Pressure Measurements in an Axial Compressor: from Design Operating Conditions to Rotating Stall Inception

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ABSTRACT

The reduction of the environmental impact is nowadays the crucial challenge for the aeronautic industry. The following of a lower consumption of the vehicles has led to more compact and high loaded engines, increasing the internal flow unsteadiness and the occurrence of unstable phenomena, especially for compression stages.
In this work the casing pressure characteristics in a single stage axial compressor both for normal-to-stall transient regime and for stalled conditions will be discussed. A special unsteady measurement window was designed, covering an entire rotor pitch, in the circumferential and in the axial extent, and allowing to solve pressure fields with high spatial resolution for several relative rotor/stator positions. A phase locked average technic was applied to obtain the pressure fields during normal and stalled operating conditions.
The emergence of a spike-type pressure perturbation was captured during transient; the gradual alignment of the tip leakage vortex trajectory with the inlet rotor section was observed before the precursor appeared; this corresponds, following [1], at one of the criteria for spike stall inception machines. An original way to observe the rotating stall phenomenon is proposed; the phase-locked technic used allowed reconstructing the average pressure field in the perturbation reference frame. The salient rotating stall pattern features will be described.

1. INTRODUCTION

The reduction of the environmental impact is nowadays the crucial challenge for the aeronautic industry. The following of a lower consumption of the vehicles has led to more compact and high loaded engines, increasing the internal flow unsteadiness and the occurrence of unstable phenomena, especially for compression stages.
A better understanding of the engines' behavior during transition from stable to unstable operating regimes should allow reducing the surge safety margin and finalizing control technics, delaying the instabilities appearance. A great effort has been done for 20 years in trying to unravel the details of stall onset processes. The multitude of stall inception patterns observed was classified by [2] in two main groupings, spike-type and modal waves. Being the most common in real aeronautical compressor engines, spike-type precursor has attracted the interest of the scientific community. It is about a rapid perturbation of the flow near the casing, extending on few rotor pitches and rotating at 70-80% of rotor speed.
Many studies have been carried out in order to understand which parameters mostly affect the emergence of this kind of precursor; Camp & Day [2] have, for instance, underlined the importance of the incidence angle, whereas [3] focused on the effects of the stagger angle.
Other works focused on the flow mechanisms leading to the emergence of this kind of perturbation. The experimental investigations of [4] and the numerical simulations of [1] are in perfect agreement, identifying two main criteria for spike initiated rotating stall: the tip leakage vortex trajectory tends to align with the rotor inlet plane, whereas at the trailing edge a backward flow is observed. Following [4], while the vortex trajectory progressively aligns with the leading edge plane the incoming flow spills to the next blade-to-blade channel. Yamada et al. [5] studied, instead, spike

flow pattern under particular conditions, "mild stall conditions"; they observed the emergence of a tornado-like vortex, connecting the blade suction side with the casing during spike evolution process.

The more common set-up used in order to capture this kind of phenomena is to analyze pressure and/or velocity evolution for some discrete circumferential positions at the rotor inlet and outlet sections. More sophisticated measurement set-ups have also been used ([5], [6], [7]) allowing capturing the instantaneous pressure field pattern on the whole blade-to-blade channel with high time and space resolution.

The aim of this work is to provide further information about the inception and the pattern of rotating instabilities. Unsteady pressure investigations were carried out in a low speed single stage axial compressor, using a specially designed measurement window. Combining frequency domain analysis and phase-locked averaging data treatment, the evolution of the pressure behavior from design conditions to stalled regime will be discussed. While the classical way to observe the instabilities involves instantaneous representations, the originality of this work consists in extracting the instability pattern, by depolluting it from all the other concurrent phenomena.

2. THE CME2 COMPRESSOR

The CME2, showed in Fig.1, is a low speed single stage axial compressor, especially designed for instabilities investigations.

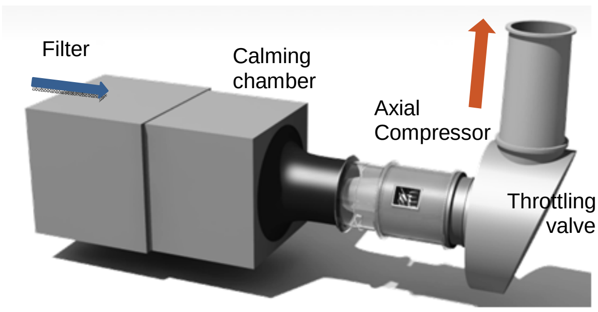

Figure 1 Compressor test rig

The operating point during stalled conditions remains effectively stable; although an unsteady phenomenon is installed, the average values of the flow rate and of the pressure rise are constant. The main features of the test rig are listed in Tab.1.

