inter.noise 2014
MELBOURNE AUSTRALIA
16-19 NOVEMBER

Stall detection using near-field low frequency and pressure modulation in turbomachines

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ABSTRACT

This work investigates on the use of unconventional sensors to measure the near field unsteady pressure on the casing of a fan in a view to detect rotating stall. Rotating stall is an aerodynamic issue with a frequency signature usually half the rotor frequency. In low speed turbomachines, such as industrial fan, this turns in very low frequencies, even lower than 10 Hz.

The authors developed and set-up a measurement system able to acquire low frequency pressure signals using dynamic microphones. Traditional methods use piezoelectric sensors, e.g., pressure tranducers or microphones, respectively in the near and far-field, to detect instability from the signal patterns with broad frequency ranges. Recently electret microphones have been proposed, but with a cut-off frequency of 20 Hz as such not suitable for signal in infrasound region.

The sensor used in this work, have a narrower frequency range than more advanced technologies.

In this paper the authors developed a measurement chain based on dynamic microphone and pressure transducer in order to create a stall warning system. They tested the system on a low speed axial fan and they validated the work against state of the art acoustic control techniques. For this reason those devices represent candidate solutions for the detection of the patterns typical of rotating stall in turbomachines.

Keywords: Axial fan, Stall, Dynamic microphone

1. INTRODUCTION

Prediction of aerodynamic instabilities, such as rotating stall, is a topic relevant to industrial turbomachines design. Rotating stall and its propagation mechanism in axial compressors and fans, have been widely studied in the past decades (1). Instability phenomena lead to vibrational issues, fatigue and mechanical failure of the rotor blades. A continuous monitoring allows the early detection of the aerodynamic instabilities, so to enable a fast intervention.

This paper describes the identification of aerodynamical instability phenomena and more precisely rotating stall, through the pressure signal emitted from the axial fan on the casing wall. Aerodynamical instabilities are detectable hydrodynamically in the near field, and acoustically since every

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turbomachine emits noise due to the high velocity flow passing on the rotating blades and on stationary objects in the duct, the noise intensity depends on the blades rotating velocity and on the position of those objects (2, 3), that means that every flow divergence from stability leads to a emitted noise variation.

Nowadays the available technologies for detecting pressure instabilities, are based on piezoelectric effect used in high frequency response pressure transducers (4),and condenser microphones (5, 6).The benefit in using this kinds of sensors is the high sensitivity in frequency range, from few mHz to 20kHz or even more. However aerodynamic instabilities have a frequency response typically lower than 100Hz, in particular rotating stall occurs at a frequency that is about half of the rotor frequency.

In the attempt to develop a low-cost sensoring solution, recently electret-based measurement microphones have been developed, exploiting the large diffusion of electret capsules in the multi-media markets (7).

In the present work, the authors propose the use of unconventional sensors for unsteady pressure measurements based on a commercial dynamic microphone capsule and electromagnetic induction working principle.

The authors compared the signals acquired with two kind of near-field sensors, namely the dynamic microphones and piezoresistive pressure transducers. The processing of signals includes a spectral analysis to study the stalled fan behaviour in the frequency domain, furthermore, the authors used the Reconstructed Phase Space methodology to detect the dynamics and non-linearity of measured pressure signals, not recognisable in the time domain analysis.

2. NOMENCLATURE

BPF	Blade Passing Frequency [Hz]
FFT	Fast Fourier Transform
n	Index of row vortex
Q	Embedding dimension
RPS	Reconstructed Phase Space
τ	Time delay
$x(n)$	Scalar time series
$x(n+\tau)$	Lagged scalar time series

3. EXPERIMENTS

3.1 Fan test rig

The turbomachine used for the experimental tests is a low speed industrial fan. Table 1 shows the specifications for the fan.

