SPLEEN

SECONDARY AND LEAKAGE FLOW EFFECTS IN HIGH-SPEED LOW PRESSURE TURBINES

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SPLEEN

Technical Summary on the linear cascade test section geometry and dimensional control of the manufactured cascade hardware

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Comments	Technical report on the geometry of the SPLEEN linear cascade test section tested in the VKI S1/C wind tunnel. This report also contains information on the dimensional control and surface finish of test section parts.

DOCUMENT HISTORY			
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1.0	30.10.2022	S. Lavagnoli	1st version

Contents

1 Introduction

The current document contains information on the geometry of the turbine cascade and test section of the experimental test case SPLEEN high-speed linear cascade (chapter 2).
In chapter 3 the results of the dimensional control and measurements of the surface roughness are reported for the main elements of the linear cascade.

2 Cascade geometry

2.1 SPLEEN C1 airfoil and passage geometry

The geometry of the turbine airfoil SPLEEN C1 considered for the experimental campaign is presented in Figure 2.1.

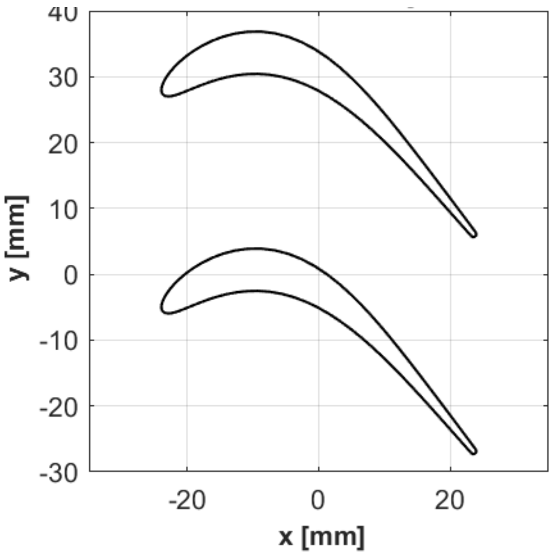


Figure 2.1: The SPLEEN C1 cascade passage.

A summary of the most important geometric characteristics of the tested turbine cascade are reported in Table 2.1.

Table 2.1: Geometric parameters of the SPLEEN C1 cascade

Parameter	SPLEEN C1
Cascade true chord, c [mm]	52.28
Cascade axial chord, c_{ax} [mm]	47.61
Cascade pitch, g [mm]	32.95
Cascade span, span [mm]	165.0
TE radius [mm]	0.435
Throat opening, *o* [mm]	19.40
Inlet metal angle, α_{in} [deg]	37.30
Outlet metal angle, α_{out} [deg]	53.80
Stagger angle, σ [deg]	24.40

2.2 SPLEEN C1 cascade

The aim of the project SPLEEN WP1 is to study the effect of cavity flows on secondary vortices and quasi-3D flows in a linear cascade arrangement. Therefore, a completely new test article to be implemented in the wind tunnel S-1/C was designed to allow the study of these flow phenomena, expanding the 2D measurement traditionally carried out in this facility. This involved the translation of one of the test-section endwalls to house the purge/leakage flow system. The modification of the endwall gave rise to the introduction of a boundary layer (BL) passive control feature, the design of the purge/leakage flow system and the modification of the wake generator (WG) geometry. The blade span is 165 mm whereas the test section height upstream of the inlet boundary layer lip is 225 mm. The final test section configuration including the WG and the cavity at the bottom endwall is shown in the sketch of Figure 2.2.

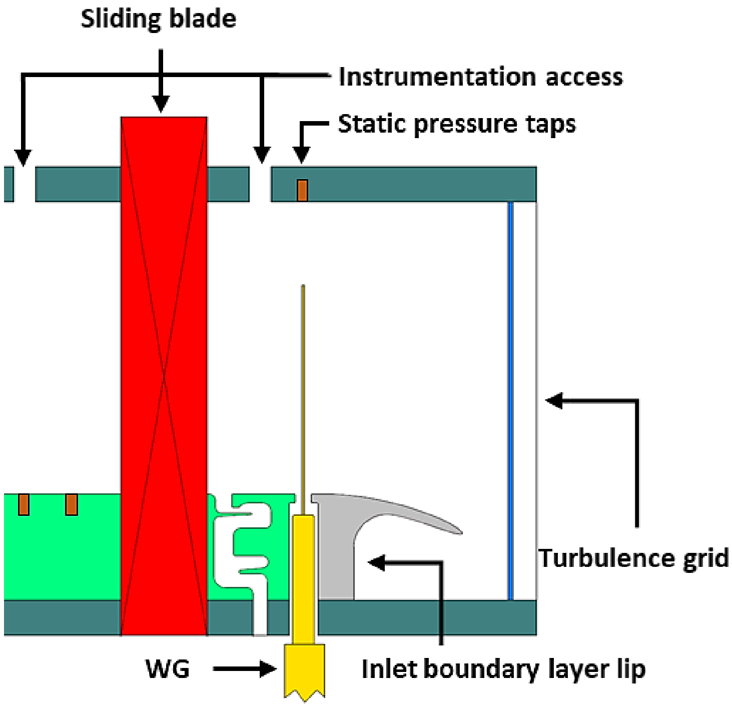


Figure 2.2: SPLEEN cascade complete test setup.

The cascade is composed of 23 airfoils. The central blade is interchangeable. One blade of a set of instrumented blades plus one smooth blade is used as the central blade depending on the scope of the measurement. A global view of the SPLEEN C1 cascade housed in the S-1/C turbomachinery test section is provided in Figure 2.3. The model in the figure represents the cascade in its most general configuration, which include upper and lower tailboards, inlet turbulence grid, boundary layer lip, wake generator and hub cavity implemented in the cavity cassette. The inlet boundary layer lip is integrated in the bottom endwall of the cascade and its leading edge is parallel to the cascade leading edge plane.