The experiments reported in this paper were realized at a rotational speed of 3200 rpm. In a general way, the desired operating point was reached by throttling the vane.

Geometric Features		Design Operating Conditions	
Rotor blades	30	Rotating speed	6330 rpm
Stator blades	40	Flow rate	10.5 kg/s
Rotor blade chord	84 mm	Total to total pressure ratio	1.15
Casing diameter	0.5 m	Axial speed	70 m/s
Hub to tip ratio	0.76	Rotor tip speed	181 m/s
Rotor tip gap	0.5 mm		

Table 1 Compressor rig features

Furthermore, the method used to stall the compressor involved non-stop slowly throttling beyond the stability limit until rotating stall was reached.

3. INSTRUMENTATION

All the results presented in this work concern unsteady pressure investigations on the casing.

A pressure field measurement window was specially designed, giving high spatial resolution and allowing solving phase-locked average for several rotor/stator relative positions.

98 measuring holes are regularly dispatched on the window, covering an entire rotor pitch for an axial extension of 78 mm (see details in Fig.2). The two possible mounting positions of the device allow doubling the amount of measuring locations (in Fig.2 green dots are consistent with one window position and the red ones with the same window turned of 180°).

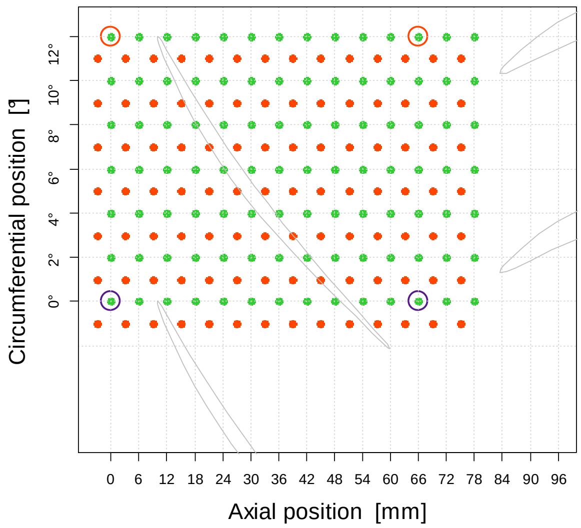

Figure 2 Measurement grid

Four miniature high response pressure transducers (ENDEVCO 8507C-1/2) were used and moved to cover the green dotted grid.

The transducers were mounted behind a small cavity; its resonance frequency is 7 times higher than the blade passing frequency (BPF). It was verified that the cavity did not produce any perturbation at low frequencies on the phenomena of interest.
The sampling rate was varied following the test purpose: 35000Hz (21 samples per blade passage) for normal regime acquisitions and 50000Hz (30 samples per blade passage) for unsteady regime tests. A low-pass filter at 10000Hz was applied by the pressure transducer conditioner to avoid aliasing.
The data were acquired by a National Instrument PXI 6123 module via a Labview™ code.

4. RESULTATS

4.1. Global Performance Curve.

Fig.3 presents the performance characteristics of the compressor, for the whole stage (dots) and the single rotor (stars). The pressure rises were obtained as difference between the calming chamber (see Fig.1) and the outlet sections, of the stator and the rotor respectively.

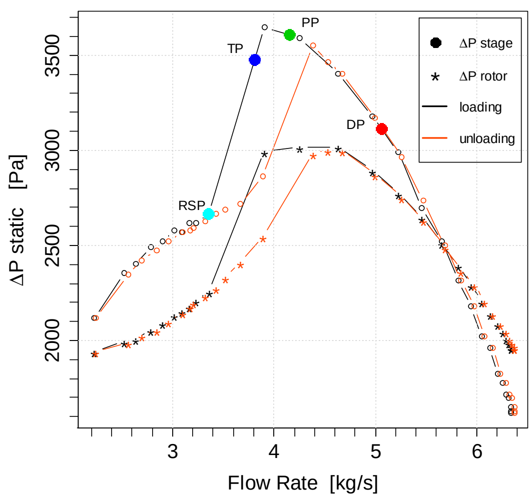

Figure 3 Performance characteristics of the compressor at 3200 rpm

A colour code distinguishes the loading and the unloading paths, highlighting the presence of a hysteresis cycle. Both performance curves obtained by throttling and opening the valve are divided in two portions:
- normal regime, positive slope region, for $q_{throttling}$> 3.85kg/s and $q_{opening}$>4.2kg/s;
- stalled regime, negative slope region, for $q_{throttling}$<3.2kg/s and $q_{opening}$<3.85kg/s;

