phase resolved angle of the front body with the y-coordinate of the structure trailing edge. Fig. 4 shows the evolution of the front body angle deflection and the structure deflection (the time-phase resolution of presented deformation lines is set to 30°) within the swiveling motion averaged period. The frequency of the resulting oscillation was measured to be 4,45 Hz.

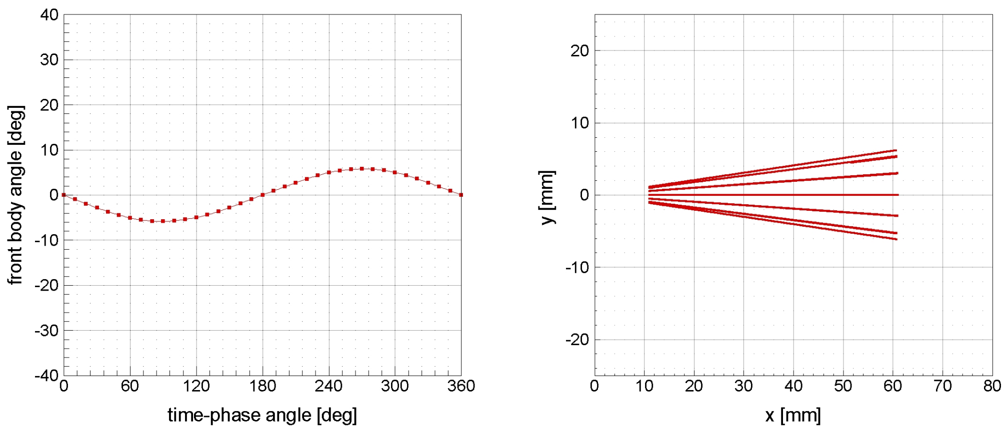

Fig. 3: Time-phase resolved front body angle, left, and structure deformation, right, within a period of motion at 0,19 m/s.

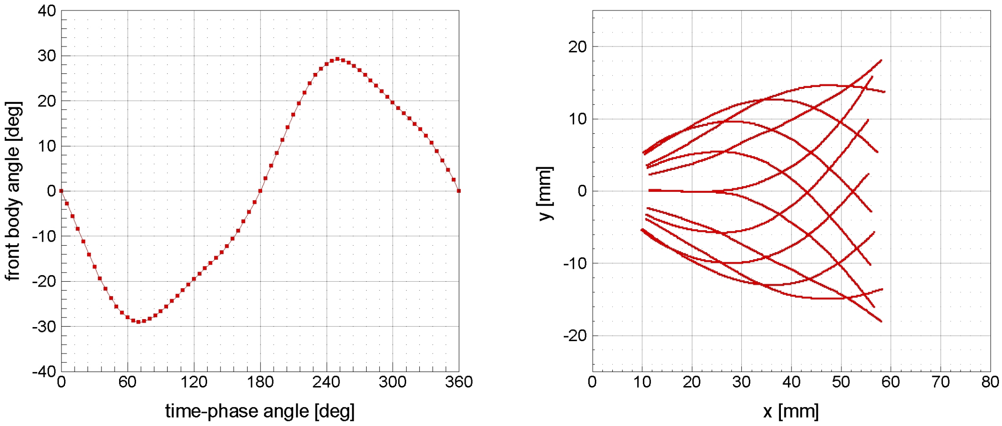

Fig. 4: Time-phase resolved front body angle, left, and structure deformation, right, within a period of motion at 0,68 m/s.

Figure 5 shows the successive positions of the structure trailing-edge during the swiveling period. As far as the flow field surrounding the structure model is concerned, Fig. 6 and Fig. 7 compile the time-phase resolved combined flow field and structure deflection at different instants of the reference swiveling period (the time-phase resolution of presented deformation lines is set to 45°). Whereas Fig. 6 presents the magnitude of the flow velocity, Fig. 7 gives an impression about the vorticity generated by the structure.

Discussion of the results

During the tests in water flows, the first mode to be excited was the rigid body mode (referred as zero swiveling mode). This mode started to be observed at really small approaching velocity and the point of maximum amplitude happed when the frequency of the vortex shedding behind the front cylinder precisely matched the rigid body natural frequency of the structure (N_0≈0,19 Hz).
The transition to the first self-excitation mode was registered at about 0,4 m/s. For this velocity, the corresponding Strouhal number (St≈0,21) and the first natural frequency of the structure (N_1≈5,9 Hz) showed a strong interconnection between the movement excitation and the classical von Karman vortex shedding. In this mode, despite a significant delay, the trailing edge could be considered in phase with the angular movement of the front cylinder.

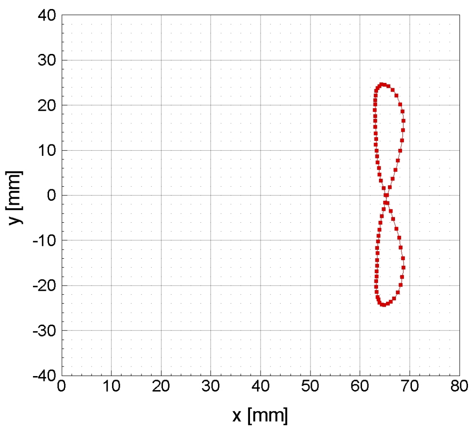

Fig. 5: Structure trailing-edge coordinates within a period of motion at 0,68 m/s.

