Use of compact laser Doppler velocimetry in reduced scale model testing of hydraulic machines

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Laser based flow survey methods such as Laser Doppler Velocimetry (LDV) or Particle Image Velocimetry (PIV) have long been used for studying the flow in hydraulic machines. Even if the results have crucially improved our understanding of potentially destabilizing flow patterns in the draft tube at off-design conditions and the prediction of the stable operating range, these techniques are not systematically used for reduced scale model measurements in the frame of customer acceptance tests or development projects. In a not too distant past, the price, size and complexity of the necessary equipment and procedures exceeded the acceptable range for these projects. Recent developments however made them more accessible. Furthermore, the collaboration with experienced research institutes provides the necessary know-how as well as an added academic value by providing researchers with realistic test cases. This work reports a case study for which a compact LDV probe was used to measure the velocity field in the draft tube cone of a reduced scale physical model of a Francis turbine. The axial and tangential velocity profiles were established by performing measurements at several radial positions between the turbine centreline and the cone wall. The overall objective was the validation of numerical flow simulations across the entire operating range of the turbine, from partial to full load.

The Plexiglas draft tube cone was slightly modified and equipped with an optical window covered by an anti-reflexion coating, minimizing the distortion effects. The LDV device is installed on a 2-D traversing system for vertical and radial positioning. The alignment of the measuring device with respect to the turbine frame of reference is of key importance for obtaining dependable results. As this has revealed itself difficult and time consuming in the past, a new, fast and accurate method was developed, which is described in detail in the paper. The measurements are repeated at six different operating points, from 40% to 110% of the rated discharge. In addition to a description of the measurement and data processing procedure, the present work includes the resulting axial and tangential velocity profiles in the draft tube cone.

1. Context

The merits of measuring the velocity field in the draft tube of hydraulic machines are manifold. In a recent research project aiming at facilitating the large scale integration of renewable energy sources into the existing power grid [1], this approach was instrumental in advancing our understanding of the destabilizing flow patterns at off-design conditions and the development of reliable hydro-acoustic models for the stability analysis. For example, in case of the precessing helical vortex rope at part load (Favrel et al. 2016, Favrel et al. 2015) or the self-oscillation of an axisymmetric vortex rope at full load (Müller et al. 2017, Müller et al. 2013). Laser based techniques are commonly used in the field of hydraulic machinery (Goyal et al. 2017, Muntean et al. 2016, Lemay et al. 2014, non-exhaustive). While there is a variety to choose from with specific benefits to each, the present paper only focuses on LDV.

In conventional hydro projects, for which the performance is commonly guaranteed based on reduced scale model tests, the knowledge of the velocity fields may help increase the confidence in the predicted stable operating range and avoid costly surprises on the prototype. Furthermore, in an industrial environment, new designs are nowadays mainly developed by employing numerical tools. This is particularly true for small hydro projects with limited budgets. A sound simulation approach is thus decisive, and the results of experimental flow surveys are an important source of validation.

In summary, the use of these techniques may represent a true added value to reduced scale model tests. This work shows how this is achieved for the typical case of a Francis turbine by standardizing and simplifying the equipment and the procedures for the setup and the measurements.

2. Experimental setup

2.1 Test case

The investigations were performed on a reduced scale physical model of a Francis turbine with a specific speed of N_{QE}=0.20 (IEC 60193 standards, 1999). The setup is shown in Fig. 1 and was installed on one of the closed-loop test rigs of the EPFL Laboratory for Hydraulic Machines in Lausanne, Switzerland. The test head of 20 m is generated by an axial double-volute pump and the discharge is set by adjusting the guide vane opening. A generator connected to the model runner regulated the rotating speed. The pressure level in the draft tube and hence the Thoma number σ is controlled with a vacuum pump over the free surface in the downstream tank.

