Fachtagung “Lasermethoden in der Strömungsmesstechnik”
6. – 8. September 2005, BTU Cottbus

TIME-RESOLVED PIV/DMI MEASUREMENTS ON FLUID-STRUCTURE INTERACTION PROBLEMS

Jorge P. Gomes
Hermann Lienhart
Lehrstuhl für Strömungsmechanik
University of Erlangen-Nuremberg
D-91058 Erlangen
Germany

Abstract

Experimental studies on fluid-structure interaction reference test cases are of capital importance to support the development of numerical methods in the field. To correctly characterize those interaction phenomena, information about the flow field and structure motion is required. From the measurement techniques view point, the unsteady behavior of such kind of problems results in additional difficulties to perform time-resolved measurements.

In the present paper the application of laser measurement techniques for the diagnostic and characterization of fluid-structure interaction problems are reported. It is shown that particle image velocimetry (PIV) is very well suited to provide the required flow velocity field information. As far as the deflection of the structure is concerned the PIV system was provided with image analysis capabilities to measure the unsteady deflection of flexible structures. This paper puts in evidence as well the implementation of a different idea to resolve the structure deflection and the velocity field measurements in time.

Finally the developed measurement techniques were successfully applied to study a fluid-structure interaction test case, and a few examples of the results are presented.

I 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. 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 knowledge is not yet available in commercial codes.

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

All of these efforts could result in new tools which permit a realistic simulation of such complex, nonlinear coupled problems. However, to ensure success, comparison with experimental studies is needed to support the ongoing research activities. In past attempts, numerical results from specific technical problems were confronted with experimental measurements performed on scaled models. But the increased complexity of such specific configurations and the modeling laws considerations involved has resulted in additional problems and limited reliability during the comparison between experimental and numerical results. Moreover this approach did not address directly to provide the details needed for numerical validation and accuracy verification purposes.

This demand underlines the need for dedicated reference experiments especially oriented towards the diagnostic and validation of numerical models. Experimental work along this line has been carried out and has resulted in the dedicated test facility and measurement techniques as well as in the definition of the reference experiment for fluid-structure interaction studies described in this paper. In Sec. II the reference experiment is defined. The facility constructed to make possible the tests is also reported. The measurement techniques used for the measurements are discussed in Sec. III and IV. In Sec. V, the problems to perform fluid-structure interaction time-resolved measurements are outlined and the solution adopted to solve the measurements in time is described. Finally, examples of experimental results are presented in Sec. VI, followed by conclusions in Sec. VII.

II Experiment definition and test facilities

As already mentioned the main goal of the present project was to collect an extended experimental data base on a reference experiment on fluid-structure interaction. The first task was to design a flexible structure in such a way to maintain a two-dimensional periodic swiveling motion induced by a constant velocity incoming fluid flow. The tests should be repeated at very low Reynolds number, laminar case, and in turbulent regime.

After a period of preliminary tests in which several flexible structures layouts were observed a combined stainless steel flexible membrane attached to a stainless steel rigid front flat plate was found to meet the criteria for the flexible structure. All structure was free to swivel around a fix rigid axel. This configuration has proven to be capable to maintain a two-dimensional periodic oscillating motion induced by the flow. In addition to be a requirement of the project the periodicity was a very important factor to make sure that reproducible results could be achieved in successive experiments as well as in numerical simulations.

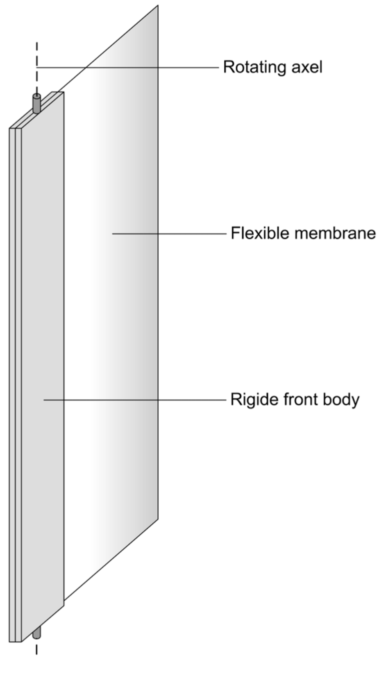

Figure 1: Flexible structure layout.