The transient between the two operating conditions, following either the loading or the unloading path, is really abrupt. Once the rotating phenomenon is installed, starting from about 3.4kg/s, the regime becomes stable again.
No intermediary pseudo-stable regions are observed. So, accordingly with [5], mild stall conditions, with multiple rotating stall cells, should not take place.
All the investigations on which is based this work were carried out by throttling the valve (black curves in Fig.2)
The four operating flow rates surveyed are color marked in Fig.3; starting from the right side: the design operating point q_{DP}=5.06 kg/s, three partial flow rates, the first one close to the stability limit q_{PP}=4.15 kg/s, the second during normal-to-stalled transition q_{TP}=3.81 kg/s and the last one for completely developed stall q_{RSP}=3.35 kg/s.

4.2. Phase-Locked Average Casing Pressure Field for Normal Regime

The data issued from all the locations marked in green in Fig.2, for the two highest flow rates, were treated by means of a phase-locked average technic to reconstruct the casing pressure field. As already mentioned, one of the advantages of the measurement window in use is the possibility to calculate the pressure field for several rotor/stator relative positions.
The results selection in Fig.4 lets emerge the presence of a low pressure region near the blade suction side evolving in magnitude and position with the flow rate; it moves progressively backward from the axial position 20mm to the leading edge plane, while the flow rate is reducing from the design value toward the stability limit.
This low pressure region is the track of the tip leakage vortex bursting zone.
According with [1], the alignment of the tip leakage vortex trajectory with the leading edge plane is a criterion for spike initiated rotating stall. As it will be presented in the next paragraph, a sudden spike-like perturbation actually appears during the normal to stall transient.
The chance that the low pressure region observed is linked to the same phenomenon as for [5], namely the casing leg of a tornado-like vortex, can be rejected. This kind of structure was observed [5] during mild stall regime that is a weak multicells rotating stall pattern, which develops progressively between the normal and completely stalled conditions. As it can be noticed from Fig.3, no intermediary pseudo-stable regions are observed in the performance curve of the CME2.

