Acoustics of Rotors Utilizing Circulation Control

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The acoustic characteristics of circulation-controlled rotors are examined by comparing data collected in the Ames 40×80-Foot Wind Tunnel from three full-scale rotors: X-Wing, rotor, Circulation Control Rotor, and conventional rotor. Both the X-Wing and Circulation Control rotor had higher sound levels than the conventional rotor at identical advancing tip Mach numbers. There is excess noise due to the unusual compressor on the X-Wing rotor and high broadband noise on the circulation control rotor. The X-Wing rotor had lower sound levels than the conventional rotor at identical forward speeds because of the lower tip speed feasible with the use of circulation control.

Nomenclature

c	= speed of sound, m/s
$\bar{c}$	= average blade chord, m
$C_{LR/\sigma}$	= rotor lift coefficient, $L/\rho(\Omega R)^2 S$
dB	= sound pressure level, 20 log (P_{rms}/P_{ref})
dBA	= A-weighted dB
L	= rotor lift, N
M_{at}	= advancing tip Mach number, $(1+\mu)\Omega R/c$
M_j	= blowing jet Mach number, V_j/c
M_{tip}	= tip Mach number, $\Omega R/c$
N	= number of blades
P_{ref}	= reference pressure, 0.00002 N/m^2
P_{rms}	= root mean square sound pressure, N/m^2
R	= rotor radius, m
r	= distance from hub, m
S	= reference area, NcR, m^2
V	= tunnel speed, knots or m/s
V_j	= jet-blowing velocity, m/s
x	= distance upstream from hub to measurement position, m
y	= lateral distance left from hub to measurement position, m
z	= vertical distance up from hub to measurement position, m
α	= shaft angle, positive aft, deg
θ	= collective pitch, deg
μ	= advance ratio, $V/\Omega R$
ρ	= air density, kg/m^3
σ	= solidity, $S/\pi R^2$
θ	= angle below rotor plane, $\tan^{-1}(-z/r)$, deg
ψ	= azimuth angle from downstream, $\tan^{-1}(-y/-x)$, deg
Ω	= rotor rotational speed, rad/s

Introduction

HELICOPTER rotors with circulation-controlled airfoils for lift augmentation and control have been developed in the last few years. The feasibility of these rotors was demonstrated in wind-tunnel tests of the Circulation Control Rotor (CCR) and the X-Wing rotor. The sound fields of these rotors are expected to be different from those of conventional rotors because of 1) changes in the usual rotor noise sources (such as thickness noise, trailing-edge noise, and rotational noise) and 2) the introduction of additional acoustic sources (such as jet noise). If this technology is to be used, its effect on rotor acoustics needs to be understood because noise is one of the factors that must be considered in the design of new rotors. The purpose of this paper is to examine the acoustics of circulation-controlled rotors. The measured noise of three rotors will be considered: two hingeless rotors that utilize circulation control and a conventional articulated rotor. The conventional rotor is included to provide a baseline for examining the characteristics of the other two rotors.

Circulation control is a method of varying the lift coefficient of an airfoil by injecting a thin jet of air tangential to the upper surface of the airfoil. The air jet follows the curved surface of the airfoil's rounded trailing edge and moves the stagnation point around the airfoil, as shown in Fig. 1. This phenomenon has application on helicopter blades where it may be used to improve the lifting capabilities of the rotor and to provide another means of handling the cyclic variations of the blade lift coefficient needed in forward flight. For a more detailed description of circulation control and its application to helicopters, see Reader et al.[1]

The application of circulation control to helicopter rotors can have an effect on all of the conventional rotor noise sources; in addition, it can introduce some new sources. The use of circulation control can provide high lift at relatively low rotor speeds. All aerodynamic sources of noise increase with an increase in Mach number and they all radiate more energy forward with an increase in forward Mach number up to 1. As shown in Refs. 2 and 3, high-speed thickness noise is an impulsive noise that most people find annoying and occurs at advancing tip Mach numbers of 0.9 and above. The low tip speed on these new rotors is expected to avoid high-speed thickness noise even though the rotor blades are thicker than conventional rotor blades. Blade vortex interaction noise is another impulsive noise source that people find very annoying. This noise is generated when the rolled-up tip vortex from a rotor blade passes close to a rotor blade, as described by Widnal and Wolf[4] and Conner and Hoad.[5] A rotor blade utilizing circulation control will have a very different aerodynamic flow field than a conventional rotor; the tip vortex from a circulation-controlled rotor and the subsequent blade/vortex interaction phenomena probably differ from a conventional rotor. The tip vortex from the circulation-controlled rotor type may be more diffuse and thus cause less impulsive noise than a conventional rotor. For the circulation-controlled rotors, the broadband trailing-edge noise may increase because the trailing edge is now rounded, with no constant rear stagnation point, and the velocity at the trailing edge is greater due to the jet; moreover, the jet may provide more turbulence. There are also new sources connected with the jet. These include jet noise sources from turbulent mixing, shear-layer instabilities, and nozzle lip noise. The compressor

Received Dec. 27, 1982; revision received March 21, 1983.