The final structure dimensions were fine adjusted to achieve the best compromise between high swiveling amplitudes and a very good general two-dimensional deflection along the chordwise direction.

To cover the required Reynolds number range polyethylene glycol (polyglycol) syrups were planned to be used as test fluid in order to control the viscosity of the tests. The kinematics viscosity of the fluid was decided to vary from $5x10^{-4}m^2/s$ (high concentrated polyglycol syrup) and $1x10^{-6}m^2/s$ (water). For the same range the density presents a minor variation from 1,1 to $1kg/m^3$.

The employment of high viscous fluids and the necessity of very precise and controllable working conditions imposed stringent restrictions in the preparation of the tests and determined the construction of a new experimental facility designed specially for the present project. It is a 24*KW* vertical closed circuit tunnel capable of being operated with high viscous fluids. Using water as working fluid the facility can ensures a continuous maximum flow speed of 4,5*m/s* in the test section.

During its construction, emphasis was placed on the design of the 180x240*mm* cross section, 372*mm* long test section to allow flow investigations involving laser measurement techniques. Therefore it was entirely made out of glass to provide it with fully optical access to all sides of the test model. To increase flexibility, the interior of the test section can be easily emptied and accessed from the exterior or completely removed to mount different types of models.

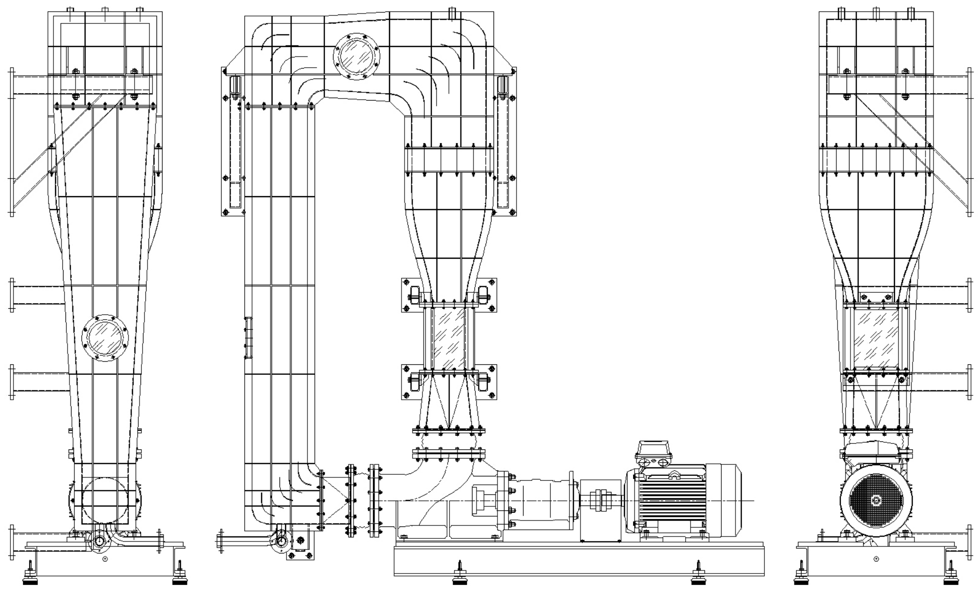

Figure 2: FLUSTRUC tunnel layout.

III Flow velocity measurements

The task of sampling the flexible structure surrounding fluid flow was addressed to a Dantec Dynamics Flowmap two-component multi-camera PIV system with a pulsed double-head New wave Gemini 120*mJ* Nd:YAG laser operating at 532*nm*. Two 1280x1024*pixel* synchronized HiSense PIV cameras mounted with AF Micro 60*mm* Nikon objectives were used to acquire two simultaneously time-dependent PIV images at constant frequency. Preliminary tests have shown that a reliable and continuous data acquisition from two synchronized cameras was possible for long periods of time using a maximum frequency of 1*Hz*.