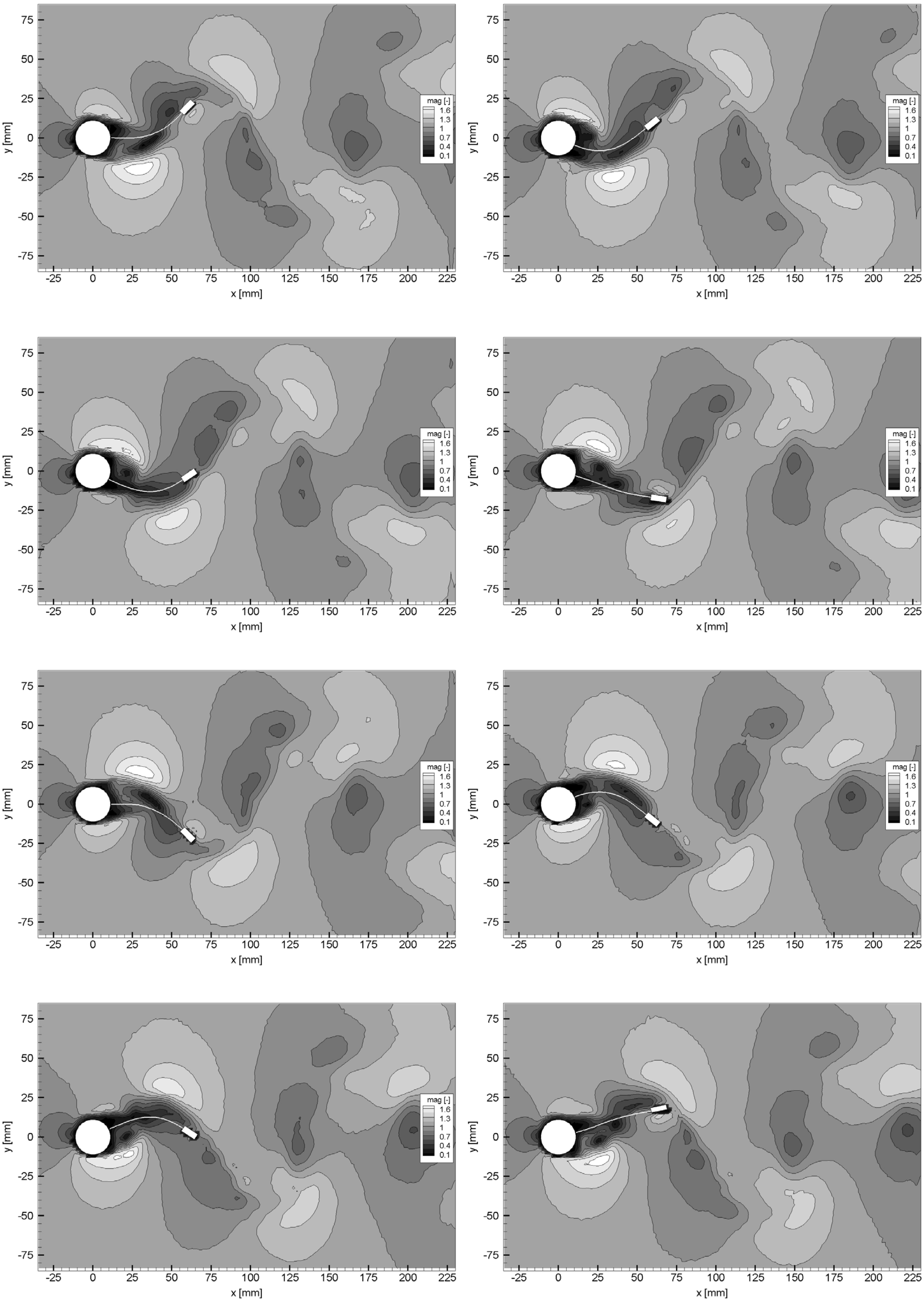

Fig. 6: Time-phase resolved combined velocity flow field / structure deflection maps for eight different instants of the averaged swivelling motion period at 0,68 m/s.

