Some Singular Acoustic Signatures Observed in a Jet Aircraft

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Abstract

SOME unusual noises characterized as grinding and resonance were reported in the cockpit of a twin-engine jet aircraft. This paper presents a physical model and the related studies on grinding by postulating the noise as due to the vortices shed from the compressor blade tips with markedly excessive clearance between the rotor blade tip and the compressor casing. Using this model an equation has been obtained for the grinding as well as the general compressor noise; the equation accounts also for the resonance and highlights the importance of uniform compressor blade tip clearances within narrow limits to eliminate noise accompanying the blade vibrations.

Contents

During production flight tests on several twin-engine jet fighter aircraft, test pilots reported occurrence of unusual cockpit noises emanating possibly from the engine and characterized them as grinding and resonance. Discussions with the pilots indicated that the noise was of low frequency; the intensity was marked at higher altitudes and feeble at low altitudes. This noise was imperceptible at low altitudes and engine speeds. Furthermore, vibration of stick, pedals and seats was reported on another aircraft at all altitudes and throttle settings in addition to grinding and resonance at higher altitudes indicating unbalance as causing the grinding, resonance and vibration. Besides alarming and distracting the pilot from his main mission, these unusual noises aggravated pilot fatigue and hence required remedial measures. Ad hoc rectification procedures followed earlier were unsuccessful in the present case.

A study of the problem conducted in conjunction with the pilots' comments indicated that the vibration and noise must originate from the compressor dynamic unbalancing factors. Unbalance must be produced by causes having acoustic side effects since dynamic unbalance cannot vary with altitude; although the noise is imperceptible at lower altitudes, it must, nevertheless, be present at all engine speeds, aircraft speeds and flight altitudes including stationary ground running conditions. For this purpose systematic ground and flight investigations were performed on a total of seven engines and two aircraft to understand and identify the causes for grinding, resonance, and vibration.

To investigate this problem in depth, an aircraft with the reported defect was equipped with a 0-20 kHz frequency-response, sensitive microphone and a tape recorder to record both cockpit noise and pilot comments. In addition vibration transducers were fixed to measure vibration levels. The cockpit noise recording was printed on a trace recorder and was analyzed using fast-Fourier techniques. Similar analyses were made of the defective engines on a ground test bed without simulating atmospheric environmental conditions and forward speeds. Studies and analyses were also made both on ground and in flight of the defective engines with their suspected rotors replaced by those having closely controlled blade tip clearance.

Grinding and resonance were found in the cockpit noise recordings from ground level up to all altitudes, 0.9 km-11 km. The phototraces and FFTs showed three distinct and well separated frequencies in the bands $f \sim 1$ Hz, $f \sim 166$ Hz, and $f \geq 5$ kHz. As may be expected, cockpit noise recordings obtained both during ground run and in flight did not reveal frequencies $f \geq 5$ kHz due to the strong absorption of the structure between the engine and the cockpit. Instead, only low acoustic frequencies $f \sim 1$ Hz and $f \sim 166$ Hz were present. Grinding and resonance are contained in the frequency domain below 166 Hz while the total noise spectrum extends over the frequency domain 0-20 kHz. A well defined noise with sharp, pronounced, but, nearly constant frequency $f \sim 166$ Hz could be observed at 100% engine rpm. This noise was related to the intermittent, but regular bursts with sharp, pronounced, but nearly constant amplitude peaks corresponding to grinding. Narrow pulses of small amplitude correspond to low grinding; wide large amplitude pulses represent moderate grinding; and a pulse train of large width and amplitude represents high grinding. Figure 1 shows typical trace recordings of grinding along with the corresponding qualitative pilot ratings (high, moderate and low) and displays the sharp amplitude peaks.

Figure 2 shows typical traces of resonance with a slow variation of the amplitude peaks of grinding modulated with a characteristic frequency $f \sim 1$ Hz. It is seen that resonance cannot appear without grinding so that grinding is a necessary condition for resonance. Define the amplitude modulation ratio $A =$(max. amplitude − min. amplitude)/(max. amplitude) for the amplitude of the enveloping waveform. When $A > 0.7$, resonance is high; when $0.5 < A < 0.75$ resonance is moderate; when $0.25 < A < 0.50$ resonance is low; and when $A < 0.25$, resonance does not occur. Normally, resonance could arise as a beat between the grinding frequencies of the two engines of twin engined aircraft due to imperfect synchronism. But, this is improbable since the same phenomenon has also been reported in another single engine aircraft. A plausible explanation of resonance is provided by the periodic tiny longitudinal movement of the engine rotor assembly resulting in longitudinal pressure waves superimposed on the pressure fluctuations of grinding. In fact, this longitudinal play of a small but finite amount was detected by independent investigations on the engine bearings. Due to the large rotor inertia, the frequency of its longitudinal movement, and the resonance frequency, $f_r \ll f_g$, the grinding frequency. Further FFTs of vibration and sound recordings of the defective engines on the test bed showed strong amplitude peaks near the second stage eigen frequency. The cumulative sum and difference frequencies contribute to a sharp peak at 6.6 kHz with smaller peaks at other higher frequencies.