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supplying the jet air adds another source, along with the dumping of unused air from the compressor. The expected effect on noise from all of these considerations is that the discrete frequency components (rotational and impulsive noise) will decrease and the broadband component will increase. Which rotor will be louder and more annoying cannot be predicted because the extent and relative importance of all of these phenomena are not known.

Three rotors will be described: two that utilize circulation control and a conventional rotor. Acoustic measurements from each of the rotors will be examined in terms of operating conditions at a low forward speed. Noise measurements from the three will be compared with each other over a forward speed range at operating conditions approximating level forward flight.

Description of Rotors

Parameters describing the three rotors are shown in Table 1. All consist of four-bladed rotors; however, due to the use of circulation control on the two new rotors, the use of four blades is all that is similar between the three rotors. The conventional rotor and CCR have the same diameter, the X-Wing rotor is considerably smaller. Both circulation-controlled rotors have elliptic airfoils that are thicker than the more conventional airfoil on the conventional rotor. The conventional rotor operates by using collective and cyclic pitch to control lift and provide propulsive force. The circulation-controlled rotors operate differently.

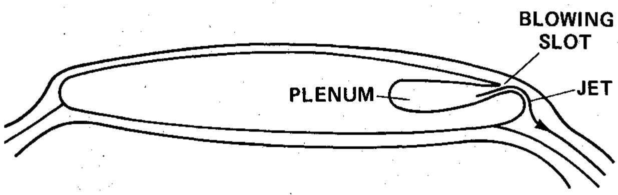

Fig. 1 Circulation control airfoil.

Table 1 Rotor descriptions

Parameter	Conventional Rotor	X-Wing rotor	Circulation Control rotor
Diameter, m	13.41	7.62	13.41
Number of blades	4	4	4
Airfoil	CS-1095 CS-1095-R8	Elliptic	Elliptic
Chord			
Root, m	0.384	0.572	0.457
Tip, m	0.384	0.286	0.457
Thickness ratio			
Root	0.095	0.20	0.25
Tip	0.095	0.10	0.15
Solidity	0.0748	0.144	0.085
Twist, deg	−10	0	−8.6
Tip Mach number	0.60	0.47	0.54
Blade passage frequency, Hz	9.5	13.5	8.5

The X-Wing rotor provides lift and only a part of the propulsive force; it will have jet engines to provide all of the thrust during cruise and a portion of the thrust during rotor operation. The rotor is designed to stop and operate as a fixed wing at high forward speed. In high-speed helicopter flight, the rotor does not tilt as far forward as the conventional rotor tilts because of the contribution of the jet engines to the propulsive force. The rotor has jet blowing through narrow slits at the leading and trailing edges on the upper surface of each blade. Jet blowing increases the lift. During all flight conditions the jet is blown out the slot near the trailing edge; in addition, during high advance ratio flight a jet is also blown out the slot near the leading edge on the retreating blade. Azimuthal variation in blowing controls the moments produced by the rotor. Due to this circulation control by blowing, the X-wing rotor has a lower geometric collective pitch angle than a conventional rotor and no mechanical cyclic pitch.

The Circulation Control Rotor (CCR) produces lift and propulsive force in the same manner as the conventional rotor; however, cyclic and collective blowing on the trailing edge of each blade controls the lift instead of geometric blade pitch. As in the X-Wing, the jet blowing of the CCR produces high lift at a low collective pitch setting and is used for cyclic lift coefficient variations around the azimuth.

Description of Tests

The three rotors were tested in the 40×80-Foot Wind Tunnel at Ames Research Center to determine their performance, loads, stability, and acoustic characteristics. Each test covered a wide range of operating conditions. Table 2 contains the range of parameters considered in this report; for more detailed descriptions of the tests, see Refs. 6-12.

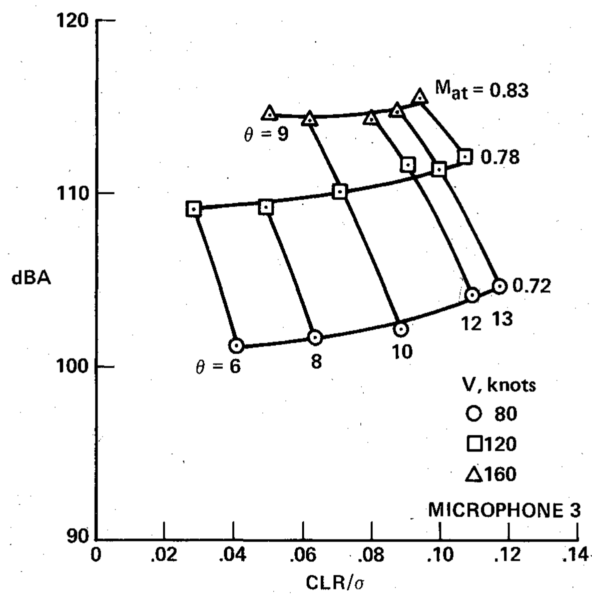

Fig. 2 Sound pressure level of a conventional rotor as a function of lift coefficient.

