77-GT-70

Printed in U.S.A.

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Some Measured and Calculated Effects of Forward Velocity on Propeller Noise

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The results of a program investigating the sources of noise in unshrouded propellers under forward flight conditions and a comparison with theory are reported. Tests were conducted using an instrumented three-bladed propeller installed on a turbine-powered, twin-engine, general aviation airplane. Measurements included far-field noise on the ground and on the aircraft wing tip, propeller blade surface pressures, atmospheric turbulence, and aircraft operating conditions. The primary result of the full-scale flight tests was to confirm that foward-flight propeller noise levels are lower than those experienced under static conditions and that the most significant reductions occur at the mid-frequencies which dominate perceived and A-weighted noise levels. Analytical techniques have been used to predict the observed experimental trends and to provide further insight into the noise generating mechanisms. Correlation with experimental data is shown to be good at low frequencies under static conditions and at all frequencies in forward flight. It is tentatively concluded that propeller noise generation in flight may result from steady loads (including blade thickness effects). Under static conditions, the principal noise source appears to be the intersection of the propeller with persistent turbulent eddies passing through the propeller disk.

Contributed by the Gas Turbine Division of The American Society of Mechanical Engineers for presentation at the Gas Turbine Conference & Products Show, Philadelphia, PA, March 27-31, 1977. Manuscript received at ASME Headquarters December 20, 1976.

Copies will be available until December 1, 1977.

Some Measured and Calculated Effects of Forward Velocity on Propeller Noise

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INTRODUCTION

Recently, it has been recognized that significant differences exist in the noise signatures of propellers operating statically and in flight (1).[1] Until recently, very little mention has been made in the literature regarding the different character of the noise of propellers under static and flight conditions. The majority of the previous experimental propeller, far-field measurements have been conducted on static test facilities (2). Fig. 1 shows a comparison of propeller noise levels measured statically and in forward flight at 120 knots. As is clearly shown, the tonal and broadband components are significantly lower in the level flight conditions.

Recent work in the development of analytical methods for predicting propulsor noise (3, 4) has revealed that ingestion of atmospheric turbulence can significantly influence the radiated noise from a propulsor operating statically. The in-flow turbulence gives rise to unsteady loading which results in the generation of narrow-band random noise. These tone-like components extend well into the mid-frequencies and may greatly affect the perceived noise level.

The analyses, however, have not been rigorously applied to the forward flight case since the level of unsteady loading components are extremely low compared with those measured under static conditions. Semi-empirical adjustments to the unsteady loading components to account for forward flight show a significant reduction in these components relative to static operation. It is thus apparent that aircraft flyover noise estimates derived from static test stand noise measurements may lead to erroneous conclusions. Also, trend studies for minimizing propeller noise based on static data may not result in the quietest in-flight propellers. Since existing aircraft noise certification rules are based on the noise measured while the aircraft is in flight, it is clear that experimental noise research programs must be carefully designed to provide data which are valid under forward flight conditions.

This paper contains a description of the preliminary results from a test program (1) during which in-flight and static acoustic data, as well as high frequency blade surface pressure information, were obtained on an operational propeller. These data are compared with predictions and show good agreement. Both the test data and the analytical techniques provide further insight into the noise generation mechanisms.

MEASUREMENT PROGRAM

In order to obtain a better understanding of the source mechanisms, a flight program was undertaken to relate fluctuating blade loads on a propeller to the noise produced. Tests were conducted at the NASA Wallops Flight Center, Wallops Island, Virginia. A ground-based acoustic measuring range was set up which consisted of four mobile data acquisition vans and 12 microphones. Aircraft tracking information was supplied by a GSN-5 radar system. The test airplane, shown in the photograph of Fig. 2, is a twin-engine, high-wing, light STOL transport with fixed, tricycle gear. The aircraft is powered by free turbine engines driving three-bladed propellers. The aircraft was instrumented to measure and record propeller blade surface pressures, propeller noise, atmospheric turbulence level, propeller position, and aircraft operating parameters.

Fluctuating blade surface pressures were sensed by flush mounted pressure transducers located in the positive pressure face of one blade of the test propeller as shown in Fig. 2. To minimize effects of slip ring noise, blade

[1] Numbers in parentheses designate References at end of paper.

