Axial Fan Monitoring by Pressure Transients Close to the Blades, a Preliminary Study

Ian Loomis and Shaun Ramsay
Virginia Polytechnic Institute and State University
Blacksburg, Virginia
U.S.A.

ABSTRACT

As the axial fan blades move within the fan case pressure transients are developed, which can be measured and qualified by a fixed point monitor. The nature of the pressure transient pattern observed close to the fan blade varies with the location on the fan performance curve. Measurement of the pressure fluctuation around the fan blade ring reveals the minute variation in pressure associated with the movement of the air within the fan. Such observations could be the basis for an on-line fan monitoring system based on the acoustic emissions from the fan blade.

This paper describes a preliminary study that was conducted to evaluate the nature of the pressure transient profiles close to the blade of a laboratory axial flow fan. A comparison is made between the transient patterns measured in the fan blade/case gap and immediately behind the fan blade ring. The experimental work involves measurements of transient pressures at various points along the fan performance curve for a series of fan speeds. Of particular interest are those points measured as the fan approaches the stall point. Analysis of the data seeks to define a relationship between the fan performance and the observations. Finally, some thoughts as to how such measurement methods could be employed in fan monitoring systems are presented.

KEYWORDS

Fans, Axial, Monitoring, Pressure, Transient, Analysis, and Stall.

INTRODUCTION

The development of airfoil propeller blades allowed for the design of axial flow fans with sufficient performance to be utilized for mechanical ventilation (McPherson,1993). There are numerous trade-offs to be weighed when selecting a fan design, either centrifugal or axial; however, there is little doubt that the axial flow fan is the predominant choice in mining applications. While the axial flow fan offers the user significant flexibility at a relatively high efficiency, the tendency of these fans to have drastic consequences associated with aerodynamic stall must be considered. Stall conditions can be encountered in both centrifugal and axial flow designs. In a centrifugal fan, this condition is char-acterized by "stall cells," which form in the regions between the impeller blades (De Le Harpe, 1982). In an axial flow fan, the stall is characterized the "sudden loss of lift and an increase in drag" (McPherson, 1993). This is the same con-sequence that is experienced in an aircraft at excessive angle of attack. In general terms the aircraft, or the fan, stops flying. In the fan, the blade angle of attack is the difference between the blade angle and the angle of advance (Kermode, 1996). As the fan flow decreases, at a constant fan speed, the angle of advance necessarily decreases resulting in an increasing angle of attack. A typical airfoil design will experience stall conditions as the angle of attack approaches 15 degrees (Kermode, 1996). At stall, a rapid loss of air movement then results in a stressing of the blade, which may cause catastrophic failure of the fan.

Blades of the type used in axial flow fans are essentially similar to the airfoils familiar as the wings on aircraft. The primary difference is the twist that must be imparted to the blade, which compensates for the change in the linear velocity along the radius, hence a change in the angle of advance. In general respects one can perform analysis on the fan blade from the consideration of the aerodynamics usually associated with conventional airfoils. This holds true for not only the aerodynamic performance, but also the aeroacoustic emissions. That is, the noise generated as a function of the movement of air over the fan blade airfoil.

The sound emitted from the fan blade will be a factor of several phenomena, including: the Reynolds number, the shape of the trailing edge, and the angle of attack. Under conditions of turbulent flow, a sharp trailing edge will tend to produce a continuous spectral emission through out the range of angles of attack (Blake and Gershfeld, 1989).

The shape of the blade trailing edge is a constant of the fan design, and is assumed to be reasonably "sharp." The emissions from the fan then can be assumed to be related to the fan speed and the airflow, which are both considered as variables.

A preliminary study of this behavior was conducted at the Virginia Polytechnic Institute and State University. The objective was to determine if there was sufficient evidence that the acoustic emission phenomenon could prove to be a tool in fan performance monitoring. Two monitoring sites were selected: between the blade tip and the fan case, and behind the blade facing directly into the flow. On the scale used for this study, only the second of these appears to offer direct evidence of a variation in the acoustic pattern that can be correlated with the fan aerodynamic performance.

