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EXPERIMENTELLE UNTERSUCHUNG SELBSTINDUZIERTER SCHWINGUNGEN FLEXIBLER STRUKTUREN IN LAMINARER STRÖMUNG

EXPERIMENTAL STUDY ON THE SELF-EXCITED MOVEMENT OF FLEXIBLE STRUCTURES IN LAMINAR FLOWS

J. Pereira Gomes; H. Lienhart
Lehrstuhl für Strömungsmechanik, Universität Erlangen-Nürnberg
Cauerstraße 4, D-91058 Erlangen, Germany
jgomes@lstm.uni-erlangen.de
lienhart@lstm.uni-erlangen.de

Fluid-structure interaction; self-excited movement; particle image velocimetry; laminar flow

Abstract

The different mechanisms which lead the vibration of a flexible structure immersed in a flowing fluid to become self-excited are complex and very difficult to predict. To better understand those mechanisms and to identify the effect of the mechanical properties of the structure as well as the properties of the incoming flow in the fluid-structure interaction coupling motion, a two-dimensional experimental study on the self-excited motion of flexible structures immersed in a high viscous fluid was carried out.

The objectives were to obtain a consistent set of data for the laminar fluid-structure interaction motion for a wide range of physical parameters and a deeper insight into the different self-exciting mechanisms. The measurements were performed using a particle image velocimetry (PIV) system specially adapted to carry out time-phase resolved measurements. The system was developed to measure the dynamic response of the structure and the two-component flow velocity field simultaneously.

This contribution presents the results obtained for a flexible cylindrical structure model in laminar flows. The presented results clearly confirm the existence of two distinct fluid-structure interaction modes for the entire Reynolds number range investigated.

Introduction

Flow-structure interaction problems, involving the coupling of unsteady fluid flow and structure motion, arise in many fields of engineering (see Naudasher and Rockwell) as well as in many other sciences, e.g. medicine. Because of their importance they have received great attention from fluid dynamicists and computational researchers (see Bungartz and Schäfer). Despite their practical relevance, results of well controlled experiments on the self-excited motion of flexible structures immersed in flowing liquids are still scarce. From previous experience one could conclude that there are several mechanisms which lead the vibration of flexible structures immersed in flowing fluids to become self-excited. All of them are very sensitive to the mechanical properties of the structure as well as to the properties of the fluid and therefore difficult to predict.

The objective of this contribution is to present the results of a detailed experimental investigation on two-dimensional fluid-structure interaction laminar test cases. The investigation performed on relatively simple structures under very well defined working conditions make possible to understand the influence of each individual physical parameter on the different excitation processes. The parameters considered in the present study included the fluid viscosity (Reynolds number), the incoming flow velocity and the geometrical and mechanical properties of the structure. The results discussed in the present contribution refer exclusively to the self-excited motion of a bluff cylindrical flexible two-dimensional immersed in a uniform laminar flow.

Model definition

The results presented in this contribution refer to the two-dimensional structure model described in Fig. 1. The choice of this specific geometry took into account five principal restrictions: (i) reproducibility of the resulting motion; (ii) two-dimensionality of the structure deflection; (iii) moderate structure motion frequency; (iv) significant excursion of the structure and (v) well defined linear mechanical proprieties of the structure.

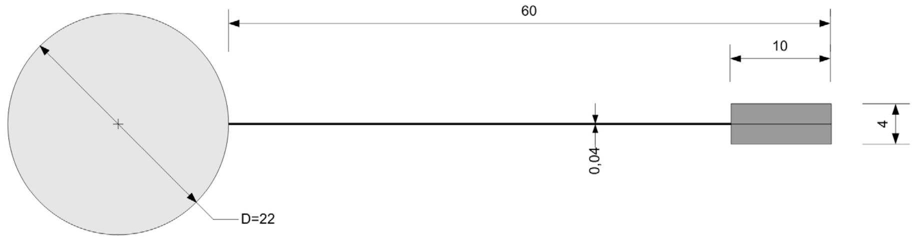


Fig. 1: Structure flexible model layout (all dimensions in mm).

