Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 82 (2015) 237 – 244

Energy Procedia

ATI 2015 - 70th Conference of the ATI Engineering Association

Unsteady end-wall pressure measurements using near-field DIY sensors on fouled fan rotor blades

Alessandro Corsini[a, b], Cecilia Tortora[a]*

[a] *Dipartimento di Ingegneria Meccanica e Aerospaziale, Sapienza University of Rome, via Eudossiana 18, Rome 00184, Italy*
[b] *SED Soluzioni Energia e Diagnostica Srl, Via Colle Baiocco, Ferentino 03013, Italy*

Abstract

The fouling is identifiable by the presence of dust on rotor and stator blades, and its main origin, in industrial turbomachinery, is the presence of a film of moist or lubricant driven to the trailing edge by the near-wall flow, or centrifuged toward the casing by impeller rotation. Solid particles pile up on them, leading to eccentricity and load unbalance. The formation of build-up results in performance reduction, and the chance of a deposit detachment while the impeller spun, may cause damages due to the impact on the machine parts.
In industrial fans, the presence of fouling influences the characteristic curve and could anticipate stall when the flow rate is throttled. Rotating stall is an aerodynamic instability with a typical frequency about half the rotor frequency, acoustically identifiable from the changes in the emitted rotor noise, due to displacement from the stability. This work investigates rotating stall dynamics on an axial fan with fouled blades. The stall is identified with time-resolved pseudo-sound measurements in the end-wall region using DIY sensors. The signals have been analysed in frequency domain, and time domain using a phase space reconstruction technique. It is demonstrated a modification of the dynamic to stall and are identified diverse stall precursors.

Peer-review under responsibility of the Scientific Committee of ATI 2015

Keywords: industrial fan; rotating stall; fouling; DIY pressure sensors.

---

1. Introduction

The rotating stall prediction is a relevant topic in design and operation of industrial turbomachinery, and its evolution has been widely studied in the past decades [1] in view of the correlated mechanical issues, i.e. vibrational and fatigue breakage of rotor blades. The fouling formation on rotating blades can alter the stall limit even in low speed fans, because of geometry (blade profile variation) or dynamic issues (blade mass increase) driven by the layering of adhesive particle deposit or the formation of ice on the

---

* Corresponding author. Tel.: +39 0773 476521
E-mail address: cecilia.tortora@uniroma1.it.

Peer-review under responsibility of the Scientific Committee of ATI 2015
doi:10.1016/j.egypro.2015.12.028

blades. These two issues can result in an alteration of the system natural frequencies and in a blade roughness variation, leading to imbalances, vibration, and a drop in pressure developing capability and efficiency as explained in Hamed et al. [2]. Narrowing the survey to stall, the presence of fouling is a potential promoter of stall cell formation. The phenomenon propagates to the rear stages, up to a stage where stall will eventually occur [3]. In industrial fans and compressors, the deposit is formed on a layer of oil or moisture on the blades where airborne particles, dust or pollen, collide and adhere. In case of high temperature operation, the deposit can undergo a baking process and become difficult to remove. The main methods for fouling detection are performance monitoring and tracking of pressure [4]. While with reference to rotating stall, the continuous machine monitoring is considered to be the only robust strategy to detect the instabilities for timely intervention [1, 5].

This paper reports on the identification of stall patterns in presence of fouling on the blades, based on the analysis of pseudo-sound signals in an industrial type low speed axial fan. The aerodynamic instabilities are hydrodynamically detectable in the near-field, and acoustically since each turbomachine emits noise due to the high speed of the flow through the rotating blades. The noise intensity depends on the blades rotation speed and on the position of the stationary vanes in the duct [6, 7], meaning that any divergence of the flow from stability leads to a change in the emitted noise. In case of pressure instabilities, the available detection technologies are based on the piezoelectric effect used in high frequency response pressure transducers [8], and condenser microphones [9, 10], with high sensitivity in a large frequency range, i.e. from a few Hz to 20 kHz or even more. Rotating stall occurs at a frequency about half of the rotor frequency, so the frequency response is typically lower than 100 Hz. Recently, diverse research efforts attempt to develop low-cost sensoring solutions, following the development of electret-based microphones exploiting the large diffusion of electret capsules in the multi-media markets [11 - 14]. In this context, the authors propose the use of unconventional DIY sensors, for unsteady pressure measurements on the basis of commercial dynamic microphone capsules and their electromagnetic induction working principle. A DIY microphone is placed in the near field, while the deposit is simulated through adhesive tape strips on the blades according to typical build-up patterns [15, 16]. A comparative validation is carried out on an industrial axial fan test-rig in a fully reverberant acoustic condition. To compare the performance of measurement methodologies during stall and fouling, the signals acquired have been analysed using frequency domain analysis, and time domain using a phase space reconstruction inspired technique. The phase space methodology, is proposed to detect non-linear dynamics of measured pressure signals, not recognisable in the visual inspection of the acquired signals.