Table 2 Rotor operating conditions

Condition	Conventional rotor Min	Conventional rotor Max	X-wing rotor Min	X-wing rotor Max	Circulation Control Rotor Min	Circulation Control Rotor Max
V, knots	79	151	59	189	59	140
M_{at}	0.72	0.83	0.55	0.74	0.63	0.71
ΩR, m/s	202	207	158	163	180	185
α, deg	−10	+10	−5	+8	−16	+8
C_{LR}/σ	−0.01	+0.14	−0.03	+0.15	+0.03	+0.15
θ, deg	0	15	−5	3	−5	5
M_j	—	—	0	0.97	0.67	0.98

Table 3 Location of microphones

Rotor	Microphone	x, m	y, m	z, m	r, m	θ, deg	ψ, deg
Conventional	3	19.2	0	−4.2	19.7	12	180
	6	3.5	−3.6	−3.9	6.3	32	134
X-Wing	3	15.5	4.9	−3.3	17.5	11	196
	6	2.7	5.5	−3.3	5.9	34	242
CCR	3	19.2	0	−4.2	19.7	12	180
	6	3.5	−3.6	−3.9	6.3	32	134

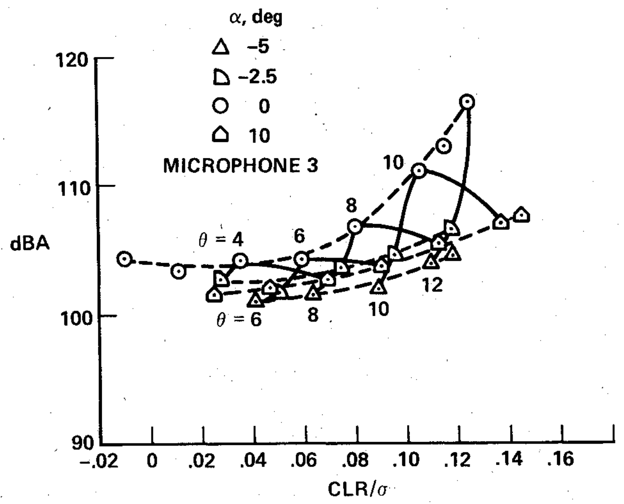

Fig. 3 Sound pressure level of a conventional rotor as a function of lift coefficient.

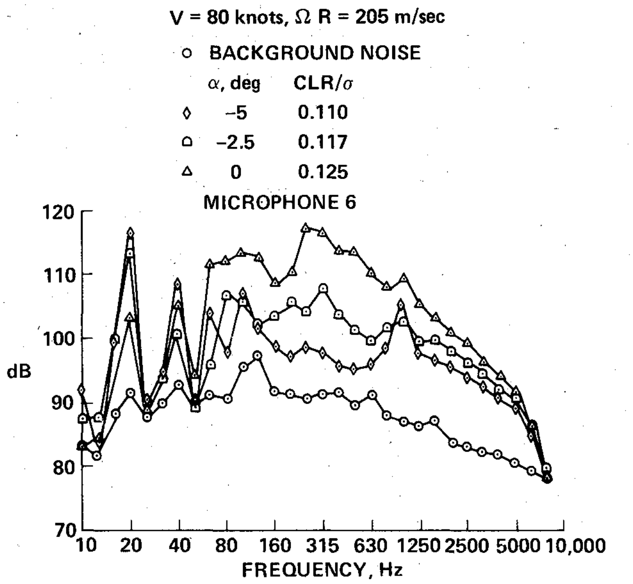

Fig. 4 One-third octave spectra measured under the conventional rotor at several shaft angles.

Acoustic data were recorded from six or seven condenser microphones (1.2 cm diameter) onto a 14-track FM tape recorder. The locations, with respect to the rotor hub, of the microphones (3 and 6) used for this report are listed in Table 3.

Description of Data Processing

Data processing was done on a minicomputer-based time-series analysis system with associated hardware for digitizing and for Fast Fourier Transform. The frequency spectrum analyzed on the conventional rotor is 20-5000 Hz and on the two circulation control rotors 20-10,000 Hz. The cut-off frequency will be apparent in the one-third octave plots. The low level of the upper cut-off frequency will make no difference in the dBA measurements because the rotor produces little energy above 5000 Hz relative to that produced at lower frequencies. No corrections have been made for background tunnel noise. For much of these data, background tunnel noise is insignificant; when the background noise is significant, it will be noted.