ACOUSTIC EMISSION

For the consideration of these experiments, two regions of pressure variation, or acoustic emission are considered. The blade tip presents the first of these. The development of a vortex at this location is associated with the difference in pressure between the upper and lower surfaces of the airfoil. The result being that the flow over the top surface tends to flow towards the center; whereas, the flow across the lower surface tends to flow outwards, setting up the tip vortex (Kermode, 1996). The second monitoring site is along the length of and behind the airfoil. This is the region where flow separation is expected to begin as a stall develops. The acoustic emission in this region is related to the movement of highly turbulent flow across the trailing edge of the aerodynamic surface (Blake and Gershfeld, 1989).

Blade Gap Region

Monitoring of the transient pressure in the region between the extreme edge of the fan blade and the fan housing was selected since this position does not require deep penetration into the fan tube. The primary pressure transient that was expected at this location is that associated with the passing of the blade. Consistent with Bernoulli's theorem, the differential velocity between the blade and the housing should produce a reduced pressure region within the gap. Furthermore, the pressure transient should be affected by the general passing of the blade, that is the pressure difference associated with the aerodynamics of the air movement when considered relative to the blade. That is, tip effects related to the termination of the airfoil, and resulting vortex.

Behind the Blade

A measurement of the variation in the total pressure at a fixed point behind the blade ring or, more literally, under the airfoil provides an observation of the passing of the blade and the associated wake. Since the characteristics of the wake are a function of the conditions of the air movement across the blade this position is well suited to observation of the variations in pressure associate with flow past the blade.

In this position the variations in the total pressure were monitored normal to the plane of the blade ring. Consequently, this measurement was also normal to the flight path of the individual blades. Thus, the pressure variations observed were those associated with the fan blades passing on a fixed path, independent of the angle of attack. Recall that in the case of the fixed pitch fan the blade angle of attack is a function of the fan speed and the air flow velocity.

EXPERIMENTAL CONFIGURATION

The experimental work of this preliminary study was conducted in the Mine Ventilation Laboratory at the Virginia Polytechnic Institute and State University. A 16 inch diameter axial flow fan–wind tunnel combination was used as the basis for evaluation. The general arrangement is shown in Figure 1. This tunnel is normally used for the instruction of fan performance testing, so was ideally suited for this work.

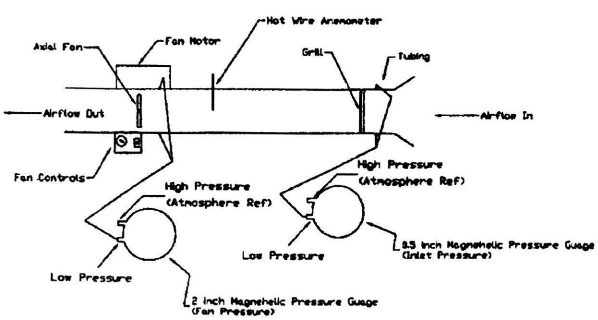

Figure 1. General configuration of wind tunnel (Ramsay, 1998).

The resistance to flow is controlled by varying the open space in the tunnel inlet using successively finer screens. The airflow rate can then be obtained as a function of the static pressure lost at the inlet. It was expected that the high levels of restriction in the inlet, for these tests, could artificially skew the static pressure measurement. Therefore, provision was made for measuring the air velocity in the duct directly using a hot-wire anemometer.

Two separate measurements of pressure transients were made. The first in the gap between the fan case and the blade ring. For this measurement a port was installed so that the microphone was positioned on the centerline of the blade ring as illustrated in Figure 2. The second location of transient measurement was located behind the blade. This measurement was made using a pitot tube directed to observe the total pressure at a location about 1/2 way up the blade, as shown in Figure 3.

