Time-phase resolved PIV/DMI measurements on two-dimensional fluid-structure interaction problems

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Abstract Flow-structure interaction problems, involving the coupling of unsteady fluid flow and structure motion have attracted more and more interest of the computational mechanics. To support the ongoing development of coupling strategies for fluid-structure interaction numerical simulations basic experimental investigation on reference fluid-structure interaction test cases are of major importance. This demand has triggered the present study to perform a detailed experimental investigation on the self-excited periodic swiveling motion of two-dimensional flexible structures driven by a constant velocity incoming flow.

The investigation of the present contribution was centered on relatively simple two-dimensional structures constituted by a thin flexible metal sheet attached to a front free rotating rigid body. Both bluff and slender front bodies were considered in the study. The first period of the present research was focused on laminar fluid-structure interaction problems. During this period the majority of the tests were performed in high viscous fluids (kinematics viscosity up to $5 \times 10^{-4}\,\mathrm{m}^2/\mathrm{s}$) to maintain the Reynolds number of the tests as low as approximately 150. In the following period the project dealt with turbulent interaction test cases in water flows with Reynolds numbers up to 20000.

From the experimental view point, investigations on these coupled problems require specially adapted test rigs and measurement techniques to obtain accurate time-phase resolved results. During the present study a new experimental facility to be operated with high viscous fluids was build exclusively to cover the required Reynolds number range. The measurements were performed using a particle image velocimetry (PIV) system specially adapted to carry out time-phase resolved measurements and aimed both the fluid velocity and structure deflection. Using such a technique was possible to characterize the flow velocity field as well as the deflection of the structure over an entire period of the motion. The latest results were used to evaluate the relevant deflection modes of the structure.

The systematic experimental investigation carried out on the high viscous flows dedicated test rig has resulted in the compilation of a detailed data base on fluid-structure interaction. The data covers a spectrum of parameters which involves the fluid viscosity (Reynolds number), the incoming velocity conditions and the geometry and mechanical parameters of the structure. The results serve not only the validation and diagnostic proposes of numerical research groups but also contribute to a better understanding of the self-excited fluid-structure motion mechanisms and the role of the different physical parameters in the phenomena.

1. Introduction

Flow-structure interaction problems, involving the coupling of unsteady fluid flow and structure motion, arise in many fields of engineering as well as in many other sciences like medicine, see Naudasher and Rockwell (1980) and (1994). From previous experience one can conclude that the mechanisms which lead the vibration of flexible structures immersed in flowing fluids to become self-excited are very sensitive to the mechanical properties of the structure as well as to the properties of the incoming fluid and very difficult to predict.

With the continuous increase of computer power, these problems have attracted more and more interest of the computational mechanics. However, in spite of the practical relevance of the prediction of coupled fluid and structural dynamics in many technical problems, this type of simulation is not yet considered a validated tool. Increased efforts in numerical research and

development are presently being observed to develop models and coupling strategies for numerical simulations and to create coupling algorithms between computational fluid dynamics (CFD) and computational structural dynamics (CSD) solvers.

However, to ensure successful simulations of such complex non-linear coupled problems comparisons with experimental studies are needed. This demand has triggered the present contribution to perform a reference experiment specially dedicated toward the diagnostic and validation of the numerical models for fluid-structure interaction simulations. The main objective was to establish a common experimental test case on fluid-structure interaction and to provide a reliable data base to serve the validation and comparison purposes of the different numerical methods and codes implementations. In parallel an analysis about the excitation mechanisms present in this type of fluid-structure interaction problems was carried out. The aim of this study was to provide a better knowledge about the principles and the basic mechanisms of these self-excited periodical oscillations of flexible bodies submerged on flowing flows.

2. Experiment definition

The experiments consisted in characterizing the resulting two-dimensional coupled periodical unsteady fluid flow and swiveling motion of flexible structures driven by a constant velocity incoming flow. To provide the details needed for numerical validation and accuracy verification purposes the test cases had to be conducted under very precise and well controlled working conditions. The requirements of the tests imposed stringent restrictions to the selection of the reference structure while the necessity of very low Reynolds numbers determined the construction of a new facility especially dedicated to fluid-structure interaction studies.

After a period of preliminary tests with different types of structures it was decided to focus the investigation on relatively simple two-dimensional structures constituted by a thin flexible metal sheet attached to a front rigid body (see examples in Fig. 1). All the structure was free to rotate around an axle located in the center point of the front body. Both bluff and slender front bodies were considered in the study. Also the effects of the presence of a rear mass at the trailing edge of the structure were investigated.