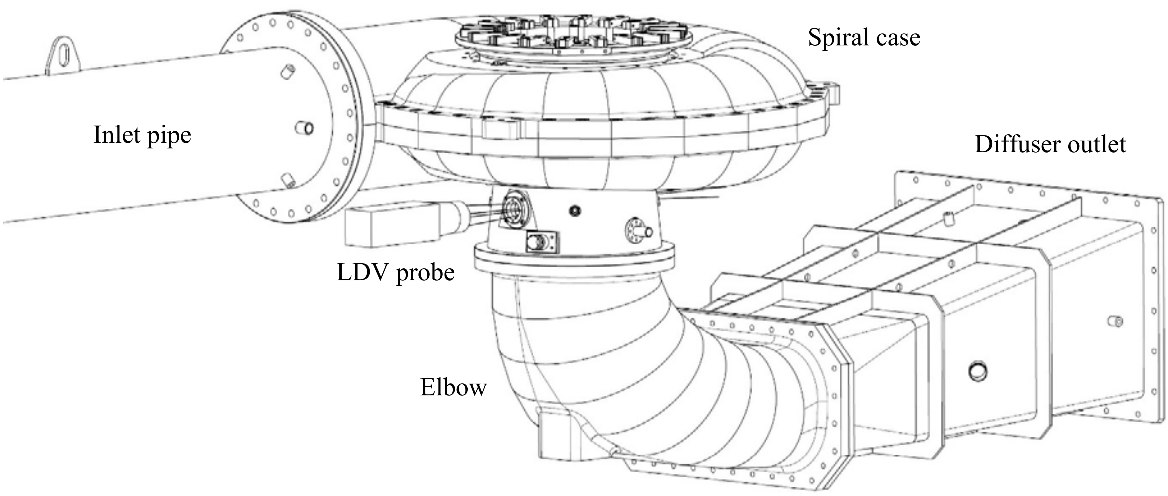

Fig. 1: Reduced scale physical model of Francis turbine with LDV probe (see also Sakamoto et al., 2018)

2.2 Data acquisition and processing

The velocity components are measured with a compact LDV system described in Table 1 in non-coincidence mode. The acquisition time is fixed at 60s for each measuring point, after studying the convergence of the mean velocity and standard deviation of the velocity during a representative test run (without further proof). The measurements are performed at high Thoma numbers to avoid optical interference with cavitation.

Table 1: Properties of the LDV system

Property	Description / value
Type	2 component factory-aligned probe
Laser	Diode Pumped Solid State (DPSS)
Model	Dantec FlowExplorer
Wavelength	660 nm (Ch. 1) and 785 nm (Ch. 2)
Power	35 mW per channel
Beam diameter	2.5 mm
Focal length	500 mm
Control volume (in air)	0.1684 × 0.1681 × 2.806 mm (Ch. 1) 0.2003 × 0.1999 × 3.338 mm (Ch. 2)
Burst Spectrum Analyzer (BSA)	Dantec F60 flow processor
Seeding particles	10µm hollow glass spheres

Fig. 2 displays a cross-section of the draft tube cone at the stream-wise position of the LDV measurements, as well as the data acquisition chain on the test rig. The measurements are triggered manually through the software via the the BSA unit. The acquisition of the LDV signal is synchronized with the one of the pressure sensors, which are recorded via a NI-PXI unit, enabling a later analysis of cyclic flow phenomena. The pressure measurements are however not included in the scope of this article.

The traversing system is remotely controlled from the computer trough the LDV user interface. The positions can be pre-programmed along with the acquisition parameters. The measurements are then executed automatically, recording velocity signals during 60s at one position, moving to the next one and starting over.