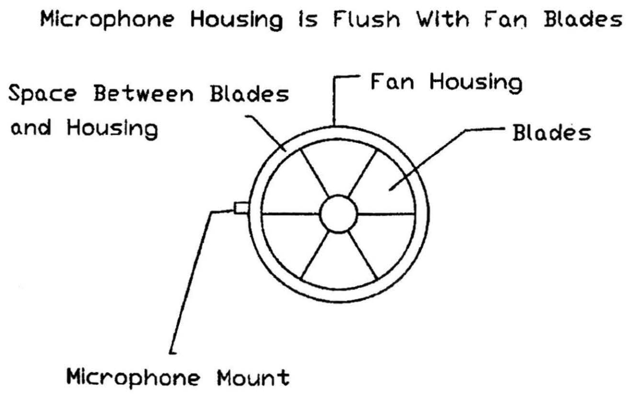

Figure 2. General location of blade gap measurement (Ramsay, 1998).

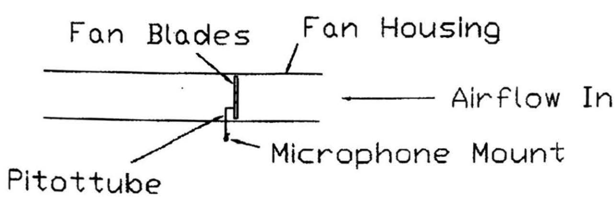

Figure 3. General location of behind the blade measurement (Ramsay, 1998).

Pressure transients were observed using a small microphone in a directional mount. The output voltage signal was measured with a recording signal analyzer. The stored time domain response was converted to the frequency domain using a built in Fast Fourier Transform function on that analyzer.

DATA

The most basic data collected was that which was sufficient to determine the fan operating performance. That is the fan speed, pressure, and flow quantity. For the purpose of these tests the fan was operated at four speeds and five levels of resistance. This provided twenty independent points of the pressure transient behavior. At each of these points the high-speed data logger was used to sample the microphone output voltage, for both the blade gap and behind the blade.

The fan performance characteristic curves are illustrated in Figure 4. For these tests the fan speed was held constant while the resistance was varied. Resistance conditions are indicated progressing from the lowest, A, to the highest, E. It can be shown, however, that the levels of resistance remain reliably consistent from speed to speed. From the fan performance data, it is apparent a true stall condition was not achieved. Although, there is sufficient range in the data to observe changes in the pressure transient profile.

ANALYSIS

Due to the highly turbulent nature of the airflow in and around the vicinity of the fan blade ring, the pressure versus time data appears to be inconsistent. The very nature of turbulence adding a degree of randomness to the pattern of the pressure–time traces. One characteristic that was ob-vious on those traces, however, was the fundamental frequency at which an individual fan blade passed by the sensor port. The overall shape of the approach and depart-ure of the blade was less evident.

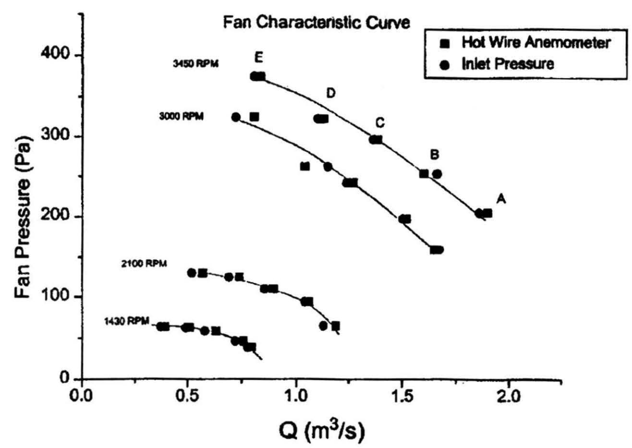

Figure 4. Experimental fan performance (Ramsay, 1998).