Results and Discussion

Conventional Rotor

Forward speed, lift coefficient, and rotor angle of attack determine the noise produced by a conventional helicopter rotor. Noise, when measured by an overall quantity such as dB, dBA, or PNdB, increases with an increase in forward speed or an increase in lift coefficient. Figure 2 shows the sound pressure level measured in dBA as a function of lift coefficient for three forward speeds of 80, 120, and 160 knots measured at a microphone in front of the rotor and slightly below the rotor tip path plane. In this figure the tip Mach number is 0.60 and the rotor shaft angle is −5 deg. The noise level increases greatly with increased forward speed and increases slighly with increased lift. The overall noise level is dependent on the combination of lift coefficient and shaft angle at a given forward speed. Figure 3 displays dBA as a fucntion of lift coefficient for shaft angles of −5, −2.5, 0, and +10 deg measured at the same microphone. The tip Mach number is 0.60 and the forward speed is 80 knots. The noise level increases substantially when the lift coefficient is high and the shaft angle is 0 deg, a condition that would be experienced when a helicopter is slowing its forward speed and descending (see Hubbard et al.[13]). This is the condition where a helicopter produces loud impulsive noise due to blade vortex interactions. This rotor also produced loud impulsive noise in high-speed forward flight when the advancing tip Mach number was above 0.9 (see Lee[8]).

A more detailed description of the sound can be given by examining one-third octave spectra, narrow-band spectra, and time histories. The noise produced by a helicopter is very complex, consisting of broadband noise and discrete frequency noise at multiples of the blade passage frequency. In the time domain the noise is basically periodic, with the period being the reciprocal of the blade passage frequency. The shape of the waveform has little significance except when it is impulsive; periodic impulses produce the loud banging or whopping sound people find annoying. The one-third octave spectra from some of the data points in Fig. 3 are shown in Fig. 4. Some features appear in the one-third octave spectra that can be related to features in narrow-band spectra and time histories. Peaks in the low-frequency range of 10-100 Hz arise from discrete narrow-band sources at the blade passage harmonics, mainly due to periodic force dipole sources on the rotor blades. Between 100 and 1000 Hz the one-third octave spectra are nearly flat. Narrow-band spectra show both broadband noise and discrete frequency harmonic noise in this range. At high frequencies the noise is broadband except for some discrete frequencies around 1000 Hz. The high-frequency discrete noise is an anomaly to this rotor and believed to originate from a tone generated by vortex shed-