Rotating axle

Flexible membrane

Rigid front body
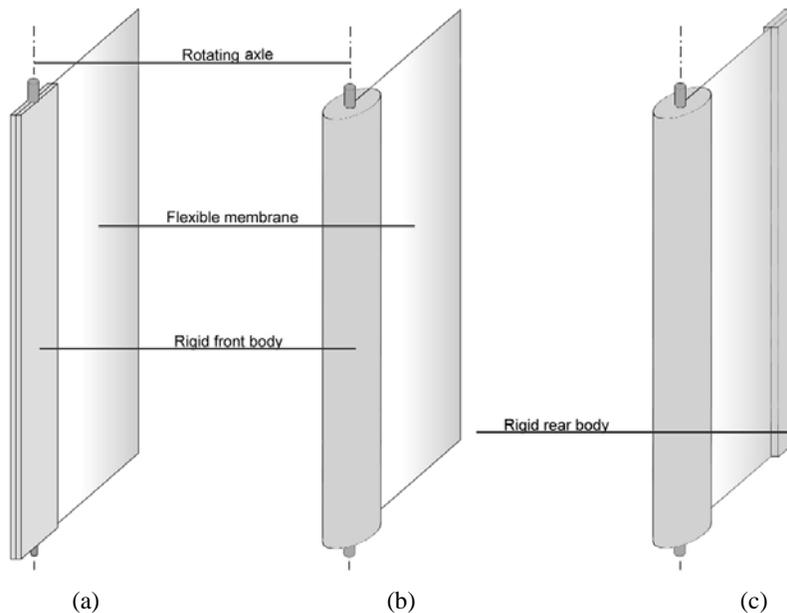
Rigid rear body

(a)　　　　　　　　　(b)　　　　　　　　　(c)

Fig. 1. Example of flexible structures under consideration: (a) flat plate; (b) and (c) cylindrical front body.

The final definition of the structure geometry to be studied in full detail took into account five principal aspects: (i) reproducibility of the resulting motion, (ii) two-dimensionality of the structure deflection, (iii) moderate structure motion frequency and (iv) significant excursion of the structure (v) well defined linear mechanical proprieties of the structure. The first tests were performed for laminar constant velocity incoming flow field, with a Reynolds number, based on the chordwise dimension of the front body, not bigger than 500. In order to achieve such a small Reynolds number, the tests were conducted in a liquid flow of high kinematic viscosity. The adopted liquid was a mixture of Polyglycol and water and could be considered incompressible. It had a kinematic viscosity of 0,000164 m^2/s and a density of 1050 kg/m^3. Later test on turbulent flows were also performed. These tests were carried out in water for a Reynolds number of the order of 20000. The data base created on those referent test cases included the description of the unsteady flow velocity field around the structure as well as the mechanical characteristics of the structure motion within the reference period of the resulting motion. The major mechanical properties registered were the deflection of the structure, main deflection modes, motion amplitudes and swiveling frequency.

3. Experimental apparatus

3.1 FLUSTRUC facility

To be able to investigate the fluid-structure interaction problem in a wide range of Reynolds number (from low laminar to turbulent) the viscosity of the working fluid was decided to be controlled during the tests. The need to perform the tests under very precise and controllable working conditions in both water and high viscous fluids determined the construction of a new experimental facility designed especially to fluid-structure interaction investigations.

The constructed facility is a vertical closed circuit tunnel powered by a 24kW axial propeller pump (see Fig. 2). Its was designed to have a kinematic viscosity operation range from 1×10^{-6} m^2/s up to 5×10^{-4} m^2/s. The facility is capable to maintain a constant maximum flow velocity in the test section of about 4,5 m/s and 2,7 m/s, when operated with water as working fluid or a 0,000164 m^2/s kinematic viscosity liquid fluid, respectively.
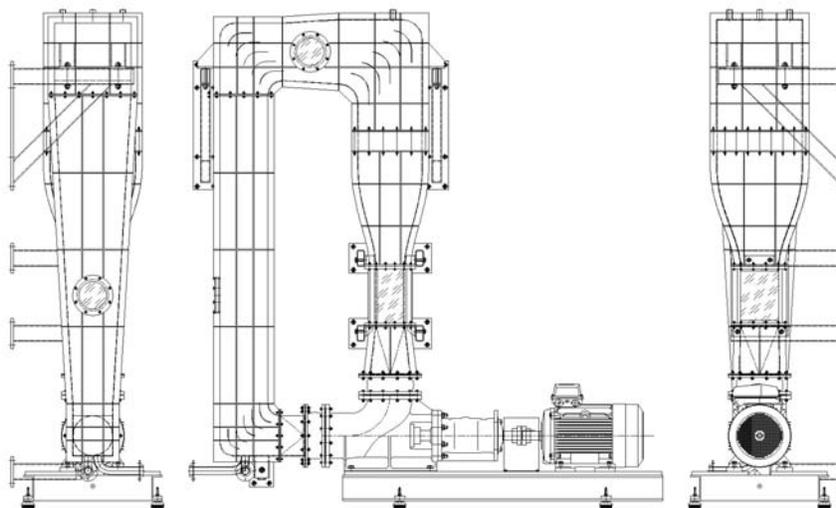

Fig. 2. FLUSTRUC facility layout.