The cameras were mounted parallel to the flexible structure rotating axel to visualize the flow in a plane perpendicular to the structure leading edge. To assure a correct position of the two adjacent images a special support was design to hold both cameras and to permit the adjustment of each individual camera in the six axes or of both cameras simultaneously. The PIV images acquired by the two cameras were then imported into a MatLab-based post-processing software to stitch the correspondent pairs of images before being cross-correlated. Opting for such solution it was possible to achieve an extended 272x170*mm* flow field measuring area without decreasing the spatial resolution more than 133x133*µm* per CCD pixel.

The laser sheet was positioned perpendicular to the flexible structure rotating axel at the middle position of the structure in the spanwise direction. Respecting the illumination of the flow, swiveling flexible structures impose extra problems. The most important of them is related to the fact that flexible structures are swiveling opaque bodies witch creates an unsteady dark region on the fluid behind the laser source. This behavior not only reduces the measuring area to almost only one side of the flexible structure but also makes the PIV images masking post-processing difficult to be preformed. To face this problem 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. Advantages and disadvantages arise from this solution; the dark region behind the structure is extinguished and all the structure surrounding flow can be accessed to perform PIV measurements at once. Moreover, the correct position of the mirror to ensure the coincidence of he forward and backward laser sheet is easy to set. As a disadvantage one could aspect different light intensity regions in the PIV image, however this problem could be minimized with a proper adjustment of the laser light focus and the cameras optics.

Different types of seeding particles were provided depending on the test fluid used. For tests in water 10*µm* mean diameter hollow glass spheres were used while for Polyglycol syrups 10*µm* mean diameter silver coated hollow glass spheres were adopted. Although

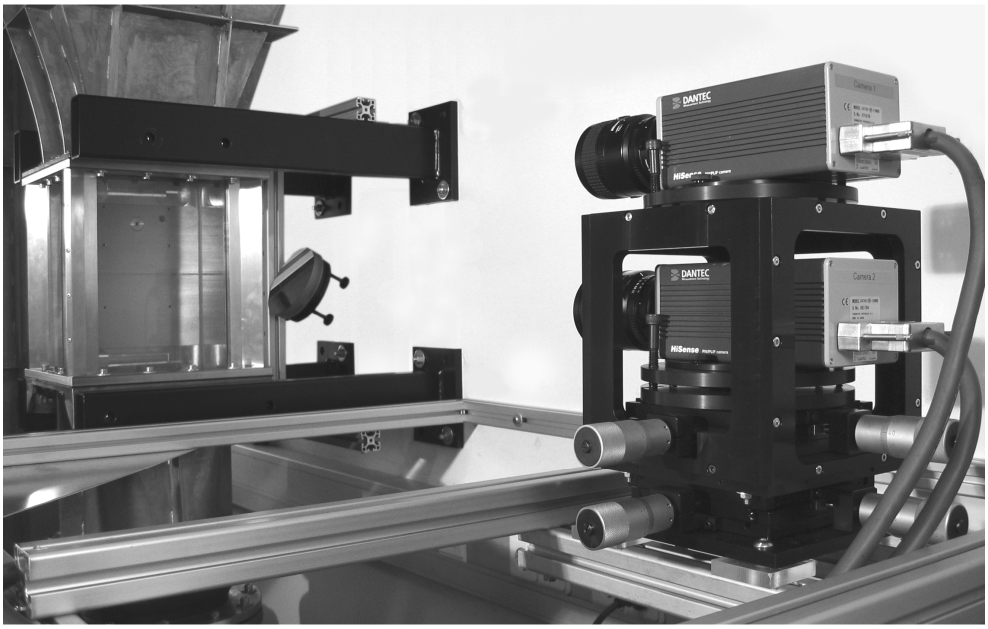

Figure 3: PIV cameras arrangement.

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 the refractive index. The refractive index of the syrups is higher than the one of the 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. One major drawback could be expect by using silver coated glass spheres; the relative density of this kind of particles is around 1,4. Nevertheless, this drawback was counterbalanced by the high viscosity and by the velocity of the flow during the tests.

