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

TITAN experiment: presentation of the data

Authors : Mr. Philippe PITEAU (CEA)

GO-VIKING - Contract Number: 101059603

Project officer: Angelgiorgio IORIZZO

Document title	TITAN experiment: presentation of the data
Author(s)	Mr. Philippe PITEAU
Number of pages	23
Document type	Deliverable
Work Package	WP4
Document number	D4.5
Issued by	CEA
Date of completion	2024-09-19 16:39:46
Dissemination level	Public

Summary

Description of the TITAN two-phase FIV experiment and benchmark setup

Approval

Date	By
2024-10-21 20:50:55	Mr. William BENGUIGUI (EDF)
2024-10-22 09:14:04	Dr. Papukchiev ANGEL (GRS)

GO VIKING

WP4 – Flow-Induced Vibrations in multiphase flows

Deliverable D4.5 of the GO-VIKING project (101060826)

TITAN experiment: presentation of the data

Version N°1
06 / 2024

Romain Lagrange, Domenico Panunzio

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	WP4
Related Task(s)	Task 4.3
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	M24
Submission Date	10th June 2024
Dissemination level	Public

History

Date	Version	Submitted by	Reviewed by	Comments
10th June 2024	V1.0	CEA		

Table of contents

List of figures

List of tables

Abbreviations and Acronyms

Acronym	Description
WP	Work package
GO-VIKING	Gathering expertise On Vibration ImpaKt In Nuclear power Generation
FIV	Flow-Induced Vibrations
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 WP4 of the project is on the FIV phenomena induced by two-phase flows. The present document, as part of WP4, reports some experiments performed at CEA Saclay (France) on a triangular tube bundle facility, named TITAN, subjected to an air-water cross-flow. The triangular bundle consists of 30 tubes with two columns of half-tubes at both lateral plates to minimize wall effects. The diameter of the tubes is 30 mm, the length is 300 mm and the bundle pitch is 43.2 mm, hence P/D = 1.44. Two flexible configurations with two or seven tubes mounted on flexible blades are tested to measure the vibration responses in the lift direction (root mean square value of the displacement of the instrumented tubes). The tests are carried out for homogeneous void ratios of 40% and 60% and for several pitch velocities. A fully rigid setup is also tested to measure the turbulent forces (lift and drag) acting on a tube and determine the corresponding power spectral densities. Data from a bi-optical probe are also provided to characterize local flow properties. For the fully rigid configuration, 6 tests are carried out, with homogeneous void fractions of 40%, 60%, 80% and 90%. This experimental data will support numerical activities within GO-VIKING.

Keywords

Cross-flow; two-phase; vibration; triangular tube bundle; experiments, RMS, PSD.

1. Introduction

D4.5 deals with providing a description of the two-phase TITAN experiment, benchmark setup and experimental results. This document first introduces the TITAN experimental setup and then presents the obtained experimental results (RMS of displacement *vs* pitch flow velocity for two flexible configurations; time history and PSD of turbulent forces for the fully rigid configuration).

2. Method

2.1 The experimental rig: TITAN

The experimental rig TITAN is shown in Figures 1 and 2. This rig was built in the CEA/SEMT/DYN laboratory to perform FIV tests on a rotated triangular tube bundle subjected to a two-phase flow made of air (an alternative of steam) and water. TITAN is connected to the air-water loop of the RESEDA platform which allows to reproduce flow conditions typically found in nuclear steam generators. In what follows, we only report the technical informations needed to our study. The reader is referred to [[1], 2] for a detailed description of the rig[1].

The two-phase flow loop includes a water centrifugal pump with maximum delivery capacity of 1100 m^3/h and an air CENTAC compressor which delivers a maximum flow rate of 3000 m^3/h (273.15 K, 101325 Pa). The air-water mixing is done directly below the test section to obtain an homogeneous mixture (see pictures of a mixer in Appendix). Measurements of the fluid process conditions were carried out upstream and downstream of the test section to determine the fluid conditions at the tube bundle.
The bundle consists of 30 stainless tubes, with two columns of half-tubes at both lateral plates to minimize wall effects. An additional bundle of 20 tubes is placed upstream the test section to regulate the inlet flow direction. The tubes have an outer diameter $D = 30$ mm, a thickness of 0.4 mm and are arranged in a rotated triangular pattern with a pitch ratio of 1.44 and an aspect ratio of 10.

2.2 Two-phase flow conditions

The two-phase fluid properties such as density, mass flow rate and void fraction, are assumed homogeneous in our tests. The homogeneous void fraction is calculated by the volume flow rate of air, Q_a and water, Q_w, measured by a flow-meter under standard references of temperature and pressure ($p_0 = 101325\ \text{Pa}, T_0 = 273.15\ \text{K}$), as:

---

[1] CATIA files were also provided for CAD files of the mockup, namely:

a step file: *(2023-03-14)_1913-01-001_ENSEMBLE MAQUETTE ITP.stp*,

a three dimensions PDF: *(2023-03-14)_1913-01-001_ENSEMBLE MAQUETTE ITP.pdf*

$$\alpha = \frac{Q_a}{Q_a + Q_w}. \tag{1.1}$$

Since the relative pressure p and the temperature T were slightly above the standard conditions during the tests, a correction coefficient is calculated, from the state equation, for each flow condition as:

$$C_{corr} = \frac{p_0}{p_0 + p}\frac{T_0 + T}{T_0} \tag{1.2}$$

to take into account the compressibility of air. It follows that the corrected flow rate of air is $Q_{a,corr} = C_{corr} Q_a$. The temperature, T, in the test section was approximately 25 °C, while the relative pressure, p, is calculated as the mean value of the downstream and upstream pressures averaged over time.

Using the real void fraction, the free-stream velocity, U_∞, is defined as follows:

$$U_\infty = \frac{Q_{a,corr}}{S} + \frac{Q_w}{S}, \tag{1.3}$$

with $S = 0.0673\ \mathrm{m}^2$ the upstream section. Finally, for a rotated triangular tube bundle of pitch P, the reference velocity or flow pitch velocity is defined as:

$$U_P = U_\infty \frac{P}{P - D} = J_a + J_w. \tag{1.4}$$

2.3 Test procedure

2.3.1 Flexible configurations tests

In this experimental study we tested two flexible configurations, shown in Figure 4:

- **Configuration n°11: 2 flexible tubes at the center of the bundle,**
- **Configuration n°3: a pattern of 7 flexible tubes at the center of the bundle.**

The flexible tubes (identified by a number, as shown in Figure 4) are mounted on a single flexible stainless steel blade (volume mass density of 7800 kg/m^3, Young modulus of 2.1 10^{11} Pa and Poisson's ratio of 0.3) of 100×25×4 mm, instrumented with a strain gauge at the root, see Figure 3. For the configuration n°11 (resp. n°3) the average natural frequency in air of the moving tubes is 14.18 Hz (resp. 31.96 Hz) and the average damping ratio is 0.045% (resp. 0.047%). To pass from a 31.96 Hz to 14.18 Hz, we actually introduce a heavy plug at the tip of the tube, allowing us to modify its natural frequency without changing its geometry. The two configurations were subjected to increasing mass flow rates until the vibration amplitude was sufficiently high to indicate fluid-elastic instability. During a given test, the void fraction was kept constant. Configuration n°11 (resp. n°3) was tested for a void fraction of 40% (resp. 60%). Data were acquired for 180 s, at a sampling rate of 250 Hz.

