



GO-VIKING

Research and Innovation Action (RIA)

This project has received funding from the Euratom
research and innovation programme 2021-2025 under
Grant Agreement No 101059603

Start date : 2022-06-01 Duration : 48 Months



Single-phase AMOVI experiments and benchmark

Authors : Mr. Domenico PANUNZIO (CEA)

GO-VIKING - Contract Number: 101059603

Project officer: Angelgiorgio IORIZZO

Document title	Single-phase AMOVI experiments and benchmark
Author(s)	Mr. Domenico PANUNZIO
Number of pages	31
Document type	Deliverable
Work Package	WP3
Document number	D3.1
Issued by	CEA
Date of completion	2023-11-21 09:42:30
Dissemination level	Public

Summary

Description of the AMOVI experimental facility and experimental data.

Approval

Date	By
2023-11-21 09:45:23	Mr. Kevin ZWIJSEN (NRG)
2023-11-21 09:45:59	Dr. Papukchiev ANGEL (GRS)



WP3 – Flow-Induced Vibrations in Steam Generators

Deliverable D3.1 of the GO-VIKING project (101060826)

Single-phase AMOVI experiments and benchmark setup

Version N°1

11 / 2023



Domenico Panunzio, Lucas Prévost, Philippe Piteau

CEA, Service d'Etudes Mécaniques et Thermiques, 91191, Gif-sur-Yvette, France



Funded by
the European Union

Disclaimer

The content of this report reflects only the author's view. The European Commission is not responsible for any use that may be made of the information it contains.

Document information

Grant Agreement / Proposal ID	101060826
Project Title	Gathering expertise On Vibration ImpaKt In Nuclear power Generation
Project Acronym	GO-VIKING
Scientific Coordinator	Angel Papukchiev, mailto:Angel.Papukchiev@grs.de , GRS
Project starting date (duration)	1st June 2022 – 31st May 2026 (48 Months)
Related Work Package	WP3
Related Task(s)	Task 3.1
Lead Organisation	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
Contributing Partner(s)	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
Due Date	M18
Submission Date	30th November 2023
Dissemination level	Public

History

Date	Version	Submitted by	Reviewed by	Comments
30th November 2023	V1.0	CEA		

Table of contents

1. Introduction	7
2. Experimental setup	7
2.1 Test rig	7
2.2 Test section	8
2.3 Instrumentation	9
3. Experimental procedure	9
3.1 Data gathering	9
3.2 Data post-processing	10
4. Results	11
4.1 Force measurements	11
4.2 Displacement measurements	13
4.3 PIV measurements	16
4.4 LDV measurements	20
5. Conclusion	26
Bibliography	28
Appendix	29
A. Flexible tube setup	29
B. Rigid tube setup	30
C. Analytical formulation of the force spectrum	30

List of figures

Figure 1: Description of the AMOVI test section (full bundle configuration)	7
Figure 2: Sketch and photo of the tested configurations: (a) single tube in a reduced channel and (b) full tube bundle.	8
Figure 3: Single rigid tube. Equivalent spectra of the turbulent force per unit length for different flow rates.	12
Figure 4: Single rigid tube. RMS value across [0, 200] Hz of the turbulent force per unit length as a function of the flow rate	12
Figure 5: Rigid tube bundle. Equivalent spectra of the turbulent force per unit length for different flow rates.	13
Figure 6: Rigid tube bundle. RMS value across [0, 200] Hz of the turbulent force per unit length as a function of the flow rate	13

D3.1: Single-phase AMOVI experiments and benchmark setup

Figure 7: Single flexible tube (lift direction). Displacement spectra for different flow rates. .	14
Figure 8: Single flexible tube (lift direction). RMS value of the displacement as a function of the flow rate.....	15
Figure 9: Flexible tube (lift direction) in a rigid tube bundle. Displacement spectra for different flow rates.	15
Figure 10: Flexible tube (lift direction) in a rigid tube bundle. RMS value of the displacement spectra as a function of the flow rate.....	16
Figure 11: Normalized incoming flow velocity extracted from PIV results as a function of time and its power spectral distribution, for all three PIV conditions.....	17
Figure 13: Time-averaged normalized velocity overlaid with selected streamlines, for all three PIV conditions.	18
Figure 14: Time-averaged normalized turbulent shear stress, for all three PIV conditions...	19
Figure 15: (a) Location of LDV measurements in the two tested configurations; (b) Cartesian coordinate system (X, Y, Z) and velocity components ($\mathbf{U}, \mathbf{V}$) over the test section.....	20
Figure 16: Single tube configuration. Time-averaged velocities ($\mathbf{U}, \mathbf{V}$) and turbulence fluctuations ($\mathbf{u}', \mathbf{v}'$) in the upstream cross section at a distance of $Z = -30.4$ mm. All profiles are normalized with respect to the reference flow velocity $U = 0.725$ m/s.....	21
Figure 17: Rigid tube bundle. Time-averaged velocities ($\mathbf{U}, \mathbf{V}$) and turbulence fluctuations ($\mathbf{u}', \mathbf{v}'$) in the upstream cross section at a distance of $Z = -71.5$ mm. All profiles are normalized with respect to the reference flow velocity $U = 0.414$ m/s.....	23
Figure 18: Rigid tube bundle. Time-averaged velocities ($\mathbf{U}, \mathbf{V}$) and turbulence fluctuations ($\mathbf{u}', \mathbf{v}'$) in the upstream cross section at a distance of $Z = -101.8$ mm. All profiles are normalized with respect to the reference flow velocity $U = 0.414$ m/s.....	25
Figure 19: Rigid tube bundle. Time-averaged velocities ($\mathbf{U}, \mathbf{V}$) and turbulence fluctuations ($\mathbf{u}', \mathbf{v}'$) in the upstream cross section at a distance of $Z = -162.6$ mm. All profiles are normalized with respect to the reference flow velocity $U = 0.414$ m/s.....	26
Figure 20: Illustration of the flexible tube setup within the test section.	29
Figure 21: Illustration of the rigid tube setup within the test section.....	30

List of tables

Table 1: Flow conditions and data gathering parameters for the force and displacement measurements.	10
Table 2: Flow conditions and data gathering parameters for the PIV measurements.....	10

Table 3: Flow conditions for the LDV measurements.	10
---	----

Table 4: Frequency, damping ratio and strain-to-displacement ratio.	29
--	----

Abbreviations and Acronyms

Acronym	Description
WP	Work package
GO-VIKING	Gathering expertise On Vibration ImpaKt In Nuclear power Generation
FIV	Flow-Induced Vibrations
SG	Steam Generator
PIV	Particle Image Velocimetry
LDV	Laser Doppler Velocimetry
YAG	Yttrium Aluminium Garnet
PSD	Power Spectral Density
RMS	Root Mean Square

Summary

The GO-VIKING project investigates FIV phenomena occurring in nuclear reactor under single- and two-phase flow conditions. The focus of the WP3 of the project is on the FIV phenomena occurring in SG tube bundle under single-phase, cross-flow conditions. The present document, as part of WP3, reports some experiments performed at CEA Saclay (France) on a square tube bundle facility, named AMOVI, subjected to a single-phase water cross-flow. The square bundle consists of 3x5 tubes plus two columns of 5 semi-tubes. The diameter of the tubes is 12.5 mm, the length is 99 mm and the bundle pitch is 17.5 mm, hence $P/D = 1.44$. The central stainless steel tube of the bundle can be mounted in a rigid or flexible setup to get force or displacement measurements, respectively. The other rigid plexiglass tubes can be plugged in and out in order to study different basic configurations. In this study, two basic arrangements are tested: a single tube in a reduced channel and a full tube bundle. Each of these configurations is tested with the central tube being rigid or flexible in the lift direction, i.e. four target configurations in total. Tests are performed for four water flow rates for each configuration and the vibrations of the central tube or the forces acting on its surface are measured. For some cases of interest, LDV and PIV measurements are also performed to characterise the flow pattern. These experimental data will support the numerical activities within GO-VIKING.

Keywords

Cross-flow; single-phase; vibration; tube bundle; experiments

1. Introduction

D3.1 deals with providing a description of the single-phase AMOVI experiment, benchmark setup and experimental results. This document first introduces the AMOVI experimental setup, and then explains the obtained experimental results of force and displacement for 16 test cases. Finally, fluid flow features, obtained through PIV and LDV measurements, are provided for the most interesting cases.

2. Experimental setup

2.1 Test rig

AMOVI is a small hydraulic loop built at CEA Saclay (France) to study the fluid-structure interaction between a square tube bundle, arranged in different configurations, and a water flow characterized by a low Reynolds number.

The hydraulic loop consists of:

- a pump, with a maximum flow rate of $Q = 4 \text{ L/s}$;
- a water tank of about 200 L as a collector for the pump;
- a test section of $70 \times 100 \times 600$ (width x depth x height) mm^3 with three Plexiglas walls.

Moreover, as AMOVI was originally built for studying air-water two-phase mixtures, before entering the test section, flow runs through a mixer (see Figure 1).

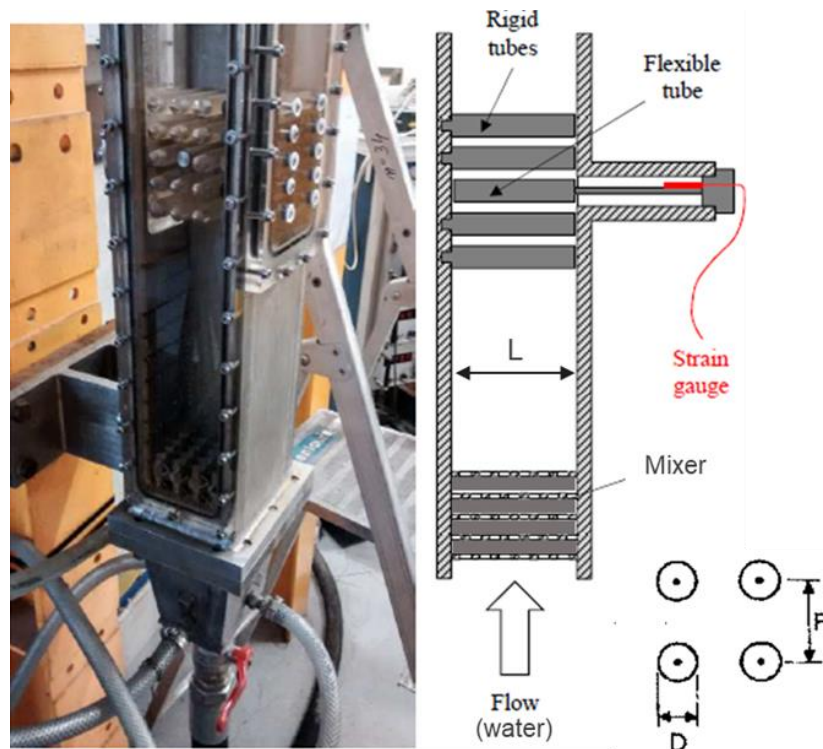


Figure 1: Description of the AMOVI test section (full bundle configuration)

2.2 Test section

The test section, shown in Figure 1, consists in a 5x3-tube bundle with five half-tubes on each side. Tubes have a diameter $D = 12.15$ mm, a length¹ $L = 99$ mm and are arranged in a square pattern with a pitch $P = 17.5$ mm. The central tube is made of stainless steel 304L and can be mounted in a rigid or flexible configuration. The other tubes are rigid, made of Plexiglas and can be plugged in and out in order to study different basic arrangements. The Plexiglas walls could remain empty or be equipped with five half-tubes each.

In this study, we propose to test two different configurations (see Figure 2): a single tube in a reduced channel and the full tube bundle.