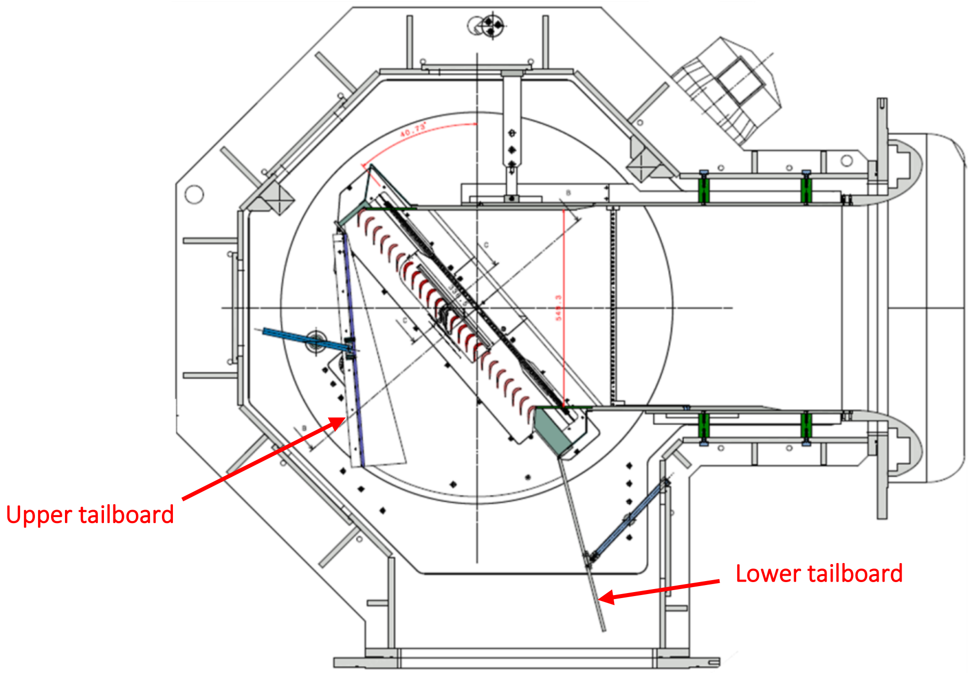


Figure 2.3: Global view of the SPLEEN AF1 cascade.

Unless explicitly mentioned, **all experimental data included in the open database have been collected on a cascade NOT equipped with the upper tailboard, and WITH the lower tailboard**.

The cascade is tested in different phases, distinguished by the installation or not of the wake generator and of the cavity for the injection/suction of secondary air to and from the mainstream:

- Phase 1: No WG nor Cavity (flat continuous bottom endwall)
- Phase 2: WG installed, no Cavity
- Phase 3: WG installed with Cavity

Note:
A reference system for the cascade geometry and for the instrumentation position is described in the document “*SPLEEN-HSTC-DB-MeasurementTechniques_v1.pdf*”.

2.2.1 SPLEEN C1 test section – Phase 1

Tests performed in phase 1 featured a test section without wake generator nor cavity; the wake generator bars were not installed and a special boundary layer lip as well as a cascade cassette without cavity were manufactured. The setup for testing phase 1 is presented in the sketch in Figure 2.4.

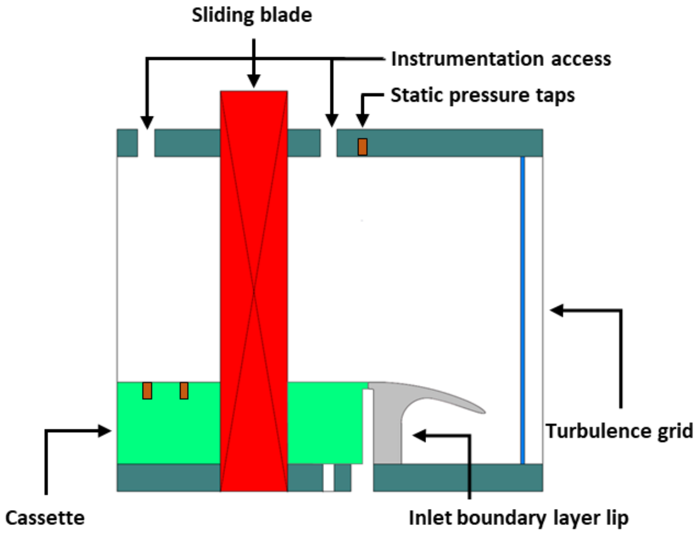


Figure 2.4: Phase 1 configuration of the SPLEEN C1 cascade.

A figure detailing the characteristics of the cascade tested in Phase 1 is shown in Figure 2.5. The setup presented hereby is used for the whole experimental activity linked with the part of the project referred to as *"Testing of Cascade C1 – Phase 1"*.

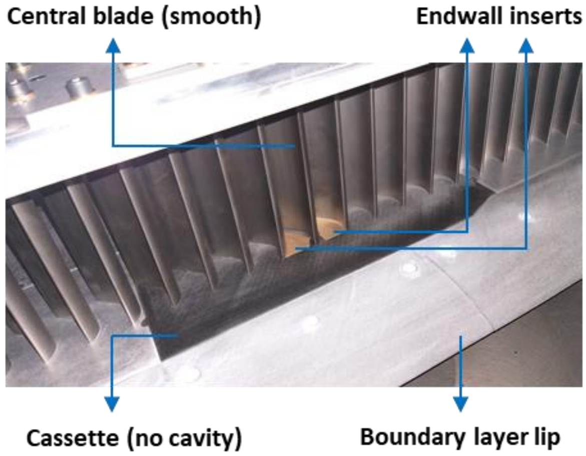


Figure 2.5: SPLEEN C1 test section with no cavity and no wake generator.

A view of the SPLEEN cascade integrated in the S1-C test facility is shown in Figure 2.6.

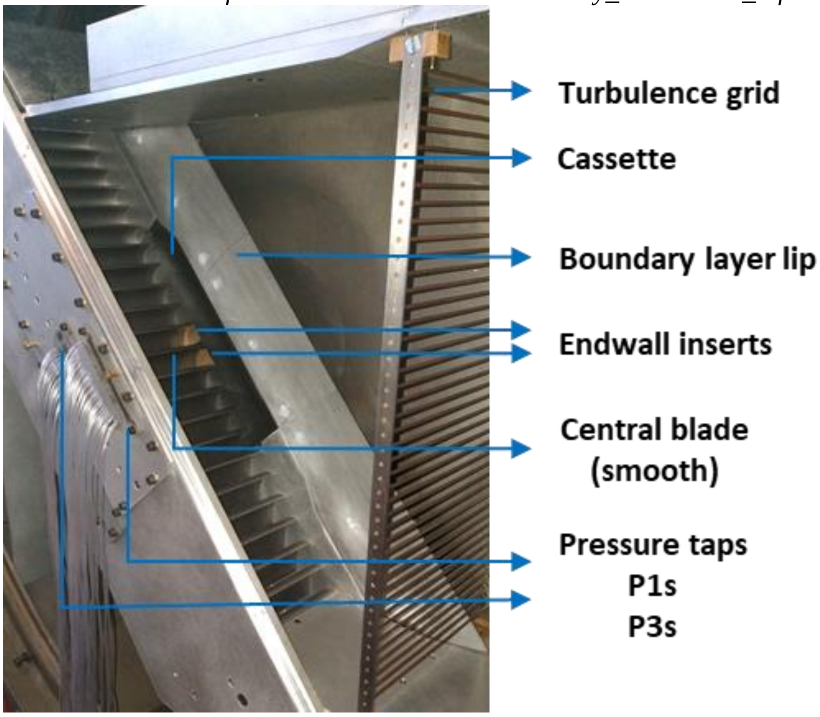


Figure 2.6: SPLEEN test section implemented in S1-C wind tunnel.