2.3.1 Rigid configuration tests

For the fully rigid configuration, **6 tests** listed in Table 1 have been carried out to measure the turbulent fluid forces (in the lift and drag directions). These forces are measured directly on an instrumented tube (see Figure 5 for location), via two force sensors, one at each extremity of the tube. The resultant force is the sum of the two forces measured by the two sensors. A Fourier transform of the fluid forces (done with the *pwelch* function from Matlab) yields the power spectral densities (PSD).To measure local quantities, a sapphire bi-optical probe is introduced through the lateral side of the vein, passing through a half tube and a plain tube, see Figure 5. The tip of the probe is positioned in the middle of a canal with an uncertainty on the lateral position estimated to ± 0.5 mm.

Test	Q_w (l/s)	Q_a (Nm³/h)	J_w (m/s)	J_a (m/s)	Corrected void fraction (%)	Time length of force signals (s)	Sampling frequency (Hz)	Downstream pressure (bar)
1	10.1	24.3	0.49	0.33	40.2	600	512	0.466
2	10.1	54.6	0.49	0.74	60.2	600	512	0.443
3	10.1	145.7	0.49	1.97	80.1	600	512	0.3932
4	9.9	321.9	0.48	4.35	90.1	600	512	0.3397
5	8.1	262.8	0.39	3.55	90.1	600	512	0.3504
6	6.6	214.5	0.32	2.90	90.1	600	512	0.3623

Table 1. Parameters for the rigid configuration tests.

3. Results

Figure 6 presents the vibration responses of the flexible tubes patterns in the form of root mean square (RMS) displacement amplitude over flow pitch velocity. The displacement considered is that of the cantilevered end of each tube, deduced from the strain gauge at the root of each blade (strain-to-displacement ratio of 67 με/mm). Results are expressed in dimensional and dimensionless form with respect to diameter. We observe that the vibration response increases considerably, confirming that instability occurs in the lift direction for the two tested configurations. Data are given in Tables 1 and 2. The time histories[2] and power spectral densities[3] of the lift and drag forces, for the fully rigid configuration, are shown in Figures 7-12. Data from the bi-optical

[2] The force measurements were also given in a text file (*XXX_Time.txt*) containing three columns, namely: Time (s) | Lift force (N) | Drag force (N).

[3] The PSD of forces were also given in a text file (*XXX_Frequency.txt*) containing three columns, namely: Frequency (Hz) | PSD of Lift force (N^2/Hz) | PSD of Drag force (N^2/Hz). The parameters used for the *pwelch* function of Matlab (*Hamming* window) are window = 2048, noverlap = 50%, nfft = 2048.

Funded by the European Union

probe are given in Table 4, containing: the number of bubbles (*N. Bulles*), the number of bubbles per unit of time (*Fr. Interf,* in s^{-1}), the local void fraction (*Tx Vide*), for the two probes (*Voie 0* and *Voie 1*), the time average (over 600 s) of the interfacial velocity (*Vit. Interf.*, in m/s), the interfacial surface area (*Aire interf.*, in mm^2) and the Sauter diameter (*D. Sauter*, in mm).