Table 1 – Fan data

Nominal speed	970 rpm
Tip speed	40.6 m/s
Internal duct diameter	800 mm
Blades count	6
Blades length	200 mm
Tip clearance	5 mm
Blade chord at the tip	125 mm

A 1.55 kW direct coupled-induction 3-phase motor was used to drive the rotor at a constant speed of 970 rpm. Under these circumstances the blade passage frequency (BPF) for the tested configuration was 97 Hz, and the rotor frequency 16.2 Hz. The test rig airway is set according to the type-D configuration ISO 5801:2007 (8).

The fan was driven to stall by throttling at the upstream end of the duct.

3.2 Instrumentation set-up

The fan rotor casing was instrumented with 2 inserts, one containing a dynamic microphone and the other containing the pressure sensor. The dynamic microphone in the near field was mounted with a slight recess from the inner wall of the casing since its diameter is 30 mm while the sensing area is only 12 mm. The probe arrangement is illustrated in Figure 1.

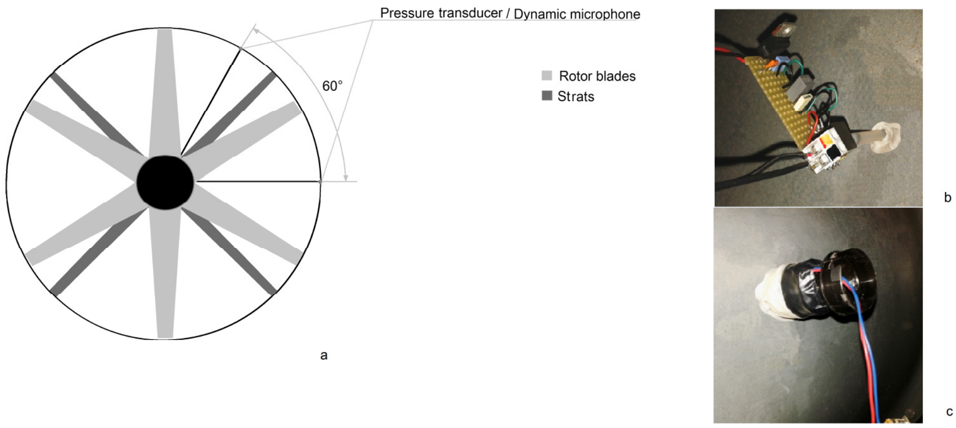

Figure 1 – a) position of the sensors, b) the pressure transducer; c) the microphone

The tests sampling time interval was 60 seconds with a sample frequency of 48 kHz, which is the acquisition board limit. In order to have significant acquired signals, it is been necessary to amplify both the instruments. The experimental procedure was to provide a reduction of the flow rate through a throttle upstream the rotor, starting from a stable work condition until reaching the rotating stall.

4. SENSORS

4.1 Dynamic microphone

The microphone used in the present study is a commercial dynamic microphones. Table 2 gives the microphone characteristics.

Table 2 – Microphone specifications

Impedance	600Ω ±30%
Sensitivity	-72 ±3dB
Frequency response	60 - 14 kHz

The lower limit of the frequency response, is not the lower frequency that the microphone is able to detect, indeed between the 60-14k Hz the frequency response is a flat curve, for lower or higher values the curve is no longer flat, and the sound perceived is attenuated.

The dynamic microphone operation is based on the electromagnetic induction: the motion of the internal components of the microphone, generates a current output. The incoming sound pressure wave displaces a thin diaphragm, wrapped with a conductive wire coil surrounded by a magnetic field. The output is a voltage signal directly proportional to the sound pressure wave magnitude. The dynamic response is lower and the frequency response is less regular than ribbon or condenser microphones. Dynamic microphones are used in harsh working conditions and high noise level, due to their resistance. As much it is considered as a solution to measure hydrodynamic pressure in the near-field of a stating equipment. Figure 3 shows the microphone capsule and its design concept.