The model is constituted by a 0,04 mm thick stainless steel sheet attached to an 22 mm diameter aluminum cylindrical front body. At the trailing edge of the structure a 10 mm × 4 mm rectangular stainless steel mass was located. All the structure was free to rotate around an axle located in the center point of the front cylinder. Both the front cylinder and the rear mass were considered rigid. The flexible section of the structure has proven to show a linear mechanical behavior 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 spanwise dimension of the structure was 177 mm.

The structure was mounted 55 mm downstream the inlet plane of the 338 mm long test section on ball bearings so the rotational degree of freedom of the front cylinder could be consider to be free of friction. The experiment domain of the reference experiment is represented in Fig. 2.

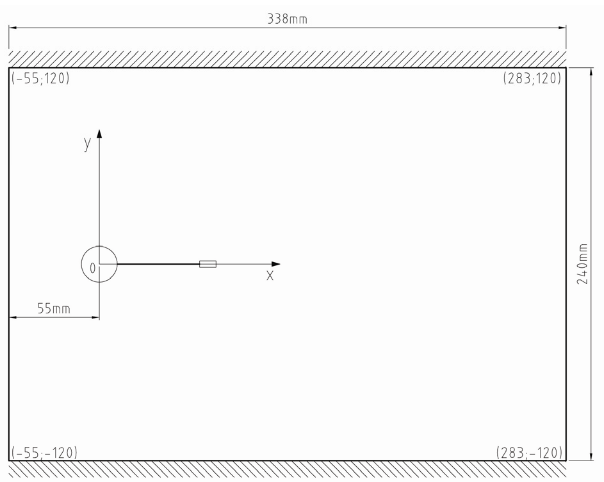


Fig. 2: Experimental domain geometry.

Experimental set-up and measuring techniques

The tests were conducted in a high viscous vertical closed circuit tunnel operating Polyethylene Glycol syrups as test liquid. Opting for such a facility it was not only possible to specify the Reynolds number of the tests controlling the viscosity of the working liquid but also to guaranty that the gravity force was aligned with the x-coordinate avoiding the introduction of any asymmetry into the problem. The kinematic viscosity and density of the liquid were measured to be $1{,}64 \times 10^{-6}$ m^s/s and 1050 Kg/m^3, respectively.

As far as the measurements are concerned, information of both structure and flow parameters are of capital importance to understand the coupled fluid and structure motion self-excited movement. Therefore, the measurements techniques were adapted to the present study in a way to measure the time-phase resolved flow velocity field around the model as well as the unsteady position of the structure within a period of motion.

Particle Image Velocimetry was the measuring technique chosen to measure the flow surrounding the flexible structure. The PIV system consisted of two 1280 pixel × 1024 pixel synchronized cameras and a pulsed Nd:YAG laser with a wave length of 532 nm.

The two cameras were arranged in parallel to the structure rotating axel to visualize the flow in a plane perpendicular to it. 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. The correspondent images acquired by the two cameras were stitched together in the MatLab work space using a post-processing software before being cross-correlated.

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 in the fluid behind it when illuminated by just one light 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 performed. 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 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.

Opting for the solution of two parallel cameras and multiple light sources 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.

As seeding particles 10 µm mean diameter silver coated hollow glass spheres were chosen. They reduce problems of light refraction and produce higher signal levels on high light absorbing media when compared with non-coated hollow glass spheres. 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 acceptable because of the high viscosity and the velocity of the flow during the test.

To determine the deflection 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 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.

The cameras were now disposed in such a way to acquire images the flexible structure illuminated by the laser sheet from each side of the model. The quantitative analysis was performed after images acquisition in Matlab workspace by a script developed for the specific task. The software analyzed 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 grayscale 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.

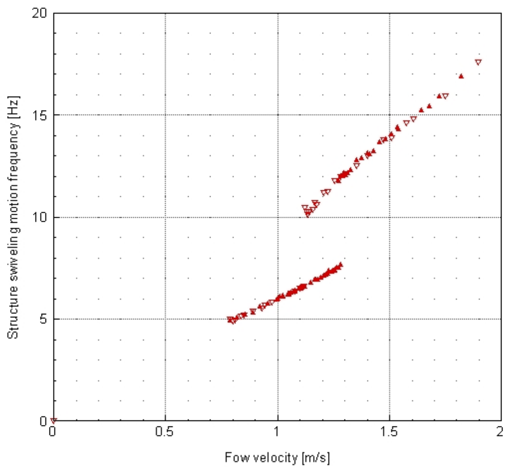
To resolve the measurements in time, it was introduced the time-phase angle $tpa = (t/T) \times 360°$ where *T* is the period of the structure swiveling motion and the *t* is the delay of the measurements in respect to the beginning of the cycle. The measurements where resolved in the time-phase space with a resolution of 2,*5°* associated to an uncertainty of *0,5°*. More detailed descriptions of the measurement techniques and their improvement to the present task are given in Bungartz and Schäfer or GALA 2005.