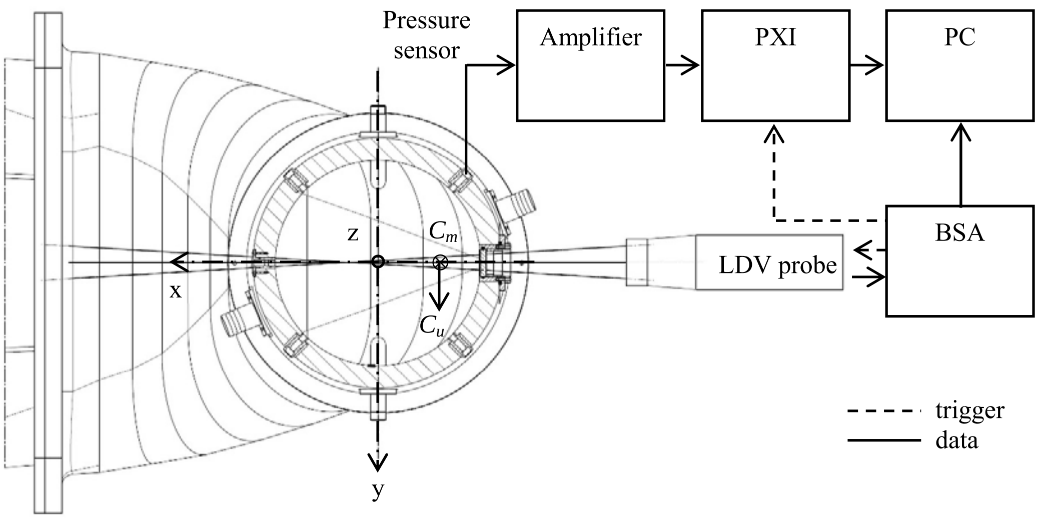

Fig. 2: LDV measurement section in the draft tube cone

2.3. Alignment of the LDV probe

As previously mentioned, the experimental results are used to validate numerical flow simulations. This requires a high certitude with regards to the position of the LDV control volume along a single radius line between the inner cone wall and the cone centreline for a fixed vertical location (according to the setup in Fig. 2). In other words, the following conditions must be met:

a) The optical axis of the LDV probe intersects with the cone centreline for all radial positions.
b) The optical axis of the LDV probe is orthogonal to the cone centreline.
c) The optical axis of the LDV probe is orthogonal to the surface of the optical window.
d) The plane defined by the pair of Laser beams for the measurement of the axial velocity component *Cm* contains the cone centreline.

For this purpose, a simple and accurate alignment method is developed. For better understanding, the general setup on the test rig is displayed in Fig. 3, consisting of the reduced scale physical model and the LDV system installed on a 2-axes traversing system. The latter stands with 4 adjustable legs on a perfectly flat surface.