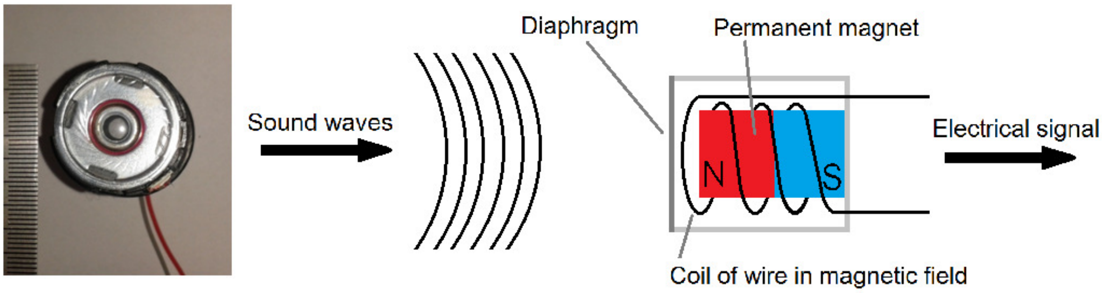

Figure 3 – The dynamic microphone

4.2 Pressure transducer

The pressure transducer used is an integrated silicon pressure sensor on-chip signal conditioned, temperature compensated and calibrated. It is a piezoresistive transducer that provide an analog output signal proportional to the measured pressure. The pressure range is -2 to 2 kPa and the output is 0.5 to 4.5 V. Table 3 gives the transducer specifications. Figure 4 shows the cross sectional diagram of the pressure sensor and the differential configuration on the basic chip carrier.

Table 3 – Pressure transducer specifications

Typical error with auto zero	2.5% (over +10°C to +60°C)
Maximum error without auto zero	6.25% (over +10°C to +60°C)
Sensitivity	1.0 V/kPa
Time response	1.0 ms
Maximum pressure	75 kPa
Configuration	Differential
Storage temperature	-30 to +100 °C
Operating compensated temperature	10 to 60 °C

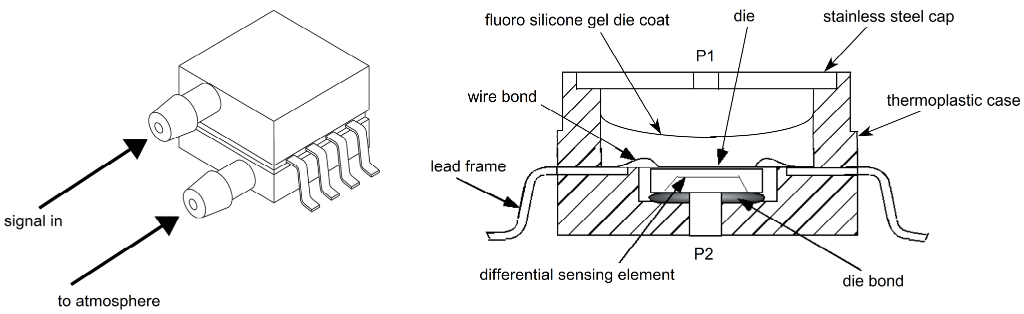

Figure 4 – Pressure sensor and its cross sectional diagram (not to scale)

The decoupling circuit shown in Figure 5, has been manufactured to interface the integrated sensor to the A/D input, and to comply with the transducer specifications.

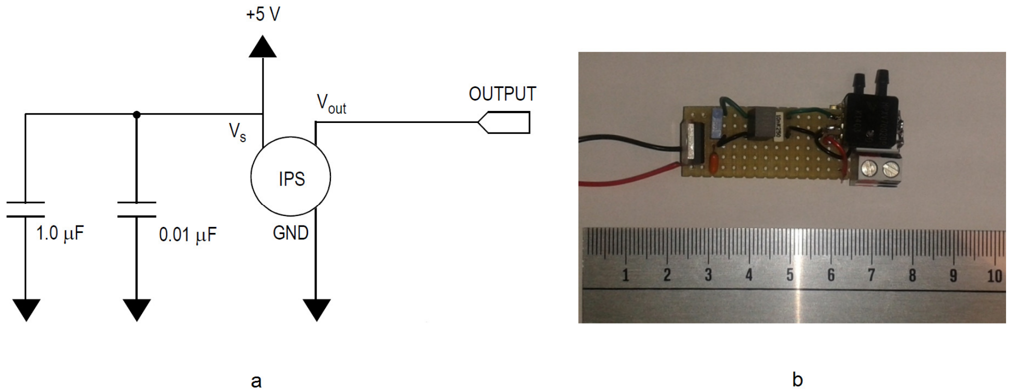

Figure 5 – Pressure transducer decoupling circuit: a) power supply decoupling and output filtering; b) pressure transducer final layout.