A measurement of the acoustic energy in the total noise and in the noise obtained after filtering out the high frequency

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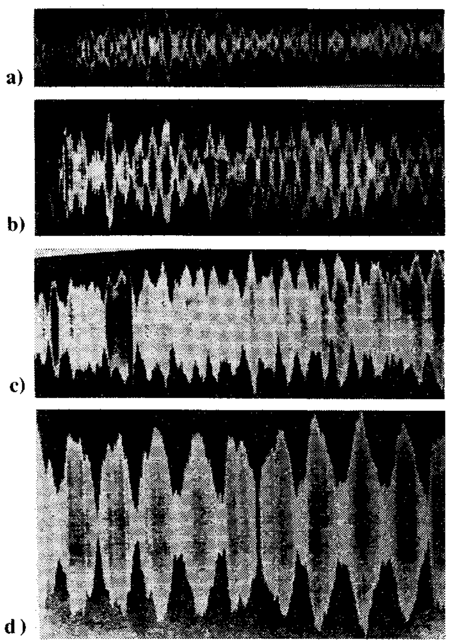
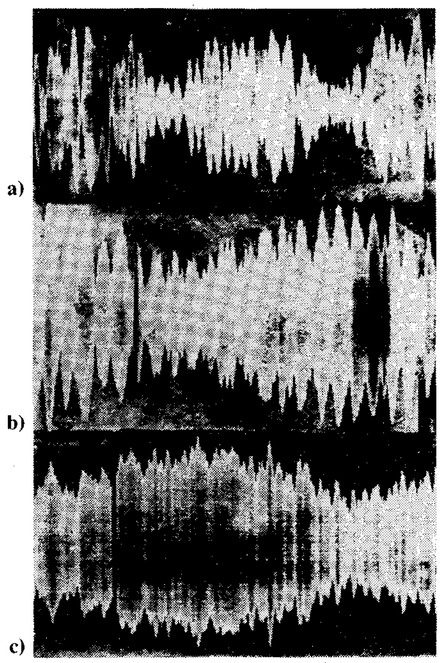


	H, kft	E	ν, %	f,Hz	G	R
a	5	3,4	100	166	0	0
b	30	3,4	100,78	135	l	0
c	30	3,4	90,98	176	m	0
d	31	3,4	95,93	161	h	0

Fig. 1 Phototraces of grinding noise.



	H, kft	E	ν, %	f, Hz	G	R
a	5	3,4	82	143	l	h
b	30	3,4	92.5	167	m	m
c	30.3	3,4	95	167	h	h

Fig. 2 Phototraces of grinding noise with resonance.

sounds was made. Defining the ratio (acoustic energy in grinding and resonance/acoustic energy in the general cockpit background) as relative grinding noise parameter, $\tilde{\sigma}$, measurements for a number of defective engines, flight speeds, altitudes and engine speeds showed good correlation with qualitative pilot ratings for grinding and resonance levels characterized as follows:

high grinding + high resonance corresponds to $\tilde{\sigma} > 1.0$
moderate grinding + moderate resonance, $0.5 < \tilde{\sigma} < 1.0$
low to nil grinding + low to nil resonance, $0.25 < \tilde{\sigma} < 0.5$

These ratings are related closely with the relative levels of grinding and resonance. Thus, $0 < S < 0.3$ corresponds to low grinding plus low resonance; $0.3 < S < 1.3$, moderate grinding plus moderate resonance; and $S > 1.3$, high grinding plus high resonance. The variation of $\tilde{\sigma}$ with altitude indicates strong attenuation in the lower dense layers of the atmosphere. Comparative cockpit noise level measurements made in aircraft B both on the ground and in flight with its defective rotor replaced by a good compressor assembly show significant reductions in cockpit noise levels.

Ideally, the tip clearance between the rotating blade and the compressor casing should be zero although a small but finite clearance is necessary for practical reasons. When the tip clearance ΔR is identical for all the B_n blades of stage n, a background noise of high frequency $f_n = B_n\omega/2\pi$, depending on the rotational velocity, emanates from each of the N compressor stages. The pressure pulses corresponding to the weak shed vortices emanating from these nearly uniform tip clearances constitute the constant background engine noise. The shed vortex strength is related to the pressure differential[1,2] produced by the blade at the tip which may in turn be assumed to be proportional to the stage pressure ratio. Similarly, the frequency and intensity of the grinding noise are related to the strong plane wave radiation emanating from compressor blade tips with markedly excessive clearance between the blade and the compressor casing.

The total compressor noise and grinding noise intensities I and I_g may be shown to be given respectively by

$$I = (\rho\omega_m^2 v^2/4\pi)\left\{\sum_{n=1}^{N}[B_nR_nC_nC_{ln}\delta_n(1+\lambda_n^2)]^2\right\}^{1/2} \tag{1}$$

$$I_g = (\rho\omega_m^2 v^2/4\pi) z R_n C_n C_{ln}\delta(1+\lambda_n^2) \tag{2}$$

$$f_g = (\omega z/2\pi) \tag{3}$$

where z = number of blades with a tip clearance $\delta \ni \delta \gg \bar{\delta}_n$, R_n, C_n, C_{ln}, λ_n are respectively the radius, chord, lift coefficient,[3] and $V_n/\omega R_n$ of stage n; and ρ equals ambient air density. $\tilde{\delta} = I_g/I$ may be written as

$$\tilde{\sigma} = k_n z R_n C_n C_{ln}\delta(1+\lambda_n^2)/\left\{\sum_{n=1}^{N} [k_nB_nR_nC_nC_{ln}\tilde{\sigma}_n(1+\lambda_n^2)]^2\right\}^{1/2} \tag{4}$$

where k (f_n), the acoustic transmissibility coefficient of the intervening medium, depends on the frequency characteristics of the air and structural partitions between the noise source and the cockpit. Thus $\tilde{\sigma}$ is seen to be a linear function of δ and is independent of the engine rpm and the flight Mach number. The earlier compressor stages contributing more to I_g and $\tilde{\sigma}$ than the later higher compression stages for a given $\delta/\bar{\delta}_n$. Assuming the engine manufacturer's specification for the mean tip clearance as unity, the tip clearance anomaly $\delta/\bar{\delta}$ can be calculated for an observed grinding noise ratio $\tilde{\sigma}$ so that a correspondence can be established between the blade tip clearance and the qualitative rating scale of grinding.

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