Results

This section is organized as follows. First the general character of the dynamic response of the structure is presented as a function of the incoming flow velocity. Then two complete sets of measurements for two specific inlet flow velocities are shown: the fist one for 1,07 m/s and the last for 1,45 m/s.

The structure was tested at different incoming velocities up to 2 m/s. Within this range the tunnel was capable to maintain a uniform inlet velocity profile across the test section except in the local regions close to the wall corresponding to the laminar boundary layers. The maximum flow angularity was measured to be lower than 0,5° and the RMS of the velocity magnitude variance better than 1%. The Reynolds number, based on the diameter of the front cylinder, varied up to 270.

In the following figures the frequency of the resulting structure movement and the peak-to-peak amplitude of the front body angle are presented versus the incoming flow field.



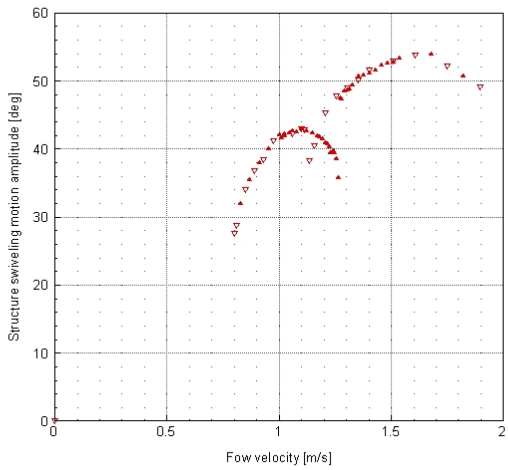


Fig. 3: Structure swiveling frequency (left) and front body angular peak-to-peak amplitude (right).

The structure stayed steady up to a velocity close to 0,8 m/s. From this lower velocity limit the structure was excited to a periodic and symmetric swiveling motion. The transition from rest to a stable periodic motion was abrupt and it was not possible to define any evolution of the structure from one stage to the other.

The most notorious behavior one can conclude from the figures is the existence of two different swiveling modes within the flow velocity range from zero up to 2 m/s. The transition between the two modes as well as the transition from rest to the first mode has shown a hysteretic behavior. The first mode stayed as the unique structure swiveling mode up to 1,12 m/s and is mainly characterized by the first deflection mode of the structure. The second swiveling mode is uniquely observed from 1,3 m/s and it was dominated by the second deflection mode of the structure.

Results at 1,07 m/s

According to Fig. 3 this flow incoming velocity almost corresponds to the maximum resonance velocity of the first swiveling mode. The structure resulting motion indicated a frequency of 6,38 Hz associated to a maximum cycle-to-cycle fluctuation of ±2%. Fig. 4 shows the angle of the front cylindrical body and the y-coordinate of the structure trailing edge within a period of motion. They display a time-phase angle difference of about 60°.

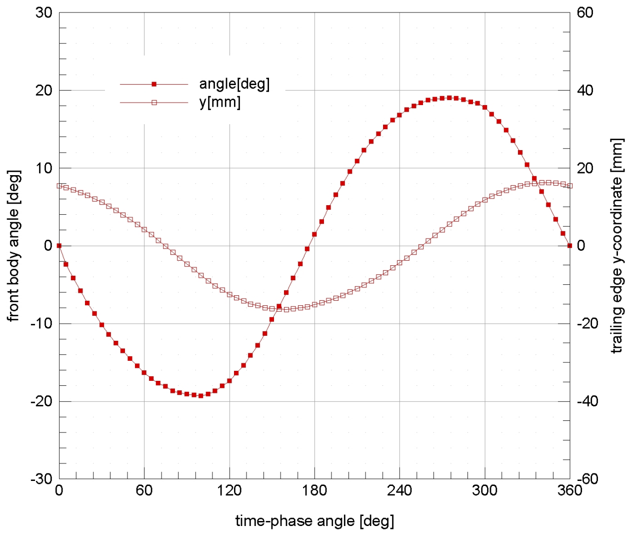


Fig.4: Structure front body angle and trailing edge y-coordinate at 1,07 m/s.