4.3 Signal amplification

The signal from the dynamic microphone and the pressure transducer have been amplified using a DIY amplifier circuit based on a TDA2003, capable of delivering 4 Wrms at 4 Ohms. The integrated circuit is thermally and short-circuit protected. The amplifier is designed to operate with the specifications given in Table 5:

Table 5 – Signal amplifier specifications

Music output power	7W / 4Ohm
RMS output power	3.5 W / 4Ohm or 2W/8Ohm
Total harmonic distortion	0.05% (1W / 1kHz)
Frequency response	20Hz - 20 kHz (-3dB)
Input sensitivity	40mV / 150kOhm
Signal/noise ratio	86 dB (A weighted)
Power supply	8 - 18 VDC / 0.5 A
Dimensions	55 x 35 mm (2.2" x 1.4")

Figure 6 shows the DIY amplifier circuit and its final appearance.

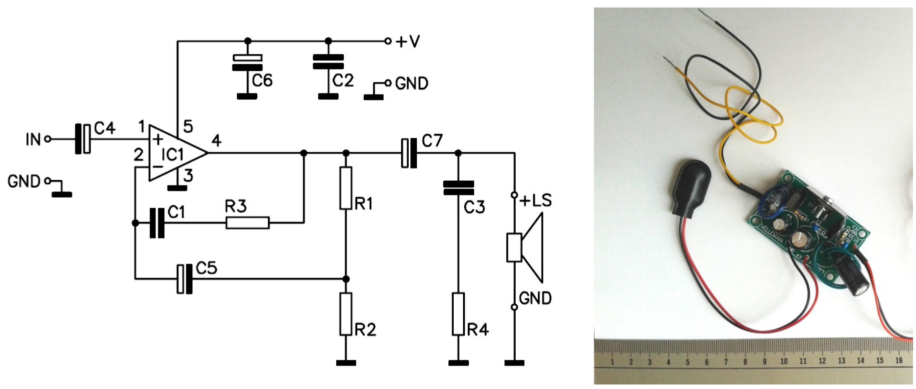

Figure 6 – The amplifier circuit

5. MEASUREMENT SET-UP AND ANALYSIS

The experimental tests were carried out using two different sensors: the dynamic microphone and the pressure sensor were placed in the near field facing the flow near the rotor. The signals acquisition duration was 60s at a sample rate of 48 kHz.

The acquired signals have been filtered with a low-pass filter to clear them from the background noise. The cut-off frequency is 4.8kHz, a tenth of the sample rate. In this way the information about the low frequency response are preserved and the following analysis have clearer results.

In the following Figure 8 are showed the acquired signals with the two different sensors, the upper graphic is related to the pressure transducer, the lower graphic is related to the dynamic microphone. In the time interval from 0s to 32s the authors identified the stable work condition; from 32s to 45s the incoming flow rate is throttled from 0% until 60%, finally from 45s to 60s the fan was operating in stalled condition. The authors applied a spectral analysis and a phase space reconstruction analysis to intervals of 1s of duration within the stable and the stalled sections for each kind of sensor.