While consistency of the specific behavior in time may not be evident between any individual windows of time, it is reasonable to assume that the average behavior will be fairly uniform. This would mean that on average one could expect a certain level of response that would, in fact, be consistent over long time periods. To make this assessment, the data sets for each observed condition were transformed from the time domain to the frequency domain, using the Fast Fourier Transform algorithm. The frequency domain data presented in this section is shown as the average response in each band for the four individual measurements of the associated conditions.

A typical frequency domain diagram is illustrated in Figure 5. In this figure, the typical bar-chart presentation has been replaced by a line graph which will make comparison easier between the various data sets. Notice that there is a definite fundamental frequency, which in Hertz is one-tenth the fan speed in revolutions per minute. This arises due to the conversion from rpm to Hertz on a six bladed fan.

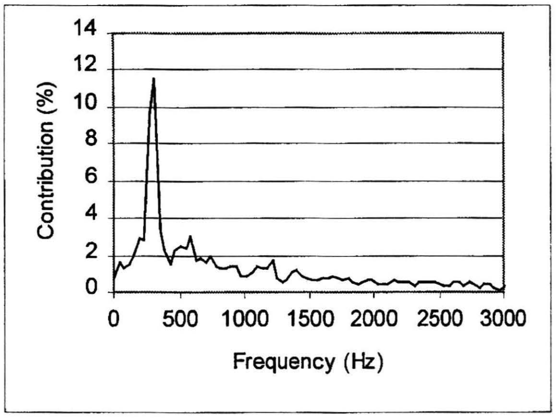

Figure 5. Typical frequency domain representation blade gap noise.

The observations associated with the two measurement locations are discussed separately. For general comparison, the full-suite of five measurements at 3000 rpm is shown to illustrate variation associated with the characteristic resistance. The behavior of the acoustic emission with respect to the fan speed is shown at the extremes of resistance.

Since the major differences between the frequency domain response occurs at the low end of the spectrum the remaining figures showing this behavior will be limited to 1500 Hertz as the upper value.

Frequency Domain Behavior in the Blade Gap Region

Figure 6 illustrates the behavior of the frequency domain data that was collected at the 3000 rpm fan speed in the blade gap location. In this figure each line is associated with a level of resistance indicated, by letter A, B, etc., corresponding to that shown on Figure 4. The data in this graph do not appear to indicate a consistent trend in any of the frequency bands, nor a trend in any region. The level of contribution at the fundamental frequency (300 Hz) drops markedly between resistance A and B, then rises with the level of resistance. The contribution at twice the fundamental frequency (600 Hz) varies erratically with the resistance. This random behavior is repeated in the region below the fundamental frequency.

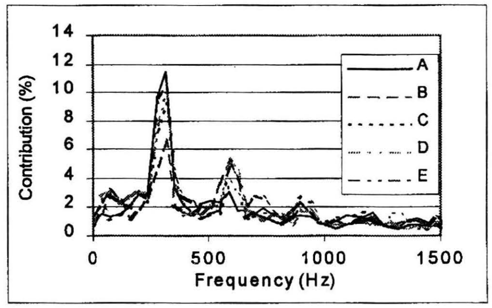

Figure 6. Blade gap frequency domain response as a function of resistance, 3000 rpm.

Figure 7 illustrates the behavior in the frequency domain that was observed at the highest level of resistance. This graph illustrates that the reduction in the level of contribution at the harmonics of the fundamental frequency decay consistently as the fan speed is increased. The frequency region below the fundamental at 2100 rpm shows significantly higher contribution than at the higher fan speeds.

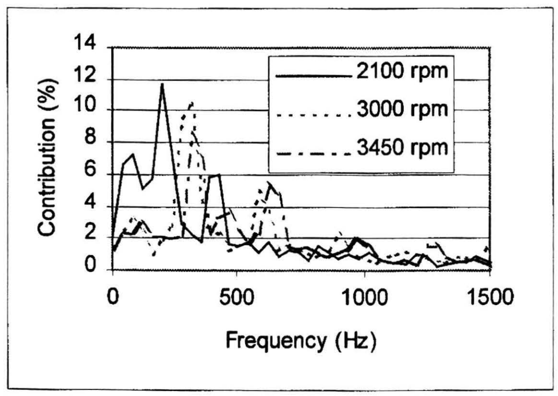

Figure 7. Blade gap frequency domain behavior at three fan speeds, fan operating point Level E.

