ADVANCED CHARACTERISATION OF A FAN SUBMITTED TO PISTON EFFECT

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ABSTRACT

In the frame of the "Grand Paris Express" network, Eiffage designed a test cell to test the behaviour of a model fan to the train piston effect. The test cell has already been presented in the last TSV conference. In this paper, it is proposed to focus on the model fan.

The model fan has been first tested by manufacturer in the unexplored area of negative pressure and negative flowrate both in forward and reverse mode. Then it has been operated on the Eiffage test cell with successive negative and positive forced pressure on hundreds of thousands of cycles.

Aeraulic, electric and mechanical parameters recording have been conducted on the model fan during these tests.

The behaviour of the fan in wind milling mode has also been tested in insufflation and extraction mode when submitted to a flow generated by train passage and piston effect.

In parallel, CFD simulations have been conducted on the model fan in steady mode to determine the velocity profile on the blades and to illustrate the passage of air through the impeller with a negative airflow. It has also been carried out for an unsteady case.

Keywords: metro tunnel, train piston effect, model fan, CFD, test cell

1. INTRODUCTION

The piston effect created by train passing in the 200 km of tunnels of the new "Grand Paris Express" network [1] ("GPE") has been estimated to create a variation of + 900 Pa / – 1400 Pa in a few seconds. These pressure fluctuations will be transmitted in the stations and in the service structures where the ventilation equipment is installed.

The fans that will allow the "push-pull" type ventilation and smoke extraction system [2] of the metro will also be operated for normal mode of ventilation.

At reduced speed, the study of operating curves [3] has demonstrated the fans will be passed through with a negative airflow and also operated in negative pressure. Therefore, they will be operated in areas that are not usually defined by the usual.

People involved were aware that the consequences could be dramatic for operation: the fans could be damaged in operational shortly after commissioning and would cause restrictions (or closure) of lines while operating.

2. THE PISTON EFFECT ON FAN

The fans that are installed by Eiffage in the ventilation service structures and train stations of lines 15 South, 16 and 17 of GPE are from Howden. The model ANR-2371/1122 will allow an operation for both fire extraction mode (operating point 1) and normal mode of ventilation (operating point 2).

In case of fire, the fan will generate a flowrate of 150 m^3/s and face a network resistance of 1,200 Pa. In normal mode, the fan will work half speed and will generate a flowrate of 75 m^3/s for a total pressure of 300 Pa.

The study of operating curves at this reduced speed raised many questions [3]. First it revealed the need for anti-stall treatment. Then it has allowed to investigate how the piston effect will influence the operation of the fan. The effect of train arriving (overpressure of + 900 Pa in the tunnel experienced as decrease of 900 Pa for the fan) suggests that the fan will face negative pressure. This implies *a priori* the operation of the motor as a generator (negative mechanical power). And the effect of train leaving (depression of – 1,400 Pa in the tunnel) suggests the fan will be passed through with a negative airflow even though the fan is still running the same direction.

It appeared the fans would be experienced in operating zones never encountered. As a consequence, they have to be characterized in these zones and have their resistance and durability tested with strong pressure variations.

3. THE MODEL FAN

The consequences of piston effect (both in the thresholds and in the pressure gradients) can be characterized on a model fan. [3] Scale consideration led Eiffage to carry out the tests on a fan with a diameter of 1,000 mm. The model fan is ANR-1000/473.

The ratio between the real size fan diameter and the model fan diameter is 2,371.

In order to have the same blade loading, the tip speed had to be the similar. With a speed of 490 rpm, the model fan had to be performed with a speed of around 1,150 rpm.

With a speed of 1,150 rpm, the Reynolds number calculated on the tip speed and tip diameter is 4 10^6 that is superior to 3 10^6 as recommended by AMCA 802 to avoid scale effect.

The tip speed Mach parameter of the real size fan at 490 rpm is 0.181. The tip speed Mach parameter of the model fan should be inferior to 0.35 in accordance with AMCA-802, which corresponds to a speed of 1,670 rpm.

The requirements for dynamic similarity were respected.

The following table gives the scaling and operating points of the model fan.