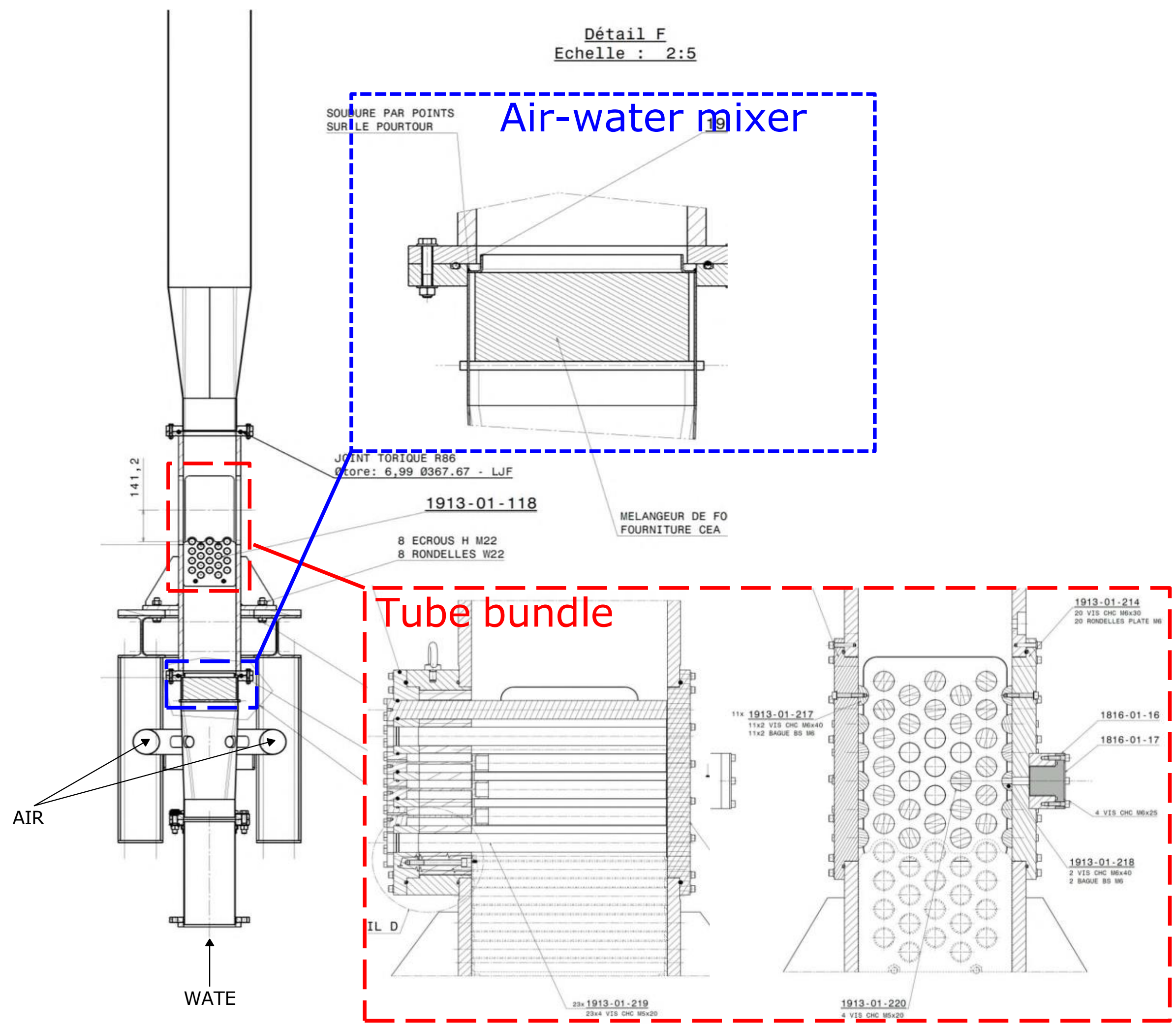

Figure 1. ***The experimental rig: TITAN. Layout and pictures of the mixer***

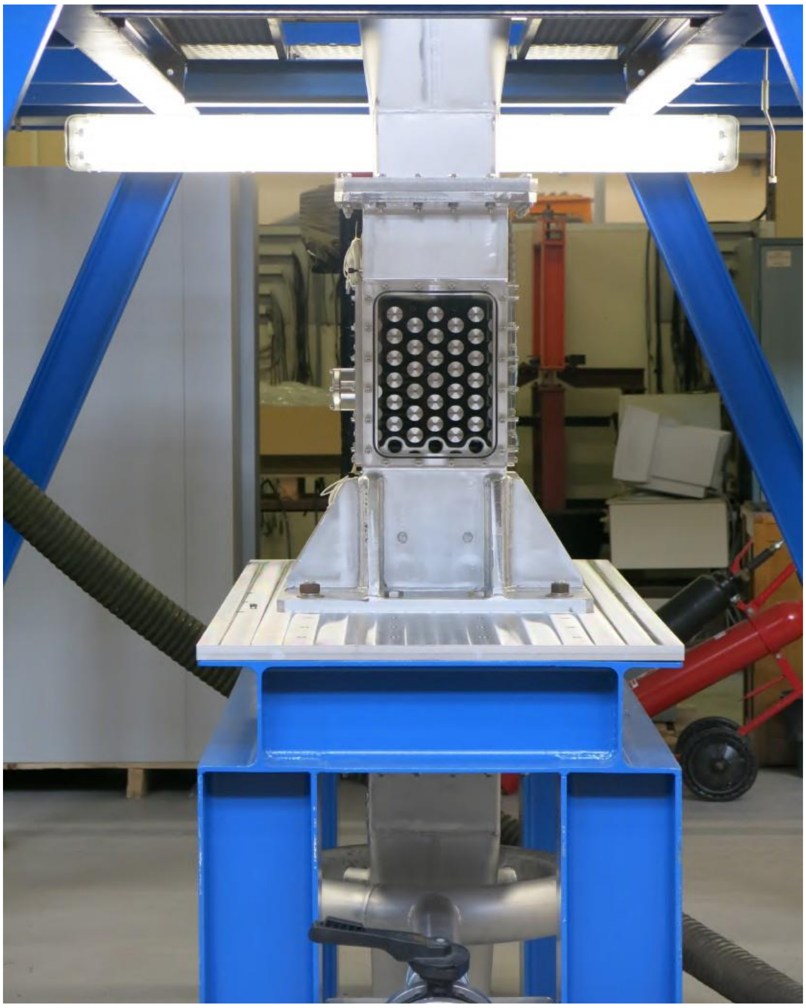

Figure 2. ***The experimental rig: TITAN. Overall view.***

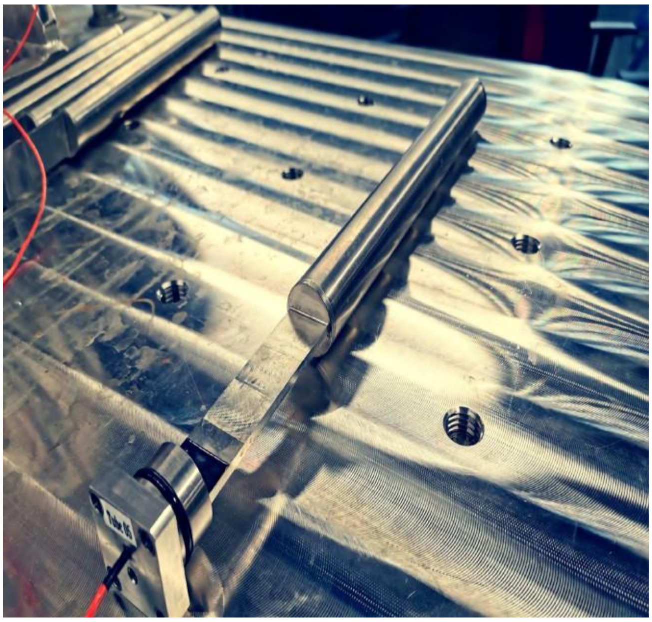

Figure 3. ***The experimental rig: TITAN. Tube instrumented with a flexible blade.***

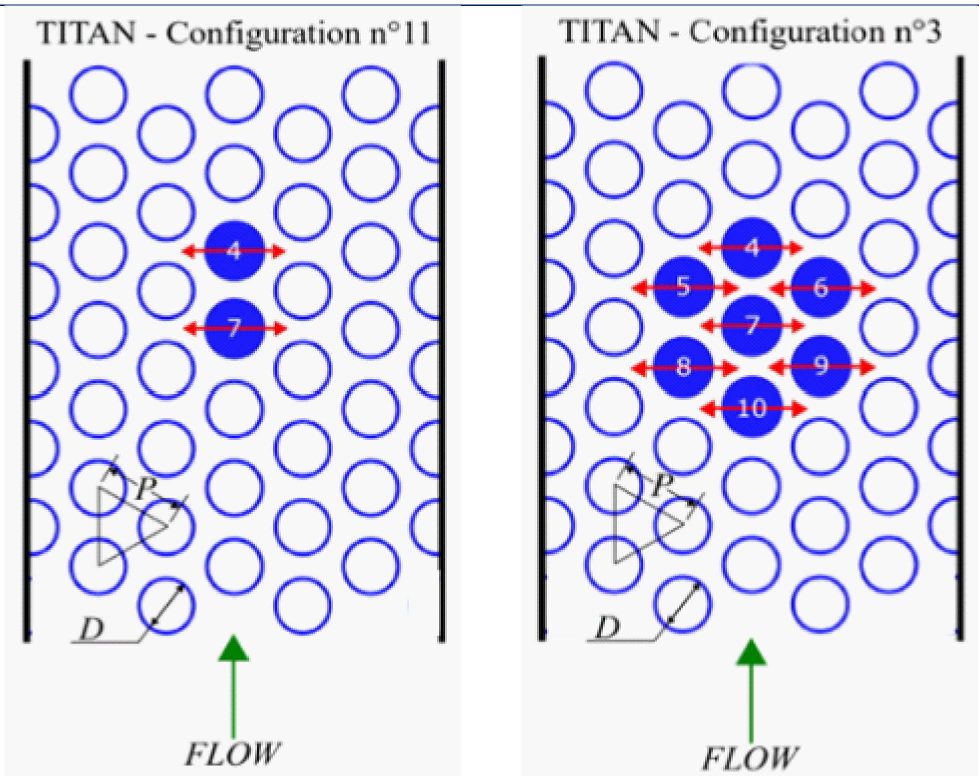

Figure 4. ***Flexible configurations. The numbered tubes are flexible, the others are rigid.***