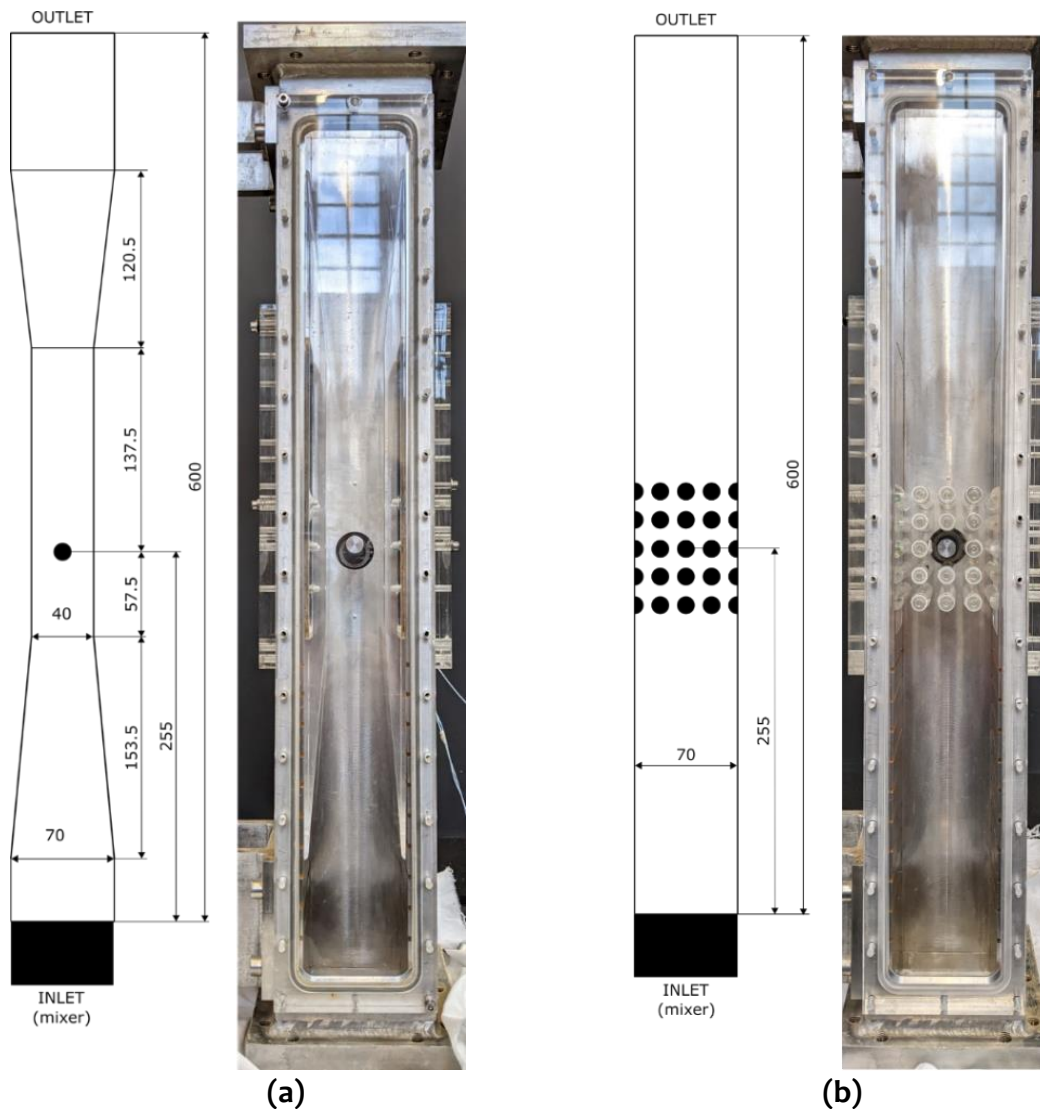


Figure 2: Sketch and photo of the tested configurations: (a) single tube in a reduced channel and (b) full tube bundle.

¹ The length of the tubes should not be confused with the depth of the test section (≈ 100 mm) used in the following for determining the inflow velocities U .

2.3 Instrumentation

In the flexible arrangement (see Appendix A), the central tube is supported by a flexible blade allowing it to vibrate in only one direction, either the drag or the lift direction, with a frequency $f_n = 27.5$ Hz and a damping ratio $\xi_n = 0.064\%$ in air. The displacement at the tip of the tube is deduced from a strain gauge instrumenting the root of the flexible blade, assuming that the first vibration mode is predominant. In the rigid arrangement (see Appendix B), a tri-axial force sensor instruments the central tube.

Fluid flow parameters are measured using PIV and LDV setups.

In the PIV setup, a high-speed camera (Phantom v710 operating up to 7500 fps in HD resolution) is used to capture the flow around tubes in a 2D central plane within the test section. A continuous YAG laser (power of 5 W, wavelength of 532 nm) illuminates the fluid flow. Two spherical convergent lenses expand the laser beam, and then a hemispherical convergent lens generates a laser sheet. In order to optimize the surface of the illuminated section, a mirror has been placed to reflect the laser sheet coming out of the camera field. To visualize the flow, spherical fluorescent particles are added to water as seeding particles.

In the LDV setup, the axial and horizontal time-average velocities and the turbulence fluctuations were probed upstream of the test section thanks to two crossed lasers (wavelength 660/785 nm, power of 90/70 mW). The particles naturally present in water made additional seeding unnecessary. An automated 3-axis traverse system (with 0.1 mm resolution) displaced the probe volume to the hundreds of locations required to cover the measurement section. Each location was held until 1000 bursts were validated in both directions or the 10-second timeout was expired.

Flow temperature T , relative pressure p and flow rate Q are monitored respectively with a thermometer placed on the tank, a pressure sensor placed upstream of the mixer and a flow meter placed downstream of the pump.

3. Experimental procedure

3.1 Data gathering

The following tables provides the flow conditions (flow rate, relative pressure and temperature) and the data gathering parameters set for the force and displacement measurements (Table 1), for the PIV measurements (Table 2) and for the LDV measurements (Table 3).

	Q (L/s)	p (bar)	T (°C)	Sample rate (Hz)	Time (s)
Single <u>rigid</u> tube	0.50	1.33	18	1000	409.6
	1.70	3.80	25	1000	409.6
	2.90	2.88	26	1000	409.6
	4.00	3.50	26	1000	409.6
<u>Rigid</u> tube bundle	0.50	0.88	20	1000	409.6
	1.70	0.90	18	1000	409.6

	2.90	3.19	41	1000	409.6
	4.00	3.60	40	1000	409.6
Single flexible tube (lift direction)	0.50	2.19	18	1000	409.6
	1.70	3.33	21	1000	409.6
	2.90	3.20	25	1000	409.6
	4.00	3.53	26	1000	409.6
Flexible tube (lift direction) in a rigid tube bundle	0.50	1.48	17	1000	409.6
	1.10	0.90	17	1000	409.6
	1.60	1.07	17	1000	409.6
	1.95	3.17	23	1000	409.6

Table 1: Flow conditions and data gathering parameters for the force and displacement measurements.

	Q (L/s)	p (bar)	T (°C)	Framerate (Hz)	N° of frames
Rigid tube bundle	1.70	Unk.	29	3000	11069
	2.90	Unk.	34	6000	11069
Flexible tube (lift direction) in a rigid tube bundle	1.60	Unk.	39 - 41.5	3000	11069

Table 2: Flow conditions and data gathering parameters for the PIV measurements.

	Q (L/s)	p (bar)	T (°C)
Single rigid tube	2.90	2.8	30-35
Rigid tube bundle	2.90	2.8	30-35

Table 3: Flow conditions for the LDV measurements.

3.2 Data post-processing

The results produced in this document are obtained as follows:

The auto-spectra (or PSD) of force and displacement signals are estimated via the Welch's method: recorded signals are divided into 100 segments of 4096 points with 50% overlap; each segment is windowed with a Hamming window. Integration of the PSD gives the square of the RMS of the signals.

The recorded images are associated into a total of 11068 pairs and processed using a standard PIV workflow. Images are first pre-processed by subtraction of the time-averaged image, followed by capping of the grayscale intensity at 3.5 standard deviation and masking. The flow field is then computed from these pre-processed images using the Dynamic Studio software (Dantec Dynamics). Images are divided into a large number of interrogation windows (IW). The displacement vector for each IW is calculated using an adaptive cross-correlation algorithm [1]: the size and shape of each individual IW are iteratively adjusted to adapt to the local flow velocity and gradient. The minimum IW size is set to 24x24 pixels and the grid size to 12x12 pixels (hence with at least 50% overlap) to increase the spatial resolution. This corresponds to a spatial resolution of around 1.2 mm. Each pair of images thus produces a 65x105 instantaneous velocity field with two components. Outlier vectors are flagged using the Westerweel universal outlier detection method [2]. Outliers are substituted by the next

D3.1: Single-phase AMOVI experiments and benchmark setup

highest valid peak in the correlation map or by the local median value if no valid peak is found. The threshold value is set to 2.5 and the minimum normalization level to $\varepsilon = 0.1$ pixel, which is found to reject and substitute around 2.5% of vectors. Finally, the uncertainty associated with each vector is quantified using the particle disparity method [3]. These steps produce a first unfiltered dataset, for which only the outlier vectors are modified. Additional post-processing steps are then applied to produce a second filtered dataset, intended for URANS comparison. Firstly, at each grid point, the two velocity components are extracted as a time series, and high-frequency variations (deemed unphysical) are filtered out. A second-order low-pass Butterworth filter is chosen for its quick roll-off around the cut-off frequency. Unwanted modifications to the phase are avoided by applying the filter twice, once forward and once backward, thus resulting in a zero-phase fourth-order low-pass filter. In the case of a fully rigid bundle, the cut-off frequency is set at 30 times the characteristic frequency U/D . The reference flow velocity U is defined as $U = Q/(d w)$, with d and w respectively the depth and width of the test section. When one tube is flexible, the cut-off frequency is set at 30 times the tube natural frequency f_n . Secondly, each instantaneous velocity field is spatially smoothed using a standard Gaussian filter of size 3x3. Uncertainties are propagated accordingly through these two steps. Each dataset is bundled into a separate HDF5 files, containing the time-resolved flow fields along with the grid coordinates and the various processing parameters.

4. Results

4.1 Force measurements

Figure 3 shows the equivalent spectra of the turbulent force per unit length (see Appendix B for the analytical formulation) measured on the single rigid tube, for $Q \in [0.5, 1.7, 2.9, 4]$ L/s. For $Q = 0.5$ L/s, the turbulent lift and drag force components are very low and appear to be disturbed by noise. For $Q > 0.5$ L/s, at low frequencies, the lift component shows a dominant peak that increases in amplitude and shifts along the frequency axis as the flow rate rises. This peak is characterised by a reduced frequency, $f_R = fD/U \approx 0.25$, where f is the vortex shedding frequency and U is the upstream velocity. The drag component, on the other hand, does not exhibit any characteristic peak. At high frequencies, spectra are biased by noise: high unphysical peaks appear in the spectra, distorting the content of interest, which should instead tend toward zero. For this reason, we estimate that above 200 Hz the spectra are not exploitable.

Figure 4 shows the RMS value (estimated across a frequency range of $[0, 200]$ Hz) as a function of the flow rate. We observe that the RMS levels increase with flow rate and that the lift component is greater than the drag one.

Figure 5 shows the equivalent spectra of the turbulent force per unit length measured on the central tube in the full bundle configuration, for $Q \in [0.5, 1.7, 2.9, 4]$ L/s. For $Q = 0.5$ L/s, once again, both components of the turbulent force are very low and appear to be distorted by noise. For $Q > 0.5$ L/s, both curves remain almost constant or slightly decrease at low frequencies, then visibly tend toward zero. The knee point shifts along the frequency axis as the flow rate increases. At high frequencies, spectra are still distorted by noise.

D3.1: Single-phase AMOVI experiments and benchmark setup

Figure 6 shows the RMS value (estimated across a frequency range of $[0, 200]$ Hz) as a function of the flow rate. We still recover that the RMS levels increase with flow rate and that the lift component is greater than the drag one.