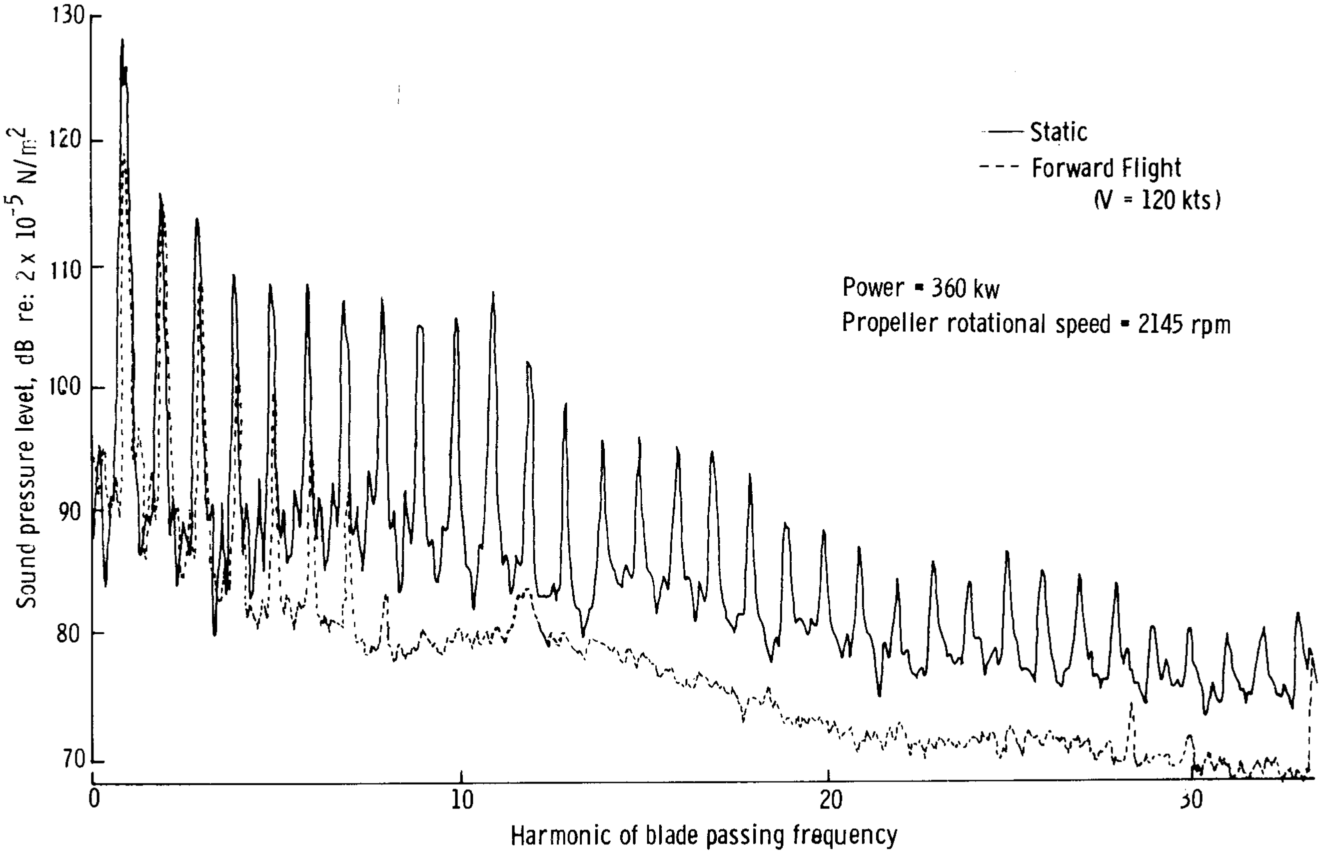

Fig. 1 Comparison of static and forward flight propeller noise levels

pressure signals were amplified by a hub-mounted rotating amplifier prior to being transmitted through the slip ring to the onboard tape recorder. A once-per-revolution pipper generated a single pulse for each propeller revolution to correlate blade position with the pressure signals.

In-flight noise was measured using two microphones mounted on the left wing tip as shown in Fig. 2. One microphone was in the plane of the propeller, 7.28 m (23.9 ft) from the center of rotation; the second microphone was below the wing tip, 7.89 m (25.9 ft) from the center of rotation at an angle of 22.7 deg behind the plane of the propeller.

Atmospheric turbulence in the longitudinal direction was sensed by a hot wire anemometer mounted on the aircraft noise boom as shown in Fig. 2.

Tests were performed for a range of air speed, altitude, propeller speed, engine power and flap settings as indicated below. Flyover tests were executed first; then high speed taxi tests and static runup tests were performed with continuations of propeller speeds and engine power settings that duplicate flight operation over the following range of conditions:

Shaft power	186-410 kw (250-550 hp)
rpm	80-97.5 percent (1760 to 2145 rpm)
Flap setting	0-30 deg
Airspeed	0-125 knots
Altitude	0-305 m (0-1000 ft)

TEST RESULTS

The test program outlined in this paper relates to a basic propeller noise source investigation with primary emphasis on the comparison of results obtained while operating statically and in flight. Only the initial results are presented in this paper.