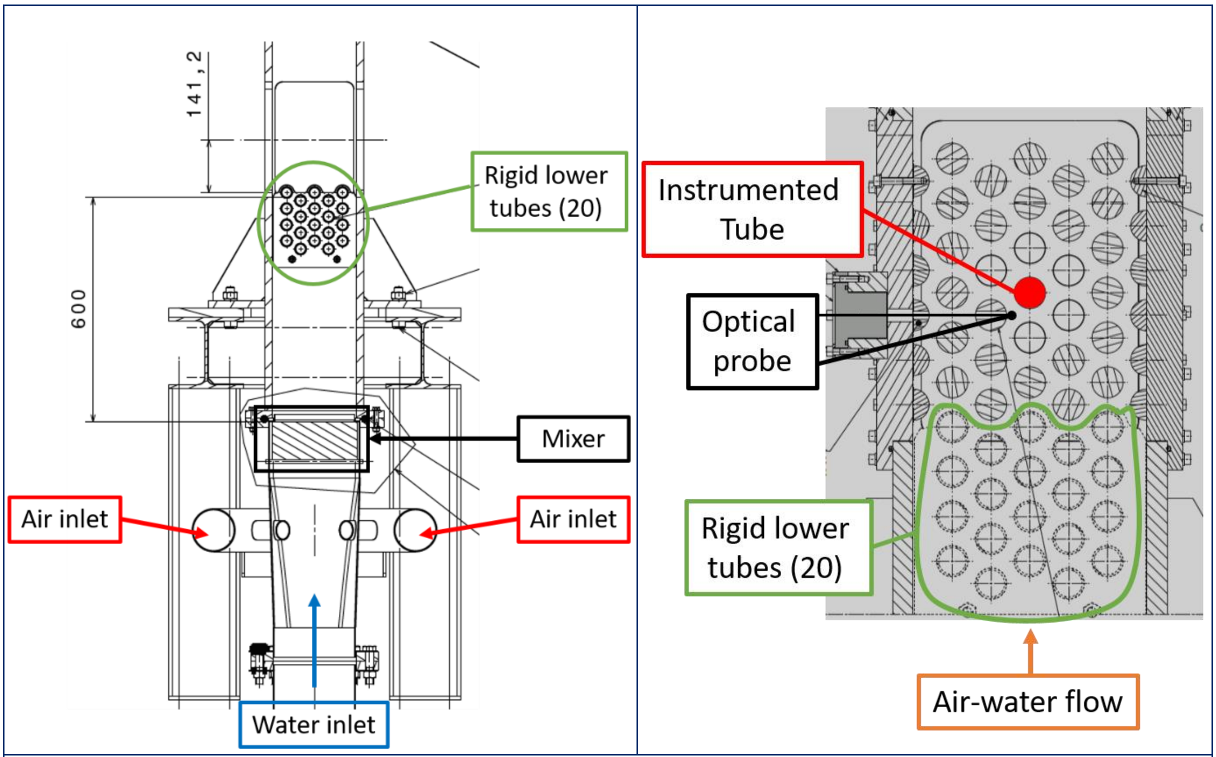

Figure 5. ***Sketch of the vein (left) and of the rigid bundle (right).***

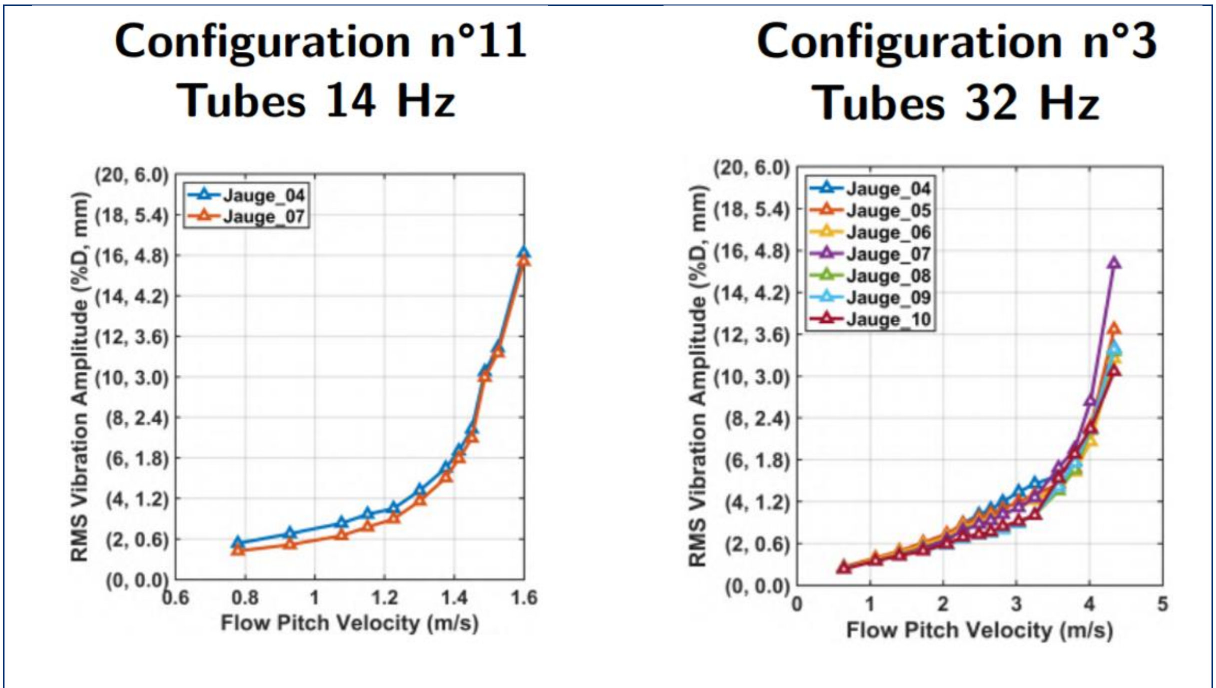

Figure 6. ***Root mean square (RMS) amplitude of vibration versus flow pitch velocity. Strain gauges (Jauges) number corresponds to tubes number.***

Funded by the European Union

Upstream pressure (Pa)	Downstream pressure (Pa)	Corrected void fraction (%)	J_a (m/s)	J_w (m/s)	U_P (m/s)	RMS_J04 (% D)	RMS_J07 (% D)
40822	36943	34,5	0,27	0,51	0,78	1,78	1,41
40421	36423	34,5	0,32	0,61	0,93	2,26	1,72
40465	36291	34,5	0,37	0,71	1,08	2,77	2,16
40321	36050	34,6	0,40	0,75	1,15	3,22	2,59
40324	35942	34,6	0,42	0,80	1,23	3,50	2,99
40228	35725	34,6	0,50	0,85	1,30	4,39	3,87
40110	35505	34,6	0,48	0,90	1,38	5,49	5,01
40125	35459	34,6	0,49	0,92	1,41	6,34	5,96
40063	35313	34,7	0,50	0,95	1,45	7,42	6,96
40158	35329	34,6	0,52	0,97	1,49	10,26	9,98
40090	35211	34,7	0,53	1,00	1,52	11,44	11,19
40212	35173	34,7	0,55	1,05	1,60	16,11	15,69

Table 2. Data for the flexible configuration n°11.