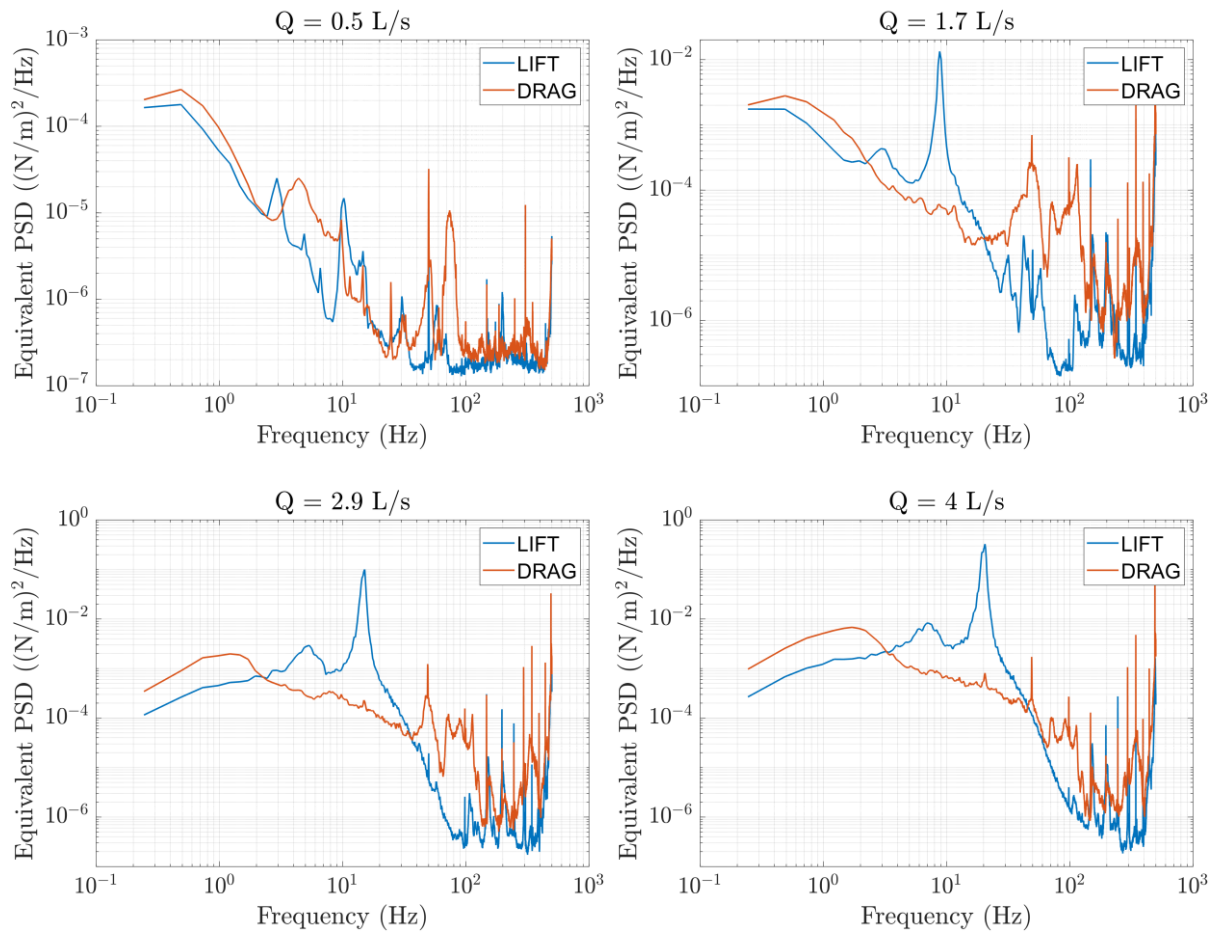
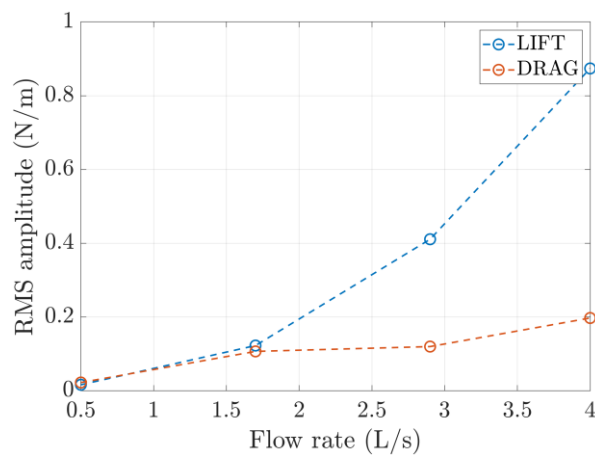


Figure 3: Single rigid tube. Equivalent spectra of the turbulent force per unit length for different flow rates.



Q (L/s)	RMS LIFT (N/m)	RMS DRAG (N/m)
0.50	0.016	0.022
1.70	0.122	0.106
2.90	0.411	0.120
4.00	0.874	0.197

Figure 4: Single rigid tube. RMS value across $[0, 200]$ Hz of the turbulent force per unit length as a function of the flow rate.

D3.1: Single-phase AMOVI experiments and benchmark setup

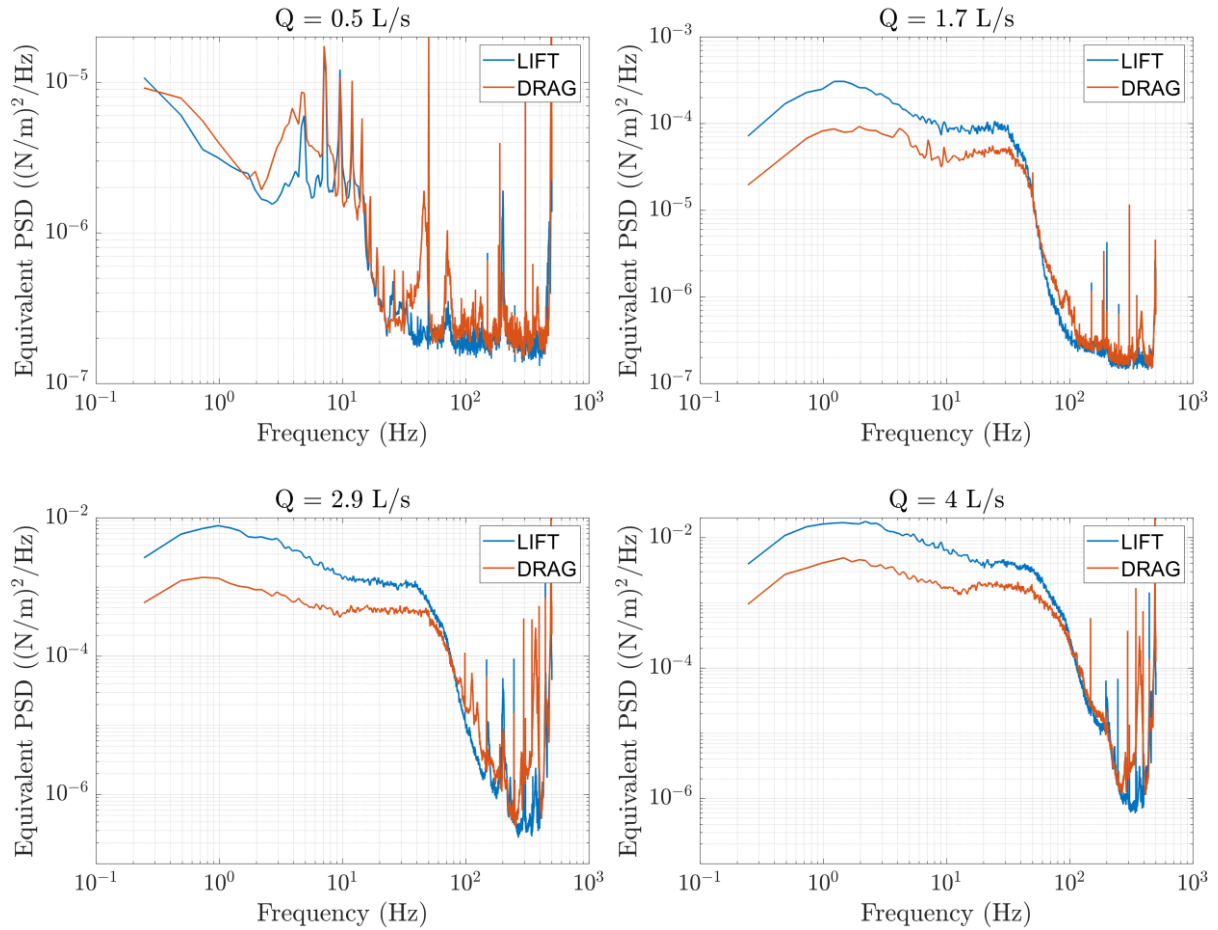


Figure 5: Rigid tube bundle. Equivalent spectra of the turbulent force per unit length for different flow rates.

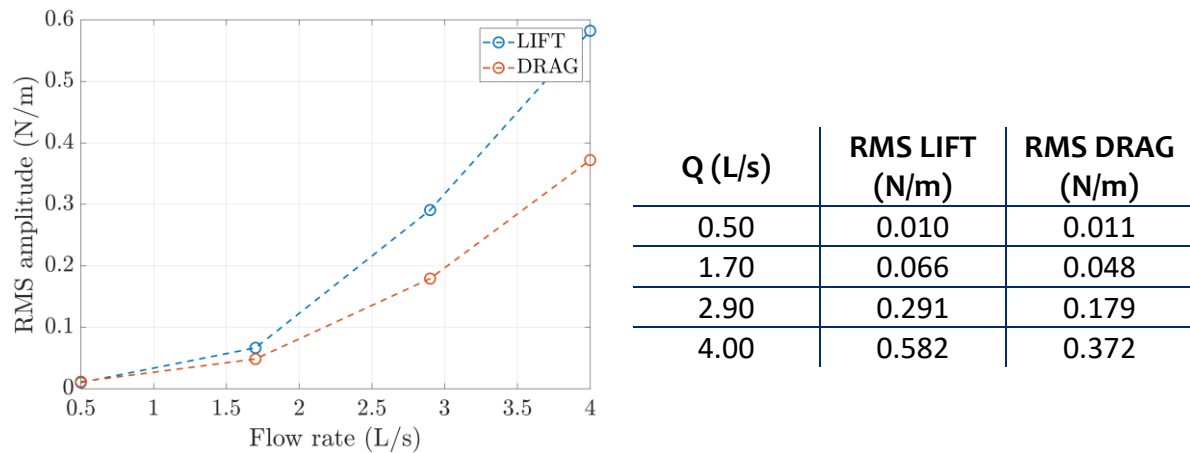


Figure 6: Rigid tube bundle. RMS value across [0, 200] Hz of the turbulent force per unit length as a function of the flow rate.

4.2 Displacement measurements

Figure 7 shows spectra of the transverse displacement measured at the tip of the single flexible tube, for $Q \in [0.5, 1.7, 2.9, 4]$ L/s. For $Q = 0.5$ L/s, displacement is very low and appears

D3.1: Single-phase AMOVI experiments and benchmark setup

to be disturbed by noise. For $Q > 0.5$ L/s, spectra show two predominant peaks. The second peak represents the natural response of the tube in water. This peak increases in amplitude but does not shift significantly as the flow rate rises, remaining at about 23 Hz. The first peak represents the vortex shedding frequency, with a reduced frequency ranging from 0.26 to 0.24. As the shedding frequency increases with increasing the flow rate, at $Q = 4.0$ L/s the shedding frequency almost equals the natural frequency of the system. This coalescence of the forcing frequency and the natural frequency makes the tube oscillate with a very large RMS value as shown in Figure 8.

Figure 9 shows spectra of transverse displacement measured at the tip of the flexible tube in the rigid tube bundle, for $Q \in [0.5, 1.1, 1.6, 1.95]$ L/s. For $Q = 0.5$ L/s, displacement is very low and appears to be disturbed by noise. For $Q > 0.5$ L/s, spectra show a dominant peak at about 23 Hz representing the natural response of the tube in water. At $Q = 1.95$ L/s the displacement amplitude increases exponentially, as can be seen in Figure 10, and the central tube touches the neighbour tubes, generating harmonics of the natural frequency in the spectrum.

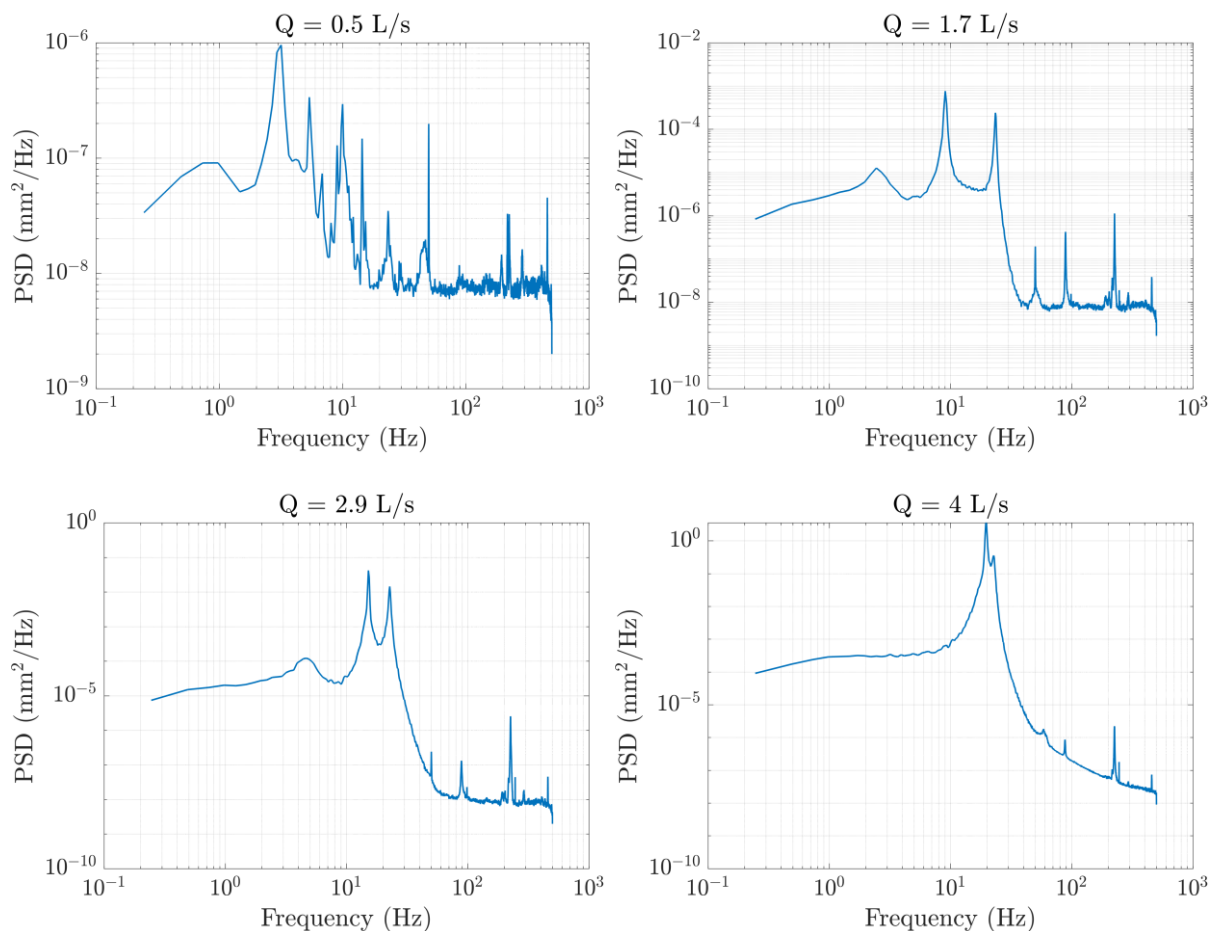


Figure 7: Single flexible tube (lift direction). Displacement spectra for different flow rates.