IV Deflection modes identification measurements

For structure deflection modes identification (DMI) measurements the PIV system was modified to provide it with structure deflection analysis capabilities. The idea behind those measurements was to use the Dantec Dynamics Flowmap 3D stereoscopic PIV module to acquire and organize images from the swiveling structure together with an especially developed software to analyze and reconstruct the time-dependent deflection of the flexible structure. One major advantage could be expected from such solution; it was possible to take advantage of the same measuring system used for velocity field measurements.

In order to generate coherent results the relative position of the Nd:YAG laser source was maintained to illuminate the time-dependent deflection of the flexible structure at the same plane of the velocity field measurements. Just one camera was positioned in a knew position to acquire the time-dependent image of the light sheet reflected by the structure. The camera optics were improved with special filters correspondent to the same wave length of the laser to increase the contrast between the reflection of the laser light in the structure and the ambient light.

After image acquisition, 3D PIV software including camera calibration routines that measure and account for perspective distortion were implemented to correct parallax errors and reconstruct the real structure deflection image. The quantitative analysis of the time-dependant structure deflection was performed in Matlab workspace by a script developed for the specific task. It maps the pixel value in the grayscale scale of the entire image and recognizes the line resulting from the intersection of the laser sheet and the structure. From there and together with the image calibration information the same algorithm reconstructs the two-dimensional deflection of the flexible structure. The communication and the transference of data back and forward between Matlab and Flowmap were ensured by the Dantec Matlab link add-on.

Finally the deflection modes present in the structure were identified and characterized based on the results of the two-dimensional deflection information.

V Time resolved measurements

Fluid-structure interaction problems are very challenging because they constitute coupled problems. The frequency of the periodic structure motion is very sensitive to the approaching flow conditions as well as to the mechanical properties of the structure. Consequently the period of the flexible structure motion always exhibits small natural perturbances. In addition, in the great majority of problems the resulting structure motion is unsteady. These reasons make the triggering of the measurements very difficult to be performed accurately. The latest in particular makes impossible to take advantage of position-resolved measurements to reconstruct time-resolved ones.

In the present project, to resolve the measurements in time a new approach was followed. Instead of triggering the measurements in advance, the measurements were acquired at constant frequency. In parallel, the moments when both the measurements were taken and the structure began a new cycle were registered using an absolute clock. That time information was then used to reorganize the acquired data in order to provide time-resolved data during the post-processing period.

This process permitted resolving the measurements just after measuring the correct period of the structure motion in which the measurements were performed. Beyond solving the measurements trigger problem, this solution has proven to optimize the measurement acquisition rate as well. With the present implementation the measurement system could always be operated at its optimized frequency independent of the structure motion frequency. It could even, without any increased difficulty, be operated at variable acquisition rate to maximize the measurements acquisition rate.

To materialize this idea a new module had to be designed and integrated in the PIV system. The constructed time phase detector module has a 1*MHz* internal clock and is capable to detect events with an accuracy of ±2*μs*. It is capable to resolve up to 250 events per second coming from 6 different input lines. During the present tests two different kinds of events were recorded; the measurements (t_{ij}) and the beginning of the flexible structure motion period (t_j).

Regarding the measurements, depending if PIV or DMI is concerned the measurement events were detected using the first laser pulse trigger signal or the camera first frame trigger signal. After deciding witch angular position of the structure front rigid body correspond to the beginning of the motion period this position was detected by a magnetic angular position sensor connected to the structure rotating axel. This sensor was elected to perform the task based on two criteria; non contacting position angular sensor and direction resolved output signal. An additional reason justified the employment of this sensor; the high sensitivity around a predefined angular position.

With that recorded events time information a specific software computed the period of each individual period (T_j) and the measurement time phase angle within the structure motion period (t_j). Finally the time resolved measurements were reorganized in a reference structure motion period equal to the mean period of all acquired periods.

$$t_j = \frac{t_{ij}}{T_i} \times 360^\circ \qquad 1 \le j \ge \text{maximum number of measurements acquired}$$

$$T_i = t_{i+1} - t_i \qquad 1 \le i \ge \text{maximum number of periods acquired} - 1$$