Blade Surface Pressures

The system used to make blade surface pressure measurements has been described in Reference (1). In order to present these blade surface pressure results in a meaningful way, data from each of the seven transducers were first displayed

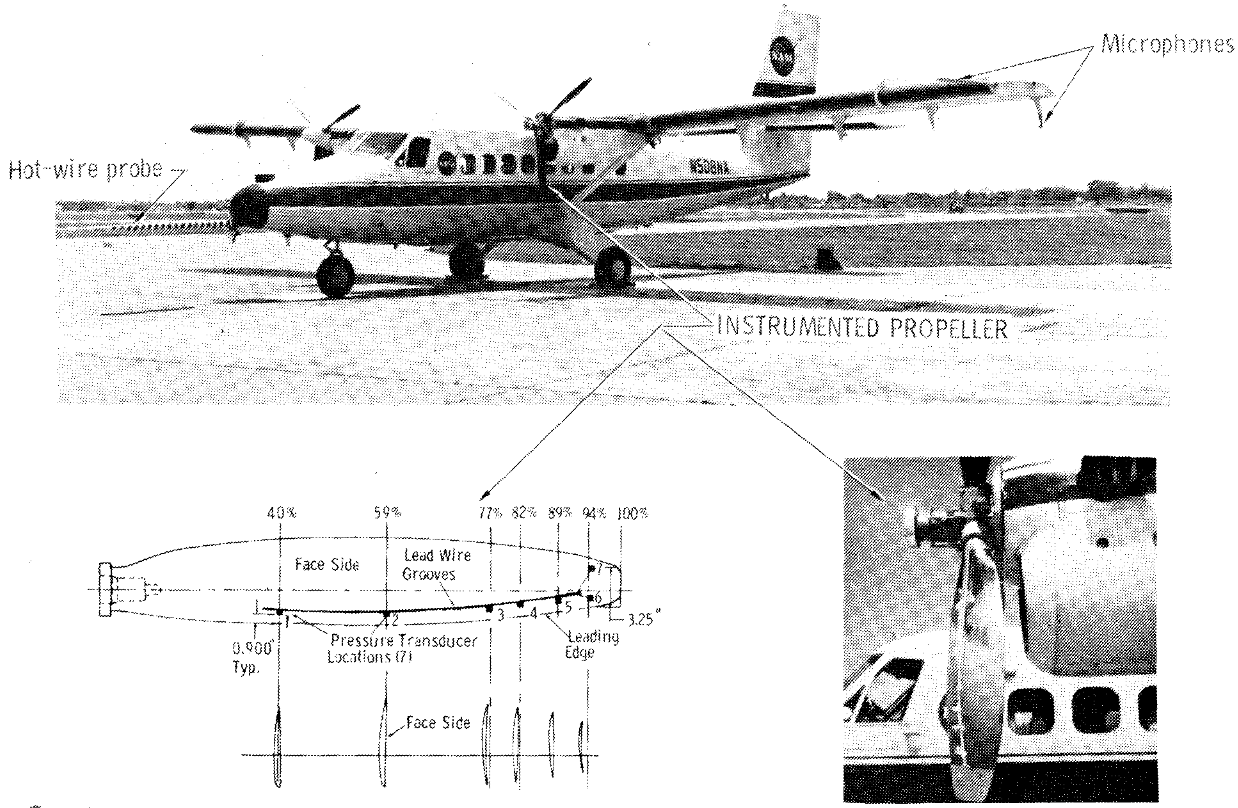

Fig. 2 Test aircraft and instrumented propeller

as an instantaneous surface pressure time history. From this it was possible to determine the length scales and azimuthal position of the turbulence patches encountered by the propeller. It was also possible to obtain fluctuating blade surface pressure information under static and flight conditions.

The crucial input to some of the discrete frequency noise prediction techniques is a detailed knowledge of the fluctuating surface pressures. The overall sound radiated by the blade is then a function of the averaged effect of these fluctuating pressures over the whole blade surface. Lowson and Ollerhead (5) analyzed helicopter experimental loading data and found that the loading harmonics obeyed an inverse square law with respect to harmonic number. For the case of a static propeller, Brown and Ollerhead (6) suggest that the loading harmonics vary more nearly as the inverse of the loading function.