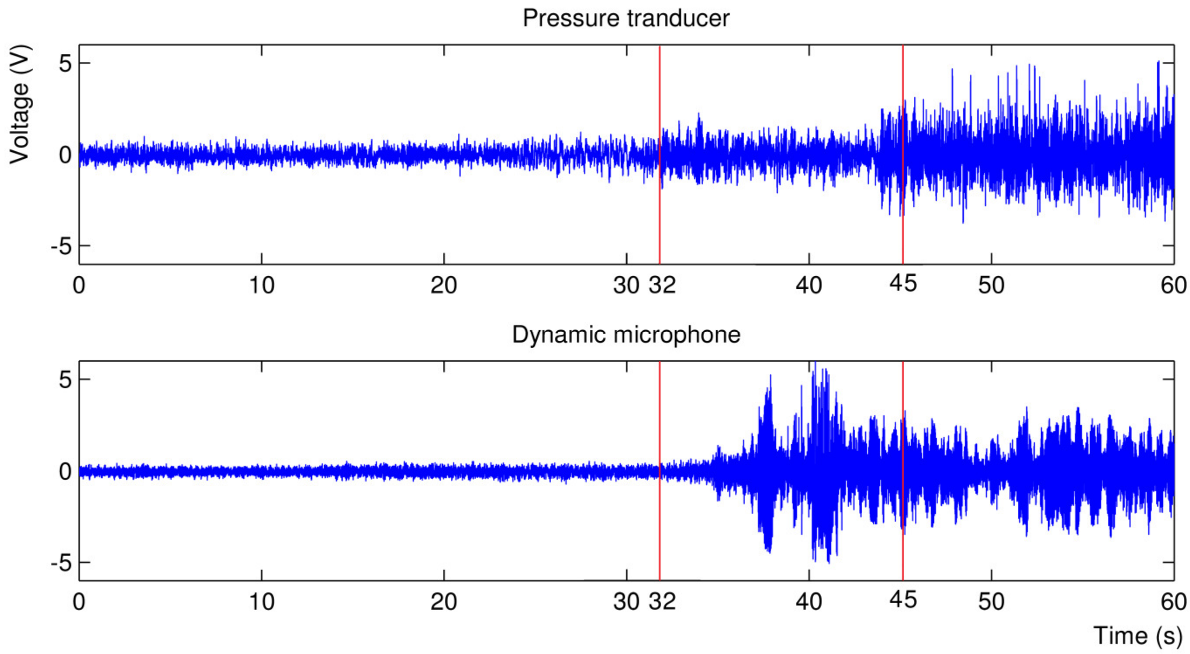

Figure 8 – The acquired signals in time domain

5.1 Signal processing

The signal processing is divided in two different types of analysis. The former is the spectral analysis through a Fast Fourier Transform (FFT), the latter is the Reconstructed Phase Space (RPS).

The spectral analysis and the RPS method have been applied over a time window of 1s, equivalent to approximately 16 rotor revolutions. The time windows have been taken in the stable and in the stalled region of the acquired signals.

The spectral analysis provides information about the power distribution over the frequency. To evaluate the spectrum of a temporal signal, the Fast Fourier Transform is implemented. The time signal is not continuous but discrete depending on the acquisition sample rate. The authors inspected the pressure signals through the spectral analysis in order to identify the frequency bands that reveal the rotating stall occurrence, as in the cross-correlation analysis already developed by Park (9).

The stall detection through acoustic methods is been investigated by Bianchi et al. (10) that reconstructed the symmetrised dot patterns from pressure sound signals in order to differentiate between critical and noncritical stall conditions, and to identify stall precursors.

The acquisition systems for signal recording, supply a single scalar u(t) used to portray the dynamics of a system which often has infinite degrees of freedom. The phase space reconstruction allows the embedding of a data sequence univariate in a Reconstructed Phase Space (RPS) through the time delay τ and embedding dimension Q estimation. In this way it is possible to obtain Q signals through time delays τ. Defining a time delay τ, we consider the functions:

$$\begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_t \\ \vdots \\ \mathbf{x}_{N-(Q-1)\tau} \end{bmatrix} = \begin{bmatrix} x_1 & x_{1+\tau} & \cdots & x_{1+(Q-1)\tau} \\ x_2 & x_{2+\tau} & \cdots & x_{2+(Q-1)\tau} \\ \vdots & \vdots & \ddots & \vdots \\ x_t & x_{t+\tau} & \cdots & x_{t+(Q-1)\tau} \\ \vdots & \vdots & \ddots & \vdots \\ x_{N-(Q-1)\tau} & x_{N-(Q-2)\tau} & \cdots & x_N \end{bmatrix}$$

By means of RPS it is possible to identify the characteristics related to dynamic and not linear systems, otherwise not identifiable through time domain analysis of the single signal.