The inlet flow is generally not aligned with the inlet metal flow angle, $\alpha_{m,in}$. Therefore, the cascade was rotated of 3.43 deg (in the clockwise direction of Figure 2.7) to align the inlet flow angle with the cascade inlet metal angle. A schematic of the cascade angle, $\alpha_{cascade}$, inlet metal flow angle, $\alpha_{m,in}$, and flow angle, β_{in}, in the cascade reference system can be seen in Figure 2.7.

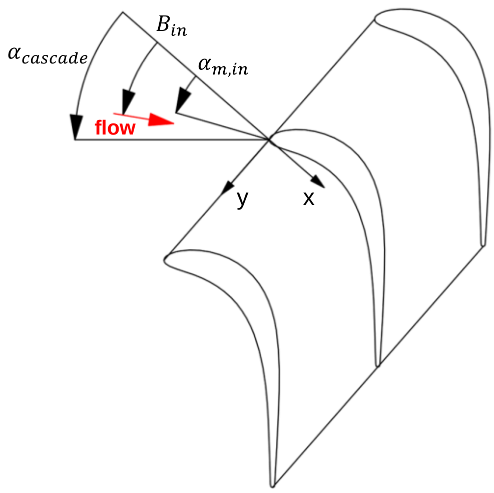


Figure 2.7: Schematic of cascade with relation between cascade angle, $\alpha_{cascade}$, inlet metal flow angle, $\alpha_{m,in}$, and flow angle, β_{in}

After the angle correction it was noted that the inlet flow angle changed accordingly. Therefore, the final inclination of the cascade used in the commission phase 1 (w/o wake generator) can be found in Table 2.2.

Table 2.2: Correction of cascade inlet angle test cases and resulting incidence for tests performed during commissioning phase 1 (without wake generator)

	Phase 1 (W/o WG)
	Angle [deg] mid-span
Cascade angle, $\alpha_{cascade}$	**40.73**
Blade metal angle, $\alpha_{m,in}$	37.3
Measured inlet flow angle w/o WG, β_{in}	36.69
Incidence, $\beta_{in} - \alpha_{m,in}$	**-0.61**

Note:
In the case of a CFD setup, the domain should be designed accounting for the inlet metal flow angle and the inlet flow incidence can be set with the data measured at Plane 02 that can be found in ..\Experimental_DataBase\SPLEENC1_NC_WGOFF\PL02\5HP\Linear_Pitchwise\

2.2.2 SPLEEN C1 test section – Phase 2

For the second phase of tests, the wake generator mounting 96 bars was installed and a specific boundary layer lip with a slot for the rotating bars was mounted in the test section. The wake generator bars rotate in correspondence of Plane 02 (53.56 mm upstream of the central airfoil LE). The same cassette without cavity used for Phase 1 was employed for this phase. The setup for the testing Phase 2 with wake generator and without cavity is presented in the sketch in Figure 2.8.

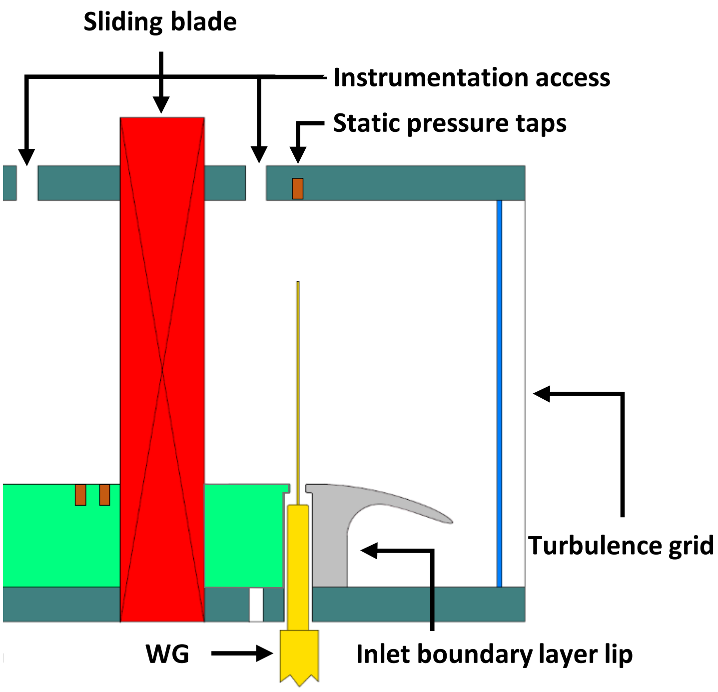


Figure 2.8: Test setup of testing Phase 2 with wake generator.

The bars of the wake generator have a length of 130 mm measured from the bar tip to its attachment to the bar support tip. The bar diameter is 1.00 mm. The bar support diameter is 12 mm.
The bar support tip is recessed with respect to the WG cavity endwall surface by 10 mm as shown in Figure 2.9. The WG cavity opening is 9 mm at the cascade endwall. The cavity slot is increased to 14 mm 4 mm away from the cascade endwall.

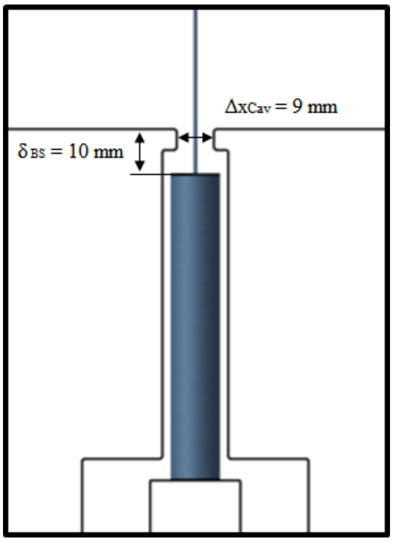


Figure 2.9: Detail of the WG geometry at the endwall interface

A figure detailing the characteristics of the cascade tested in Phase 2 is shown in Figure 2.10. This setup of the test section is used for the whole experimental activity linked with the part of the project referred to as *"Testing of Cascade SPLEEN C1 – Phase 2"*.