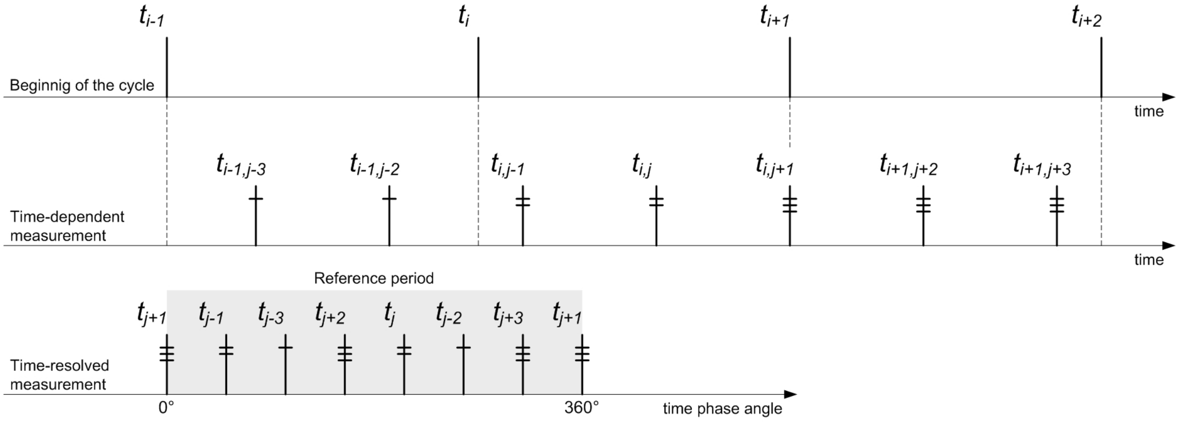

Figure 4: Time-resolved measurement reconstruction scheme.

VI Results

As a first reference test case the periodic swiveling motion of a stainless steel flexible structure in water flow was characterized. The overall chordwise and spanwise dimensions of the flexible structure were 85*mm* and 178*mm*, respectively. The front flat body had a thickness of 1*mm* and a chordwise dimension of 25*mm*. The thickness of the rear membrane was 0,03*mm*.

For each incoming velocity tested the velocity field around the flexible structure and the deflection of the structure were registered for each degree of time phase angle. The accuracy associated with those measurements was ±0,2 degree.

In Fig. 5, examples of measurements for a uniform incoming velocity of 0,67*m/s* and a Reynolds number of 56950 based on the overall chordwise structure dimension are presented. Under such conditions the flexible structure exhibited a 3,17*Hz* periodic swiveling motion. The fluctuation of the motion frequency was registered to be smaller than 2%.

The analysis of the reported results reveals a local maximum absolute velocity and a displacement of the structure trailing edge from the central line of, respectively, 1,31*m/s* and 37,9*mm* for t_j=0° and 1,38*m/s* and 33,2*mm* for t_j=120°. In the first case the front flat plate is rotating counter-clockwise while in the later it is rotating in the opposite direction.

VII 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.

The present paper summarizes the research work done along that line. Within this work, new test facilities were constructed to permit precise tests in laminar and turbulent regimes. As far as the measurement techniques are concerned particle image velocimetry was successfully applied to measure the flexible structure surrounding velocity fluid flow field and, with some improvements, to measure the deflection of the structure.

The inclusion of the time phase detector module made the unsteady periodic time-resolved measurements reconstruction reliable and extremely accurate. Because of its architecture, this approach is more memory consuming comparing with other solutions but yield an accurate time-resolved measurements reconstruction independently from the nature of the structure motion.

Examples of results of time-resolved measurements performed in water are presented. Velocity field, structure deflection and structure periodic motion frequency were measured and the time-resolved characterization of the unsteady fluid flow and structure motion compiled. The set of facilities and experimental measurement techniques developed for the present research work are now ready to perform a complete study of different fluid-structure interaction reference test cases. First studies will be focused on two-dimensional flexible structures in both laminar and turbulent flows. Further three-dimensional test cases will be considered as well but they will require the definition of a new reference structure layout.

Acknowledgments

The present research project is integrated in the DFG Forschergruppe 493 – Fluid-Struktur-Wechselwirkung: Modellierung, Simulation, Optimierung. The authors gratefully acknowledge the financial support for their research work through the German Science Foundation (DFG) – Germany and Fundação para a Ciência e Tecnologia (FCT) – Portugal.