As far as the deflection of the structure is concerned two kinds of results are presented. Fig. 5 represents the successive shapes of the structure membrane within a swiveling period and shows the trajectory of the trailing edge for the same period.

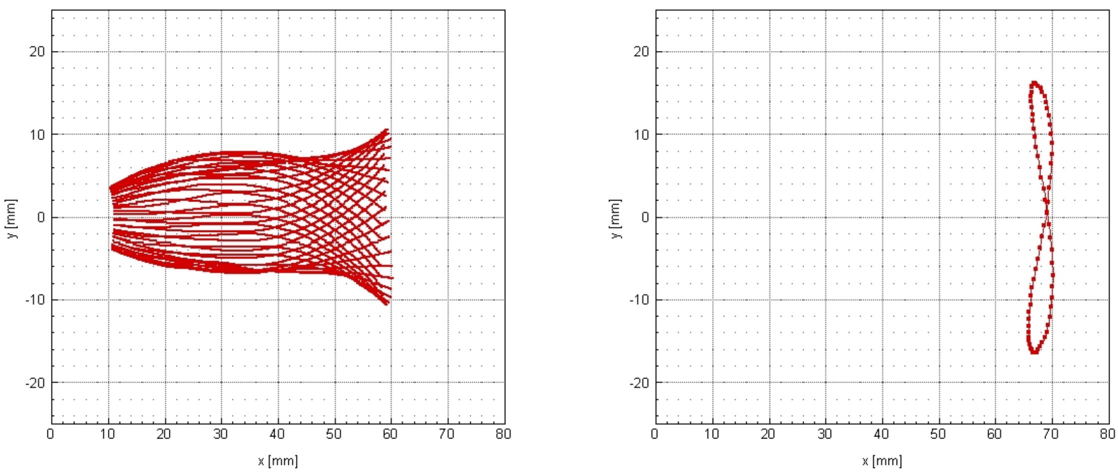


Fig.5: Structure deflection shapes (left) and position of the trailing edge (right) at 1,07 m/s.

Results at 1,45 m/s

A similar set of measurements were performed for a second incoming flow velocity. At 1,45 m/s the structure exhibited a more complex and faster swiveling motion. The resulting motion frequency was measured to be 13,58 Hz ±2% and the maximum front body angular amplitude equal to ±22°. In the following figure the angle of the front body is displayed simultaneously with the displacement of the trailing edge along the y-direction within the motion period. The time-phase difference between the two increased to about 210°.

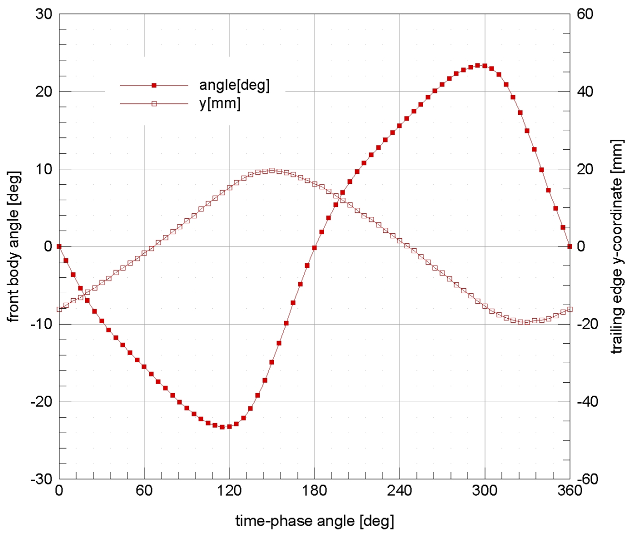


Fig.6: Structure front body angle and trailing edge y-coordinate at 1,45 m/s.

The fact that the second swiveling mode is strongly characterized by the second deflection mode of the structure can be seen in the Fig. 7 which displays a pronounced node. In this figure both the position of the structure membrane and of the model trailing edge within a swiveling motion are represented.