Upstream pressure (Pa)	Downstream pressure (Pa)	Corrected void fraction (%)	J_a (m/s)	J_w (m/s)	U_P (m/s)	RMS_J04 (% D)	RMS_J05 (% D)	RMS_J06 (% D)
39428	35928	54,41	0,35	0,292	0,64	0,86	0,89	0,80
38099	34454	54,66	0,59	0,486	1,07	1,27	1,31	1,24
37563	33663	54,78	0,77	0,632	1,40	1,52	1,64	1,56
37233	32949	54,88	0,95	0,778	1,72	1,86	2,04	1,92
37014	32240	54,96	1,13	0,923	2,05	2,34	2,46	2,31
36804	31514	55,05	1,25	1,021	2,27	2,95	2,94	2,78
36791	31052	55,09	1,37	1,118	2,49	3,37	3,22	3,03
37061	30915	55,08	1,46	1,191	2,65	3,63	3,42	3,21
37133	30451	55,11	1,55	1,264	2,82	3,98	3,64	3,41
37297	30028	55,10	1,67	1,361	3,03	4,46	4,00	3,71
37545	29467	55,17	1,79	1,458	3,25	4,85	4,33	4,07
38167	28804	55,17	1,97	1,604	3,58	5,25	4,85	4,73
38447	27995	55,22	2,10	1,701	3,80	5,94	5,60	5,42
38955	27610	55,21	2,22	1,798	4,01	7,55	7,56	6,87
39953	27034	55,17	2,39	1,944	4,34	11,35	12,24	10,83

Upstream pressure (Pa)	Downstream pressure (Pa)	Corrected void fraction (%)	J_a (m/s)	J_w (m/s)	U_P (m/s)	RMS_J07 (% D)	RMS_J08 (% D)	RMS_J09 (% D)	RMS_J10 (% D)
39428	35928	54,41	0,35	0,292	0,64	0,78	0,82	0,81	0,78
38099	34454	54,66	0,59	0,486	1,07	1,17	1,17	1,16	1,17
37563	33663	54,78	0,77	0,632	1,40	1,45	1,42	1,40	1,41
37233	32949	54,88	0,95	0,778	1,72	1,77	1,68	1,65	1,65
37014	32240	54,96	1,13	0,923	2,05	2,18	1,93	1,92	1,97
36804	31514	55,05	1,25	1,021	2,27	2,63	2,27	2,22	2,31
36791	31052	55,09	1,37	1,118	2,49	2,92	2,44	2,41	2,44
37061	30915	55,08	1,46	1,191	2,65	3,09	2,57	2,49	2,56
37133	30451	55,11	1,55	1,264	2,82	3,39	2,75	2,66	2,82
37297	30028	55,10	1,67	1,361	3,03	3,72	3,05	2,95	3,05
37545	29467	55,17	1,79	1,458	3,25	4,19	3,37	3,38	3,35
38167	28804	55,17	1,97	1,604	3,58	5,61	4,52	4,71	5,11
38447	27995	55,22	2,10	1,701	3,80	6,52	5,53	5,85	6,27
38955	27610	55,21	2,22	1,798	4,01	8,79	7,41	7,46	7,48
39953	27034	55,17	2,39	1,944	4,34	15,36	11,18	11,28	10,23

Table 3. Data for the flexible configuration n°3.

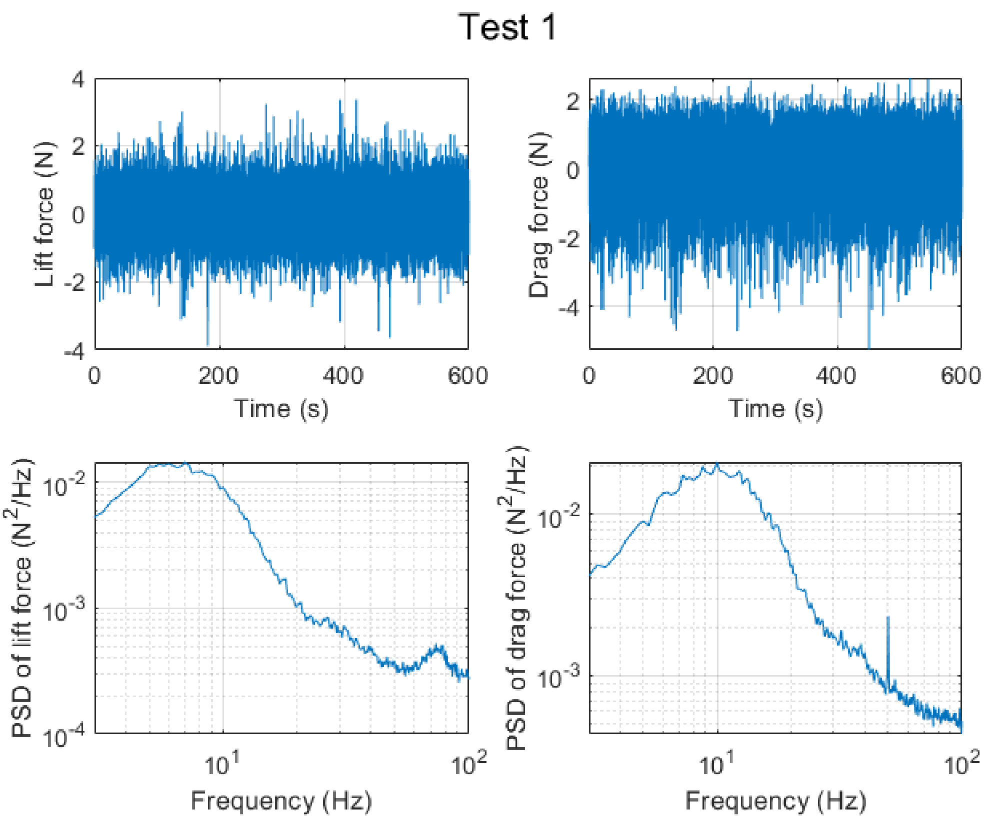

Figure 7. Test 1. Time evolution and PSD of the drag lift and forces.