To obtain an accurate phase space reconstruction it is necessary to find the τ and Q able to optimize the RPS, and so to make emerge the more it is possible the system characteristics.

To detect τ is been used the method called First Minimum of Average Mutual Information. The Mutual Information $I(a_i, b_k)$ is the relative entropy between the joint distribution and the distributions product:

$$I_{AB}(a_i, b_k) = \log_2 \left[\frac{P_{AB}(a_i, b_k)}{P_A(a_i) P_B(b_k)} \right]$$

After computing the Average Mutual Information of the input signal between the signal t and t-τ, for every τ is selected as time delay, the corresponding τ at the first minimum of the curve corresponding to the mutual information, considering the varying τ.

To identify the embedding dimension Q is been used the False Nearest Neighbors method. In this case, once detected the Nearest Neighbors for the single signal elements, the Euclidean distance is calculated in the Q dimensions between the signal elements and their nearest neighbors. If such a distance is greater than a certain R_k value, the neighbors are called false. Than the percentage number of false nearest neighbors is analyzed with respect to the variation of the embedding dimension Q, and the Q selected is the one for which the false nearest neighbors value is null (11,12).

6. RESULTS

The Spectral Analysis and the RPS method is been applied to two different sections of each signal, for a 1 s duration; the first section is taken when the fan is operating in a stable condition, the second section is taken with the fan operating in stalled condition. On the abscissa axis x(n) corresponds to the scalar time series, and on the ordinate axis x(n+τ) is the legged scalar time series, where n is the index of row vortex and τ is the time delay.

6.1 Spectral analysis

Figure 9 shows the spectral analysis for the pressure transducer and the dynamic microphone signals during the stable condition. It is evident how the pressure transducer have a higher frequency response than the dynamic microphone.

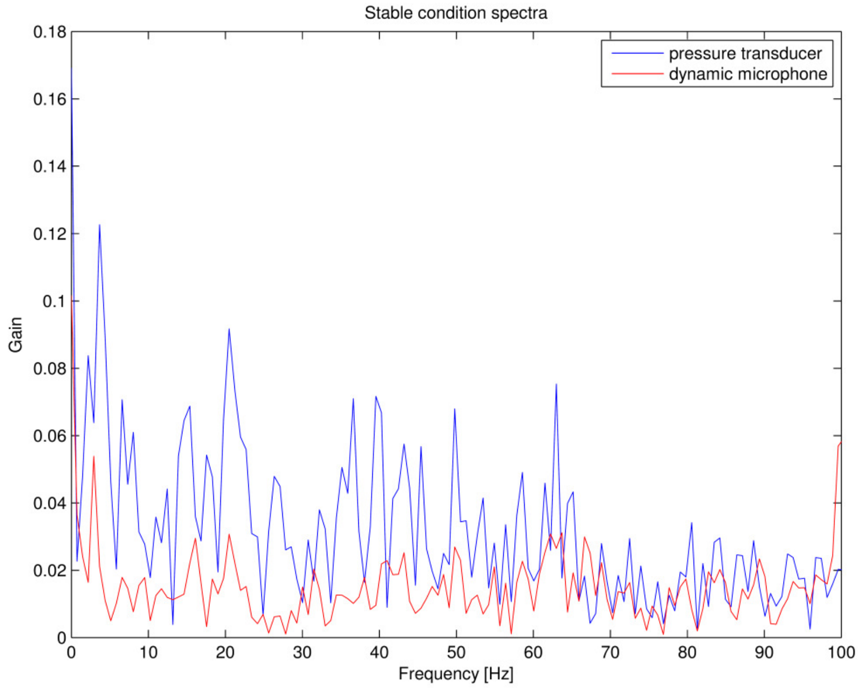

Figure 9 – Stable condition spectra

Figure 10 shows the spectra for the pressure transducer and microphone signals in the stalled condition.