Strong emphasis was placed on the design of the 180 mm × 240 mm cross section, 338 mm long test section to allow flow investigation using laser measurement techniques (specially PIV and LDA). Among other features it was entirely built out of glass to provide full optical access to all sides of the test model and it has a built in image calibration target dedicated for PIV investigations. The model is mounted between two opposite walls on low friction bearings 55 mm downstream of the test section inlet. The gravity force is aligned with the x-axis and so it does not introduce any asymmetry.

To control the viscosity of the working liquid Polyetylene Glycol (Polyglycol) PG-12000 syrups were used. They permitted an accurate control of the kinematic viscosity of the tests within the operation range of the facility. From a kinematic viscosity of 1×10^{-6} m^2/s up to 5×10^{-4} m^2/s the density of the Polyglycol syrups exhibit a minor variation of 10% in respect to water.

3.2 Time-phase resolved measurements

When investigating periodical fluid-structure interaction problems two additional difficulties appear when it comes to resolve the measured data in time-phase space. Firstly, the periodicity of the structure motion is quite sensitive to the flow conditions and structure mechanical properties; therefore, there are cycle-to-cycle variations of the period time. Secondly, the velocity of the structure within a motion period is not predefined (as it is for crank shaft driven set-ups) which makes it impossible to reconstruct the time-phase resolved data from position resolved measurements. Because of this it was decided not to trigger the data acquisition by the experiment and to implement a different time-phase resolving system.

In the present approach the measuring system was operated at constant acquisition rate and both events, the acquisition of a measurement and the start of a new cycle of the structure motion were recorded based upon an absolute clock. Using the recorded events time information the data was reorganized in a post-processing software in order to generate the time-phase resolved data. Besides solving the trigger problem, this solution also resulted in a minimum acquisition time needed, because the measuring system could be always operated at its optimum measuring rate independent of the structure swiveling frequency.

To execute this idea a time-phase detector module was designed to perform the event monitoring and integrated in the measuring system. The hardware module is based on a FPGA (Field Programmable Gate Array) and a 1 MHz internal clock. It is capable to monitor up to 250 events per second from 6 different lines with an accuracy of 2 μs.
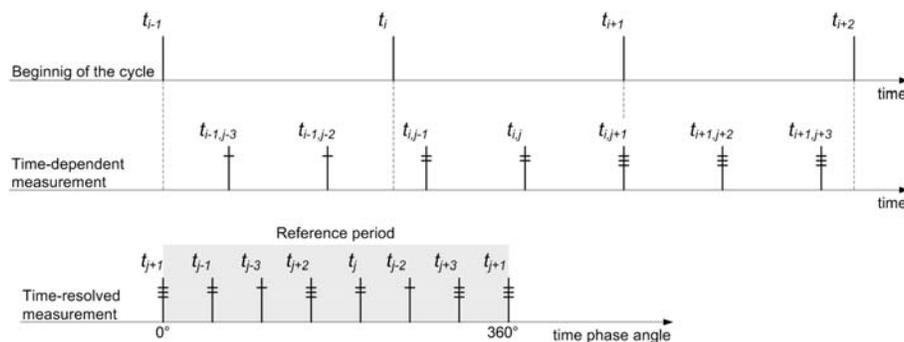

Fig. 3. Time-phase resolved measurement reconstruction time scheme.

Figure 3 shows a typical time-phase resolved data reconstruction. During the tests two main events were recorded; the measurements (t_{ij}) and the beginning of a structure motion cycle (t_i). The measurement events were detected using the first laser pulse trigger signal. As far as the beginning

of the structure motion cycle is concerned the swiveling period starting position was detected using an electronic angular position sensor. This sensor was developed to monitor the angular position of the structure front body and to generate an impulse triggering signal every time the front body reaches a predefined angular position. The decision for such kind of a sensor to perform the task was based on two criteria: it is a non-contacting position angular sensor and provides a direction resolved output signal.