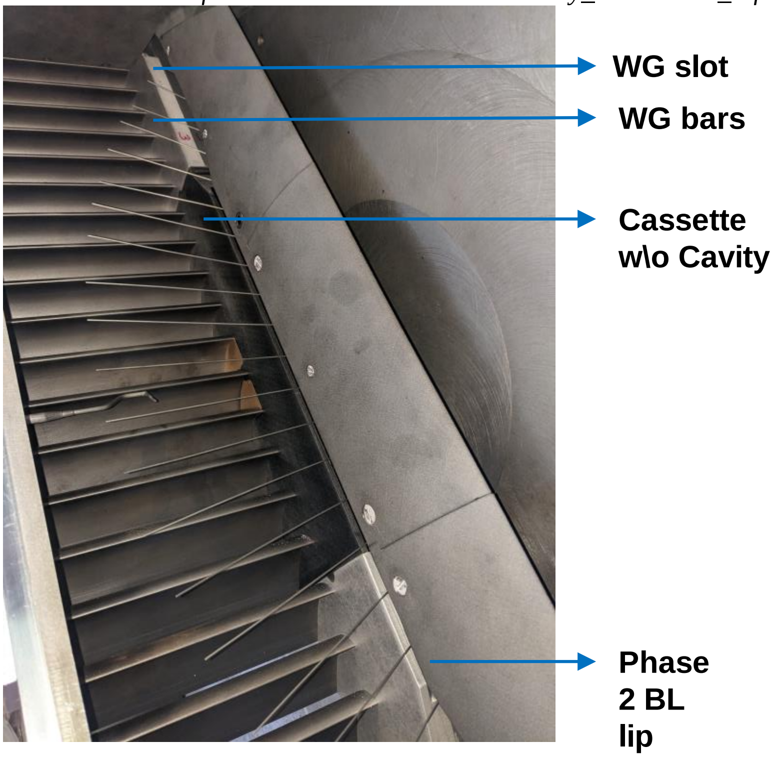


Figure 2.10: SPLEEN AF1 test section with wake generator and no cavity.

The wake generator is of the spoked-wheel type. The wake generator consists of a brass disk of 625 mm in diameter with cylindrical bars mounted on the perimeter. The radius of the disk with the bars corresponds to 517.5 mm. The bar tips rotate at a radius corresponding to 72% of the blade span (165 mm), guaranteeing that no bar tip flow pollutes the flow at the cascade midspan (limit of the region of interest for the measurements). The wake generator has an operating range of [0, 3500] RPM.

To compensate for the inlet flow turning generated by the rotating bars, the cascade was rotated clockwise by 6.2 degrees with respect to the cascade rotation set in testing Phase 1 (40.73 deg). This cascade rotation angle was defined after a series of tests performed to assess the flow incidence on the central blade. The cascade rotation for Phase 2 testing is 46.9 deg.

The measured incidence averaged over the two central pitches is -2 degrees. This value was accepted and maintained over the complete testing Phase 2 with rotating bars.

The cascade positioning in the test section for phase 2 is summarised in Table 2.3.

Table 2.3: Correction of cascade inlet angle test cases and resulting incidence for tests performed during commissioning phase 2 (with wake generator)

	Phase 2 (w/ WG)
	Angle [deg] mid-span
Cascade angle, $\alpha_{cascade}$	**46.90**
Blade metal angle, $\alpha_{m,in}$	37.30
Measured inlet flow angle w/o WG, β_{in}	35.30
Incidence, $\beta_{in} - \alpha_{m,in}$	**-2.00**

2.2.3 Turbulence grid

The free-stream turbulence intensity at the cascade inlet is increased with respect to the natural levels of the wind tunnel by installing a turbulence grid normal to the incoming flow. The grid can be observed in Figure 2.6. The grid is composed of horizontal brass rods with a nominal spacing between their centrelines of 12 mm (mesh size). The rods have a round section with a diameter of 3 mm, resulting in a geometric solidity of 0.25. A close-up view of the turbulence grid is presented in Figure 2.11, while its geometrical characteristics are summarized in Table 2.4. The grid is positioned perpendicular to the incoming flow at an axial distance of 400 mm from the central blade LE. The angle and position of the turbulence grid are regularly checked during each change of test setup configuration.

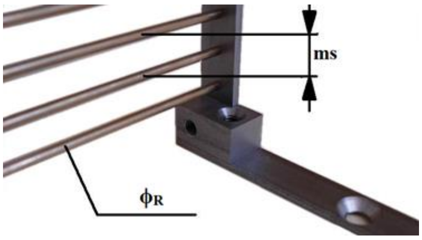


Figure 2.11: Close-up view of the turbulence grid.

Table 2.4: Geometric characteristic of the turbulence grid.

Rods diameter [mm]	ϕ_R	3
Mesh size [mm]	ms	12
Solidity	σ	0.25
Distance from LE [mm]		400
Angle to the incoming flow [deg]		90

3 Dimensional control

3.1 Cascade airfoils

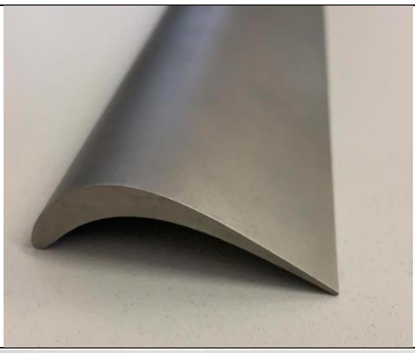
The cascade is composed of 23 airfoils:

- **13 airfoils** mounted out of the cavity cassette,
- **9 airfoils** mounted on the cavity cassette,
- **1 non-instrumented** central airfoil (**B-SMOOTH**).

The central instrumented (sliding) airfoils are:

- **1 airfoil instrumented on the suction side** with 24 pneumatic taps (**B-PNEU-SS**),
- **1 airfoil instrumented on the suction side** with 7 fast response sensors (**B- FR-SS**),
- **1 airfoil instrumented on the pressure side** with 1 fast response sensor and 17 pneumatic taps (**B-PNEU-FR-PS**),
- **1 instrumented with 53 hot-films** with 32 sensors on the suction side and 21 sensors on the pressure side (**B-HF**).