Table 1: Real size and model fan characteristics

	Real size	**Model**
Impeller diameter	2,371 mm	1,000 mm
Hub diameter	1,122 mm	473 mm
	Operating point 1	
Airflow	150 m^3/s	26.7 m^3/s
Total pressure	1,200 Pa	1,200 Pa
Rotation speed	980 rpm	2,324 rpm
	Operating point 2	

Airflow	75 m³/s	13.3 m³/s
Total pressure	300 Pa	300 Pa
Rotation speed	490 rpm	1,162 rpm

4. THE MODEL FAN CHARACTERIZATION

4.1. Aerodynamic test by manufacturer

The test fan had to be characterized by manufacturer for the specified operating points in smoke extraction mode and normal mode. It had also to be tested at negative pressure and negative flow, both in forward and reverse direction. In total, 6 tests had to be conducted.

Figure 1: The tests at manufacturer facilities – Howden Denmark on the left, Howden France on the right

First the model fan has been characterized by manufacturer in Howden facilities (Denmark) in accordance with AMCA 802. The operating curves at 1,150 rpm is presented below:

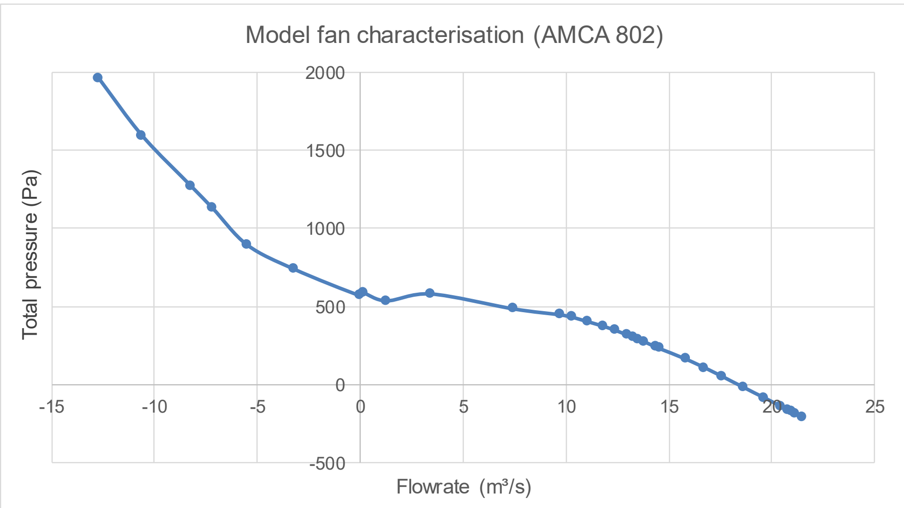

Figure 2: The characterization of model fan according to AMCA 802

Then the model fan has been characterized in accordance with standard ISO 5801 (ex NF X 10-200) in Howden France facilities. The tests have been realized at the speed of 1,470 rpm with many diaphragms that allowed to determine total pressure for a flowrate from 20 to 0.01 m³/s in both directions.

The transposed operating curve is presented on the figure below:

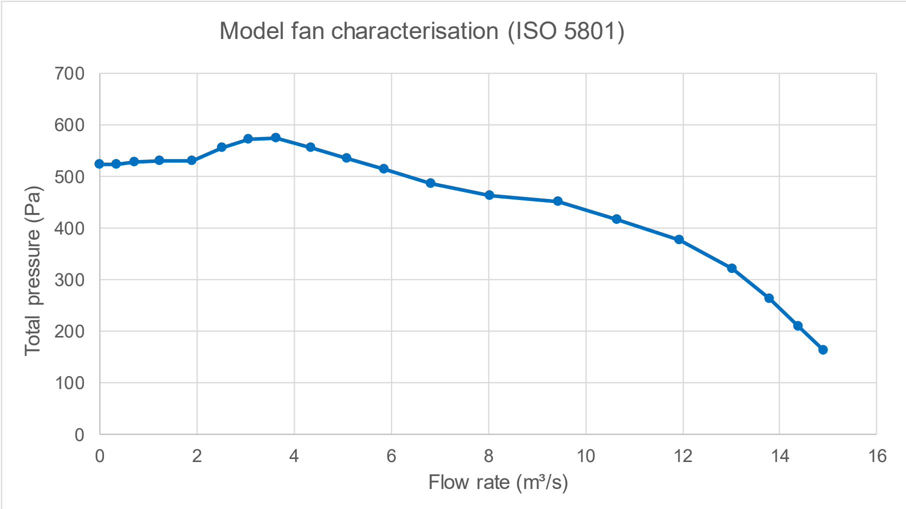

Figure 3: The characterization of model fan according to ISO 5801

The model fan has been tested by two methods: the first one (in Denmark) has allowed to characterize the operating curve in negative airflow and negative pressure; the second one (in France) carried out in a second time has allowed to refine the "stall" zone of the operating curve. Both measurements series are complementary. Even if some differences can be noticed on the curve, the results present a quite satisfactory matching.