The frequency domain behavior at the lowest level of resistance is illustrated in Figure 8. Again, this figure illustrates a decreasing level of contribution at the fundamental and harmonic frequencies as the speed of the fan is increased. As in the response associated with the highest level of resistance, this figure indicates additional contribution in the region below the fundamental frequency for the lowest fan speed. This behavior is also clearly visible in the intermediate levels of resistance.

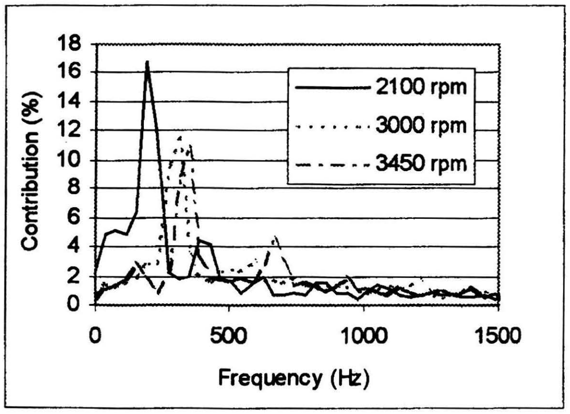

Figure 8. Blade gap frequency domain behavior at three fan speeds, fan operating point Level A.

Frequency Domain Behavior Behind the Blade

The frequency domain behavior at the measuring location behind the blade, at 3000 rpm, is shown in Figure 9. Notice in this figure that there is a fairly uniform increase of the response in the frequency bands below the fundamental frequency. There is also a consistent, although not constant, decay in the contribution associated with the fundamental frequency as the level of resistance is increased.

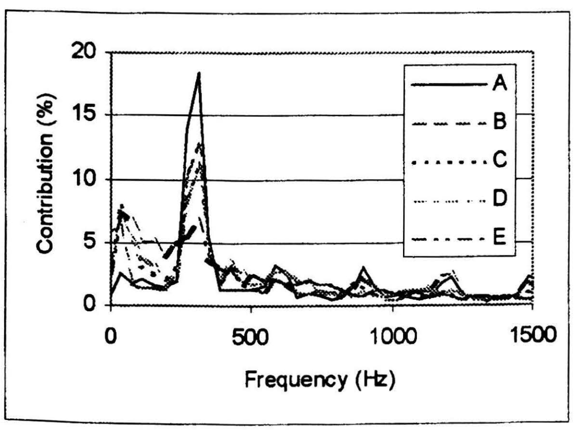

Figure 9. Behind the blade frequency domain response as a function of resistance, 3000 rpm.

At the lowest level of resistance the frequency domain behavior behind the blade shows a consistently low level of contribution at frequencies below the fundamental. (Figure 10). The general pattern of decay in contribution at the higher frequencies is also evident, with the spikes visible at the harmonics of the individual fundamentals.

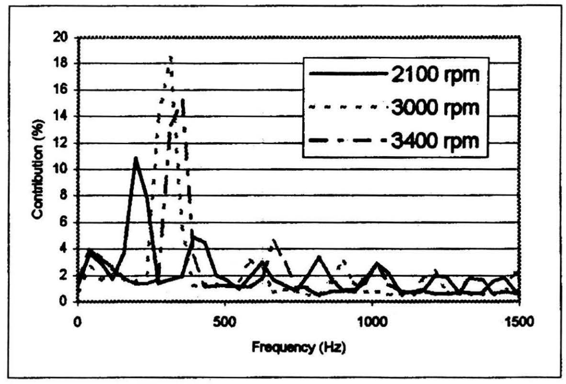

Figure 10. Behind the blade frequency domain behavior at three fans speeds, fan operating point Level A.