A picture of the manufactured blades is given in Table 3.1:

B-SMOOTH	
B-PNEU-SS	
B-FR-SS	

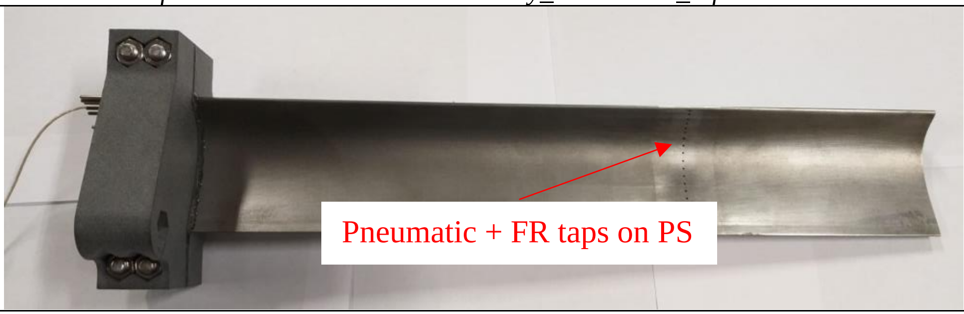
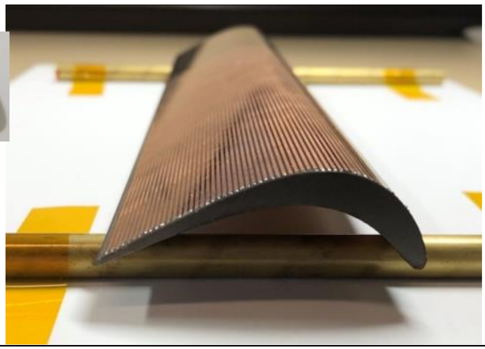
B-PNEU-FR-PS	
B-HF	 

Table 3.1: Central Airfoils for cascade SPLEEN C1

A quality control of the manufactured SPLEEN C1 airfoils has been performed on 28.08.2020 at SLS (which stands for "Steen Laser Survey") company in Beaufays, Belgium.
Measurements of the airfoil 2D profile dimensions and roughness parameters have been performed on a total of 6 blades (3 non-instrumented smooth airfoils and 3 instrumented airfoils) at 3 span locations (25%-50%-75% of the airfoil total height).
The smooth blade instrumented with hot-films has not been measured due to the fragility of the hot-film sensors. Please note that this blade was manufactured with a reduced section to account for the actual thickness of the plastic foil containing the hot-film array, and thus reconstruct the original profile geometry.

At each span location, four measurements have been performed to interrogate the entire section profile: Leading Edge – Trailing Edge – Pressure Side – Suction Side profile parts.
The dimensional control measurements have been performed on the airfoils in their final form, ready for installation in the test section, and already instrumented when the case.

A total amount of **72 measurements** has been performed (**6 airfoils** * **3 span locations** * **4 sections**).

The device used to perform the quality control is a digital contact profilometer “Jenoptik Waveline W800RC”. Its characteristics are summarized in Table 3.2.

Accuracy of dimension control	**[µm]**	0.8
Speed	**[mm/sec]**	1.0
X-axis scale resolution	**[µm]**	0.1
Accuracy of roughness	**[nm]**	6.0
Spatial sampling along the X-axis	**[µm]**	1.0

Table 3.2: Characteristics of the digital contact profilometer “Jenoptik Waveline W800RC”

2D profile and roughness measurements have been performed on the following 6 airfoils:

- **“Blade adjacent right”** and **“Blade adjacent left”:** 2 airfoils adjacent to the central airfoil (span: 165 mm) mounted on the cavity cassette,
- **B-SMOOTH:** 1 central smooth airfoil with a span of 185 mm,
- **B-Pneu-SS:** 1 airfoil with a span of 320 mm instrumented on the suction side with 24 pneumatic taps,
- **B-FR- SS:** 1 airfoil with a span of 320 mm instrumented on the suction side with 7 fast response sensors,
- **B-PNEU-FR-SS:** 1 airfoil with a span of 320 mm instrumented on the pressure side with 1 fast response sensor and 17 pneumatic taps.

The nomenclature used for the smooth blades is shown in Figure 3.1:

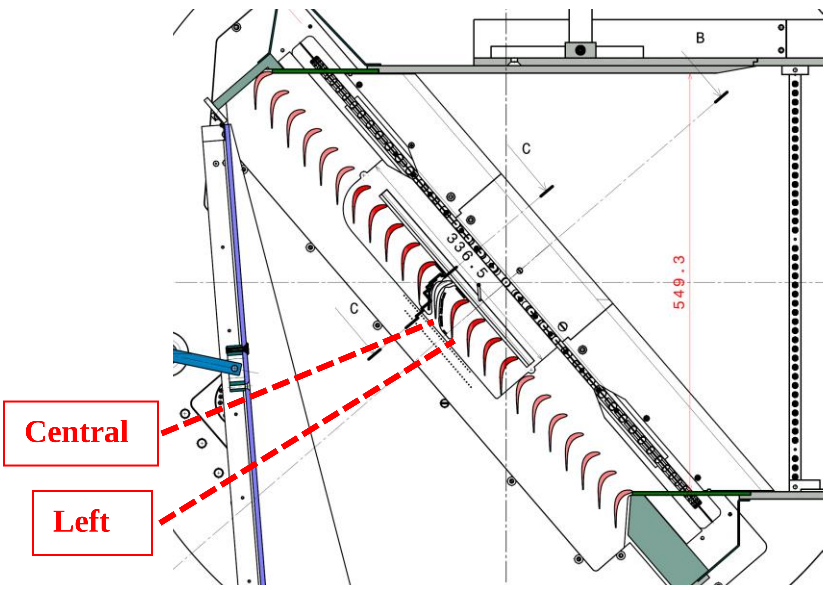


Figure 3.1: Definition of central, left and right blade

The prescribed shape tolerance was set to ±0.050 mm as shown in the blueprint shown in Figure 3.2. The target (maximum) airfoil roughness was 2.0 µm.

Measurements of the profile 2D dimensions and roughness parameters are available for each measured airfoil. The X/Y coordinates of the measured profiles are provided in the database under the folder *"/Test_Case_Setup/ SPLEENC1_Airfoil_DimControl"*.

Maximum and minimum 2D profile deviations and measured roughness parameters (the centreline average roughness Ra [µm] and the rms roughness Rq [µm]) are reported in the following for each controlled airfoil.