Nomenclature

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

2. The DIY dynamic sensor

The DIY sensor was assembled using commercial dynamic microphone capsule, with the characteristics specified in Table 1. The microphone operating principle exploited the electromagnetic induction and the motion of internal components generates the output signal. Dynamic microphones are used in harsh working conditions and high noise levels, due to their resistance. In detail, the incoming sound pressure wave displaces a thin diaphragm, wrapped with a conductive coil of wire surrounded by a magnetic field. The output is a voltage signal directly proportional to the pressure wave magnitude. Fig. 1 shows a microphone capsule and its basic design concept. The DIY sensor includes an amplifier circuit based on the TL082 operational amplifier arranged according to a non-inverting architecture. The amplifier circuit, shown in Fig. 2, is powered by two 9V batteries. A 10 kOhm linear potentiometer permits to control the suitable impedance for the sensor.

Table 1. Microphone specifications

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

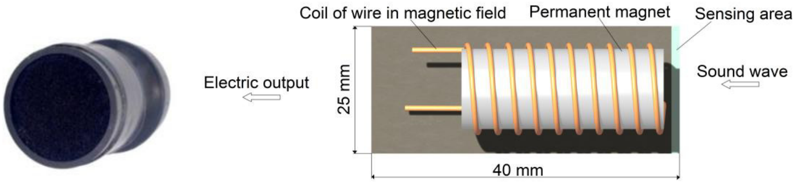

Fig. 1. DIY sensor based on dynamic microphone

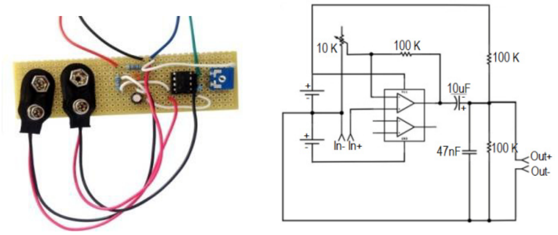

Fig. 2. DIY sensor amplifier circuit

3. Axial fan test-rig

The experimental campaign investigates a low speed industrial fan. A 1.55 kW direct coupled-induction 3-phase motor was used to drive the rotor at a constant speed of 1000 rpm. The blade passage frequency for the tested configuration was 100 Hz, and the rotor frequency 16 Hz. The test rig airway is set according to the type-D configuration ISO 5801:2007 [17]. Table 3 shows the fan specifications.

Table 3. Fan data

Nominal speed	Tip speed	Internal duct diameter	Blades count	Blades length	Tip clearance	Blade chord at the tip
1000 rpm	40.6 m/s	800 mm	6	200 mm	5 mm	125 mm

3.1. Instrumentation set-up

The fan rotor casing end-wall was instrumented with insert containing a dynamic microphone flush-mounted on the fan rotor. The fan is driven to stall throttling at the upstream end of the duct. The experimental procedure was to reduce the flow rate through a throttle upstream the rotor, starting from a stable work condition to the full stall. The throttling, during the transient, results in a flow rate reduction of 1% per second, assuming the direct proportion between the inlet section and the incoming flow rate. The tests sampling time interval was 65 seconds with a sample frequency of 24 kHz.