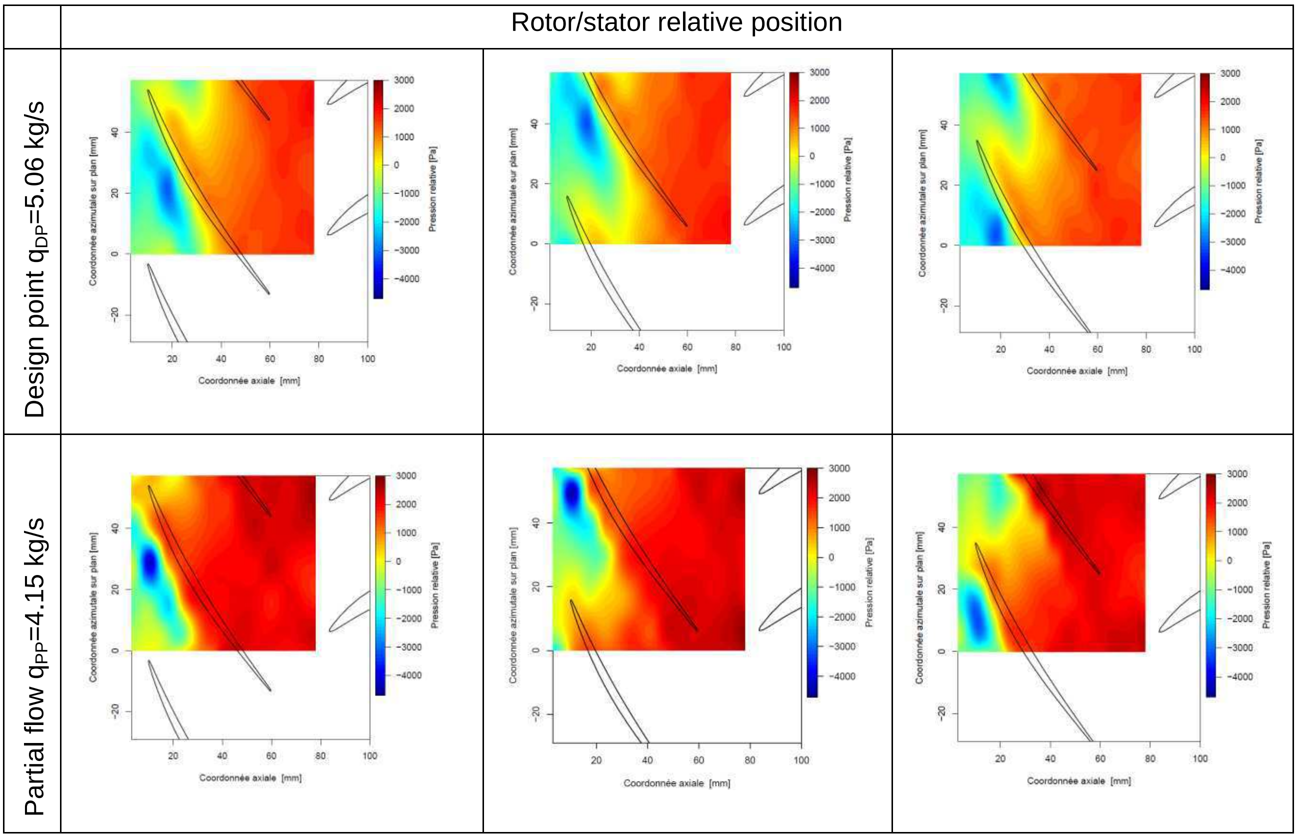

Figure 4 Phase-averaged pressure fields for normal operating conditions

4.3. Spike-Type Rotating Stall Inception

The common way to investigate the flow during rotating stall onset is to perform simultaneous acquisitions at several locations dispatched on the inlet section circumference.

A different point of view was adopted in this work, trying to rationalize the placement of the measurement means on the available grid. The four pressure transducers were placed in pair, at the inlet and outlet rotor sections respectively, as marked in Fig.2 (Circumferential locations 0°- violet rings - and 12°- orange rings - for the axia l coordinates 0mm and 66mm).

The throttling valve was slowly closed, starting from the normal regime, passing through the stability limit to reach the perturbed operating conditions.

The Fig.5 focuses on the transient from normal to stalled regime, the time period observed corresponding to the operating point marked in dark blue in Fig.3 (q_{TP}=3.81kg/s). The pressure signal was smoothed by means of a 3rd order Butterworth filter with a cut frequency of 250 Hz. While the spectrum analysis could not provide any information about the transient regime, the time pressure evolution (top box) clearly reveals the emergence of a perturbation before the stall develops, both at the inlet and the outlet sections (bottom boxes). The phenomenon appears approximately 5 rotor revolutions before the rotating stall is completely established (point A).

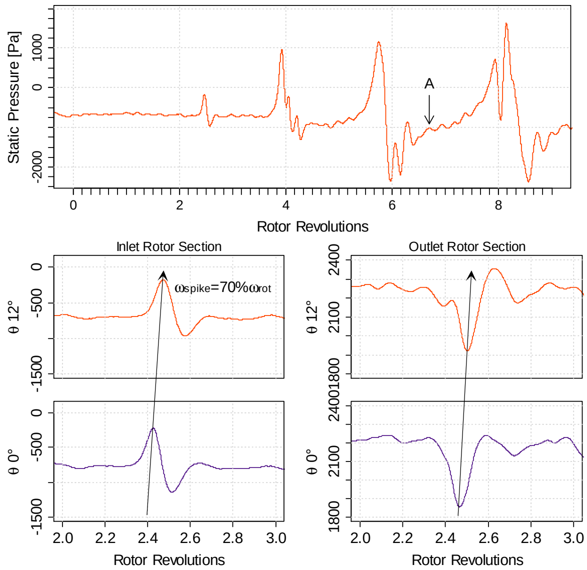

Figure 5 Spike stall inception

By convoluting the signals at the same axial position, it was calculated that the perturbation rotates in the same circumferential direction as the machine but with a speed ratio of 0.7

approximately. Using its angular velocity and its time duration, it was evaluated that the circumferential perturbation extent is about 6 rotor pitches. Its shape and all of the characteristics given above bring to consider the phenomenon as a spike-type stall precursor [2].