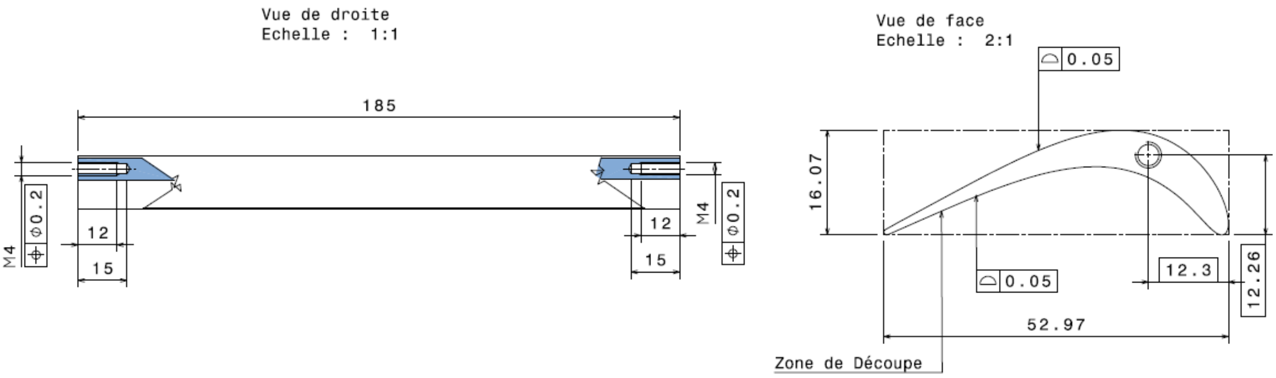


Figure 3.2: B-SMOOTH profile shape tolerances (snapshot of technical drawing shared with the manufacturer)

Table 3.3 summarizes the maximal and minimal deviation for the "blade adjacent left" with respect to the theoretical profile, as well as the main roughness parameters:

Measurement	Span location	Max. deviation [µm]	Min. deviation [µm]	Ra [µm]	Rq [µm]
PS	25%	+28.2	-27.1	1.75	2.19
	50%	+46.8	-99.1	1.49	1.96
	75%	+27.6	-21.3	1.71	2.15
SS	25%	+35.0	-35.0	1.83	2.28
	50%	+34.9	-38.4	2.01	2.48
	75%	+32.6	-33.5	1.99	2.44
TE	25%	+15.5	-29.5	Not measured	
	50%	+19.0	-43.5		
	75%	+20.6	-45.1		
LE	25%	+57.9	-39.9	Not measured	
	50%	+53.3	-40.1		
	75%	+50.8	-42.9		

Table 3.3: Blade adjacent left summary results

Note: the reported minimal deviation of -99.1µm is attributed to an error of the measurement device. The minimal deviation is most likely to be around -30.0 µm.

Table 3.4 summarizes the maximal and minimal deviation for the "blade adjacent right" with respect to the theoretical profile, as well as the main roughness parameters:

Measurement	Span location	Max. deviation [µm]	Min. deviation [µm]	Ra [µm]	Rq [µm]
PS	**25%**	+58.9	-36.2	1.80	2.25
	50%	+35.8	-33.9	1.76	2.19
	75%	+63.6	-50.8	1.68	2.13
SS	**25%**	+34.5	-46.0	1.99	2.42
	50%	+39.0	-46.4	2.02	2.47
	75%	+32.1	-36.5	1.95	2.40
TE	**25%**	+14.9	-24.3	Not measured	
	50%	+12.6	-37.0		
	75%	+13.8	-42.4		
LE	**25%**	+49.3	-52.3	Not measured	
	50%	+58.0	-43.4		
	75%	+51.2	-45.2		

Table 3.4: Blade adjacent right summary results

Table 3.5 summarizes the maximal and minimal deviation for the "blade central" with respect to the theoretical profile, as well as the main roughness parameters:

Measurement	Span location	Max. deviation [µm]	Min. deviation [µm]	Ra [µm]	Rq [µm]
PS	**25%**	+36.7	-62.2	1.57	1.97
	50%	+28.2	-19.5	1.51	1.91
	75%	+31.7	-21.3	1.46	1.88
SS	**25%**	+32.4	-38.1	1.63	1.93
	50%	+29.1	-36.6	1.67	1.98
	75%	+27.4	-34.7	1.46	1.73
TE	**25%**	+15.8	-36.1	Not measured	
	50%	+13.9	-30.5		
	75%	+11.1	-31.5		
LE	**25%**	+53.7	-46.6	Not measured	
	50%	+55.5	-48.0		
	75%	+54.0	-56.1		

Table 3.5: B-SMOOTH summary results

Table 3.6 summarizes the maximal and minimal deviation for **B-PNEU-SS** blade with respect to the theoretical profile, as well as the main roughness parameters:

Measurement	Span location	Max. deviation [µm]	Min. deviation [µm]	Ra [µm]	Rq [µm]
PS	25%	+77.3	-52.7	1.23	1.67
	50%	+25.6	-19.4	1.40	1.82
	75%	+47.1	-32.1	1.43	1.89
SS	25%	+31.2	-42.0	1.64	1.96
	50%	+47.1	-32.1	1.61	1.93
	75%	+33.2	-33.9	1.57	1.87
TE	25%	+32.6	-40.2	Not measured	
	50%	+16.8	-33.5		
	75%	+11.3	-24.4		
LE	25%	+25.5	-57.7	Not measured	
	50%	+45.4	-72.6		
	75%	+35.2	-65.6		

Table 3.6: B-PNEU-SS summary results

Table 3.7 summarizes the maximal and minimal deviation for the **B-FR-SS** blade with respect to the theoretical profile, as well as the main roughness parameters:

Measurement	Span location	Max. deviation [µm]	Min. deviation [µm]	Ra [µm]	Rq [µm]
PS	25%	+32.8	-30.7	1.62	2.03
	50%	+24.9	-23.3	1.37	1.81
	75%	+75.3	-21.0	1.45	1.92
SS	25%	+36.5	-40.2	1.44	1.74
	50%	+37.1	-38.1	1.43	1.69
	75%	+37.7	-52.1	1.36	1.62
TE	25%	+17.1	-48.2	Not measured	
	50%	+19.6	-62.2		
	75%	+18.2	-46.0		
LE	25%	+42.3	-61.9	Not measured	
	50%	+43.0	-69.2		
	75%	+41.7	-52.9		