Funded by
the European Union

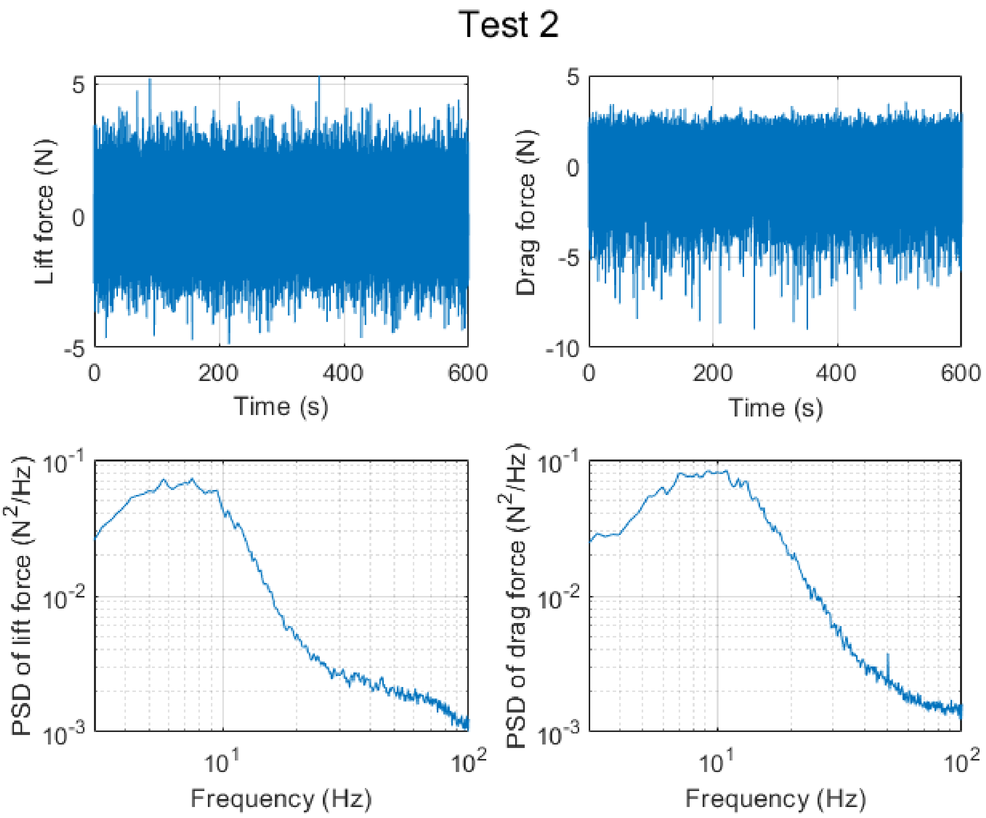

Figure 8. Test 2. Time evolution and PSD of the drag lift and forces.

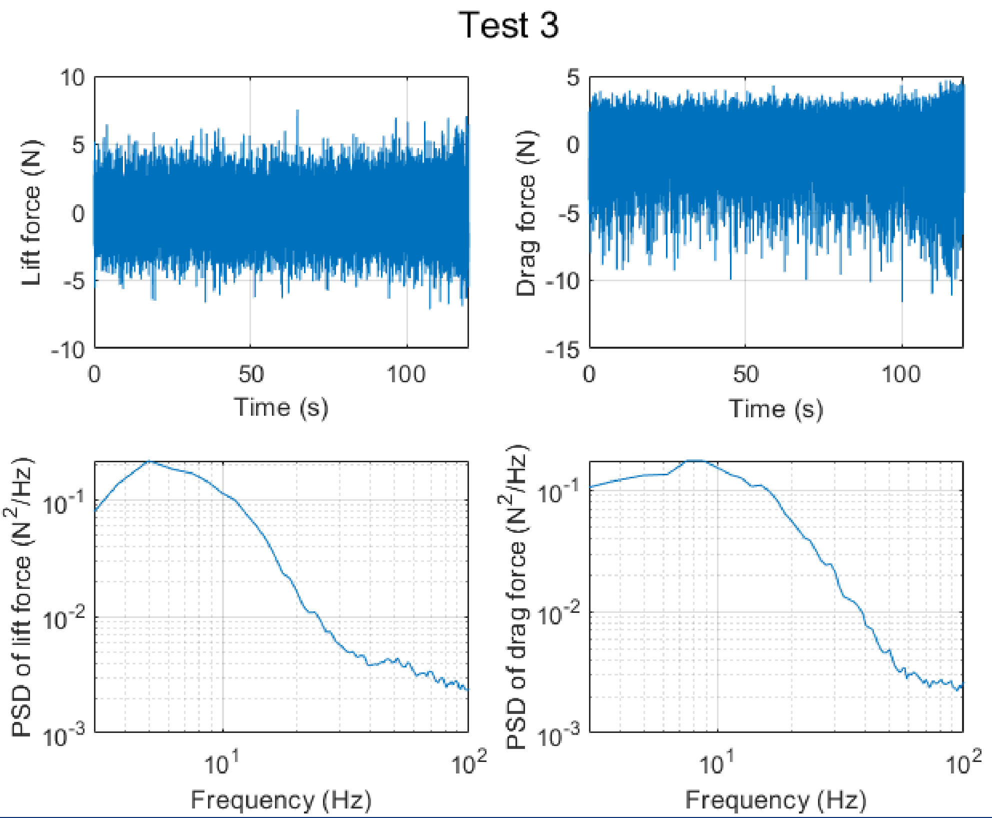

Figure 9. Test 3. Time evolution and PSD of the drag lift and forces.

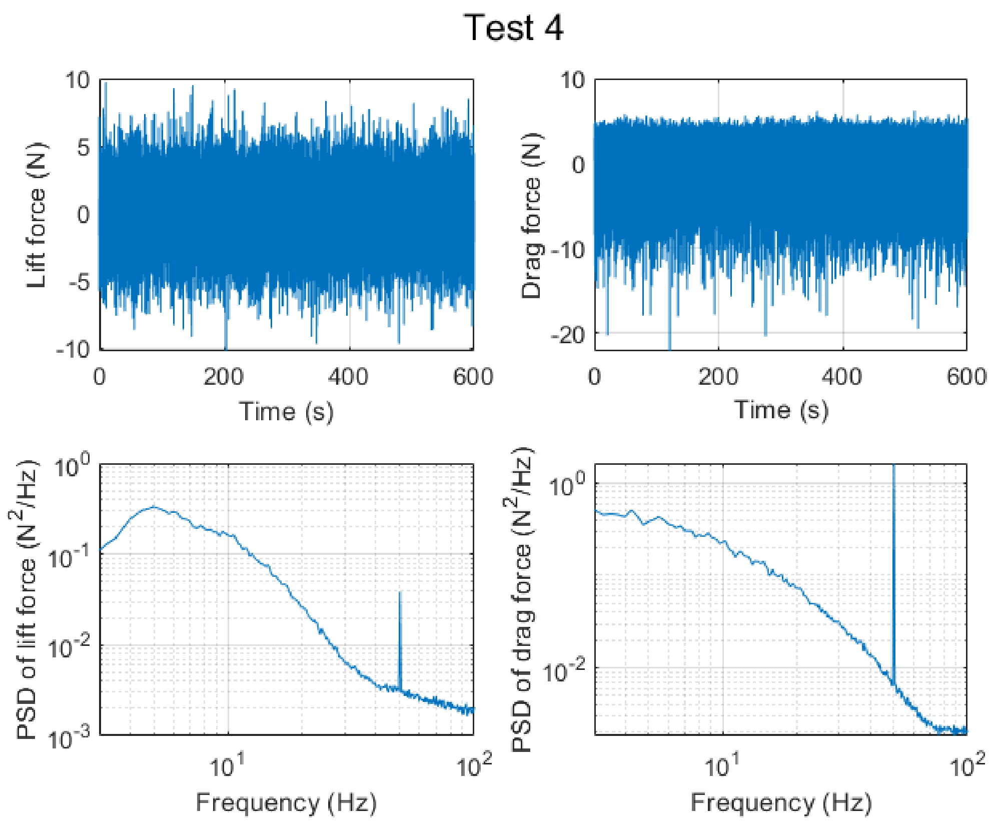

Figure 10. Test 4. Time evolution and PSD of the drag lift and forces.