As already mentioned, a pressure signal perturbation is also seen at the outlet section. It is slightly delayed and it presents an inverse pattern with respect to the leading edge side perturbation. Future works, including finer casing pressure investigations, coupled with hot-wire anemometry at the inlet and outlet sections, should give a better understanding of the flow pattern during the transient.

4.4. Stalled Operating Conditions.

Rotating stall pattern for the test rig under survey will be presented in this paragraph. The results discussed concern the operating point marked in light blue on the performance curve in Fig.3 (q_{RSP}=3.35kg/s). It is remembered that during stalled regime the compressor operating point is stable.

The same transducers arrangement as for transient investigations (previous paragraph) was used to get the main features of the unsteady phenomenon.

The Fast Fourier Transform was calculated for the four locations, by 50000-sample Hanning windows corresponding to 1 second acquisition. Fig.6 presents the results for the grid location 0mm-0°.

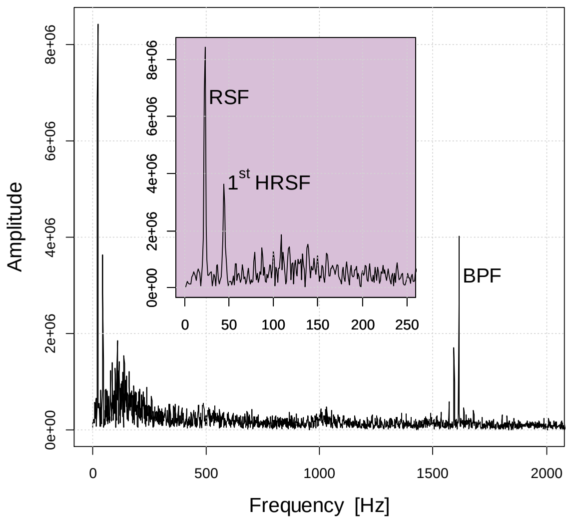

Figure 6 Frequency domain analysis, q_{RSP}=3.35kg/s, transducer location 0mm-0°

Firstly, it can be observed that the analysis correctly captures the blade passage for a frequency of 1610Hz. A detail of the low frequency range is also given in Fig. 6. Two peaks are emerging, the lowest one (f=21Hz) due to the rotating stall phenomenon (RSF=rotating stall frequency), the second being its first harmonic (1^{st} HRSF). The cross-spectrum calculated between the two circumferential locations 0° and 12°, both for the inlet and the outlet sections (axial positions 0mm and 66mm), allows concluding that the rotating stall observed is characterized by a single cell pattern rotating at a velocity which is 40% of the rotor speed.