Table 3.7: B-FR-SS summary results

Table 3.8 summarizes the maximal and minimal deviation for the B-PNEU-FR-PS blade with respect to the theoretical profile, as well as the main roughness parameters:

Measurement	Span location	Max. deviation [µm]	Min. deviation [µm]	Ra [µm]	Rq [µm]
PS	**25%**	+42.4	-64.4	1.88	2.35
	50%	+59.3	-29.7	1.88	2.34
	75%	+68.8	-34.1	2.01	2.51
SS	**25%**	+48.2	-69.4	1.31	1.55
	50%	+43.2	-70.4	1.35	1.59
	75%	+36.1	-45.0	1.23	1.49
TE	**25%**	+22.7	-50.8	Not measured	
	50%	+15.3	-46.7		
	75%	+17.9	-41.9		
LE	**25%**	+48.6	-46.5	Not measured	
	50%	+48.0	-38.9		
	75%	+58.8	-48.3		

Table 3.8: B-PNEU-FR-PS summary results

3.2 Cascade lower endwall (aka the cavity cassette)

Figure 3.3 shows the cavity cassette in the configuration without cavity. The central blade is missing on the picture and one can see the endwall insert slots filled with the plastic inserts for hot-film endwall measurements (at the time the picture was taken the inserts had not yet been instrumented with the hot-film plastic sheets).

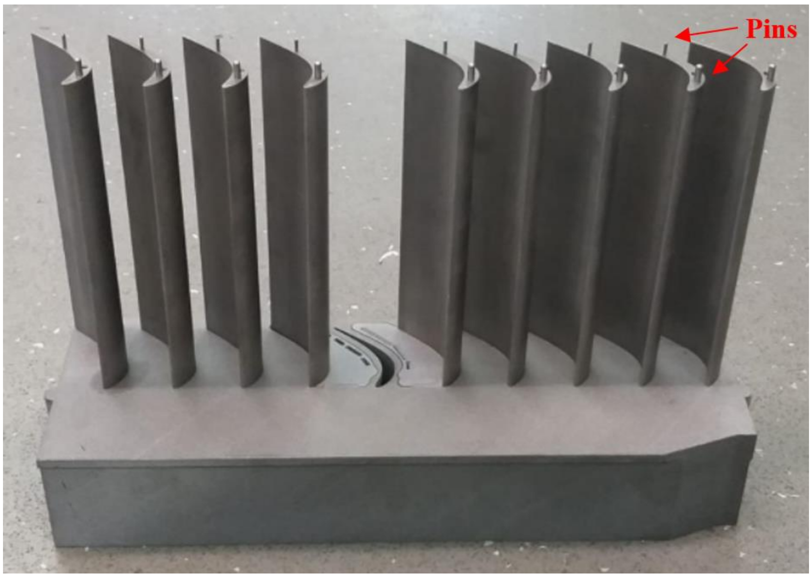


Figure 3.3: Blade and cavity cassette (SPLEEN baseline)

The positioning of the airfoils is made possible by means of 4 pins inserted on both the cavity cassette (2 pins) and on the aluminum part located on the opposite side (2 pins). The tolerance on the blade pins positioning is 0.02 mm, as highlighted in the technical drawing shown in Figure 3.4.

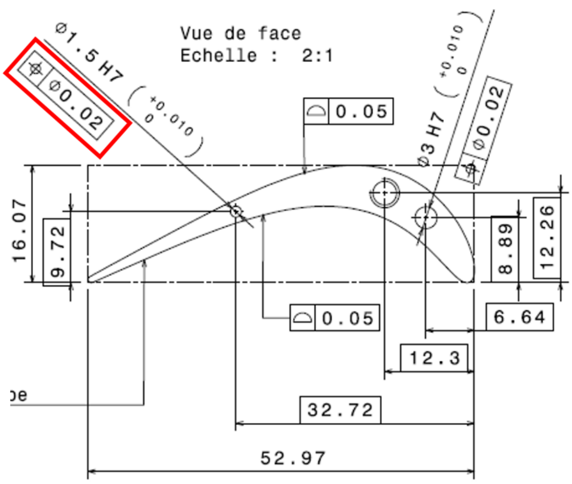


Figure 3.4 : Blade pins tolerance

The bottom endwall cassette was hand-polished after 3D printing. The surface roughness was measured by the surface roughness tester "148 460 Mitutoyo Surftests SJ 201P" after the polishing treatment. The roughness was measured on multiple points distributed all over the entire cassette surface, at each point along 3 orthogonal directions.
The average roughness was comprised between **Ra= [1.65, 1.75] µm.**

3.3 Endwall inserts

The two endwall passages adjacent to the central blade are instrumented with pneumatic and fast-response pressure taps, and surface mounted hot-films. Two smooth inserts were manufactured and always installed when endwall measurements are not performed.

The 3D printed cavity cassette that hosts the endwall inserts, is manufactured with an extra thickness of 0.3 mm that is removed gradually by hand polishing. This procedure guarantees that the inserts are flush mounted with the cavity cassette within ±0.02 mm.

Figure 3.5 represents the integration of the smooth and instrumented inserts in the SPLEEN cascade:

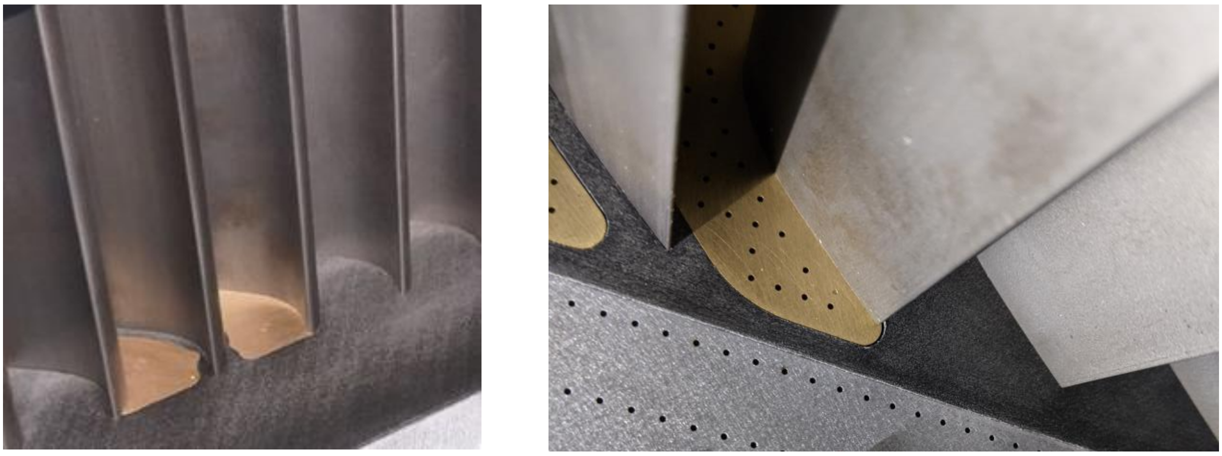


Figure 3.5: Integration of the smooth and instrumented inserts into the SPLEEN cascade

The roughness of the metallic inserts has been measured by means of a Surface Roughness Tester: "148 460 Mitutoyo Surftest SJ 201P" with the following characteristics:
- Range: 0.01 µm < Ra < 100 µm,
- Resolution: 0.01 to 0.4 µm depending on the measurement range (0.01µm for the measurement performed in SPLEEN).