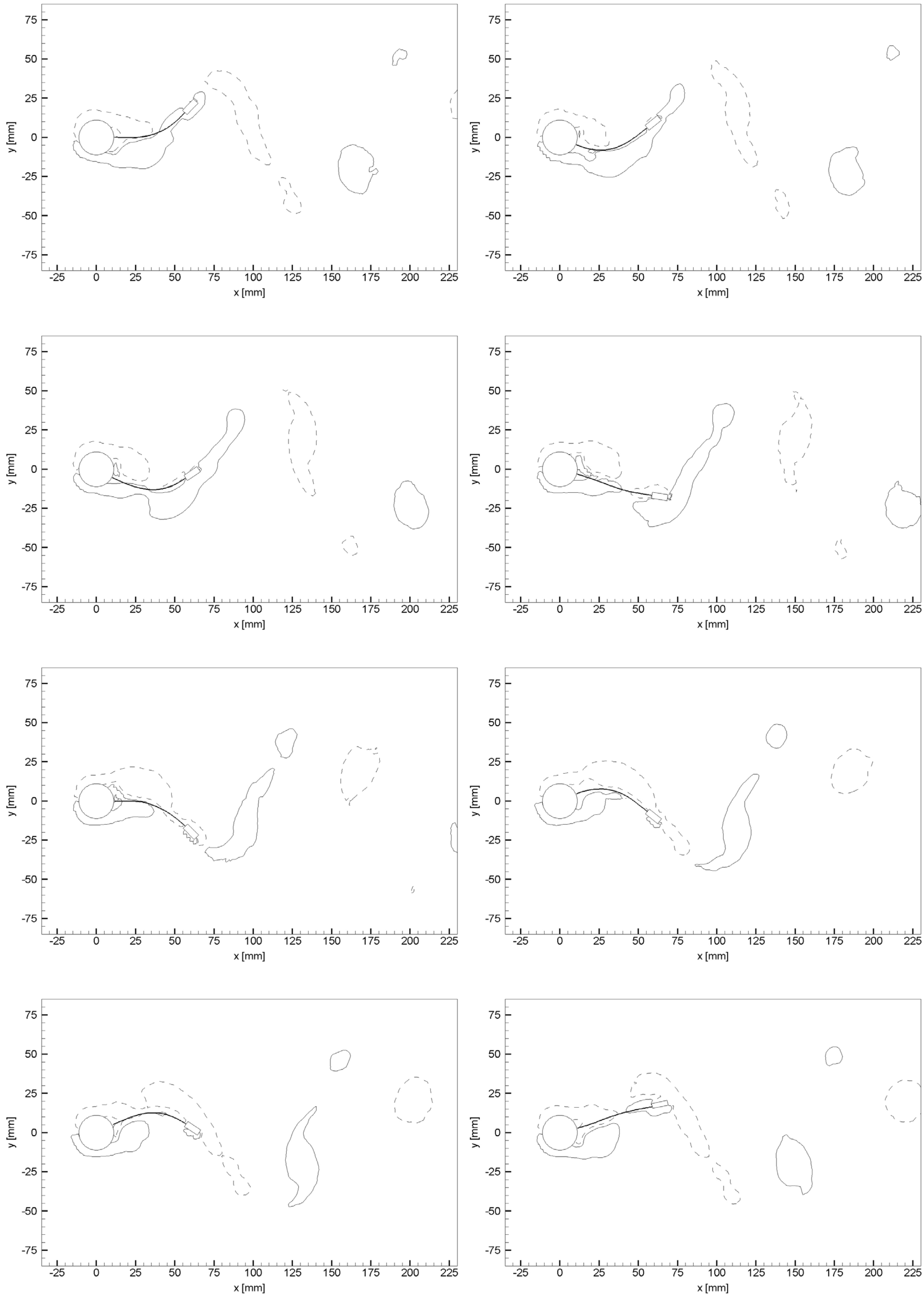

Fig. 7: Time-phase resolved vortices formation results
for eight different instants of the averaged swivelling motion period at 0,68 m/s.
(solid-line: ↺; dashed line: ↻)

Beyond 0,9 m/s it was not possible to registered the dynamic behavior of the structure. However, the analysis of the frequency signal and movement visualizations indicated that the structure should be in the transition to a new exciting mode.

Comparing the tests performed at 0,68 m/s in water (Re≈15000) with the tests at 1,45 m/s in Polyglycol syrups (Re≈140) [Gomes and Lienhart (2007)], one can conclude that the first swiveling mode in laminar and turbulent regimes are similar in nature. The differences between the two can be attributed to the fact that, for turbulent flows, the damping of the coupled system was significantly reduced. So, for the first case, it was observed higher excursions from the trailing edge and front body as well as higher deflection of the flexible part of the structure. Because of the lower damping imposed by water, the structure was exposed to higher accelerations during its swiveling movement in the turbulent tests, see Fig. 4.

Finally, it was proved that both are triggered by the vortex shedding created around the front cylinder. Because the Strouhal number is not so sensitive to the Reynolds number in the range of 140 to 15000, the resulting movements presented similar frequencies. Considering all the evidences it can be concluded that both first modes are attributed to IIE. The same applies to the rigid body mode observed in the turbulent tests. In the laminar regime a similar rigid body mode could not to be registered.

Regarding the flow velocity results. The distance between successive vortices confirmed the measured structure motion frequency values. The major difference observed when comparing turbulent with laminar results is related to the number of generated vortices per swiveling cycle. As can be concluded from Fig. 7, two pairs of vortices were created every swiveling cycle in the turbulent regime. In laminar flows, the second pair was never observed.

Acknowledgments

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