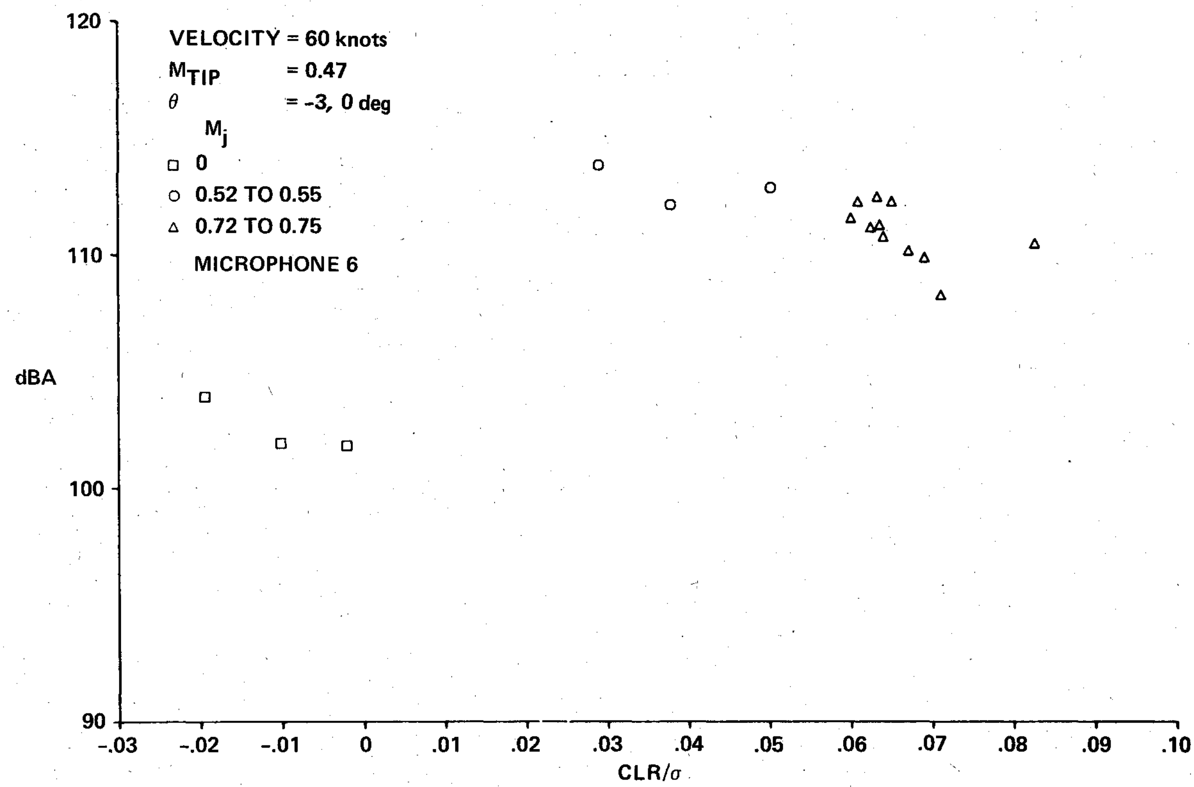

Fig. 5 Sound pressure level of X-Wing rotor as a function of lift coefficient

ding off the attachment hardware for interchangeable blade tips at 95% radius. Figure 4 shows that during conditions of high lift the increase in noise at vertical shaft angles occurs in the mid-frequency range. Narrow-band spectra would attribute this noise to blade passage frequency harmonics, and time histories would show impulsive noise.

X-Wing Rotor

Jet-blowing velocity and forward speed determine the noise produced by the X-wing rotor. Noise is strongly dependent on the jet blowing, a factor not present in a conventional rotor. Forward speed plays less of a role than on a conventional rotor. The shaft angle has no effect on noise, unlike a conventional rotor. The lift coefficient has an effect on the noise, but not directly. Both the blade collective pitch and the jet blowing determine the lift; however, only the jet blowing has an effect on the rotor noise. No impulsive noise was measured on the X-Wing model, either from high-speed thickness noise or blade vortex interactions.

Figure 5 shows the sound pressure level as a function of rotor lift coefficient for jet-blowing Mach numbers of 0.0, 0.53, and 0.73 measured at a microphone under the rotor. The forward speed is 60 knots, the tip Mach number is 0.47, the geometric pitch covers the range from −3 to 0 deg, and the shaft angle covers the range from −2 to +4 deg. The noise level does not vary much within one jet-blowing level, but it has a different noise level for each jet-blowing level. Noise measurements are the highest when the jet Mach number is 0.54 and the least when there is no jet blowing.

The one-third octave spectra from some of the points in Fig. 5 are shown in Fig. 6 along with the background noise. As with measurements from the conventional rotor, the spectra show peaks in the low-frequency range at the blade passage frequency with a fairly constant level in the mid-frequency range. Spectra levels in the high-frequency range remain constant or contain peaks, unlike measurements from the conventional rotor where the noise level falls off above 1000 Hz. This noise in the high-frequency range of the spectra

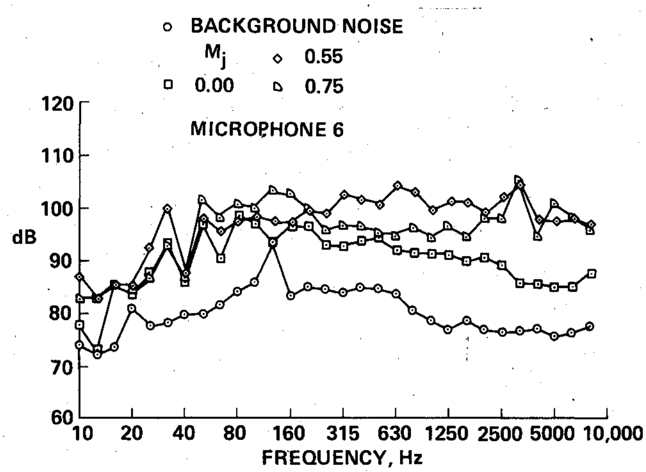

Fig. 6 One-third octave spectra measured under the X-Wing rotor at several jet-blowing velocities.

consists of broadband noise and tones from the first and second harmonics of the compressor blade passage frequency. The compressor was located under the floor and was not representative of a flight vehicle.

Circulation Control Rotor

Jet-blowing Mach number and geometric collective pitch determine the noise level of the Circulation Control Rotor. Forward speed has little, if any, effect on the noise, and the shaft angle affects the noise for only a few conditions. No high-speed impulsive noise was measured on this model. At low speed (60 knots), low positive shaft angle, and moderate jet blowing, some blade vortex interaction noise was found.

Figure 7 shows the sound pressure level measured in dBA as a function of lift coefficient for a microphone under the rotor. The forward speed was 100 knots, the tip Mach number 0.54, and the shaft angle was −6 deg. Data recorded at a constant collective pitch show the sound level increasing with increasing blowing velocity. Curves of constant blowing velocity have a decrease in sound level for collective pitch increases from 0 to 4 deg and then level off at higher collective pitch levels.