After the acquisition of the time dependent measurements a specific software computed the period of each individual cycle (T_i) and the time-phase angle of each individual measurement within the correspondent structure cycle (t_j). Finally the time-phase resolved data was sorted in a reference structure motion period according to a desire time-phase resolution and accuracy.

$$T_i = t_{i+1} - t_i \qquad 1 \leq i \leq \text{maximum number of cycles acquired} - 1 \tag{1}$$

$$t_j = \frac{t_{ij} - t_i}{T_i} \times 360° \qquad 1 \leq j \leq \text{maximum number of measurements acquired} \tag{2}$$

3.3 Flow velocity measurements

The task of sampling the velocity of the flow surrounding the flexible structure was addressed to a Dantec Dynamics Flowmap two-component multi-camera particle image velocimetry system. The PIV system adopted for the measurements consisted of two 1280 pixel × 1024 pixel synchronized HiSense cameras and a pulsed double-head New wave Gemini 120 mJ Nd:YAG laser with a wave length of 532 nm.

The two cameras mounted with AF Micro 60 mm Nikon objectives were arranged in parallel to the structure rotating axel to visualize the flow in a plane perpendicular to it. Opting for the solution of two parallel cameras it was possible to acquire time-dependent composed PIV images at constant frequency of an extended 272 mm × 170 mm flow field measuring area while keeping the spatial resolution as low as 133 µm × 133 µm per CCD pixel.

Fig. 4. Two synchronized two-component PIV cameras arrangement.

To assure the correct position of the two adjacent images a special support was designed to hold both cameras and to permit the adjustment of each individual camera or both cameras simultaneously in the 6 spatial axis (see Fig. 4). The correspondent images acquired by the two cameras were stitched (see Fig. 7) in the MatLab work space using a post-processing software before being cross-correlated.

Another improvement of the measuring technique to the specific task was related to the illumination of the flow field. When it comes to measure the flow field surrounding swiveling flexible structures some extra problems appear. The most important of them was related to the fact that the swiveling structure was a swiveling opaque body witch created an unsteady dark shadow region in the fluid behind the model and the laser source. This behavior not only reduced the measuring area to almost one side of the flexible structure but also made the masking of the PIV images in post-processing difficult to be preformed. To cope with this problem two different solutions were adopted according to the working liquid used in the tests.

For turbulent tests (using water as the working liquid) the solution represented in the figure 5 was adopted: a mirror was mounted on the opposite side of the test section to take advantage from the outgoing laser light with the objective to deflect the laser sheet backwards and to illuminate the flow dark region. This solution enabled the optical access to both sides of the model with a single laser source. However, for the test with high viscous liquids (tests in laminar range) because of the significant light absorption of the Polyglycol syrups the previous solution was not successful.

1   Test section
2   Flexible structure
3   Laser source
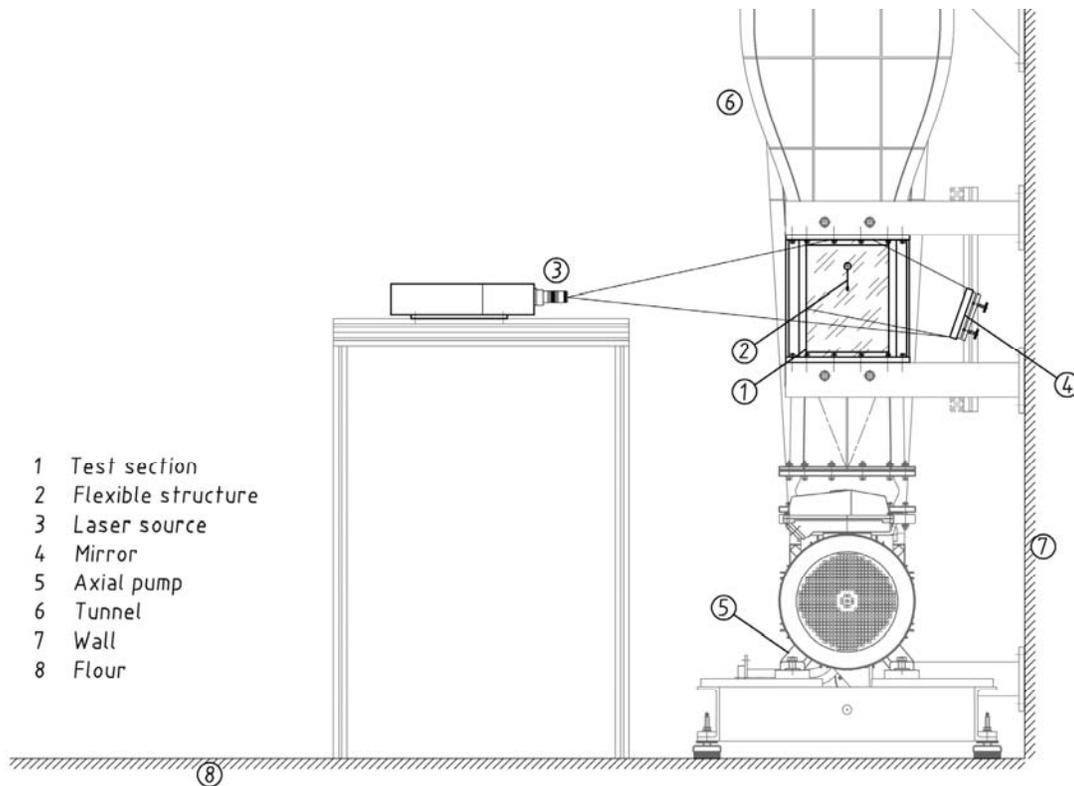4   Mirror
5   Axial pump
6   Tunnel
7   Wall
8   Flour