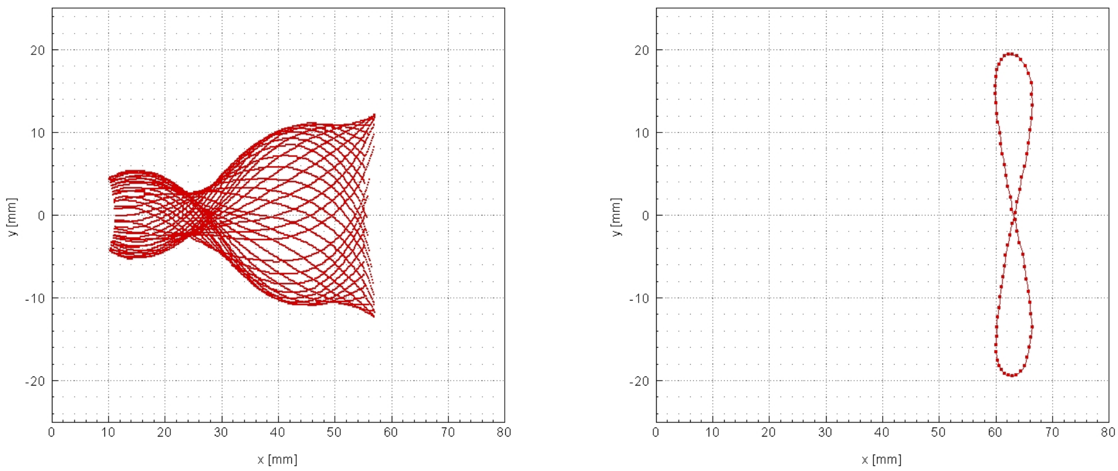


Fig.7: Structure deflection shapes (left) and position of the trailing edge (right) at 1,45 m/s.

Regarding the unsteady flow field results Fig. 8 compares the velocity field around the structure for two different velocities at four different instants of the motion period. Each map corresponds to the average value of 100 maps acquired for the same time-phase angle and it combines the flow velocity field and the position of the structure.