One-third octave spectra for three combinations of jet-blowing Mach number and collective pitch are shown in Fig. 8. Like a conventional rotor, a few of the blade passage harmonics cause peaks in the low-frequency end of the spectra, and higher frequency harmonics and broadband noise produce flat spectra in the mid-frequency range. Unlike the conventional rotor, levels are relatively high in the high-frequency range: spectra contain a peak in the 5000 Hz band from a compressor blade passage frequency tone and sometimes contain a maximum centered in the 2000 Hz band. The compressor was located under the floor and was not typical of a flight vehicle. This extra broadband noise is present when the jet-blowing level is high and the geometric blade pitch is low.

Comparison of the Three Rotors

The influence of flight conditions and control settings on the sound levels of the three rotors has been discussed in the previous sections. Now the rotors will be compared with each other at forward flight conditions. Because the rotors had different sizes, tip speeds, and different means of producing thrust, they cannot be compared at identical control settings. The data to be compared for the three rotors were chosen to come from typical forward flight conditions for each rotor and at similar nondimensional rotor lift coefficients. The control settings are in ranges where small changes in collective pitch and shaft angle have little or no effect on the sound levels. For the conventional rotor, the settings are a tip Mach number of 0.6, a shaft angle of −5 deg, a collective pitch of 8-10 deg, and a lift coefficient of 0.07. Two X-Wing curves are shown, one with no jet blowing and one with a jet-blowing Mach number of 0.74 and the compressor tone removed. The X-Wing rotor noise without blowing is shown so that the effect of blowing on the noise level can be seen. The X-Wing rotor cannot produce enough lift to fly without the jet blowing. The tip Mach number was 0.47, the shaft angle 0 deg, the geometric pitch −3 deg, and the lift coefficient slightly negative without blowing and 0.07 with blowing. Two curves from the Circulation Control Rotor are shown with jet-blowing Mach numbers of 0.74 and 0.82. The tip Mach number was 0.53; the shaft angle was −4 deg at 60 and 80 knots, −6 deg at 100 knots, and −10 deg at 120 and 140 knots; the collective pitch was 0 deg; and the lift coefficient was 0.08 with a jet Mach number of 0.74 and 0.10 with a jet Mach number of 0.82.

The dBA measurements for the three rotors and background noise are shown in Fig. 9 with the microphone in front of the rotor and in Fig. 10 with the microphone under the rotor. Both microphones show the same trends. The noise level of the conventional rotor increases steadily with increased forward speed. With a jet-blowing Mach number of 0.74, the X-Wing noise measurements are constant up to 120 knots; thereafter, they increase with increasing tunnel speed. Noise measurements of the CCR are nearly constant, in a 2 dB range, for each blowing level and microphone. The background noise does not interfere with the noise from the conventional rotor or Circulation Control Rotor. At high tunnel speeds (above 90 knots) the background noise in-

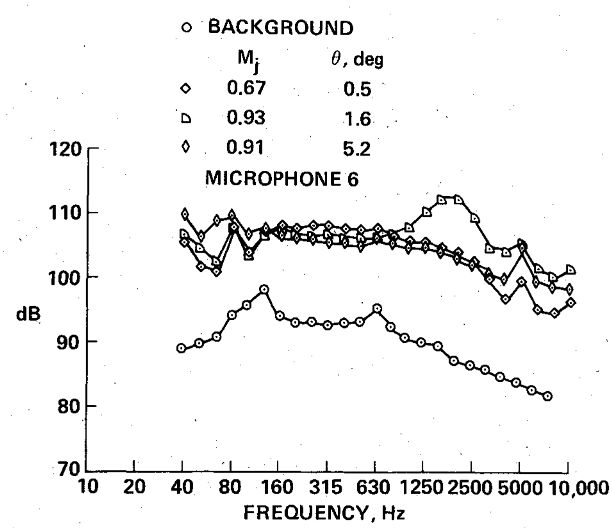

Fig. 8 One-third octave spectra measured under the Circulation Control Rotor at several jet-blowing velocities and blade pitch angles.

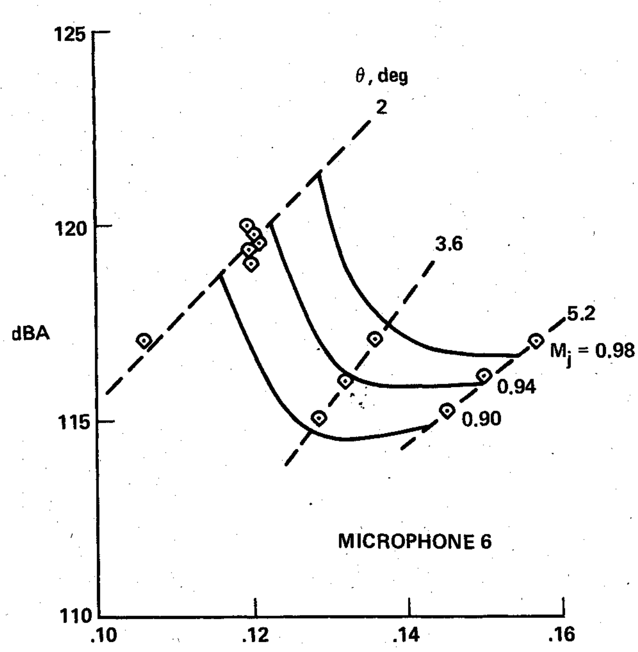

Fig. 7 Sound pressure level of Circulation Control Rotor as a function of lift coefficient.