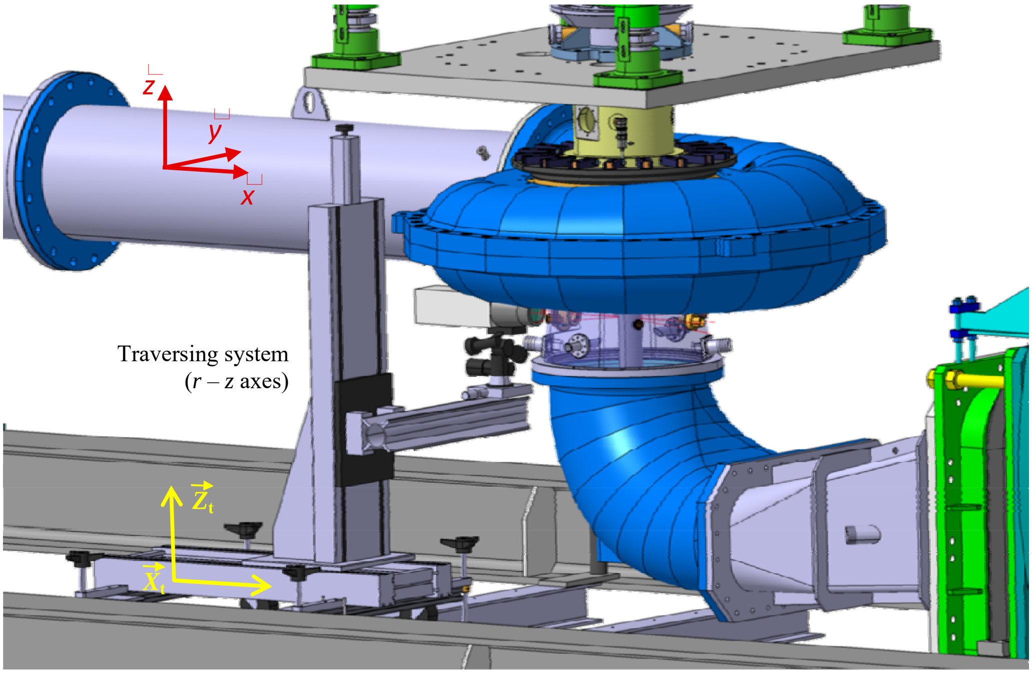

Fig. 3: Reduced scale model with LDV measurement setup

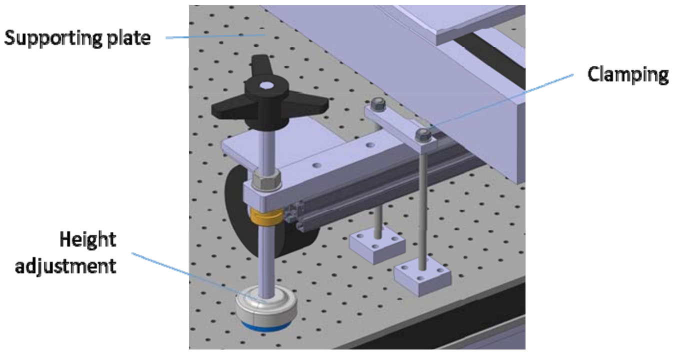

Fig. 4: Adjustment mechanism for the traversing system positioning

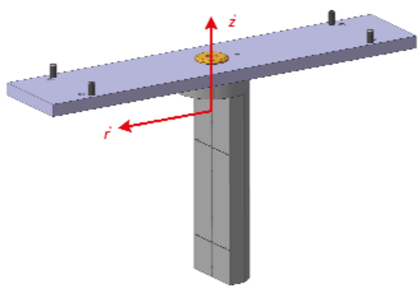

Fig. 5: Reference alignment piece

The alignment procedure is summarized by Fig. 6 – Fig. 9 and consists of the following steps.

1) The traversing system's longitudinal (horizontal) X_t displacement axis (see yellow arrow in Fig. 3) is aligned roughly with the normal direction of the optical window on the draft tube cone.

2) The draft tube cone and elbow are disassembled and the reference alignment piece shown in Fig. 5 is centred on the bottom ring of the reduced scale model, thus providing a physical reference for the turbine axis and its radius (see also Fig. 6 – Fig. 8).

3) The reference piece is rotated around the *z*-axis, until its upper lateral (sideways) surface is aligned with the longitudinal (horizontal) displacement X_t – axis of the traversing system (see yellow arrows in Fig. 3). This is verified with a dial indicator mounted onto the traversing system, as shown in Fig. 6, and by moving the latter back and forth along the X_t – axis.

4) Zero pitch and roll angles of the traversing system are achieved by adjusting the feet of the traversing system with the black handles in Fig. 4. For this purpose, the probe of the dial indicator is placed on the frontal and lateral surfaces of the reference piece's lower part and the traversing system is then moved up and down along its vertical Z_t – axis. When the final setting is found, the clamps in Fig. 4 are fastened to fix the system. A movement of the LDV measurement volume in a purely horizontal plane is thus secured.

5) The LDV probe is now installed on the traversing system, more precisely on a geared lightweight aluminium tripod head with three angular degrees of freedom, adjustable by micrometric knobs.

6) The purely horizontal orientation of the LDV probe is verified by moving the traversing system back and forth along its longitudinal (horizontal) X_t – axis, while observing the position of the four points generated by the Laser beams on the alignment piece during the movement (see Fig. 8). The points must remain in the horizontal respectively vertical grooves wile converging to or diverging from the centre. The adjustment is performed through the micrometric knobs of the tripod head.

7) The reference position ($X_t = 0$) of the traversing system is defined as the location for which the focal point of the LDV probe (in air) coincides with the central axis of the runner (intersection of the grooves in Fig. 8).

8) The alignment piece is removed.

9) The draft tube cone and the elbow are installed.

10) The draft tube cone position is adjusted so that the optical window is perpendicular to the optical axis of the LDV probe. This is achieved by rotating the cone around the *z*-axis, until the four points generated by the Laser beams remain in the horizontal respectively vertical grooves of a metallic plate, which is temporarily installed on the mounting fixture of the optical window, when moving the traversing system along its longitudinal (horizontal) X_t – axis (see Fig. 9).

2.4 Health and safety precautions

Laser safety measures must be taken during the alignment procedure. Goggles with an appropriate protection factor should be worn whenever possible, and for obvious reasons it has to be avoided to stare directly into the Laser beams, while also being mindful of reflective surfaces around the test rig.