D3.1: Single-phase AMOVI experiments and benchmark setup

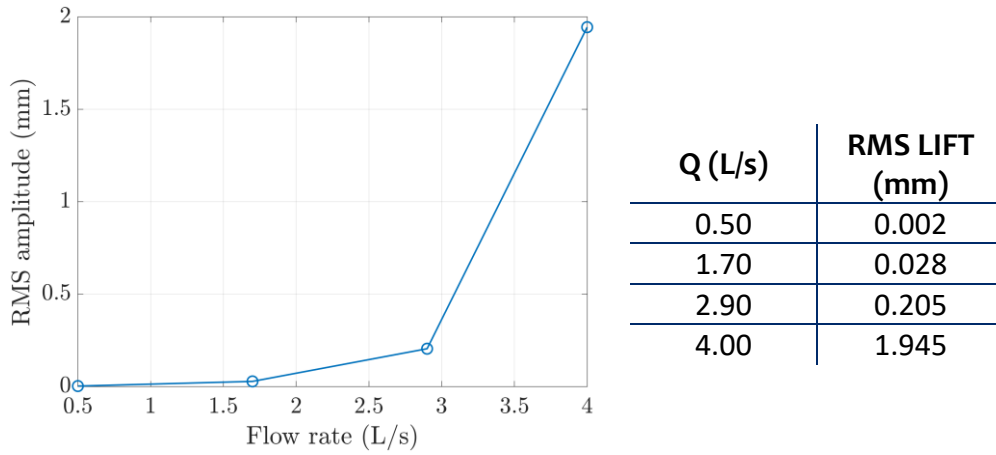


Figure 8: Single flexible tube (lift direction). RMS value of the displacement as a function of the flow rate.

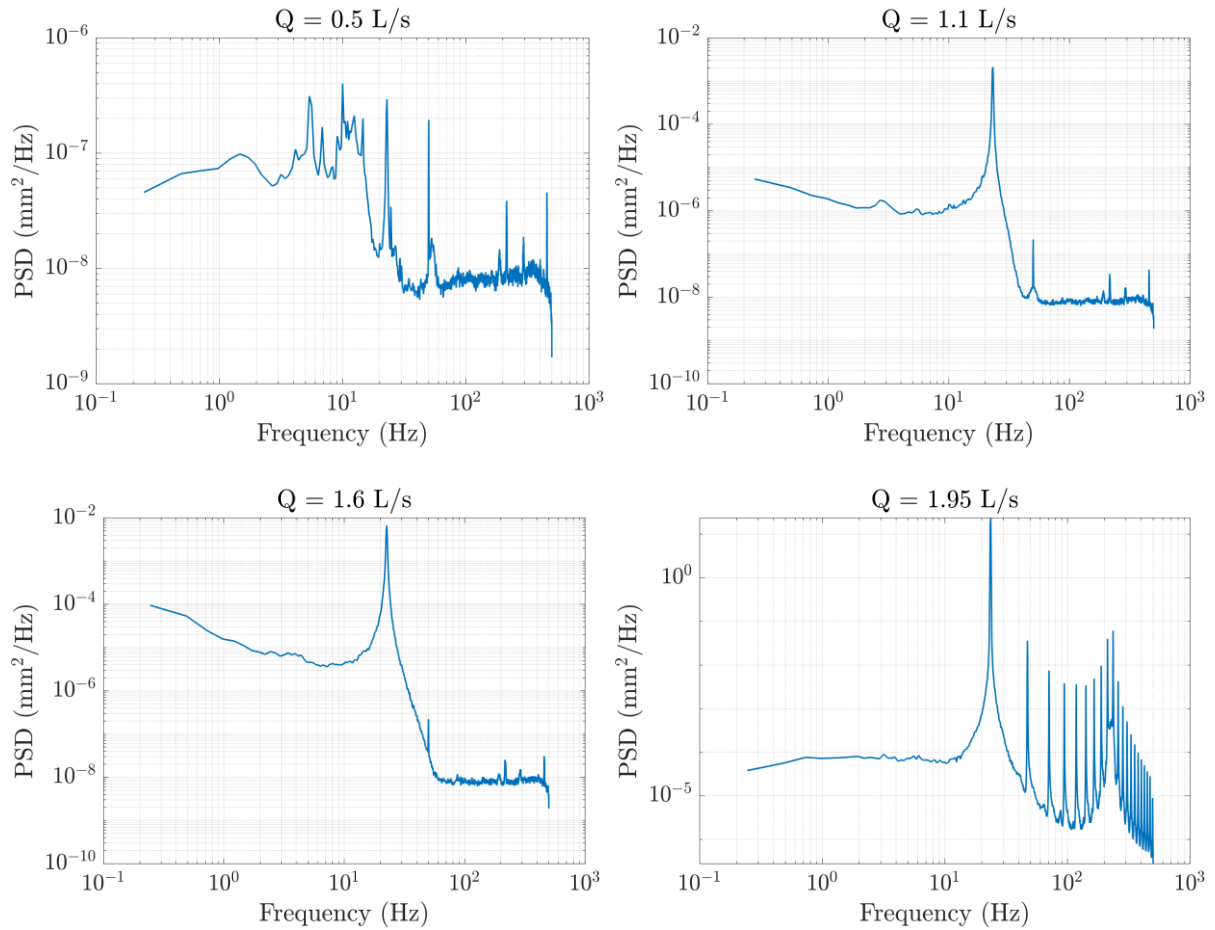


Figure 9: Flexible tube (lift direction) in a rigid tube bundle. Displacement spectra for different flow rates.

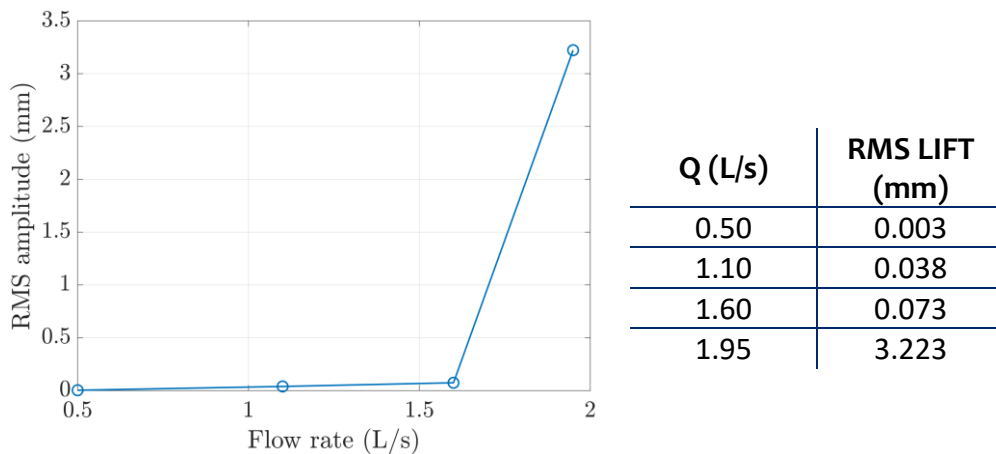


Figure 10: Flexible tube (lift direction) in a rigid tube bundle. RMS value of the displacement spectra as a function of the flow rate.

4.3 PIV measurements

In this section, succinct PIV results for the three conditions referenced in Table 2 are presented.

Figure 11 displays the normalized incoming flow velocity, extracted from the time-resolved PIV velocity field, as a function of time, as well as its power spectral distribution. The incoming flow velocity is taken as the average of the u -component over the rightmost column in the flow field array (Figure 12). As shown, the inlet velocity fluctuates within 10 to 15% of its mean value, which is, as expected, close to the reference flow velocity U . Since variations in the incoming flow rate were measured at around ± 0.02 L/s, they are insufficient to account for the fluctuations observed in the incoming flow velocity. Rather, these fluctuations most likely stem from three-dimensional turbulent structures in the incoming flow. More information on the incoming flow are provided by the LDV measurement presented in the next section.

Figure 12 displays the time-averaged velocity field overlaid with corresponding streamlines. The white patches correspond to the locations of the tubes and are masked. Despite the central tube being flexible, for $Q = 1.6$ L/s, a static mask was still employed as the tube displacement is very low. Please note that some streamlines interrupt when intersecting with a tube, which is obviously unphysical, but is a consequence of the spatial discretization. The time-averaged flow field shows good symmetry before and within the tube bundle in all three conditions. Asymmetries are, however, visible in the wake of the bundle, which is a sign of the turbulence that develops there. As expected, the flow converges and accelerates inside the tube bundle, arranging itself into a succession of flow channels in the inter-tube gaps. The acceleration factor is around 3 - 3.5, which is consistent with the pitch-to-gap ratio, $P/(P - D) = 3.27$. Interestingly, each flow channel exits the bundle forming a specific angle that is roughly constant throughout an experiment. This angle, however, varies across the different flow channels and the different conditions.

Figure 13 displays the time-averaged turbulent shear stress. In all three conditions, high values of turbulent shear stress are observed along the edges of the flow jets, especially in the wake of the tube bundle, where local turbulence intensity is high. Across the three conditions, we

find similar values for the normalized turbulent stress in the bundle's wake. Figure 13 also reveals high stress values around some of the tubes. The stress is then highly localized, forming peaks located at about 45° from the incoming flow direction. These local peaks are the result of flow impingement on the tube wall and are thus especially visible for first-rows tubes. For tubes deeper in the bundle, the peaks are much weaker, a consequence of the formation of the flow channels. This flow impingement mechanism is most visible and persists deeper in the bundle for the second configuration, which corresponds to the highest reference velocity.