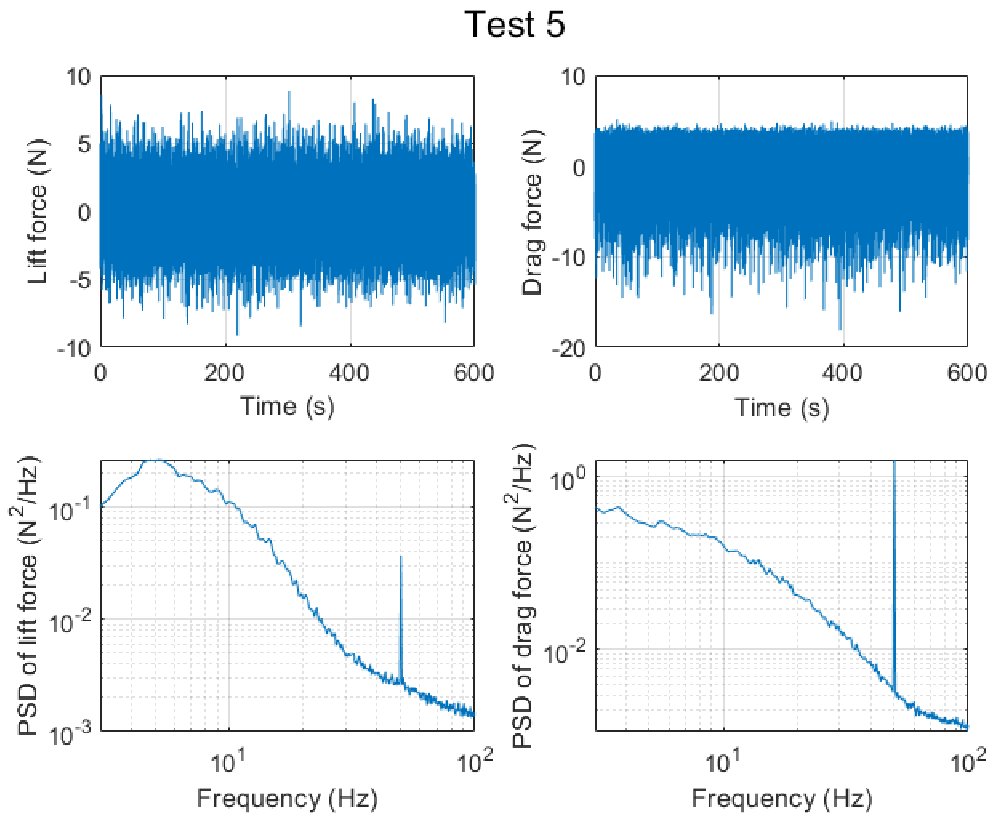

Figure 11. Test 5. Time evolution and PSD of the drag lift and forces.

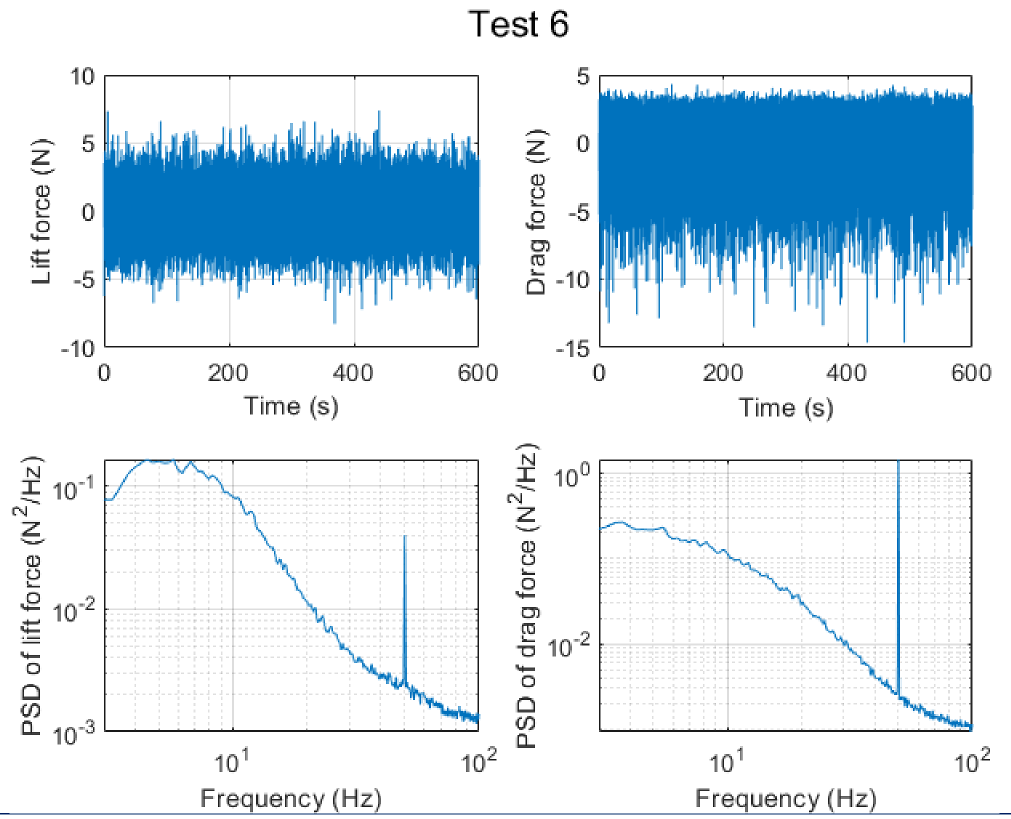

Figure 12. Test 6. Time evolution and PSD of the drag lift and forces.