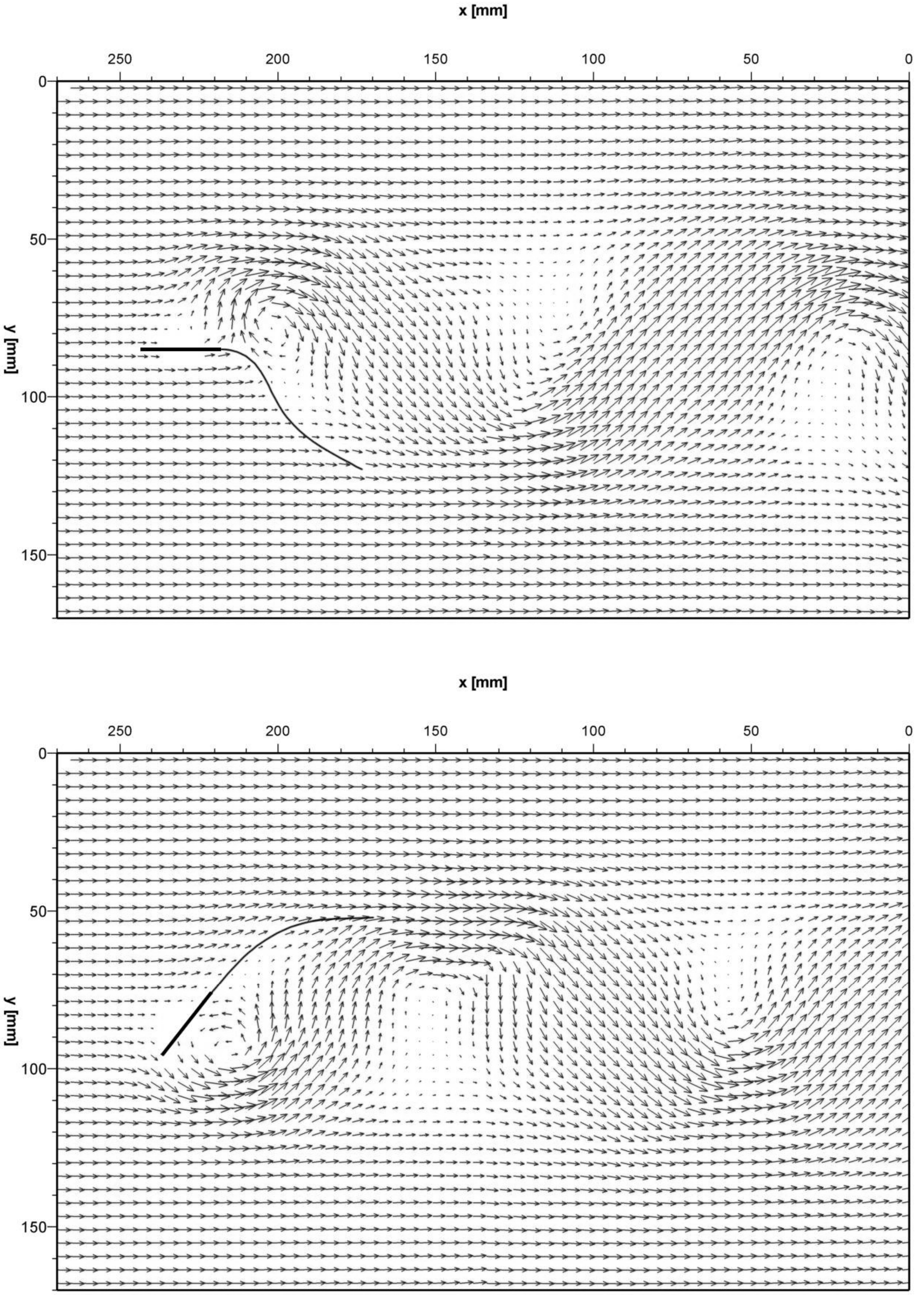

Figure 5: Example of time-resolved combined velocity flow field/structure deflection measurement results for *tj* = 0° and *tj* = 120°.