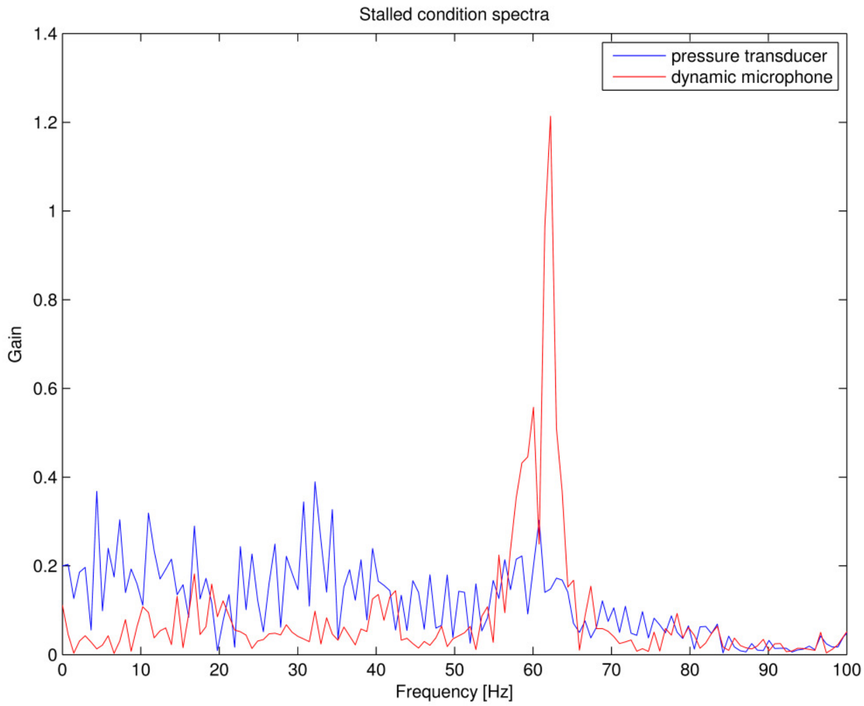

Figure 10 – Stalled condition spectra

The dynamic microphone is able to detect the frequencies at about 15 Hz, which is near the rotor frequency. The peak at 64 Hz is considered to be a resonance frequency due to the rotor-strats interaction, and in comparison with the stable condition shown in Figure 9, the in the stalled condition, the frequency response shows a peak 7 times greater for the pressure transducer, and 30 times greater for the dynamic microphone, while in the other cases the amplitude is about 3 times greater for the stalled condition.

6.2 RSP analysis

The following Figure 11 shows the evolution of the RPS starting from a stable operating condition towards the aerodynamic instability for the signal acquired with the pressure transducer.