3.2. Deposit simulation

In a study of Hilger et al. [18], on fouling detection, the deposit has been simulated with a textured paint to have a thin and rough layer on the blades surface. In this study, in order to simulate the build-up on the blades, the authors used duct tape stripes and shims (to facilitate the change in the configuration) (Fig. 4). The layer realised is uneven, to simulate an irregular deposit as in real operations, as in Fig. 4.a. The fouling model has been applied to be predominant on the pressure side (PS), where it is extended to the entire blade surface and it is more thick near the trailing edge. On the suction side (SS) the fouling is usually present only near the leading edge but it has a higher thickness than on the PS. Concerning the deposit thicknesses, on the PS the layer is distributed on all the blade surface, with a maximum thickness of 2 mm near the trailing edge while on the SS the layer has a maximum thickness of 5 mm and it is located in vicinity of the leading edge (Fig. 4.b).

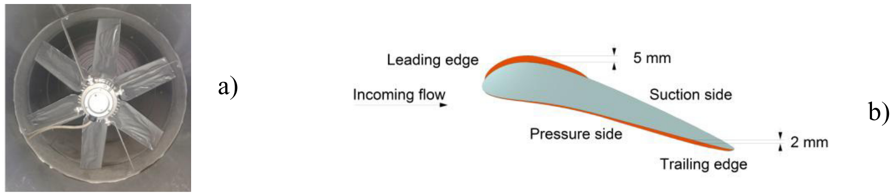

Fig.4. Deposit on the fan rotor (a) view of the blade pressure side; (b) deposit geometry on pressure and suction blade surfaces

4. Signal processing techniques

The signal processing combines the frequency-domain analysis, based on the Fast Fourier Transform (FFT), and a time-domain analysis, based on the Reconstructed Phase Space (RPS) portraits, to study the non-linear dynamics of stall evolution.

The inspection of the signals with the spectral analysis serves to identify the frequency bands that reveal the rotating stall occurrence, as in the cross-correlation analysis already developed by Park [19]. On the other hand, the time-domain signal analysis was carried out following the method proposed by Palomba co-workers [20] or the stall detection through acoustic investigated by Bianchi et al. [21]. In [20], Palomba et al. studied the chaotic dynamics on which the rotating stall is based using the phase space portraits of velocity, static pressure and vibration signals data series. Bianchi and co-workers [21], proposed the symmetrised dot pattern representation of pressure sound and pseudo-sound signals in order to differentiate stall patterns, and to identify stall precursors. The basic idea was to represent the system dynamics and the transient phenomena, on the basis of patterns identification and trajectories inspection. In particular, with the RPS is possible to do the embedding of univariate sequence of data evaluating the time lag T and the embedding dimension D, i.e. in order to obtain D vectors from the original signals using T as the time delay [22]. The RPS allows the identification of the characteristics enveloped in non linear dynamic systems, which are not identifiable with the time domain analysis of the signal, as already demonstrated in [23]. The accurate reconstruction of the phase space depends on the definition of D and T. The optimal time delay T is identified with the first minimum of the mutual information technique [24], while the embedding dimension D is computed with the false nearest neighbours method [25].

5. Results

5.1. Time domain visual inspection

The pressure signals have been acquired at a sample frequency f_S of 24 kHz, corresponding to a Nyquist frequency f_N of 12 kHz. The non filtered signals are shown in Fig. 5, respectively for the clean blade (Fig. 5.a) and fouled blades (Fig. 5.b). It is visible how in the deposit case, the signal amplitude is higher for all the duration of the acquisition. In view of the visual inspection, it was decided to use a time windows lasting 1 s, equivalent to approximately 16 rotor revolutions, in either the spectral and the RPS analyses. Three time windows were selected to be representative of stable condition, stall inception and stalled operations. The initial time abscissae of the three intervals are 1 s (corresponding to 0% of throttling), 46 s (corresponding to 45% of throttling) and 61 s (corresponding to 60% of throttling).