Lowson and Ollerhead have formulated an equation which relates the harmonic noise levels to fluctuating blade loading harmonics (5). When fitted through the available test data, an equation of the form

$$L_n = L_o n^k$$

was obtained, where L_n is the amplitude of the n'th loading harmonic and k is the slope of a straight line fit through the data plotted on a log-log scale. This form has been used extensively for calculating nonsteady blade loading noise. In Fig. 3, typical narrow-band frequency spectra from a particular blade surface pressure gage at the 82 percent radial station for both static and flight conditions are shown.

Superimposed on these spectra are curves that best approximate the harmonic amplitudes. Under static conditions the spectrum shows tonal content to the 50th harmonic; a loading fall-off rate, k, of -1.4 based on the amplitude of the first harmonic best fits the data. In flight, however, blade surface pressure harmonics are evident only to the 10th harmonic before the instrumentation noise floor is encountered. A fall-off rate of -6 best fits this data. Data for other transducer locations were similar in character except that different fall-off rates

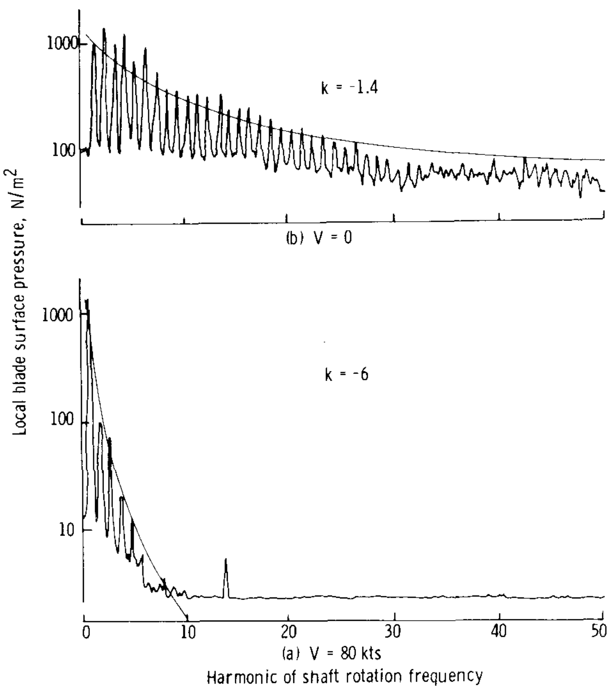

Fig. 3 Propeller blade surface pressure spectra for two flight conditions

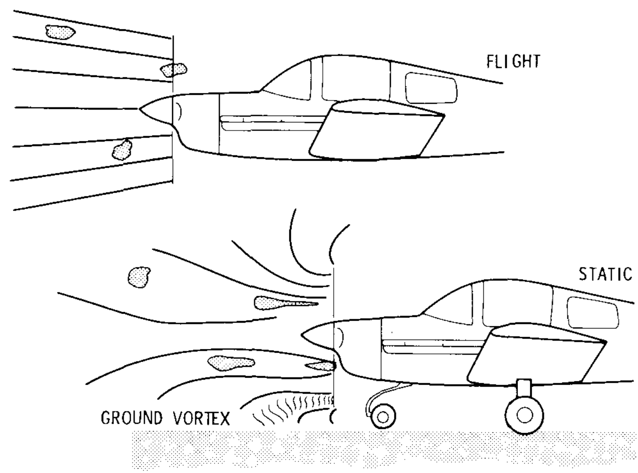

Fig. 4 Propeller turbulence ingestion

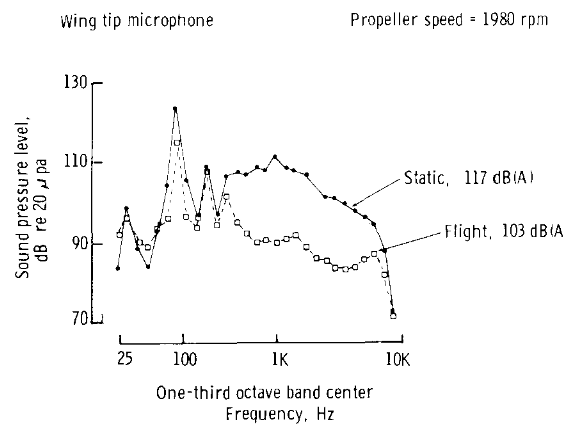

Fig. 5 Comparison of static and flight noise measurements

were observed. The range of fall-off rates was approximately -1 to -3 for the static case. Inflow turbulence increases the level of the blade surface fluctuating pressures. As is indicated by Fig. 3, the loading harmonics are higher for static conditions than for flight.