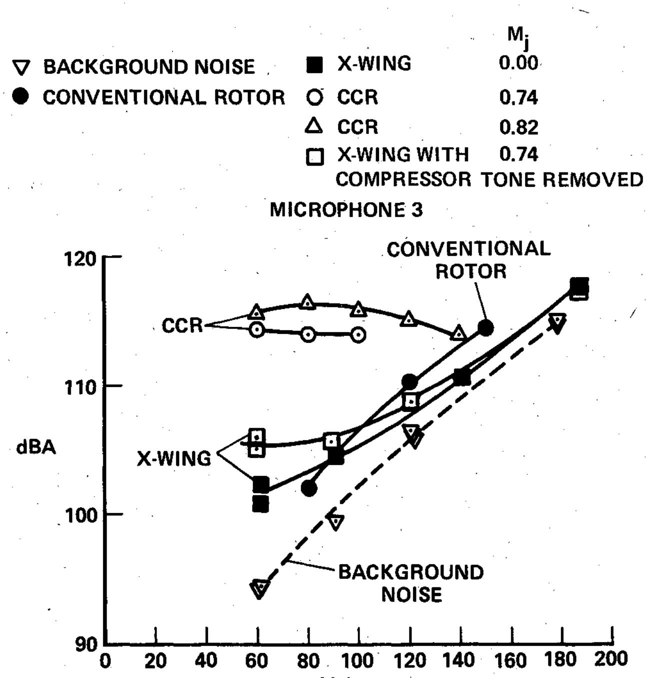

Fig. 9 Sound pressure level of three rotors as a function of forward velocity measured in front of the rotors.

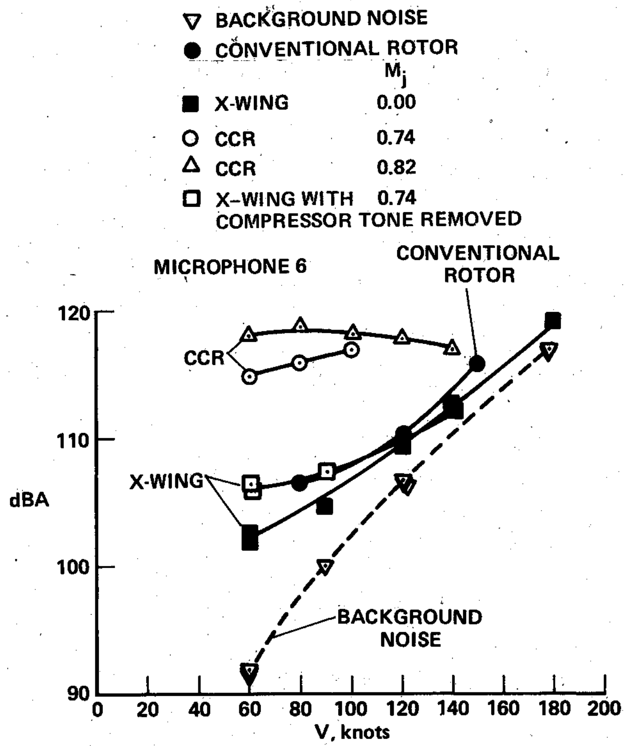

Fig. 10 Sound pressure level of three rotors as a function of forward velocity measured under the rotors.

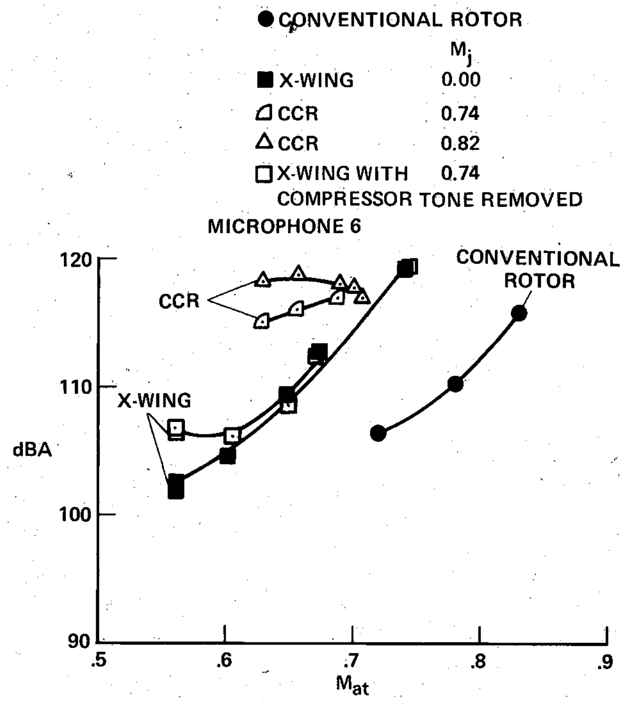

Fig. 11 Sound pressure level of three rotors as a function of advancing tip Mach number measured under the rotors.

terferes with the X-Wing noise measurements. As a result, the X-Wing noise cannot be determined at high forward speeds.