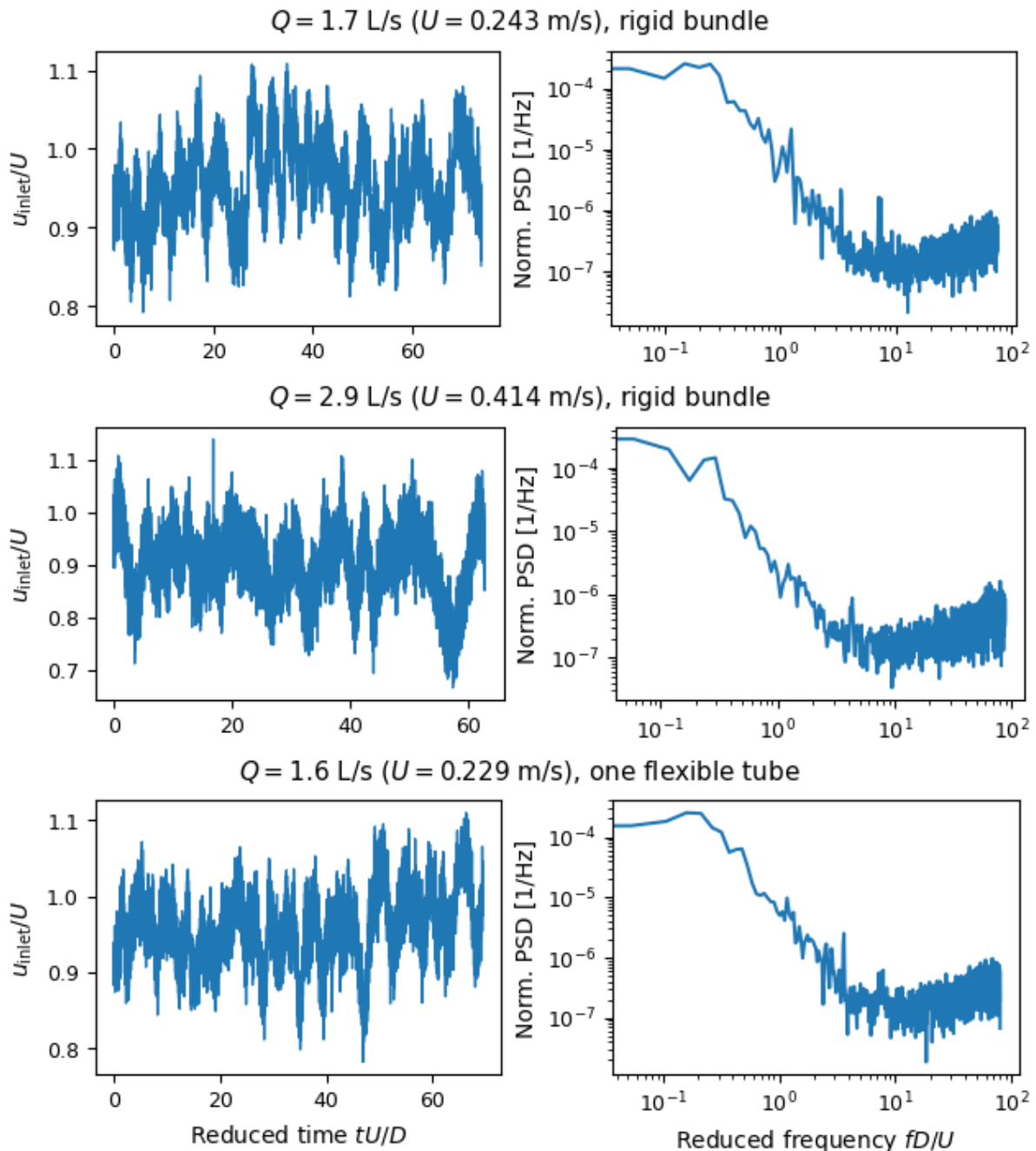


Figure 11: Normalized incoming flow velocity extracted from PIV results as a function of time and its power spectral distribution, for all three PIV conditions.

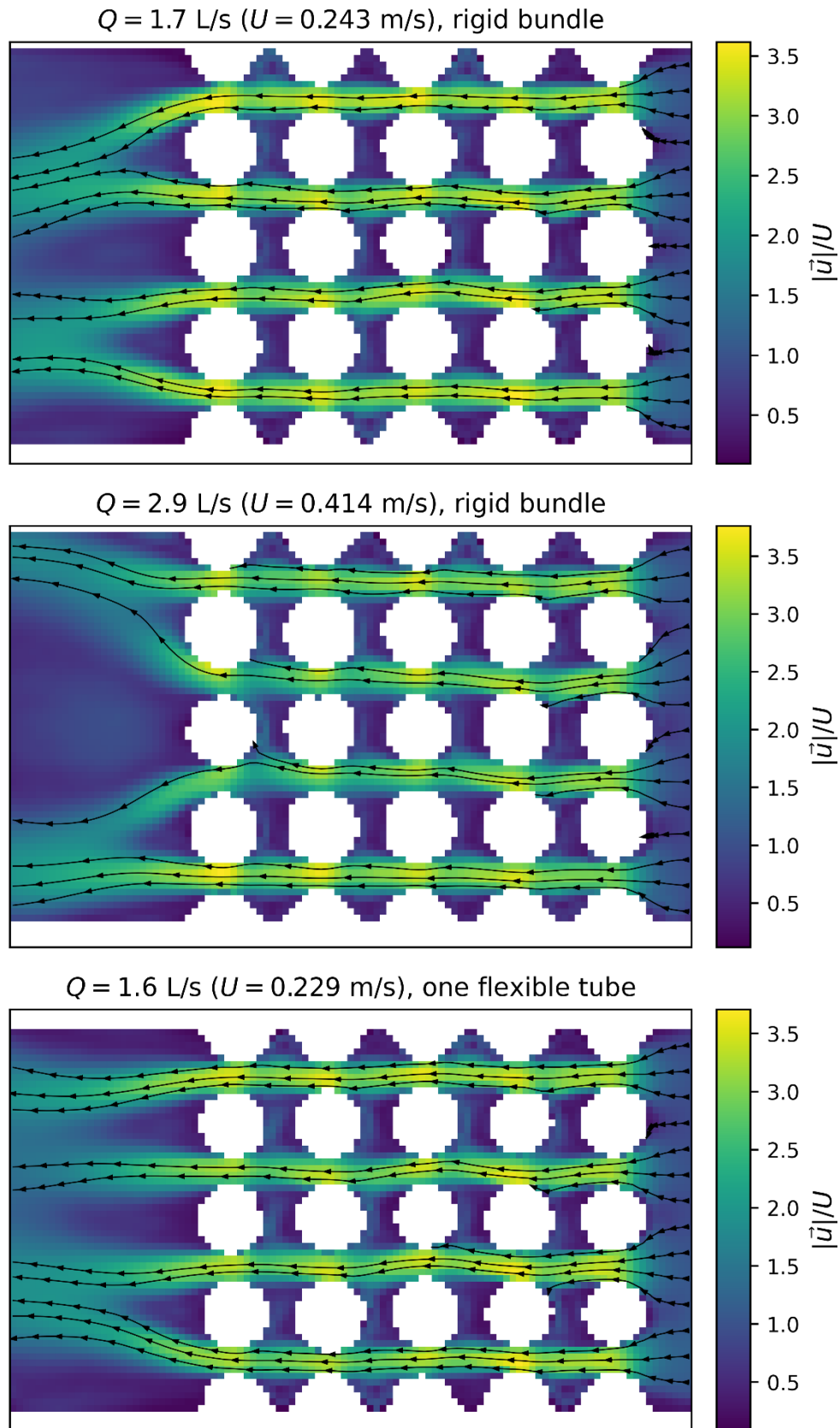


Figure 12: Time-averaged normalized velocity overlaid with selected streamlines, for all three PIV conditions.

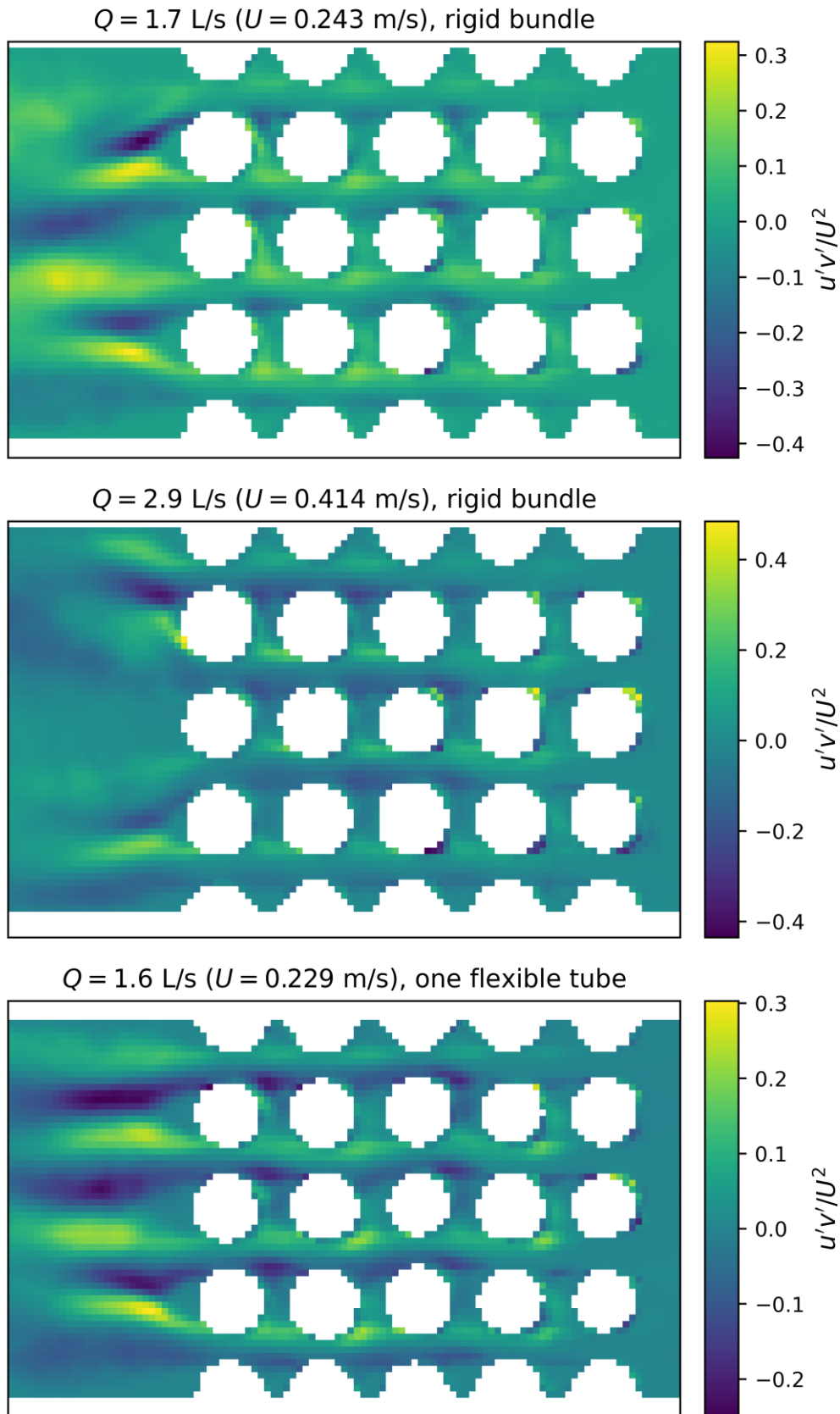


Figure 13: Time-averaged normalized turbulent shear stress, for all three PIV conditions.

4.4 LDV measurements

In this section, LDV results for the two conditions referenced in Table 3 are presented.

To characterize the upstream flow pattern we took LDV measurements at $Z = -30.4$ mm for the single tube test section and at $Z = [-71.5, -101.8, -162.6]$ mm for the tube bundle test section (see Figure 14 (a)). The flow rate was set at $Q = 2.9$ L/s for both configurations, which corresponds to an inlet velocity $U = 0.414$ m/s for the tube bundle test section of 70×100 mm², and $U = 0.725$ m/s for the single tube configuration where the test section reduces to 40×100 mm².

For reference, a Cartesian coordinate-system (X, Y, Z) is used as shown in Figure 14 (b). The axial velocity $\vec{U}$ is positive if oriented towards $+Z$, while the horizontal velocity $\vec{V}$ is positive if oriented towards $+Y$.

To ensure high-quality, low-distortion optical measurements, the LDV probe spanned the upstream test section, with a pitch of 3 mm in both directions, up to 5 mm from the front and side walls and 11 mm from the rear wall. For optical reasons, however, the horizontal velocity $\vec{V}$ was accessible up to 8 mm from the side walls.