As the level of resistance is increased the contribution of frequencies below the fundamental, at each speed, shows a definite increase. This is shown in Figures 11 and 12, for operating points C and E, respectively.

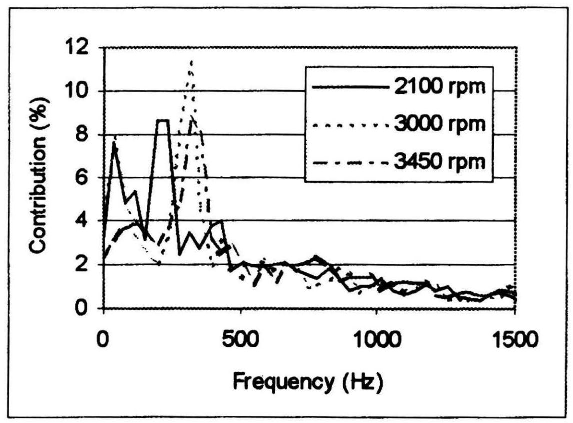

Figure 11. Behind the blade frequency domain behavior at three fan speeds, fan operating point Level C.

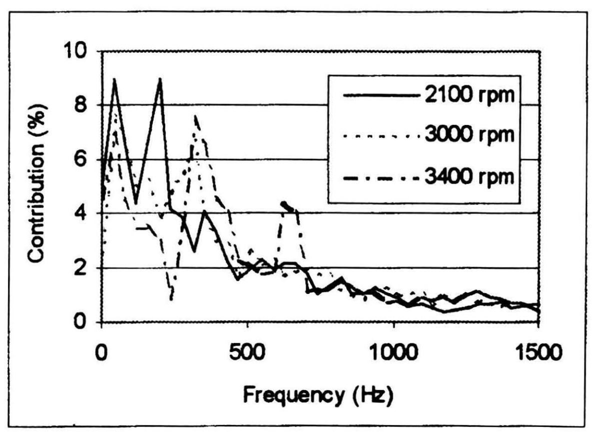

Figure 12. Behind the blade frequency domain behavior at three fan speeds, fan operating point Level E.

CONCLUSION

The purpose of this preliminary study was to determine if there was a basis by which acoustic emission from an axial flow fan could be used to monitor the performance of that fan. In the presence of substantiating evidence further investigation could be warranted to more deeply study the relationships between the fan performance and the acoustic emission. Research documented in this study investigated the acoustic emissions at two positions on the fan, the gap between the blade tip and the fan case and a point behind the blade normal to the plane of rotation. Furthermore, measurements were obtained at 20 points in the fan performance range, four rotational speeds against five levels of resistance.

A general review of the frequency domain data obtained from the series of measurements differs between the two positions of observation. In the blade gap region, variations without systematic differences tend to indicate that one could not directly, and easily, use such an observation as a basis of performance monitoring.

On the other hand, there appears to be systematic variations in the acoustic emission monitored behind the fan blade. A pattern of increasing low frequency contribution is observed at the various fan speeds as the level of resistance is increased. This fact is consistent with the conditions prevalent in a fan stall, that is deepening of the sound emitted by the operating fan (McPherson, 1993). Considering the two positions monitored, this one appears to be the most likely to provide consistent information on the operating condition of the fan.

The results of this investigation show that there is some basis to assume that the acoustic emission from an axial flow fan can provide information on the level of performance. That is to indicate the position along the pressure versus volume curve for a given speed. While not conclusive at this time, there appears to be evidence that such an approach is worthy of a more detailed study.

Should further research confirm the utilization of fan blade acoustic emission as a form of fan monitoring, it is likely that a small electronics package could make this a relatively inexpensive method to monitor a fan in operation.

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[1] Mr. Ramsay currently with Arundel Corporation, Maryland