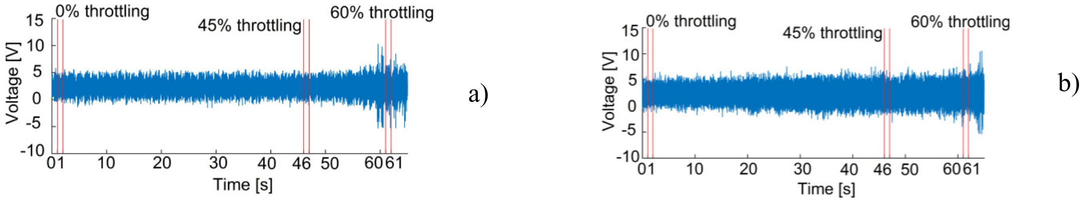

Fig. 5. Time signal measured by the DIY sensor: (a) clean blades, and (b) fouled blades.

5.2. Spectral analysis

The auto-spectra of the signals, in the three segments selected, it is visible the different behaviour in absence or presence of fouling on the blades. The behaviour in the steady condition is approximately the same for both the cases, as visible in Fig 6.a).

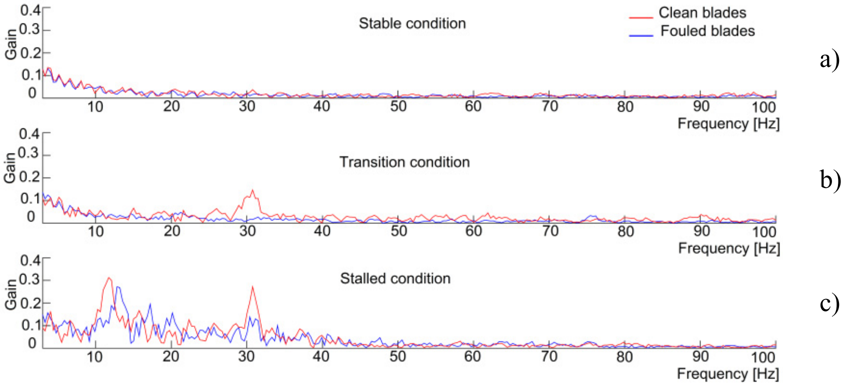

Fig. 6. Auto-spectra comparison of the three signals segments: throttling at (a) 0% of throttling; (b) 45% of throttling; (c) 60% of throttling.

In the fouling case at 45% of throttling, shown in Fig 6.b), there is a clear peak at about 30 Hz, and another peak of lower amplitude at about 15 Hz, while the curve corresponding to the clean blades case does not show any clear difference from the stable working condition curve. In the autospectra at 60% of throttling, corresponding to the stalled behaviour shown in Fig 6.c), for the clean blades case, there are two visible peaks at about 30Hz and 15 Hz, that is approximately the rotor blade frequency. The peaks are also visible in the case of fouled blades, but slightly shifted toward the lower frequencies.

5.3. Phase-space portraits RPS

The used value of the embedding dimension D is always 2. The used value of the time delay T are summarized in Table 4.

Table 4 – Used T values

% of throttling	Δt (s)	T clean blades	T fouled blades
0	1 -2	6	6
45	46 - 47	6	9
60	61 - 62	6	5

Fig 7.a) and 7.b) show the differences in the RPS at 0% of throttling with clean and fouled blades respectively. It is visible how the patterns are very similar, although in the fouling case it is a little wider than in the clean blades situation. Fig 7.c) and 7.d) show the differences in the RPS at 45% of throttling in the case of clean and fouled blades respectively. In this case it is clear the enlargement of the pattern in case of fouling. Fig 7.e) and 7.f) show the differences in the RPS at 60% of throttling in the case of clean and fouled blades. At this stage the presence of rotating stall is confirmed and both the patterns show an enlarged and stretched behaviour, although that is milder in the fouled case, as visible in Fig 7.f).