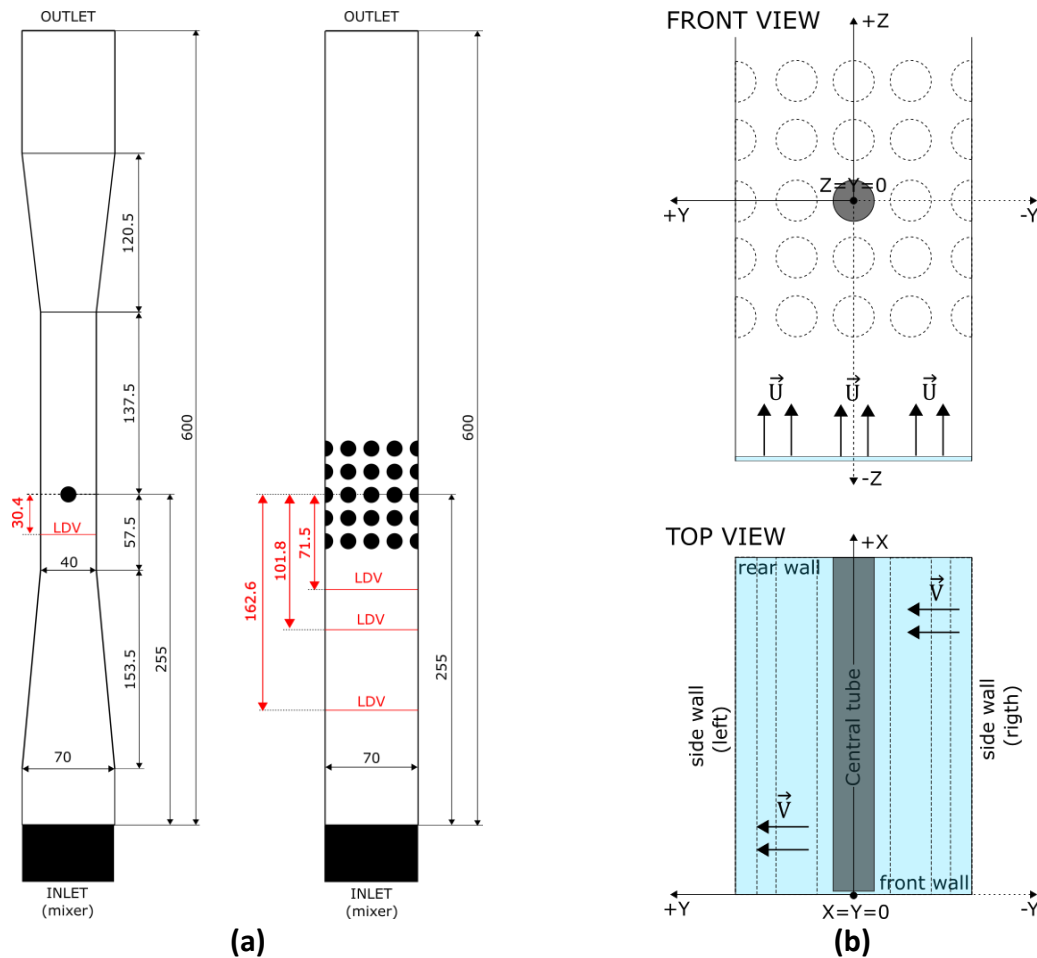


Figure 14: (a) Location of LDV measurements in the two tested configurations; (b) Cartesian coordinate system (X, Y, Z) and velocity components ($\vec{U}, \vec{V}$) over the test section.

D3.1: Single-phase AMOVI experiments and benchmark setup

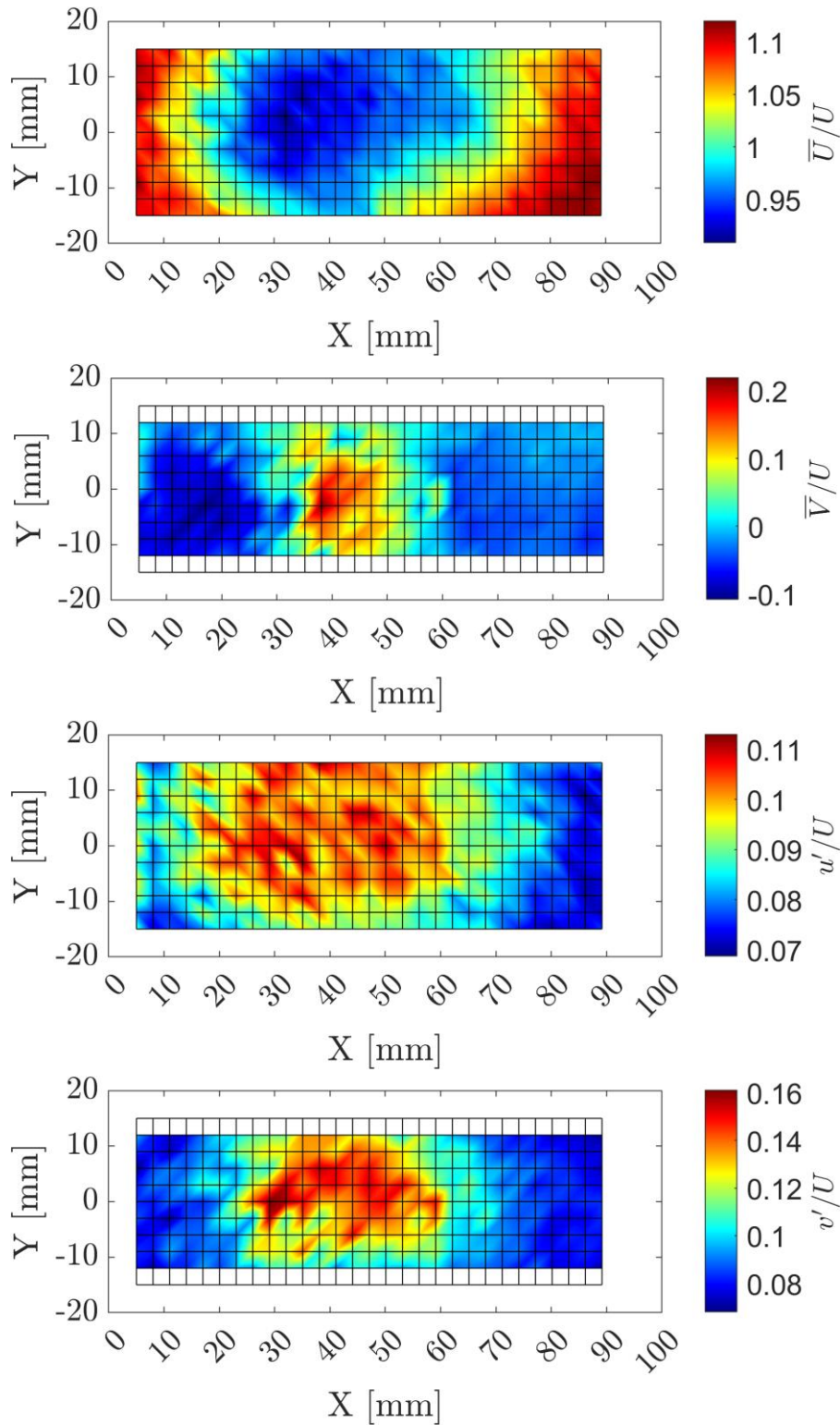


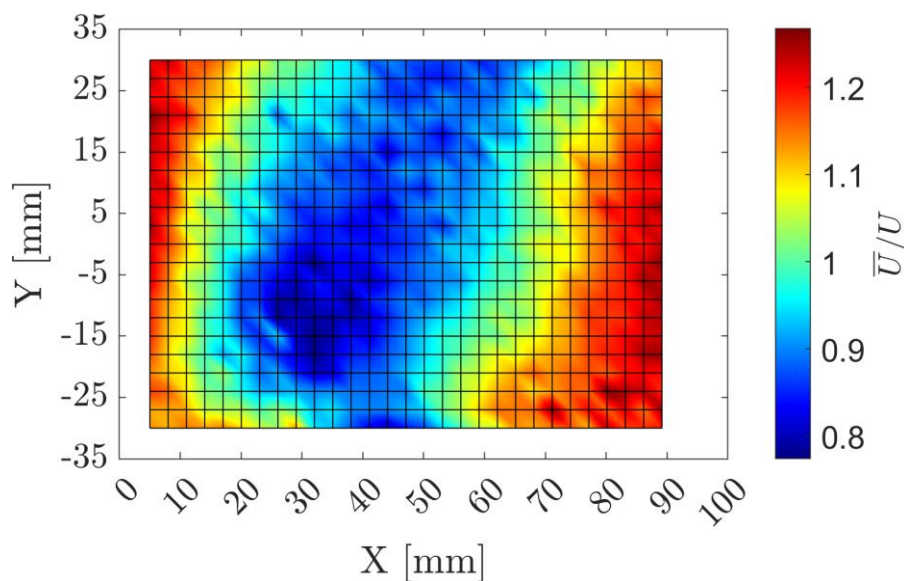
Figure 15: Single tube configuration. Time-averaged velocities ($\bar{U}, \bar{V}$) and turbulence fluctuations (u', v') in the upstream cross section at a distance of $Z = -30.4$ mm. All profiles are normalized with respect to the reference flow velocity $U = 0.725$ m/s.

Figure 15 shows the LDV results for the single tube configuration at $Z = -30.4$ mm. The time-averaged velocity components ($\bar{U}, \bar{V}$) and the turbulence fluctuations (u', v') are made dimensionless with the inlet velocity $U = 0.725$ m/s. An unexpected finding is that the time-average axial velocity profile $\bar{U}/U$ increases near the front and rear walls up to 1.1 and clearly

D3.1: Single-phase AMOVI experiments and benchmark setup

decreases in the middle up to 0.9, causing a saddle-shaped appearance with a plateau in the middle. On the contrary, the time-average horizontal velocity profile $\bar{V}/U$ is negative near the front and rear walls and positive in the middle. Despite this flow redistribution, which most likely stems from large-scale three-dimensional turbulent structures in the incoming flow, the spatial average of $\bar{U}/U$ and $\bar{V}/U$ over the measurement section remains close to one and zero, respectively. The turbulence fluctuations (u'/U , v'/U) have instead similar levels and vary mostly between 0.07 and 0.15, with a spatial average of 0.1.

Figure 16, Figure 17 and Figure 18 show the LDV results for the tube bundle configuration at $Z = [-71.5, -101.8, -162.6]$ mm, respectively. The time-averaged velocity components ($\bar{U}, \bar{V}$) and the turbulence fluctuations (u', v') are made dimensionless with the inlet velocity $U = 0.414$ m/s. At $Z = -162.8$ mm, $\bar{U}/U$ mostly increases in the whole test section and decreases in the negative Y half-plane while, at $Z = [-71.5, -101.8]$ mm we recover the saddle-shaped appearance found in the previous configuration. The time-average horizontal velocity profile $\bar{V}/U$ instead, is generally close to zero everywhere except in the negative Y half-plane, where it is negative near the front and rear walls and positive in the middle. As Z increases, there is also a reduction of the turbulence levels within the whole cross-section. The turbulence fluctuations (u'/U , v'/U) vary mostly between 0.25 and 0.35 at $Z = -162.6$ mm, between 0.15 and 0.25 at $Z = -101.8$ mm and between 0.15 and 0.20 at $Z = -71.5$ mm.