4.2. Tests at Eiffage

Then the model fan has been installed and operated on the test cell designed by Eiffage to simulate the train piston effect. Pictures can be found in [4] and below.

The test cell is equipped by many sensors. On each upper and lower ducts of the circuit, there at least two means of airflow determination which could be:

- Vane anemometers;
- Static pressure probes;
- Measurement wings.

There are 3 anemometers: one is placed in the upper duct to measure airflow upstream the fan when operated in negative direction (equivalent to train leaving) and the two others are in the lower duct to measure airflow upstream and downstream the fan when operated in positive direction (equivalent to train arriving).

Flow is also measured with pressure probes in the area of the model fan impeller and the flow straighteners. Moreover, a measurement damper (a classic damper whose blades are fitted with pressure taps [5]) was placed in the upper duct that allow to determine the flow through the duct.

The bench has been calibrating with Pitot probe measurement on 36 vertical and horizontal points on a section with log-Tchebycheff distribution (according to NF EN ISO 5802). All the sections close to anemometers have been tested. In parallel, the "dzeta" or pressure drop coefficient of the grid (or "flow straightener disposal") that has been added in the duct has been determined.

Figure 4: The model fan with anemometers and pressure probes

The fan is also equipped with vibration sensors. Temperature bearings and windings are also measured. Voltage, intensity, torque, power, etc. are recorded too.

The model fan has been tested on the test platform for several months. More than 400,000 cycles have been performed, corresponding to 400,000 train passing with maximum overpressure and depression, which can be equivalent to an operation over more than 10 years.

Aeraulic data

The flow rates measured are those expected according to the operating curve of the fan. The variation takes place around a nominal flow of 13 m³/s to reach 19.5 m³/s when operated in positive direction and – 8 m³/s when operated in negative direction.

The total pressure maximum and minimum that were measured correspond to those expected. The variations reach a peak around 1,200 Pa in negative flow and another peak around – 200 Pa with flow in the same direction than fan airflow generation.

An example of the model fan total pressure variation is represented below:

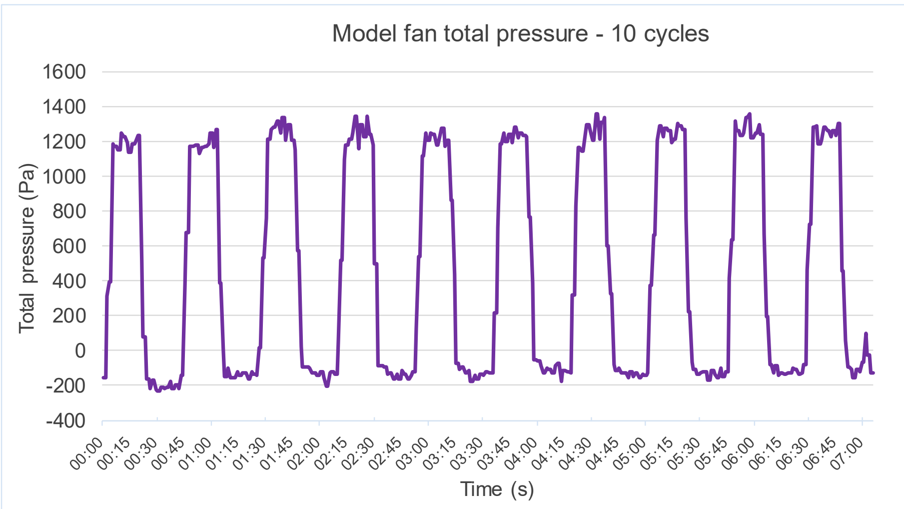

Figure 5: Total pressure variation of model fan

Electric data

This variation is faced by the inverter which accelerates or brakes the motor to meet its parameter settings.

In negative direction, the model fan is facing high pressure. Despite a slight decrease in speed rotation, the motor runs in the same direction (driven by inverter). From an electric point of view, the engine torque increases significantly.

In positive position, the limit of driving by the centrifugal fan (corresponding to an almost zero pressure) is reached. From an electric point of view, the mechanical power at the shaft is then negative. T fan works as a generator.

There is a significant increase in the level of vibration during a complete cycle, while remaining within the acceptable limits defined by standards for this type of fan.