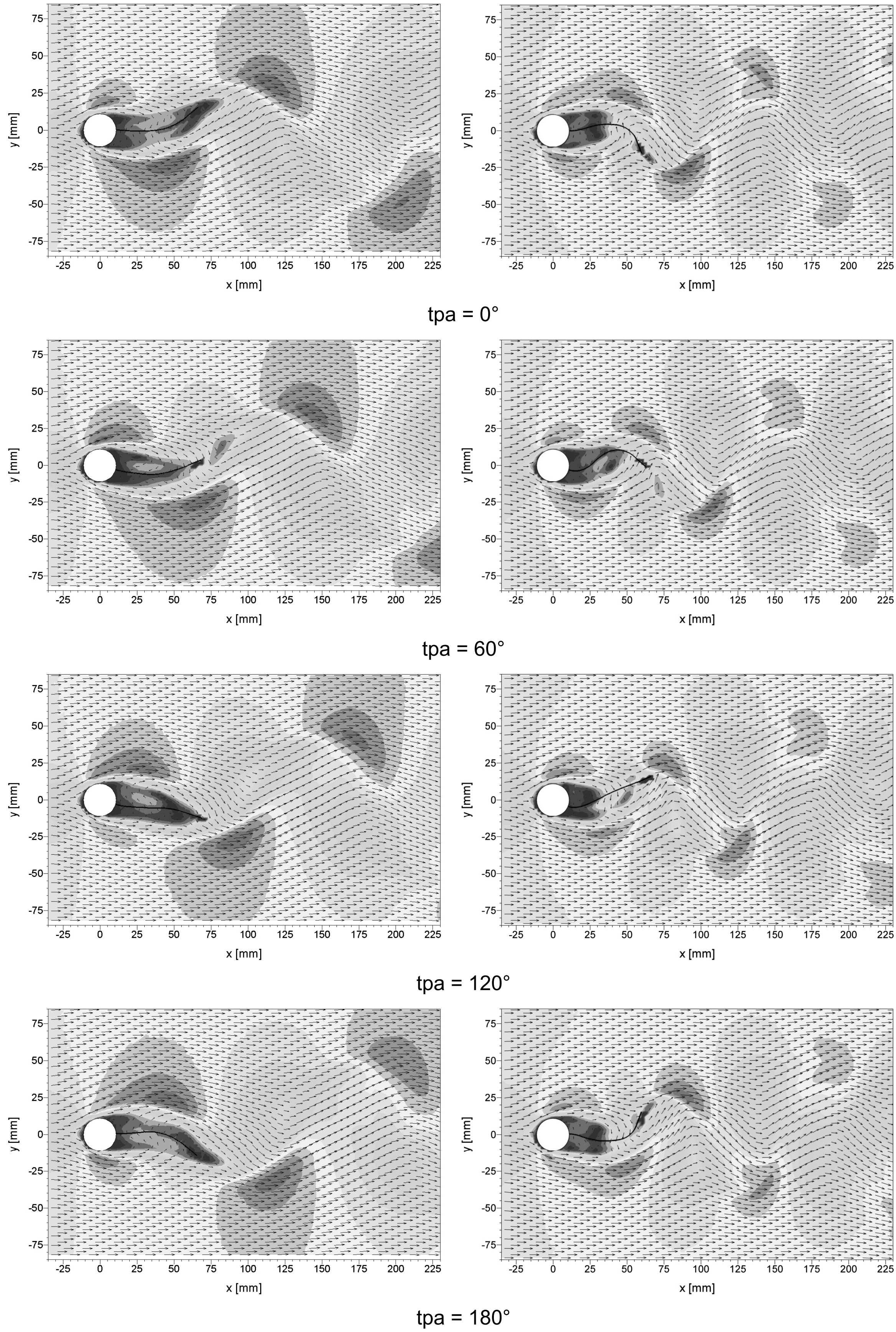


Fig.8: Time-phase resolved combined velocity flow field / structure deflection results for four different instants on the reference swiveling motion period at 1,07 m/s (left) and 1,45 m/s (right).

Discussion of the results

The self-excited movement of a bluff flexible two-dimensional structure in laminar flows for a Reynolds number range up to 270 was investigated. The tests were performed in a Polyethylene Glycol syrup with a kinematic viscosity of $1{,}64\text{x}10^{-4}$ m^2/s for an incoming flow velocity up to 2 m/s. The structure was constituted by a thin metal sheet attached to an aluminum front cylindrical free rotating body. At the trailing edge of the metal sheet a rear mass was located.

For the range of Reynolds number tested the structure clearly shown two distinctive fluid-structure interaction swiveling modes depending on the flow velocity. For the two modes, the resulting two-dimensional motion has proved to be very reproducible and symmetric. Along the tests a maximum cycle-to-cycle fluctuation in the structure movement frequency and maximum deflection amplitude was measured to be 2% and 1°, respectively.

The first mode was excited for the first time at 0,8 m/s. For this flow velocity, the corresponding Strouhal number (St≈0,175) and the first natural frequency of the structure (N_1≈6,12 Hz) shown a strong interconnection between the movement excitation and the classical von Karman vortex shedding. Despite a small delay, the trailing edge movement could be considered in phase with the angular movement of the front cylinder. About the deflection of the structure, the first mode was characterized almost exclusively by the existence of the first bending mode. Therefore, at the maximum resonance velocity of the first swiveling mode (1,1 m/s) the structure vibrates around its first natural frequency. At 1,07 m/s the coupled fluid and structure unsteady motion occurred at 6,38 Hz associated to a maximum excursion of the front body and trailing edge of 19° and 16 mm, respectively.

The transition to the second, more complex mode was observed at 1,3 m/s and has shown a strong hysteretic behavior. Between 1,12 m/s and 1,3 m/s both swiveling modes could be observed depending on the previous conditions. This behavior is in agreement with the galloping response of square cross-section prisms as reported by Parkinson and Novak. For both swiveling modes the locked-in structure and motion frequency increased linearly with the fluid velocity.

The excitation of the second swiveling mode was characterized by a vortex shedding frequency much lower than the second natural frequency of the structure (N_2≈30,1 Hz). The trailing edge was now almost in phase opposition in relation to the front body position and the structure deflection within a period of motion was mainly characterized by the second structure bending mode. At 1,46 m/s the fluid-structure interaction motion frequency was measured to be 13,58 Hz associated to a wider body amplitude. The front cylinder reached a maximum deflection of 26° while the trailing edge excursion was limited to 19 mm.

Acknowledgment

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