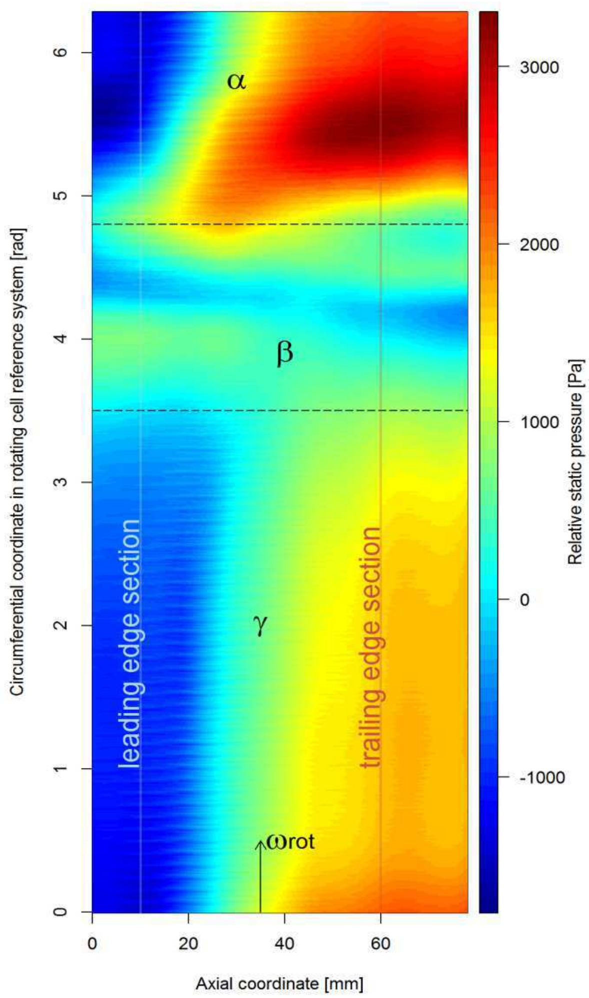

Figure 7 Average casing pressure field during rotating stall

More details about the flow structure near the casing can be obtained by observing Fig.7. The color map was calculated from the data for one circumferential position in the measurement grid: the transducers were moved to cover all the axial locations for the line 12° in Fig.2.

A phase-locked average technic was applied, similarly to what it had been done for normal operating conditions. Due to single circumferential

location used, average pressure field could not be solved with respect to the relative rotor/stator position. The field is expressed in a reference system linked to the rotating stall cell, the compressor rotational direction being represented by the arrow in the bottom side.
Three main regions can be distinguished in Fig.7, characterized by different circumferential extent and pressure gradient.
The completely stalled behavior is recognizable in region β, where no pressure gradient exists between the outlet and inlet sections. The pressure field is not completely homogenous on the whole of this no-load region which extends on 6 rotor pitches; a phase of lower pressure stands out (dark blue colored in region β), presenting two cores placed upstream and downstream of the rotor wheel.
The stalled flow region is preceded by a long non-perturbed phase (region γ in Fig.7), extending on 17 rotor pitches. The pressure gradient corresponds to the average rotor pressure rise for the operating flow rate investigated (q_{RSP}).
A very high loaded sector (α in Fig.7) follows the stalling region. It extends on almost 7 rotor pitches and is characterized by a pressure gradient higher than 2 times the average rotor pressure rise expected for the regime.
While during normal operating regime the whole circumference is on average submitted to the same pressure conditions, an important redistribution of the load takes place during stall.
It seems to be reasonable that a circumferential redistribution of the flow rate takes place in the same time as the load. A stronger flow rate passing across region α could explain the improved operating conditions: the better flow incidence would be responsible of losses reduction.

5. CONCLUSIONS AND PERSPECTIVE

The need of a better understanding of the flow behaviour during rotating stall regime and its onset phase motivated this work. A special measurement window was designed in order to perform fine casing pressure investigations on an entire blade to blade channel, both in the circumferential and axial directions. Phase-locked average data treatment was performed for normal and stalled regimes. The pressure fields for normal operating conditions let emerge the evolution of the tip leakage vortex trajectory while the flow rate was reducing. This phenomenon was identified as one of the criteria proposed by [1] for spike-stall inception compressors. The emergence of a spike-stall precursor during normal to stall transition was actually confirmed by the time analysis of the pressure signals at inlet rotor section. A localized perturbation, extending on 6 rotor pitches, was rotating in circumferential direction at 70% of the rotational shaft speed. Simultaneous acquisitions at the outlet axial section showed the presence of a concurrent perturbation, with similar behaviour in speed and extent but with an inverse pattern. The limited circumferential extent (due to the window dimension) of the present measurement region does not allow observing the phenomenon all along its evolution. A new set-up with several circumferentially dispersed measurement locations will be realized. Furthermore, instantaneous and phase-locked average pressure field will be also calculated. Coupled with hot-wire anemometry explorations they will provide another point of view on the flow pattern during precursor emergence.
The original approach used to characterize the rotating stall allowed representing the average pressure field throughout a whole stall cycle. A single stalled flow cell, rotating with an angular speed equal to 40% of the shaft speed, was extending on 6 rotor pitches. Two other regions, of non-perturbed flow field, are also observed:
- The first one was extending on 17 rotor pitches and its average load was in agreement with the average pressure rise for the stalled operating conditions investigated.
- The second one was more localized, occupying only 7 rotor pitches, and presented a very high load conditions.

It is supposed that this particular configuration of the pressure load along the circumference is connected with a redistribution of the flow rate. Further investigation, involving hot wire anemometry measurements at the rotor inlet and outlet sections, will be carried out to verify this statement. They will provide a fine characterization of the circumferential and radial distribution of the flow during one stall period.

6. ACKNOWLEDGEMENTS

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