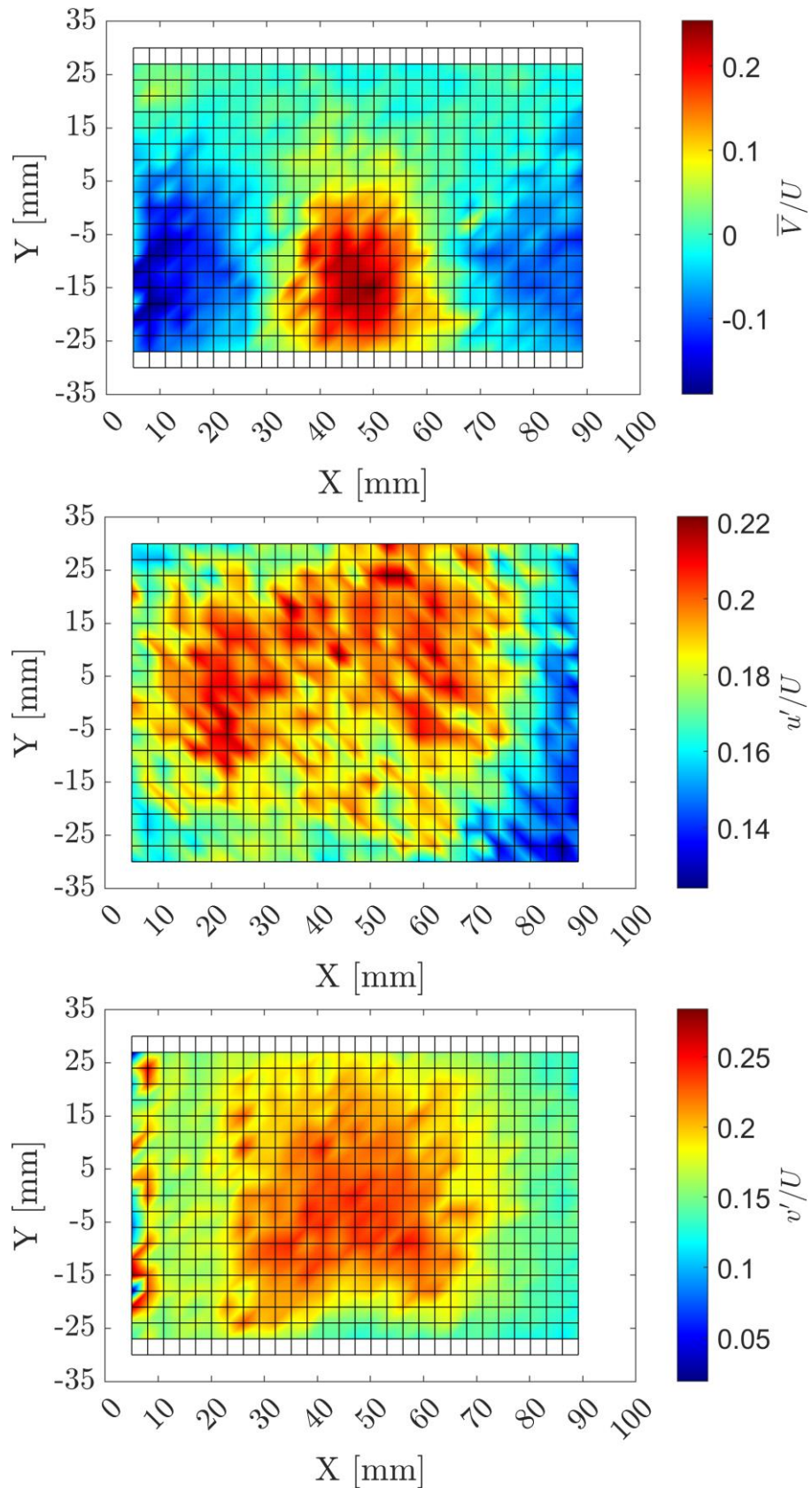
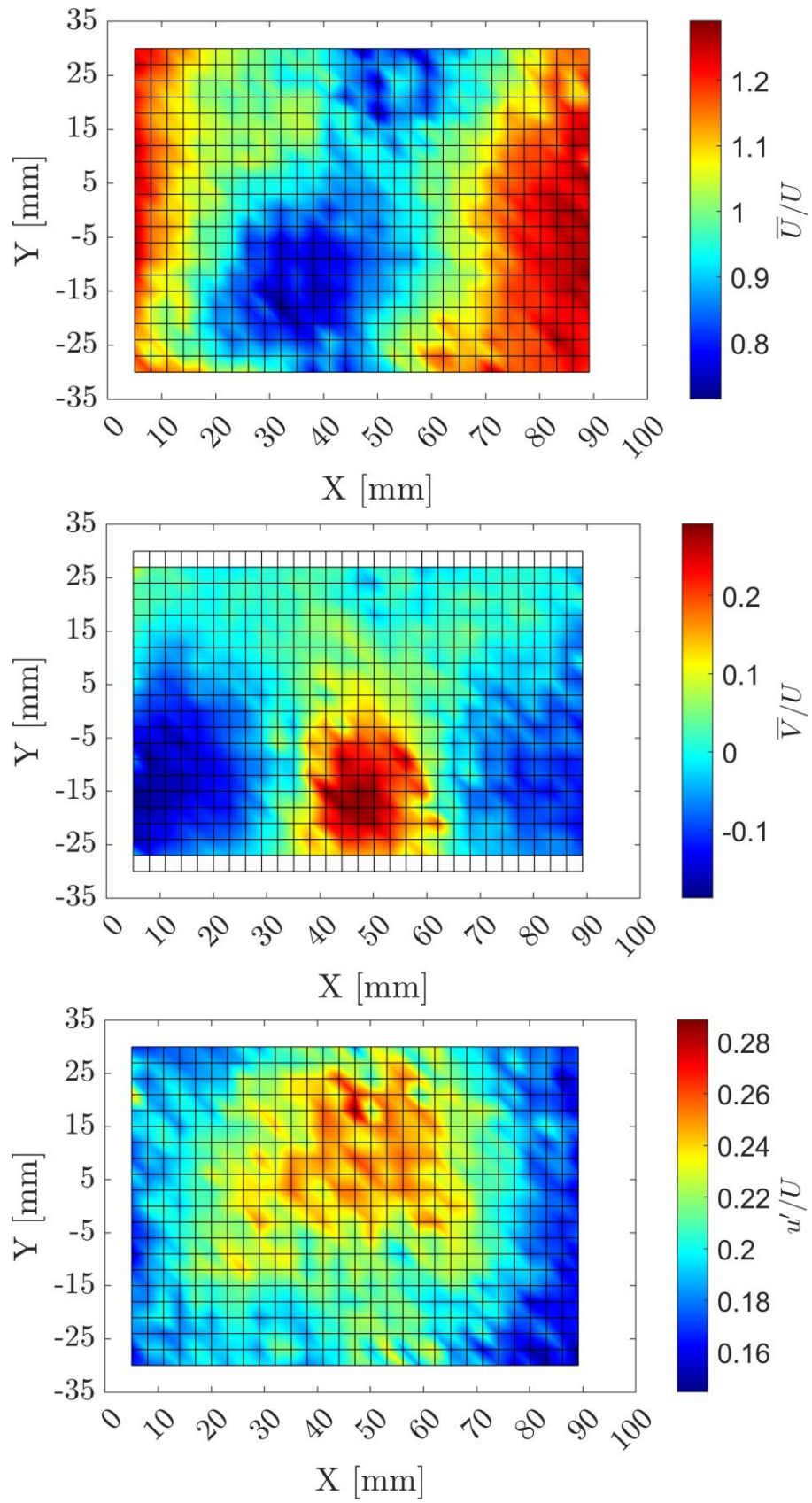


Figure 16: Rigid tube bundle. Time-averaged velocities ($\bar{U}, \bar{V}$) and turbulence fluctuations (u', v') in the upstream cross section at a distance of $Z = -71.5$ mm. All profiles are normalized with respect to the reference flow velocity $U = 0.414$ m/s.

D3.1: Single-phase AMOVI experiments and benchmark setup



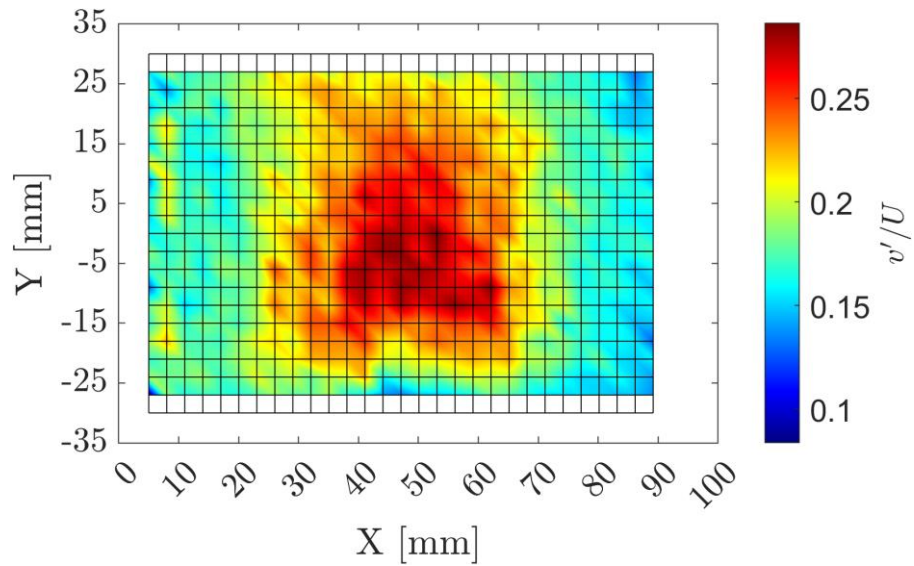
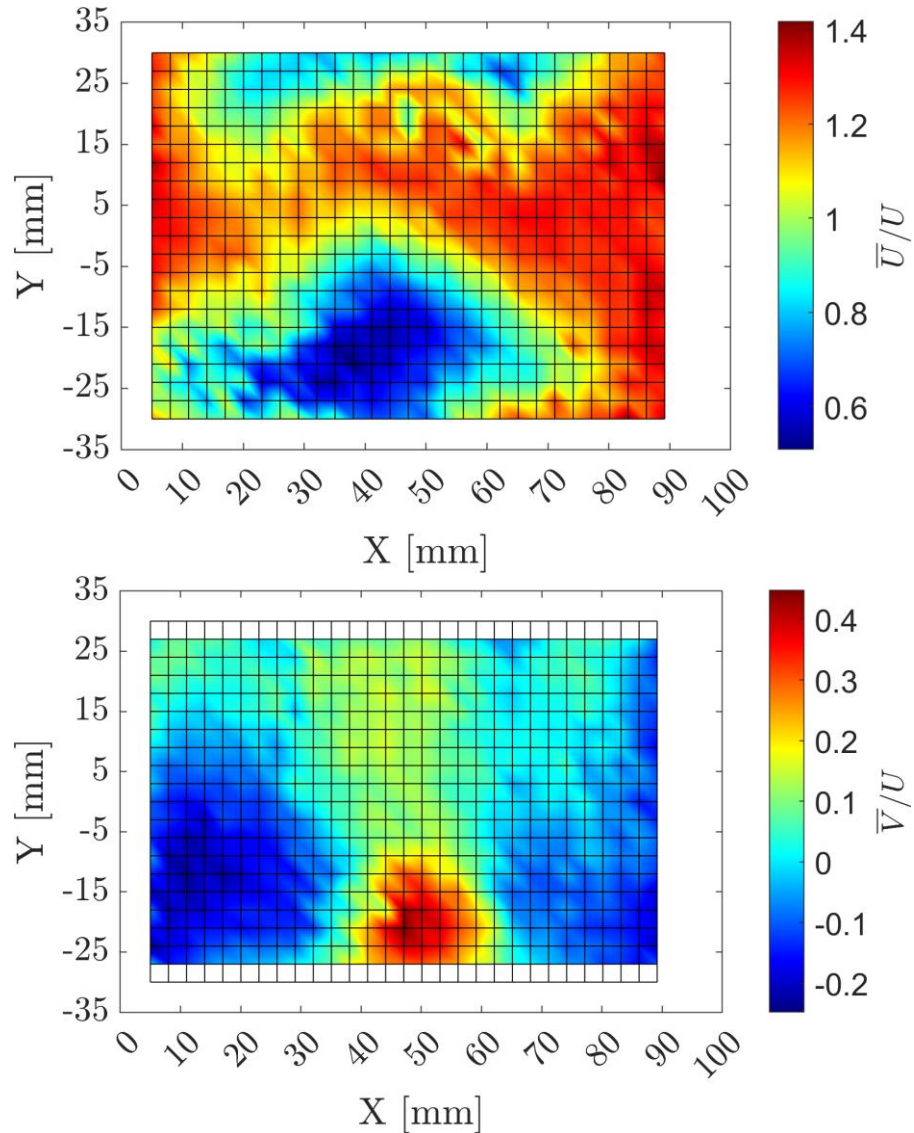


Figure 17: Rigid tube bundle. Time-averaged velocities ($\bar{U}, \bar{V}$) and turbulence fluctuations (u', v') in the upstream cross section at a distance of $Z = -101.8$ mm. All profiles are normalized with respect to the reference flow velocity $U = 0.414$ m/s.



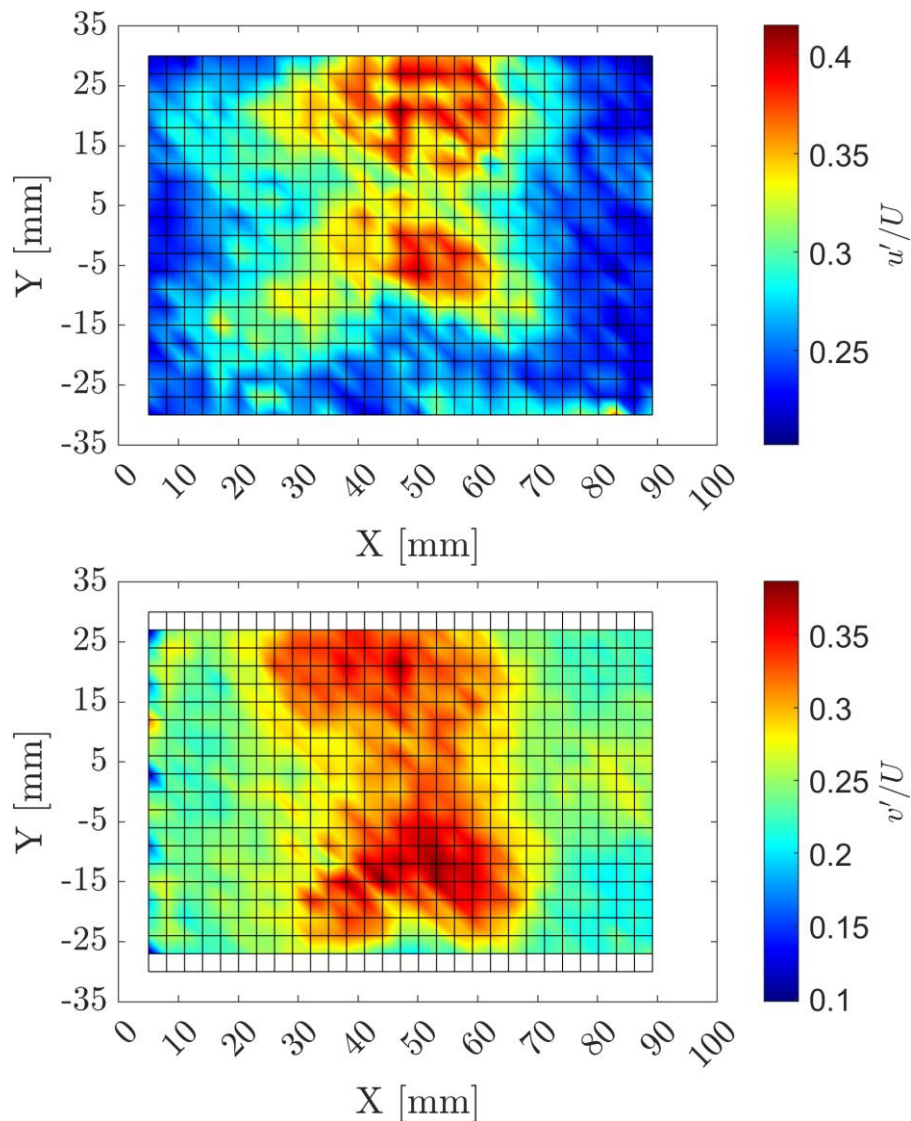


Figure 18: Rigid tube bundle. Time-averaged velocities ($\bar{U}, \bar{V}$) and turbulence fluctuations (u', v') in the upstream cross section at a distance of $Z = -162.6$ mm. All profiles are normalized with respect to the reference flow velocity $U = 0.414$ m/s.