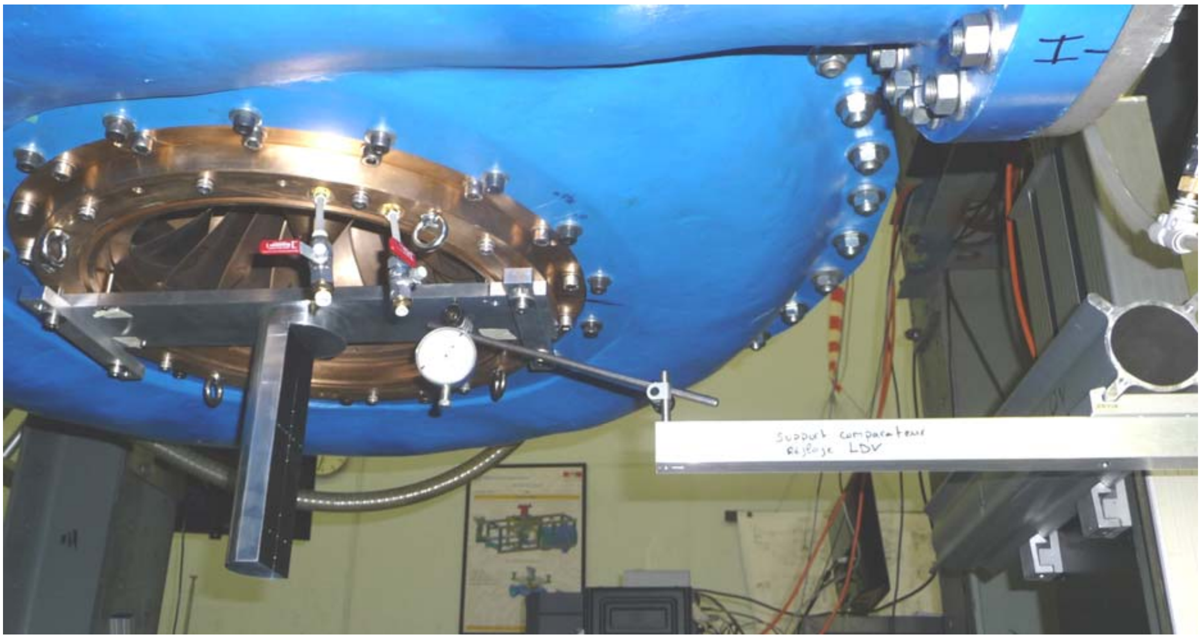

Fig. 6: Alignment of x-axis (radial displacement)

Fig. 7: z-axis alignment

Fig. 8: Alignment check

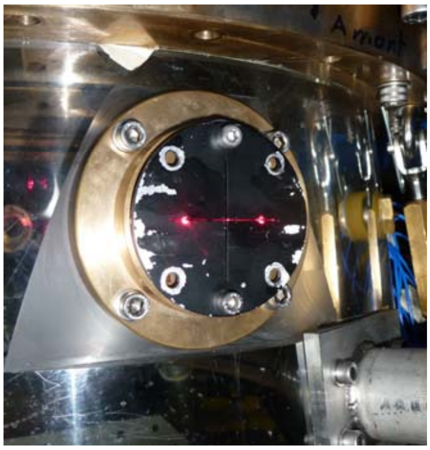

Fig. 9: Draft tube cone alignment check

3. LDV results

3.1 Operating conditions

The investigated operating conditions are summarized in. The measurements are performed at six values of the discharge factor Q_{11}, whereas the value of the speed factor n_{11} is kept constant at the BEP value. The variables n_{11} and Q_{11} are defined as follows:

$$n_{11} = \frac{nD}{\sqrt{H}}, Q_{11} = \frac{Q}{D^2\sqrt{H}}$$

Table 2: Summary of operating conditions for the LDV measurements

	OP1	**OP2**	**OP3**	**OP4**	**OP5**	**OP6**
n_{11}	72	72	72	72	72	72
Q_{11}	0.326	0.490	0.653	0.734	0.816	0.898
$Q_{11}/Q_{11,BEP}$	0.4	0.6	0.8	0.9	1.0	1.1

3.2 Velocity profiles

Fig. 10 and Fig. 11 show the axial and tangential velocity profiles on the LDV measurement section between the cone centreline (R/R_{max}=0) and the inner wall of the optical window (R/R_{max}=1). The axial velocity is made non-dimensional with the mean discharge speed C_Q=Q/A, where Q is the discharge at the given operating point and A the surface area of the LDV measurement section. The tangential velocity is made non-dimensional with the circumferential speed of the runner at its outlet.