During the 400,000 cycles, no warm-up in the windings or the bearings were measured. The temperatures of the windings were stabilized at 50 °C and those of the bearings at 45 °C.

Mechanical data

Strain gauge measurement have been recorded on 2 blades of the model fan in order to investigate blade stress at train passage. The strain gauges were mounted on both side of one blade and one side another blade.

Stress blade has been measured during a complete cycle from negative air flow under high pressure to negative pressure. The level of stress measured on the blades is of the order of 4 / 5 MPa. A comparable stress level is expected on the real size blades.

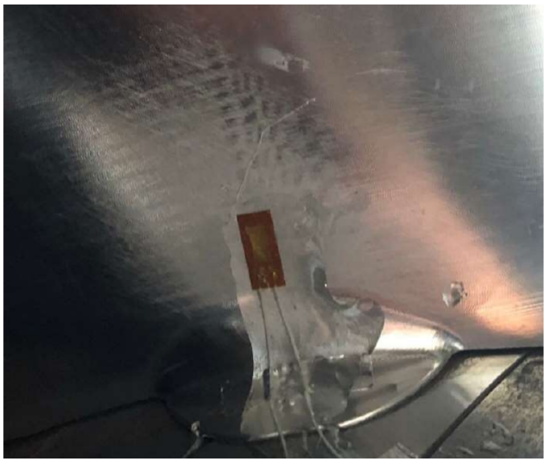

Figure 6: Strain gauge on blade

The finite element analysis report provided by manufacturer for the real size fan indicated values of the order of 3.5 / 4 MPa (at the exact position of the gauges). These tests therefore made it possible to conclude to the validity of the calculation note carried out on the real-size blades and to validate the limit of 22.9 MPa for an infinite number of cycles.

5. CFD

The pressure and speed sensors distributed across the test cell allow to determine the air flow rates in the different ducts and on either side of the model fan propeller. However, they do not allow to measure and represent what is happening at the propeller.

The aim is to study, using numerical simulation, the flow in the vicinity of the propeller and particularly between the blades. The profiles on "common" operating points are generally well known; on the other hand, a visualization of the counter-current speed profiles is not well known. To better define the later, a dedicated study of the speed profiles on the blade (from the hub to the tip of the impeller) as well as in the spaces between the blades was performed.

5.1. Mesh and methodology

The mesh is produced in ANSYS MESHING.

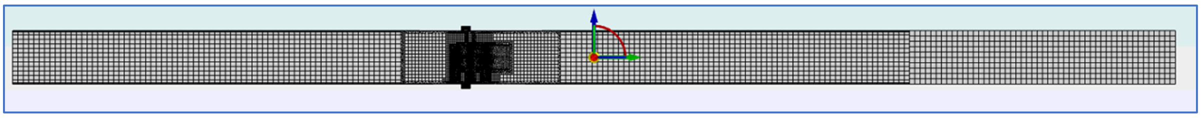

Figure 7: Mesh of platform

Numerous tests were carried out to define the meshing methodology. The latter was chosen as a result from a compromise between accuracy and size of the model. The optimal number of meshes used to model the Ivanov ring was defined to have precise results without generating models that are too large and difficult to use.

The turbulence model k-w SST was used to account for the flow around the impeller. Wall law is modelized using low y+ model.

Boundary limits are "mass-flow inlet" to the left of the domain and "pressure outlet" to the right of the domain.

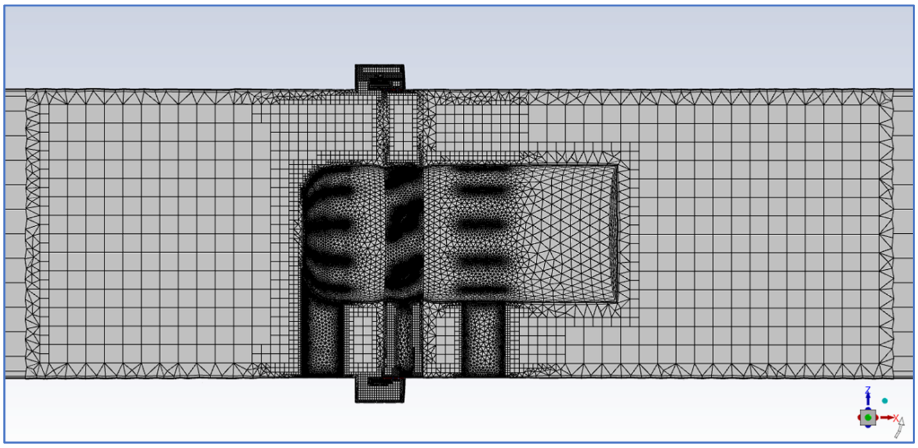

Figure 8: Mesh of model fan

Fan rotation is simulated. It is taken into account in two ways:

- with Multi Reference Frame: the impeller is stationary, and a drive speed is applied in the fluid domain containing the impeller;
- with Sliding Mesh: the impeller physically rotates; the simulation is therefore by definition unsteady.