TEST 1								
Tx Vide, Voie 0.	Fr. Interf. Voie 0. (s^{-1})	N. Bulles, Voie 0.	Tx Vide, Voie 1.	Fr. Interf. Voie 1. (s^{-1})	N. Bulles, Voie 1.	Vit. Interf. (m/s)	Aire Interf. (mm^2)	D. Sauter (mm)
0,256	69,833	42289	0,254	69,019	41796	0,978	285,362	5,382

TEST 2								
Tx Vide, Voie 0.	Fr. Interf. Voie 0. (s^{-1})	N. Bulles, Voie 0.	Tx Vide, Voie 1.	Fr. Interf. Voie 1. (s^{-1})	N. Bulles, Voie 1.	Vit. Interf. (m/s)	Aire Interf. (mm^2)	D. Sauter (mm)
0,3839	113,516	68742	0,377	110,983	67208	1,155	392,907	5,8635

TEST 3								
Tx Vide, Voie 0.	Fr. Interf. Voie 0. (s^{-1})	N. Bulles, Voie 0.	Tx Vide, Voie 1.	Fr. Interf. Voie 1. (s^{-1})	N. Bulles, Voie 1.	Vit. Interf. (m/s)	Aire Interf. (mm^2)	D. Sauter (mm)
0,596	205,249	124292	0,584	203,252	123083	1,655	495,949	7,221

TEST 4								
Tx Vide, Voie 0.	Fr. Interf. Voie 0. (s^{-1})	N. Bulles, Voie 0.	Tx Vide, Voie 1.	Fr. Interf. Voie 1. (s^{-1})	N. Bulles, Voie 1.	Vit. Interf. (m/s)	Aire Interf. (mm^2)	D. Sauter (mm)
0,777	387,526	234673	0,767	385,941	233713	2,630	589,312	7,919

TEST 5								
Tx Vide, Voie 0.	Fr. Interf. Voie 0. (s^{-1})	N. Bulles, Voie 0.	Tx Vide, Voie 1.	Fr. Interf. Voie 1. (s^{-1})	N. Bulles, Voie 1.	Vit. Interf. (m/s)	Aire Interf. (mm^2)	D. Sauter (mm)
0,761	259,271	157006	0,747	258,008	156241	2,122	488,609	9,350

TEST 6								
Tx Vide, Voie 0.	Fr. Interf. Voie 0. (s^{-1})	N. Bulles, Voie 0.	Tx Vide, Voie 1.	Fr. Interf. Voie 1. (s^{-1})	N. Bulles, Voie 1.	Vit. Interf. (m/s)	Aire Interf. (mm^2)	D. Sauter (mm)
0,710	189,540	114779	0,693	188,427	114105	1,732	437,655	9,741

Table 4. Data from the bi-optical probe for tests from 1 to 6.

Funded by the European Union

4. Conclusion

This document provided a description and the experimental data obtained from the TITAN facility, a hydraulic loop built at CEA Saclay (France) to study the fluid-structure interaction between a triangular tube bundle and an air-water cross-flow. The triangular cluster comprises 30 tubes, featuring two half-tube columns on each lateral plate to minimize wall effects. Each tube has a diameter of 30 mm and a length of 300 mm, with a bundle pitch of 43.2 mm, resulting in a P/D ratio of 1.44. Two flexible setups, one with two tubes and the other with seven tubes mounted on flexible blades, are subjected to vibration tests in the lift direction, measuring the root mean square value of tube displacement. These tests are conducted under homogeneous void ratios of 40% and 60%, at various pitch velocities. Additionally, a fully rigid setup is tested to assess random forces (lift and drag) acting on a tube and to determine corresponding power spectral densities. Data from a bi-optical probe is also included to characterize local flow properties. For the fully rigid configuration, six tests are conducted with homogeneous void fractions of 40%, 60%, 80%, and 90%. This experimental data will support numerical simulations within GO-VIKING.

Funded by
the European Union

Appendix

In this appendix, we show, see Fig. 13, some pictures of a mixer used on the square tube bundle mockup DIVA. The mixer used on TITAN is similar. The basic pattern of the mixer is a diamond with a side of 1.5 cm.

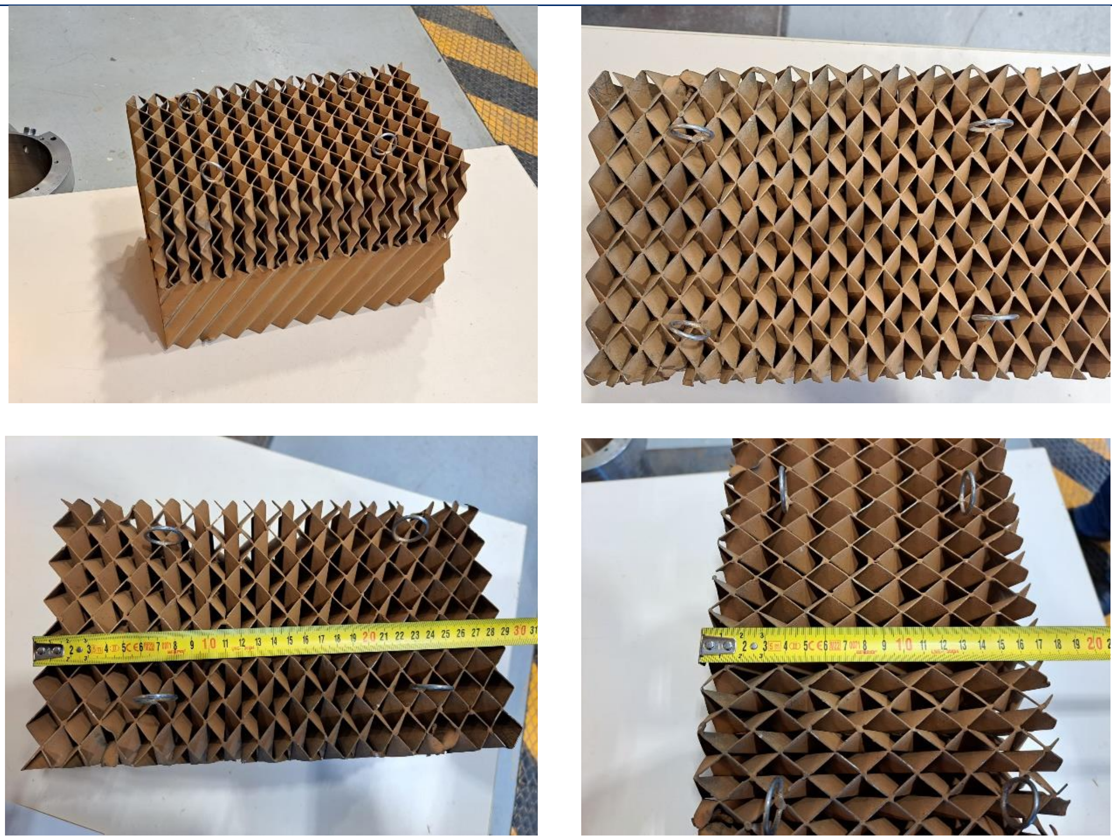

Figure 13. Picture of a mixer similar to the one used on TITAN.

Bibliography

[1] P. Piteau, X. Delaune, D. Panunzio, R. Lagrange, J. Antunes, Experimental investigation of in-flow fluidelastic instability for rotated triangular tube bundles subjected to single-phase and two-phase transverse flows, Journal of Fluids and Structures, Volume 123, 2023.

[2] D. Panunzio, R. Lagrange, P. Piteau, X. Delaune, J. Antunes, Experimental investigation of out-of-flow fluidelastic instability for rotated triangular bundles subjected to single-phase and two-phase transverse flow. Proceedings of the Flow Induced Vibration conference, Paris-Saclay, 2022.