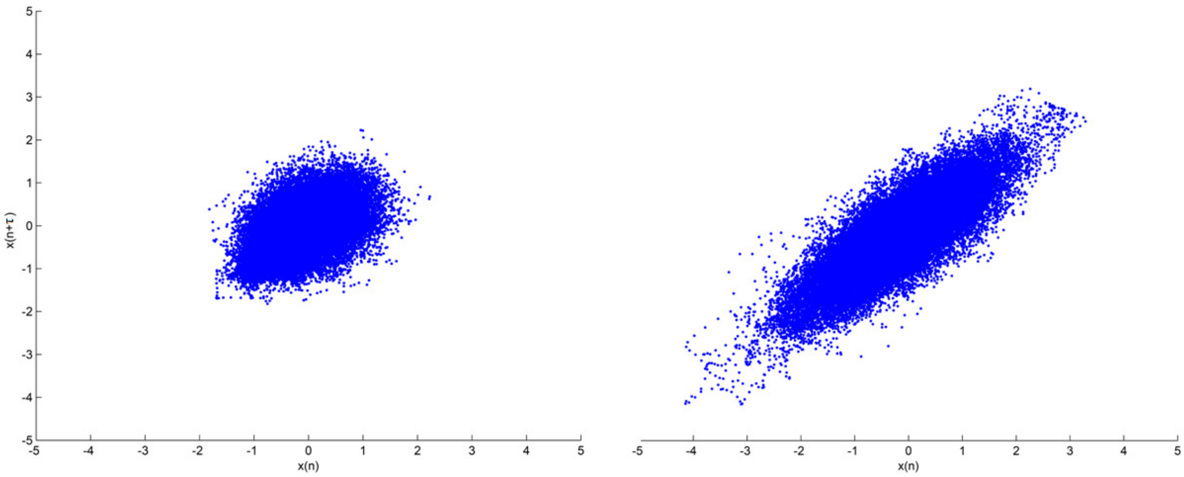

Figure 11 – The stable and stalled operations for the pressure transducer

The following Figure 12 shows the evolution of the RPS in the stable operating condition and in the stalled condition for the signal acquired with the dynamic microphone.

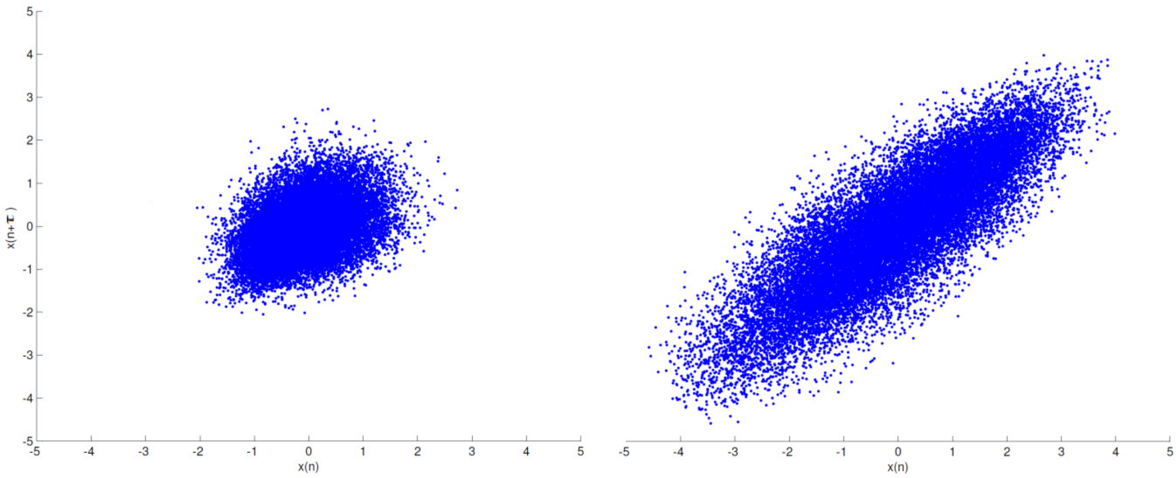

Figure 12 – The stable and stalled operation for the dynamic microphone

In both the pressure transducer and the dynamic microphone, the stalled condition is clearly identifiable from the stable one, since the patterns result enlarged in the diagonal direction. Unlike the spectral analysis, in the RPS both the sensors show almost the same response.

7. CONCLUSION

From the frequency domain analysis through the Fast Fourier Transform is noticeable that rotating stall occurs at low frequencies, lower than 100Hz; more importantly the rotating stall is visible with both the instruments. The clearly visible frequency peak at 64Hz during stalled operations is considered to be a resonant frequency due to the rotor-strats interaction. The experiment proves that the dynamic microphone is able to detect the presence of aerodynamic instabilities at frequencies lower than 20Hz with a 50÷60%precision. Indeed applying the Spectral Analysis on the dynamic microphone signal, it is possible to detect a peak at about 15Hz which is near the value 16.2Hz of the rotor frequency. Using the RPS method the authors identified the rotating stall typical pattern. As in the Spectral Analysis, the method response is more chaotic, and the pattern tends to enlarge and extend while approaching the unsteady condition.

Both the pressure transducer and the dynamic microphone have detected the presence of the rotating stall phenomenon, and the analysis methods used confirmed the validity of the used instruments.

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