Fig. 5. One laser source arrangement used to illuminate water flows.

For the laminar cases a second laser source had to be added to illuminate the dark region area created by the first one. Because of space limitations around the experimental facility the second laser source had to be mounted parallel to the facility and a mirror was used to deflect the second

laser light towards the test section (see details in Fig. 6).

There are common advantages and disadvantages arising from these two solutions; the dark region behind the structure was extinguished and all the flow surrounding the structure was accessible to perform PIV measurements at once. As a disadvantage it turned out that there were regions of different light intensity in the flow, however, this problem could be minimized with a proper adjustment of the laser light focus and cameras optics.
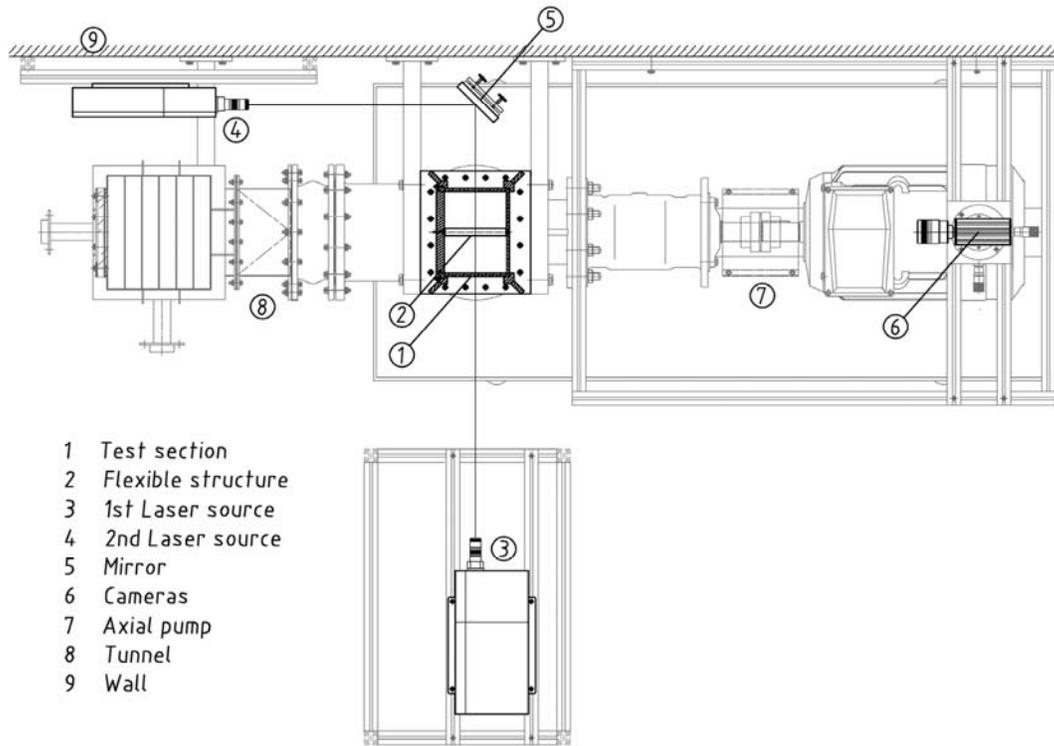

1   Test section
2   Flexible structure
3   1st Laser source
4   2nd Laser source
5   Mirror
6   Cameras
7   Axial pump
8   Tunnel
9   Wall

Fig. 6. Two laser sources arrangement used to illuminate high viscous Polyglycol syrup flows.

For seeding different types of particles were employed again depending on the test fluid used. For test in water 10 µm mean diameter hollow glass spheres were used while for Polyplycol syrups 10 µm mean diameter silver coated hollow glass spheres were adopted. Although hollow glass spheres appear to be the most suitable choice to be used in Polyglycol syrups as far as density is concerned (the relative density of those spheres are about 1,1) they introduce an additional problem because of their refractive index. The refractive index of the syrups is higher than the one of water and closer to the refractive index of the non coated spheres. On the other hand, silver coated hollow glass spheres are non-transparent particles and produce higher signal levels on high light absorption media. The major drawback of using silver coated glass spheres is related to their density; the relative density of this kind of particles is about 1,4. Nevertheless, this drawback was accepted because of the high viscosity and the velocity of the flow during the test.