The simulations and post-processing are produced in ANSYS FLUENT.

5.2. Results

First, steady cases were considered. Six cases with flowrate as input and total pressure difference as output were studied:

Table 2: Steady cases

	Qv	Pt		Qv	Pt
Case 1	- 5 m³/s	840 Pa	Case 4	11 m³/s	410 Pa
Case 2	0 m³/s	570 Pa	Case 5	13 m³/s	320 Pa
Case 3	6 m³/s	510 Pa	Case 6	20 m³/s	- 100 Pa

The figure below summarises the results for the 6 cases. It shows the speed at the trailing edge of the blade from the hub to the tip of the impeller. The normal mode ventilation operating point is represented by Case 5.

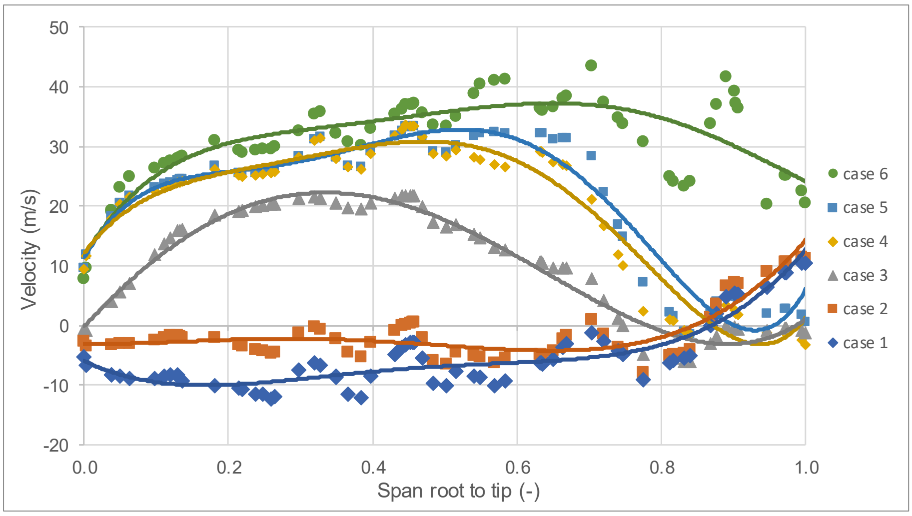

Figure 9: Profiles of axial speeds at the trailing edge of a blade of model fan

It can be noted that for all cases the maximum flow rate through the impeller moves from the root of the blades towards the tip as the flow rate increases.

For the Case 1 and 2, a shear flow is observed at the tip of the blade. As expected for an axial fan with such a blade angle, the negative flow simulated in Case1 is observed close to the hub. It could be explained also by the presence of Ivanov ring at the periphery.

Other results as streamlines between the blades or velocity vectors in Ivanov ring were recorded for further analysis.

Then unsteady case has been studied. The signal of pressure has been used as input for a flow rate range [-10 m³/s; 25 m³/s]. Unsteady results will be presented during the conference.

6. CONCLUSION

The test cell has allowed to test the resistance and the durability of the fan submitted to pressure variations with very strong pressure gradients both positive and negative over a very short time interval. Tests with pressure gauges have proven the blade to be compliant to resist millions of cycles.

All these tests have allowed to characterize the behaviour of the fan with significant airflow disturbances in operation. This test cell has confirmed the project stakeholders and especially the owner, Société des Grands Projets, on the resistance and durability of the fans subjected to the piston effect of the trains.

The CFD study has highlighted the flow patterns. It could be kept in mind that maximum flow through the impeller moves from the root of the blades towards the tip and that vortices in the Ivanov ring change from transverse to longitudinal as the flow increases.

7. ACKOLEGEMENT

We would like to thank Aurelien Auzias who conducted the CFD simulations.

8. REFERENCES

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