The roughness levels for all metallic inserts (smooth and instrumented pressure inserts) were measured to range between **Ra = [0.8, 0.9] µm.** Measurements have been taken all over the inserts surface in three different directions. Due to the fragility of the hot-film sensors, **no roughness measurement has been performed** on the hot-film endwall inserts.

3.4 Wake generator bars

As shown in Figure 3.6, the wake generator of the S1 high-speed linear cascade facility consists of a set of cylindrical bars mounted on a rotating disk, with an operating range of [0, 3500] RPM. The bars are fixed to supports that are connected to the disk by means of a mechanical fixation (threads), the rotating disk as well as supports are made of brass while the bars are made of Molybdenum.

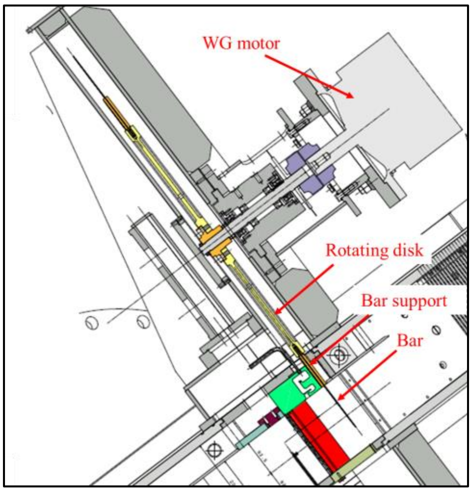


Figure 3.6: S1 facility wake generator

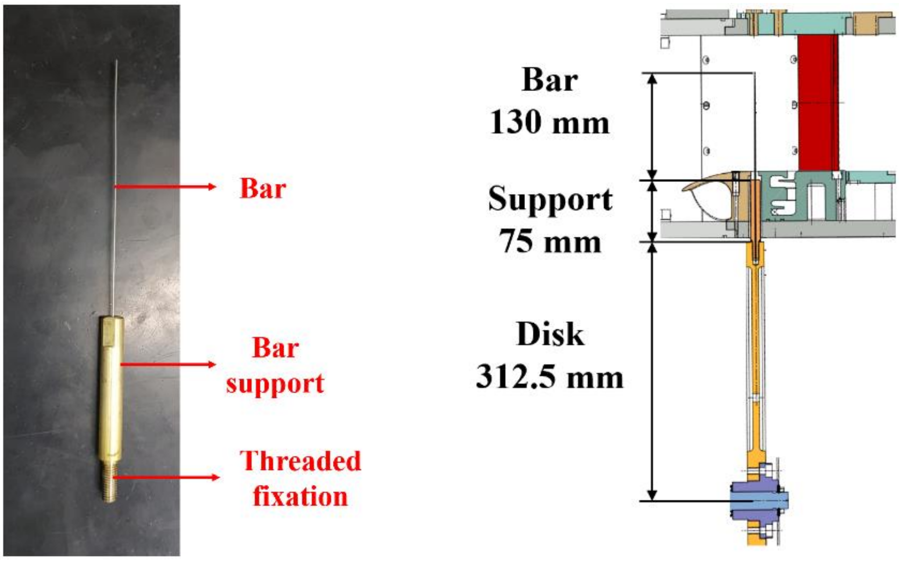


Figure 3.7: Bar-support assembly (left), full rotating assembly (disk, support and bar) dimensions in the test section (right)

Figure 3.8 shows an example of the Molybdenum bar inserted in the bar support:

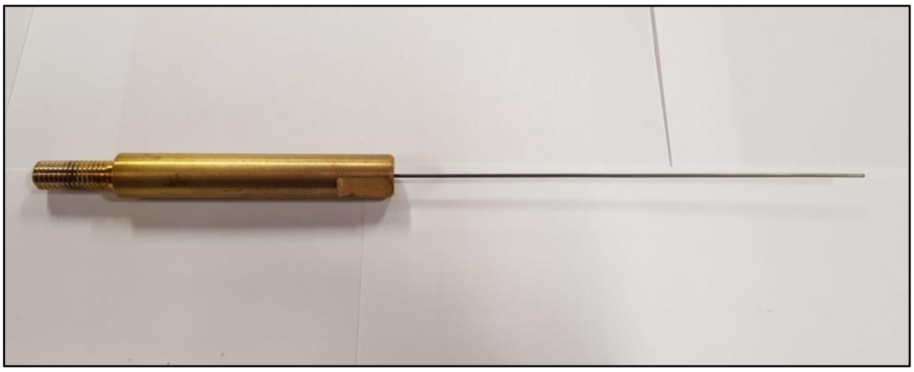


Figure 3.8: Molybdenum bar inserted in the bar support

A dimensional control on the wake generator elements was performed. All critical dimensions were verified to be design compliant. In particular, the bar diameter was measured to be compliant with the design specification, with an average diameter of **Φ=1.00 mm ±0.01 mm**.

3.5 Turbulence grid

Figure 3.9 shows the integration of the turbulence grid in the wind tunnel.

Figure 3.9: Turbulence grid installation in the wind tunnel

The critical dimensions of the turbulence grid have been measured in-situ, on the assembled turbulence grid. The geometric characteristics of all the rods and distance between each of them was measured by means of an electronic calliper. Results are summarized in Table 3.9.

Number of bars	**$\#_{bars}$ [-]**	44
Diameter of rods	**Φ_{rods} [mm]**	between [2.97-3.00]
Distance between rods (centreline)	**Δ_{rods} [mm]**	between [12.03-12.05]

Table 3.9: Turbulence grid characteristics