3.4 Structure deflection measurements

For structure deflection modes identification (DMI) measurements the PIV system was modified to provide it with structure deflection analysis capabilities. The idea behind this setup was to use the PIV system to acquire and organize images from the swiveling structure and to use an especially

developed software to analyze 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.
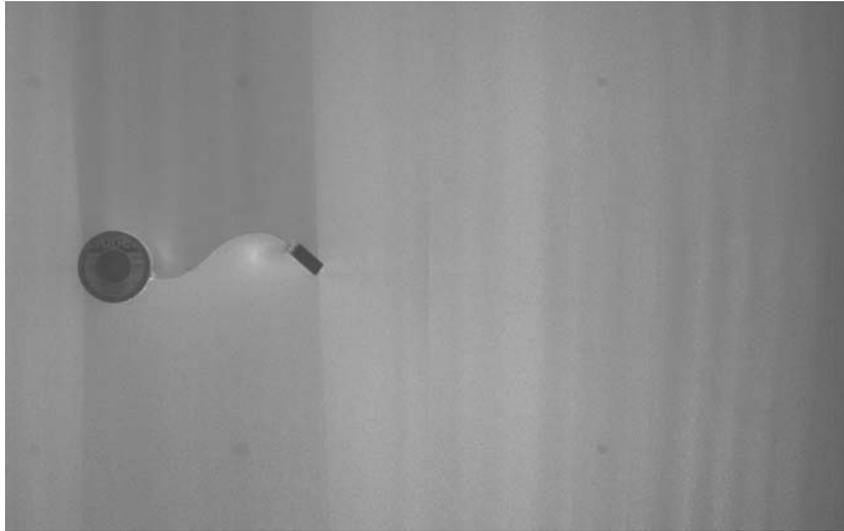

Fig. 7. Stitched image from two synchronized PIV cameras using two laser sources in a high viscous flow.

In order to generate coherent results, the relative position of the laser source was maintained to illuminate the time-dependent deflection of the flexible structure at the same plane as for the velocity field measurements. For the deflection measurements only one camera was positioned to acquire images of the flexible structure illuminated by the laser sheet from each side of the model in separate. After image acquisition, 3D PIV software including camera calibration routines that measure and account for perspective distortion were implemented to correct parallax errors and to compute the real scale of the structure deflection images.

The quantitative analysis was performed in Matlab workspace by a script developed for the specific task. The software analyzed and compared the PIV images with different illumination 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 and of the time-phase detector module the algorithm finally computed all the relevant time-phase resolved data about the structure movement such as, time-phase resolved angle of attack of the front body, structure deformation shape and coordinates of the structure trailing edge. Based on this data the modes present in the structure were identified and characterized.

4. Experimental results

In the present paper, examples of results from measurements in laminar flows are presented. The structure under consideration consisted of a 0,04 mm thick stainless steel membrane attached to an aluminum cylindrical front body. The overall chordwise and spanwise dimensions of the flexible structure were 85 mm and 177 mm, respectively. The front body had a diameter of 22 mm. At the trailing edge of the membrane a 10 mm × 4 mm cross section stainless steel rectangular mass was located. Both the rear mass and the front body were considered rigid.