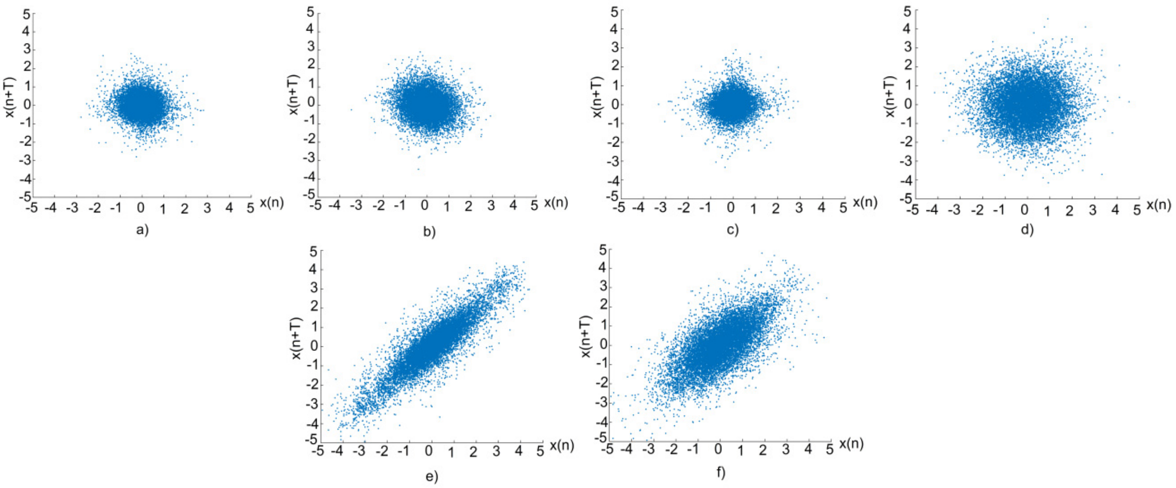

Fig. 7. RPS at 0% throttling for (a) clan blades and (b) fouled blades, RPS at 45 % throttling for (c) clan blades and (d) fouled blades, RPS at 60 % throttling for (e) clan blades and (f) fouled blades

The portraits comparison indicates that both the signals from the clean and fouled blades are able to create phase-space patterns which identify the evolution from stable to stalled operations. The signature of such evolution is the diagonal stretching of patterns. This circumstance is supposed to be correlated with the predominance at stall of a chaotic behaviour with the orbits of RPS attractor evolving in a complex shape; whereby some directions are contracted and others are stretched. Furthermore it is observable that in the fouled blades case, for every time interval, the pattern is larger than in the event of clean blades, this is considered to be an indicator of the fouling presence.

6. Conclusions

From the frequency domain analysis through the Fast Fourier Transform it is noticeable that rotating stall occurs at frequencies lower than 50 Hz, more importantly the rotating stall is visible with the DIY dynamic microphones. The experiment proves that the dynamic microphone is able to detect the presence of aerodynamic instabilities at frequencies lower than 20 Hz, and it has been possible to discern the fouling case, because it appears to be a redistribution of the energy content on the lower frequencies. Applying the spectral analysis on the dynamic microphone signal, it has been possible to detect a peak at about 15 Hz which is near the value 16.2 Hz of the rotor frequency. Using the RPS method it has been possible the identification of 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; moreover, when the blades are fouled the pattern is generally larger than in the clean blades case, and this behaviour starts to be visible when the fan is throttled at 45%. The results shown, demonstrate that the dynamic microphone, combined with the analysis methods, is able to identify the aerodynamic instabilities such as rotating stall, and the instabilities due to the blade fouling.

Acknowledgements

The authors wish to express their gratitude to Graziano Ullucci and Federico Squillante at SED Soluzioni, and Sara Feudo who were instrumental in the definition of the hardware configuration and in the discussion around chaos dynamics.

References

[1] Bianchi S, Corsini A, Sheard AG, Tortora C. A Critical Review of Stall Control Techniques in Industrial Fans. *ISRN Mechanical Engineering*, Volume 2013; Article ID 526192.

[2] Hamed A, Tabakoff W. Erosion and deposition in turbomachinery. *J.of Propulsion and Power;* April 2006, Vol.22, No.2.

[3] Stone A. Effects of Stage Characteristics and Matching on Axial-Flow-Compressor Performance. *Transactions of the ASME;* 1958, Vol. 80, pp. 1273- 1293.

[4] Meher-Homji CB, Bromley A. Gas turbine axial compressor fouling and washing. *Proceedings of the thirty-third turbomachinery symposium;*2004.

[5] de Jager B. Rotating stall and surge: A survey. *Proceedings of the 34th Conference on Decision and Control*, New Orleans, LA , USA, 1995.

[6] Cumpsty NA. A critical review of turbomachinery noise. *J. of Fluids Engineering*; 1977, pp. 278-293.