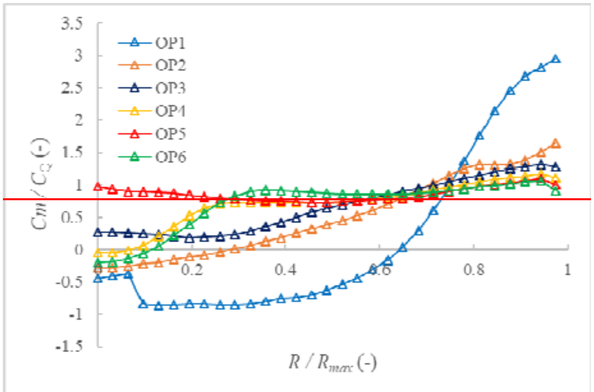

Fig. 10: Axial velocity component Cm

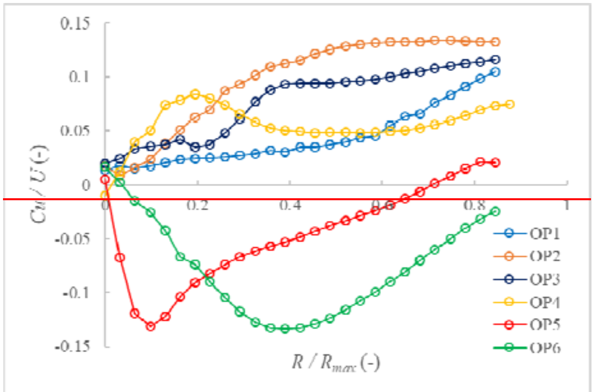

Fig. 11: Tangential velocity component Cu

As the velocity components on display are average values, the sampling statistics have to be considered. This is done for OP1 and OP5 in Fig. 12 and Fig. 13, showing the distribution of all velocities measured in the control volume of the LDV probe during the entire acquisition time.

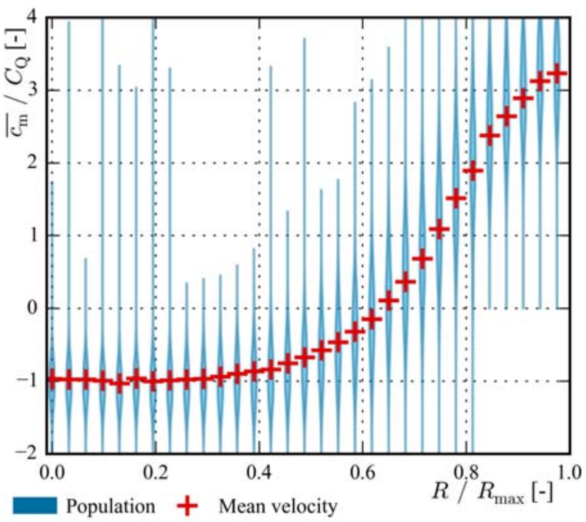

Fig. 12: Axial velocity component Cm at OP1

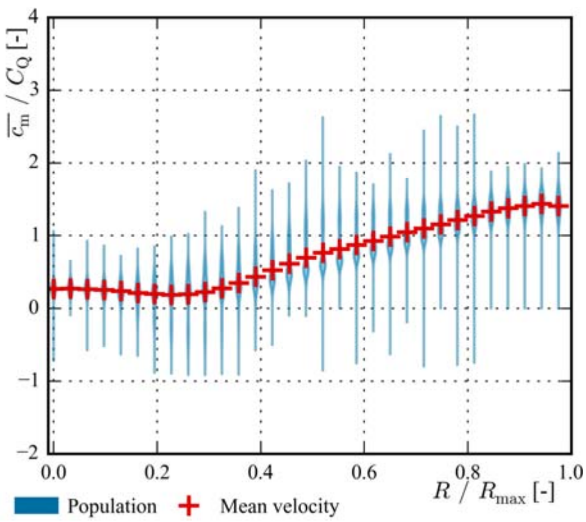

Fig. 13: Axial velocity component Cm at OP5

4. Discussion and conclusions

This paper demonstrates how to use a compact LDV probe during reduced scale model testing of a Francis turbine to obtain the axial and tangential velocity profiles in the draft tube. The alignment of the measurement equipment with respect to the turbine frame of reference is achieved with a simplified 10-steps procedure. The results can be used to validate numerical flow models; in this case they were compared to unsteady RANS simulations on the same model geometry in [10], triggering significant improvements to the numerical approach. The standardization of the experimental setup greatly shortened the necessary time for the measurements and thus the costs, which opens the door to a more frequent use of this experimental technique in reduced scale model testing.

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