The next figures show time-phase resolved measurements for a uniform incoming velocity of 1,45 m/s and a Reynolds number, based on the diameter of the front body, of 195 (kinematic viscosity of the test fluid: 0,000164 m^2/s). Under such conditions the flexible structure exhibited a 13,58 Hz periodic swiveling motion. The cycle-to-cycle fluctuation of the motion frequency was registered to be smaller than 2%. The flow field surrounding the model as well as the deflection of the flexible structure were reconstructed with a time-phase resolution of 2,5° within an uncertainty of 0,5° and it corresponded to the average of 100 measurements. Figure 8 represents both the evolution of the angle of attack of the structure front body and the trailing edge coordinates within the reference motion period. Figure 9 sketches time-phase resolved combined flow velocity field/structure deflection results. For the present time-phase resolution and uncertainty it was possible to detect the position of the structure with an accuracy better than 0,3mm. The velocity map corresponds to a flow measuring area of 272 mm × 170 mm.
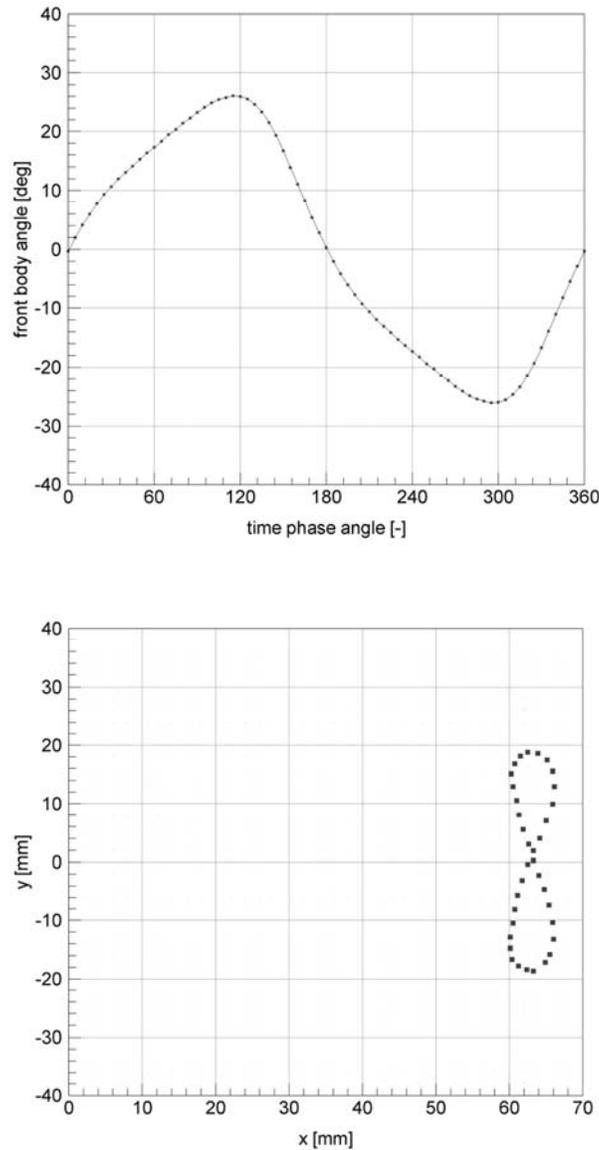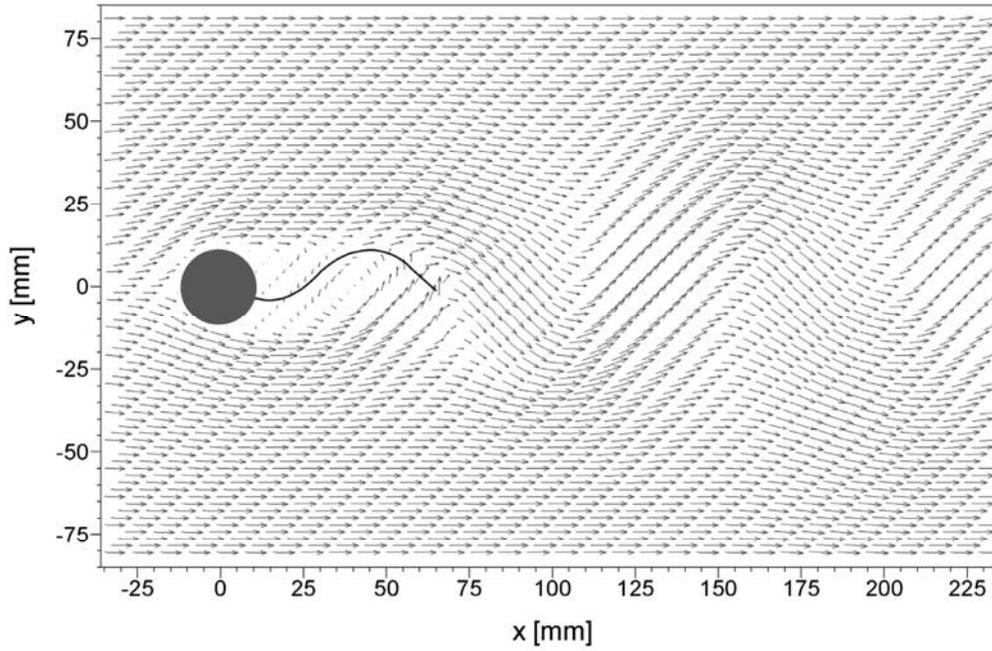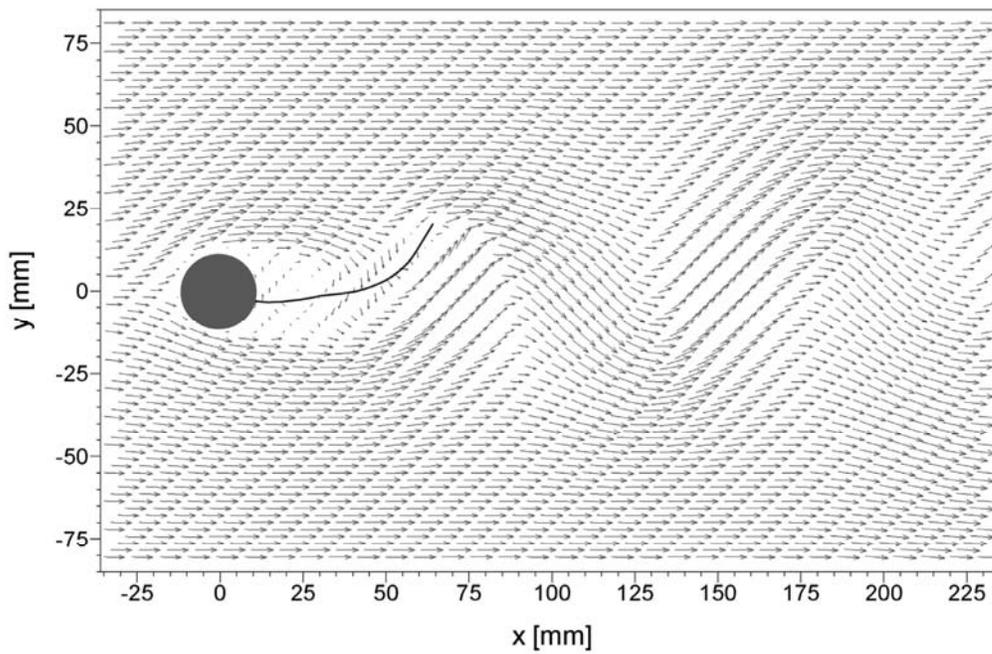