At low forward speed the highest noise level measured was for the CCR with a jet-blowing Mach number of 0.82 and the CCR with a jet-blowing Mach number of 0.74 was next highest; the X-Wing with a jet-blowing Mach number of 0.74, the conventional rotor, and the X-Wing rotor without jet blowing follow in that order. Sound levels under the X-Wing rotor were less than or equal to those of the conventional rotor. At forward velocities above 130 knots the conventional rotor had higher noise levels than the X-Wing rotor with jet blowing. At 150 knots the conventional rotor noise is about the same level as that of the CCR rotor at all speeds. No CCR data were taken at this high tunnel speed for direct comparison; however, unless the sound level became abruptly higher at this forward velocity, the CCR noise would no longer be higher than the conventional rotor at about 150 knots. Noise levels measured at the microphone under the rotor are consistently higher than those at the microphone in front of the rotor. The measured levels are about 1 dB higher for the conventional rotor and for the X-Wing. For the CCR with jet blowing the difference is more, by as much as 4 dB.

Noise from the three rotors is shown as a function of advancing tip Mach number in Fig. 11. The Mach number is of major concern in helicopter noise because aerodynamic noise source strengths increase with Mach number. Also, when the source is moving toward the observer, convective amplification increases the noise level at the observer, and this increase is larger when the Mach number approaches 1. The rotors used in these tests all had different tip Mach numbers, so their advancing tip Mach numbers were different at identical forward speed. At a given advancing tip Mach number, the CCR with highest blowing level had the highest sound level, followed (in order of decreasing sound level) by the CCR with lower jet-blowing level, the X-Wing rotor with jet blowing, the X-Wing rotor without jet blowing, and the conventional rotor. These are the same data points as those in the previous graph, so the sound level for the X-Wing with high Mach numbers are contaminated by background noise and do not truly reflect the X-Wing model. When matching advancing tip Mach number, the rotors with circulation control have higher noise levels than the conventional rotor.

Noise measurements of the three rotors include detailed characteristics. All rotors have discrete frequency noise at their blade passage harmonics. Under the rotors, this noise increases as the lift produced by the rotors increases, whether the lift is due to mechanical collective or jet-blowing circulation control. In front of the rotors there were no consistent patterns, probably because the sound field there is a complicated mix of direct and reflected waves. The mid-frequency range was relatively constant except for low positive shaft angles on the conventional rotor and on the Circulation Control Rotor. On those rotors, but not the X-Wing rotor, there is blade/vortex interaction noise at high lift (but low jet blowing on the CCR). All rotors showed a peak in the high-frequency range; however, the source of the noise is different in each case. For the conventional rotor, the noise originates from two discrete frequencies. One source is in the rotating frame and the other is in the fixed frame. Neither noise source is normally found on a conventional rotor. For the X-Wing rotor, the noise peak is a discrete frequency tone generated by the compressor. For the Circulation Control Rotor the noise is broadband noise associated with high jet blowing and a compressor tone.

Conclusions

The three rotors tested exhibit different noise levels and characteristics as listed below:

1) At identical advancing tip Mach numbers, the conventional rotor had the lowest sound levels followed by the X-Wing rotor and the circulation control rotor in that order.

2) At identical forward speeds, the X-Wing rotor had the lowest sound level followed by the conventional rotor and the circulation control rotor.

3) Neither the Circulation Control Rotor nor the X-Wing rotor had any high-speed impulsive noise.

4) The X-Wing rotor showed no signs of blade/vortex interaction noise. The circulation control rotor had blade/vortex interaction noise at low jet-blowing levels, but not at high jet-blowing levels.

5) The CCR also had excess broadband noise around 2000 Hz at high blowing velocities, producing the high dBA levels. At high collective pitch angles this noise disappeared. The excess broadband noise on the Circulation Control Rotor caused it to be the noisiest rotor tested. The source of the noise is unknown, but is connected with the jet blowing. Perhaps the jet blowing is affecting the trailing-edge broadband noise.

6) This excess broadband noise was not present in the X-Wing rotor.

7) The X-Wing rotor showed potential for being quieter than the conventional rotor; indeed, in many flight regimes it was quieter. It is important to note that the X-Wing rotor had no high-speed impulsive or blade/vortex interaction noise. These are the two most annoying noise sources of conventional rotors.

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