5. Conclusion

This document provided a description and the experimental data obtained from the AMOVI facility, a small hydraulic loop built at CEA Saclay (France) to study the fluid-structure interaction between a 5x3 square tube bundle (plus five half-tubes on each side) and a water cross-flow. The central tube of the bundle can be mounted in a rigid or flexible setup to get force or displacement measurements, respectively. The other tubes are rigid and can be plugged in and out in order to study different basic configurations. In this study, two basic arrangements were tested: a single tube in a reduced channel and the full tube bundle. Each of these configurations was tested with the central tube being rigid or flexible in the lift direction, i.e. four target configurations in total. Tests were performed for four water flow rates for each configuration. The vibrations of the central tube or the forces acting on its surface are recorded and RMS value and PSD are presented. Fluid flow features in the tube bundle were measured using a PIV setup for three cases of interest, and succinct results have

D3.1: Single-phase AMOVI experiments and benchmark setup

been shown. Finally, in order to characterize the upstream flow we took LDV measurements for two cases of interest, at different distances from the tube bundle. These experimental results will support the numerical activities within GO-VIKING.

Bibliography

- [1] R. Theunissen, F. Scarano, M.L. Riethmuller. Spatially adaptive PIV interrogation based on data ensemble. Experiments in Fluids, Issue 48, 2010, Pages 875–887, <https://doi.org/10.1007/s00348-009-0782-7>
- [2] J. Westerweel, F. Scarano. Universal outlier detection for PIV data. Experiments in Fluids, Issue 39, 2005, Pages 1096-1100, <https://doi.org/10.1007/s00348-005-0016-6>
- [3] A. Sciacchitano, B. Wieneke, F. Scarano. PIV uncertainty quantification by image matching. Measurement Science and Technology, Volume 24, Issue 4, 2013, Pages 045302, <https://doi.org/10.1088/0957-0233/24/4/045302>
- [4] F. Axisa, J. Antunes, B. Villard. Random excitation of heat exchanger tubes by cross-flows. Journal of Fluids and Structures, Volume 4, Issue 3, 1990, Pages 321-341, ISSN 0889-9746, [https://doi.org/10.1016/S0889-9746\(05\)80018-0](https://doi.org/10.1016/S0889-9746(05)80018-0).



Appendix

A. Flexible tube setup

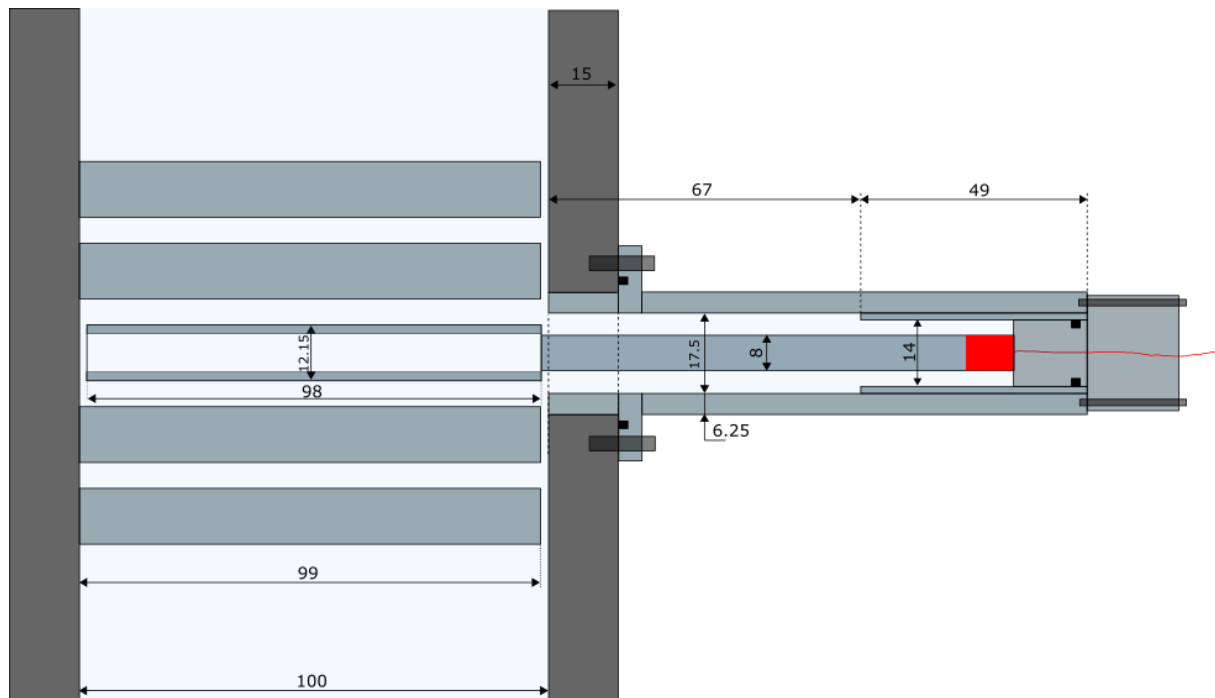


Figure 19: Illustration of the flexible tube setup within the test section.

Figure 19 provides a more detailed illustration of the moving tube setup within the test section. The central tube is supported through a flexible rectangular blade positioned such that maximum flexibility is along the lift direction. The tube-blade system is made of 304L steel and its theoretical weight is 131 g (the measured weight is 136.6 g).

The displacement at the tip of the tube is deduced from a strain gauge instrumenting the root of the flexible blade, assuming that mode 1 is predominant. Calibration tests have been performed within air to estimate this strain-to-displacement ratio. During these tests, the tube-blade system is left free to vibrate in its first mode of vibration, i.e. the one assumed to be the most involved in the vibratory response in water. The strain at the root of the blade and the displacement at the tip of the tube are recorded simultaneously, by the strain gauge and a laser sensor pointed at the tip of the tube, respectively. A modal identification method is then applied to the recorded data to extract the frequency, the damping ratio and the strain-to-displacement ratio.

A good estimate of these parameters has been numerically obtained (see Table 4) considering the following material properties: density = 8300 kg/m³, Young's modulus = 200 GPa and Poisson's ratio = 0.3.

	Frequency (Hz)	Damping ratio (%)	Strain-to-displacement ratio ($\mu\epsilon/\text{mm}$)
Experimental	27.5	0.064	98.47
Numeric	29.3	/	99.36

Table 4: Frequency, damping ratio and strain-to-displacement ratio.

B. Rigid tube setup

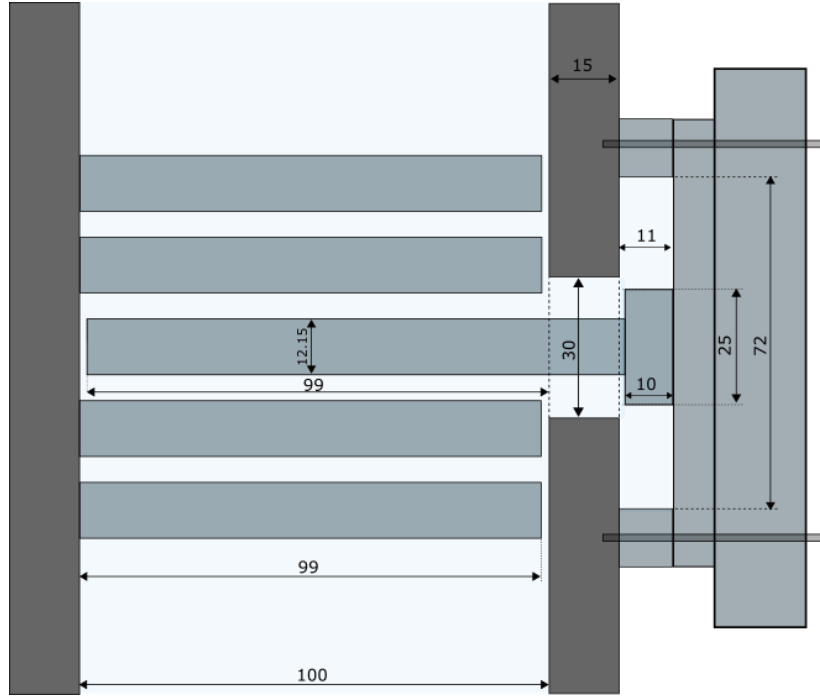


Figure 20: Illustration of the rigid tube setup within the test section.

Figure 20 provides a more detailed illustration of the rigid tube setup within the test section.

C. Analytical formulation of the force spectrum

We recall here the analytical formulation proposed by Axisa et al. [4] for the calculation of the vibratory responses of a tube to random excitations induced by turbulence.

We consider a rigid tube subjected to a fluctuating force per unit tube length $F(z, t)$ induced by cross-flow turbulence (also called random excitation).

For random signals it is more convenient to work in the frequency domain by considering the inter-correlation spectrum of the random excitation $\Psi_F(z_1, z_2, f)$ between two points of the tube located at z_1 and z_2 .

This inter-correlation spectrum can be expressed as the product of the auto-spectra of the linear force densities $\Phi_F(z, f)$ at z_1 and z_2 and a function $\gamma(z_1, z_2)$ reflecting the spatio-temporal coherence of the turbulence:

$$\Psi_F(z_1, z_2, f) = \sqrt{\Phi_F(z_1, f)\Phi_F(z_2, f)}\gamma(z_1, z_2) \quad (1)$$

Assuming that flow is homogeneous along the central tube, the auto-spectrum of the linear forces no longer depends on the z -position. The relation (1) rewrites:

$$\Psi_F(z_1, z_2, f) = \Phi_F(f)\gamma(z_1, z_2) \quad (2)$$

The coherence function γ can be approximated by:

D3.1: Single-phase AMOVI experiments and benchmark setup

$$\gamma(z_1, z_2) \approx e^{-\frac{|z_2 - z_1|}{\lambda_c}} \quad (3)$$

In (3), the frequency dependence of the correlation length λ_c has been neglected.

The auto-spectrum of the resultant force $\Phi_R(f)$ measured on a rigid and motionless tube writes:

$$\Phi_R(f) = \int_0^L \int_0^L H(z, z_1) H^*(z, z_2) \Phi_F(f) e^{-\frac{|z_2 - z_1|}{\lambda_c}} dz_1 dz_2 \quad (4)$$

where $H(z, z_j)$ is the static transfer function between the resultant force measured in z and a force applied in z_j ($j = 1, 2$) and $*$ denotes its complex conjugate. In (4), the frequency dependence of the transfer function has been neglected as the tube is rigid ($f \ll f_n$).

Making the assumption that $\lambda_c \ll L$, eq. (4) becomes:

$$\Phi_R(f) \approx \Phi_F(f) 2\lambda_c \int_0^L H(z) H^*(z) dz \quad (5)$$

In order to compare experiments with numerical simulations, an equivalent spectrum, integrating automatically the effect of λ_c , is defined as:

$$\Phi_F^e(f) = \frac{\lambda_c}{L} \Phi_F(f) = \frac{\Phi_R(f)}{2L \int_0^L H(z) H^*(z) dz} \quad (6)$$

Note that, in numerical simulations, the transfer function is unitary and the above integral reduces to L , whereas this is not always true in experiments.