[7] Cumpsty NA. Sum and difference tones from turbomachines. *Journal of Sound and Vibration*; 1974,Vol. 32/3, pp.383-386.

[8] Bianchi S, Corsini A, Mazzucco L, Monteleone L, Sheard AG. Stall Inception, Evolution and Control in a Low Speed Axial Fan With Variable Pitch in Motion. *Journal of Engineering for Gas Turbines and Power;* APRIL 2012, Vol. 134 / 042602-1.

[9] Bianchi S, Corsini A, Sheard AG. Detection of stall regions in a low-speed axial fan. Part i - Azimuthal acoustic

measurements. *Proceedings of ASME Turbo Expo*; 2010, GT2010-22753.

[10] Zhu T, Carolus TH. Experimental and unsteady numerical investigation of the tip clearance noise of an axial fan. *Procedings of ASME*; 2013, TBTS2013-2043.

[11] Bennett GJ, Mahon J, Hunt S, Harris C. Design of an Electret Based Measurement Microphone. *26th International Manufacturing Conference (IMC26);* 2009, 411–418.

[12] Bianchi S, Corsini A, Sheard AG. Experiments on the use of sdp for in-service stall detection in industrial fans. *Proceedings of Fan 2012*; 2012.

[13] Corsini A, Feudo S, Tortora C, Ullucci G. Stall detection using near-field low frequency and pressure modulation in turbomachines. *Proceedings of Inter-noise 2014,* Melbourne, Australia 16-19 November 2014.

[14] Louw FG, von Backström TW, van der Spuy SJ. Experimental investigation of the blade surface pressure distribution in an axial flow fan for a range of flow rates. *Proceedings of ASME Turbo Expo 2015*, GT2015- 43620.

[15] Tarabrin AP, Schurovsky VA, Bodrov AI, Stalder JP. An Analysis of Axial Compressor Fouling and a Blade Cleaning Method. *Journal of Turbomachinery*, Transactions of the ASME, Vol. 120, APRIL, 1998.

[16] Igie U, Pilidis P, Fouflias D, Ramsden K, Laskaridis P. Industrial Gas Turbine Performance: Compressor Fouling and On-Line Washing. *Journal of Turbomachinery*, Transactions of the ASME, Vol. 136, OCTOBER, 2014.

[17] ISO 5801. *Industrial Fans—Performance Testing Using Standardized Airways;* 2007.

[18] Hilger AW, Herwart H, Heinz EG. *Process for detecting fouling of an axial compressor*. US 5479818 A; 1996.

[19] Park HG. *Unsteady disturbance structures in axial flow compressor stall inception*, [M.S. thesis]. Massachusetts Institute of Technology, Cambridge,MA, USA, 1994.

[20] Breugelmans FAE, Palomba C, Funk T. Application of strange attractors to the problem of rotating stall. *Unsteady Aerodynamics and Aeroelasticity in Turbomachinery*. Y. Tanida and M. Namba, Eds., Elsevier Science; 1995.

[21] Bianchi S, Corsini A, Sheard AG. Demonstration of a stall detection system for induced-draft fans. *Journal of Power & Energy;* 2013.

[22] Abarbanel HDI, Brown R, Sidorowich JJ, Tsimring LS. The analysis of observed data in physical systems. *Reviews of Modern Physics*, October 1993, Vol. 65, No. 4,.p.1343-51.

[23] Corsini A, Feudo S, Sheard AG, Tortora C, Ullucci G. Implementation of an acoustic stall detection system using near-field diy pressure sensors. *Proceedings of Fan 2015*; 2015.

[24] Gallager RG. *Information Theory and Reliable Communication*. New York: John Wiley and Sons; 1968.

[25] Kennel MB, Brown R, Abarbanel HDI. Determining embedding dimension for phase space reconstruction using a geometrical construction. *Phisical review A*; March 1992,Vol 45, No 6, 15, pp.3403-3411.

Biography

Cecilia Tortora is a PhD candidate in Energy, at Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, since November 2012. Her research activity mainly focuses on DIY measurement technologies, active and passive stall control systems, noise control in rotating turbomachines and industrial processes.