Fig. 8. Structure front body angle of attack (top) and trailing edge coordinates (bottom) within the reference swiveling motion period.

(a) $t_j = 60°$

(b) $t_j = 150°$

Fig. 9. Time-phase resolved combined velocity flow field / structure deflection results for two different instants of the reference swiveling motion period.

5. Conclusions

The increased efforts in numerical research to develop coupling strategies for the simulation of fluid-structure interaction problems have triggered the development of a reference experiment on the same research field. Within this work, a new test facility was constructed to perform tests in laminar and turbulent flows under well defined boundary conditions. The dedicated tunnel was designed to be operated with liquid fluids of different viscosities (kinematic viscosity operation range: 1×10^{-6} m^2/s up to 5×10^{-4} m^2/s) and has satisfied all the design objectives. The facility permits to perform the tests under very precise boundary and working conditions and it has shown to be capable to maintain a constant velocity inlet profile in the test section through all the viscosity operation range. Using a 0,000164 m^2/s kinematic viscosity liquid fluid it was possible to achieve a maximum velocity of 2,7 m/s while with water that value increases up to 4,5 m/s.

As far as the measurement techniques are concerned Particle Image Velocimetry was successfully applied to measure the velocities in the flow surrounding the flexible structure and, with some modifications, to measure the deflection of the structure. Opting for the solution of two synchronized cameras and multi laser sources it was possible to have access to an extended 272 mm $\times$ 170 mm flow field area surrounding the flexible structures to perform PIV measurements. To resolve the measurements in time-phase the measuring system was improved with a time-phase detector module. This hardware module made the reconstruction of the unsteady periodic time-phase resolved measurements reliable and extremely accurate independently from the nature of the structure motion. The integrated PIV/time-phase detector module has proven that a reliable and continuous data acquisition was possible for long periods of time using a maximum acquisition rate of 1 Hz.

After implementing the PIV system to the current study it was extended with structure deflection analysis capabilities. The PIV images of the structure were analyzed in MatLab work space by a script specifically developed to reconstruct the time dependent deflection of the structure. This solution has shown to be capable to perform a complete detection of the two-dimensional position of the flexible structure with an accuracy better than 0,3 mm.

The set of facilities and experimental measurement techniques developed for the present research work were used to perform a complete characterization of different fluid-structure interaction reference test cases. For each one the velocity field, structure deflection, and unsteady fluid flow and structure coupled motion frequency were recorded. The first tests were focused on two-dimensional problems in laminar flows. Later the investigations were expanded to two-dimensional turbulent cases. In this paper, examples of time-phase resolved measurements in high viscous fluids are presented.

6. Acknowledgements

References

1. Naudasher, E. and Rockwell (1980) Practical Experiences with Flow-Induced Vibrations: Symposium Proceedings. New-York: Springer Verlag.

2. Naudasher, E. and Rockwell (1994) Flow-Induced Vibrations – An engineering guide. Rotterdam: A.A. Balkema.