Hanson (4) has postulated that the blade pressure spectra described above result from ingestion of natural atmospheric turbulence. As Fig. 4 suggests, turbulent eddies are ingested into the propeller disk in the sink-like flow process which occurs when the propeller operates statically. The chopping of these stretched eddies by the propeller blade leads to tone-like peaks at blade passage frequency and its harmonics. In flight, the contraction ratio as air moves through the propeller disk is much reduced so the long coherent eddies generally do not occur. Using blade surface pressure time history data obtained from the flight tests and Hanson's procedure (4) for establishing an average turbulent eddy length scale, average eddy lengths of 15 m have been derived. This length is sufficient to generate tone-like peaks at blade passage frequency and its harmonics.

Samples of static and flight noise spectra measured at the aft wing location are presented in Fig. 5. The most striking feature of the spectra in Fig. 5 is the marked reduction of noise levels in the frequency range 500 to 10,000 Hz, from static to flight. The corresponding overall decrease in noise level is 14 dB(A) from static to flight. Tests also show that large differences existed between static and flight conditions at the lower propeller tip speeds. These data are taken at the aft wing tip microphone but are indicative of the differences observed from the ground measurement stations and the wing tip microphones at other propeller speeds.

Prediction Capability

Theories for propeller noise prediction have recently been developed by Hanson (7) and Farassat (8); both of these procedures were developed from the work of Ffowcs Williams and Hawkings (9) which includes all possible sources of sound. In this paper the steady loading noise and thickness noise have been calculated based on the noncompact procedure of Farassat (8). Similar calculations using Hanson's procedure are presented in Reference (10).

Although several forms of the solution of the Ffowcs Williams-Hawkings differential equation are available for general body shapes and arbitrary motion, one of these forms has been singled out as the most appropriate for numerical calculations. Factors involved in the selection of the solutions are:

(a) The details of the source distribution which are required for obtaining the acoustic pressure,

(b) The singularities in the solution, and

(c) The simplicity of the computations and execution time on a computer.

The governing equation for the determination of the acoustic pressure signature when the Lighthill stress term is neglected is:

$$\frac{1}{c^2}\frac{\partial^2 p}{\partial \tau^2} - \nabla^2 p = \frac{\partial}{\partial \tau}\left[\rho_0 v_n |\nabla f| \delta(f)\right] - \frac{\partial}{\partial y_i}\left[F_i |\nabla f| \delta(f)\right]$$

where p is the acoustic pressure, τ is time, c is the speed of sound and ρ_0 is the density of the undisturbed medium. Here $f(\vec{y},\tau) = 0$ is the equation of the moving body whose local normal velocity is v_n and F_i is the local stress acting on the medium at the body surface. The symbol $\delta(f)$ stands for Dirac delta function. The contribution of the first term on the right of the pressure equation is called the thickness noise, and the second is the loading noise.

The effect of unsteady blade loading is of considerable importance in determining an accurate prediction of the sound pressure level. The exact cause for these high frequency loads is not fully understood, but one source is hypothesized to be localized patches of turbulence entering the propeller disk at random locations. It has been shown in Reference (5) that a large number of loading harmonics are required to calculate a moderate number of sound harmonics. Accurate theoretical methods for determining these higher order airload data are not currently available. To provide this loading information an empirical approach is used based on the technique of Lowson and Ollerhead (5) and discussed in the previous section. An example of the correlation obtained between measured data and predicted results including the effect of unsteady loading is shown in the next two figures. Fig. 6 shows a comparison of the measured and calculated acoustic pressure pulse from one propeller blade at the wing tip of the test aircraft. The measured pressure pulse is representative of those

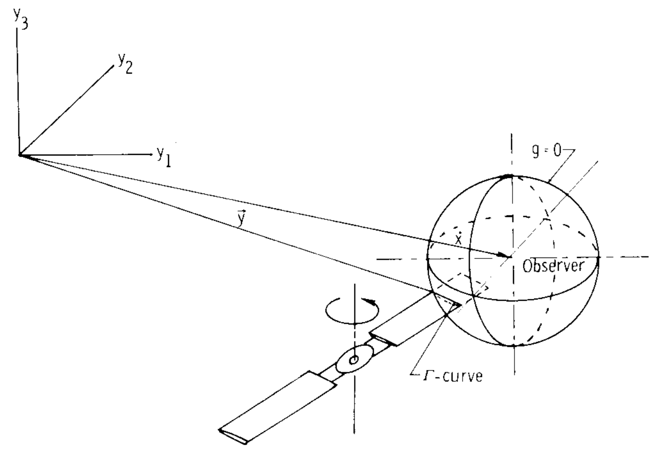

Fig. 6 Illustration of the blade system intersecting the collapsing sphere

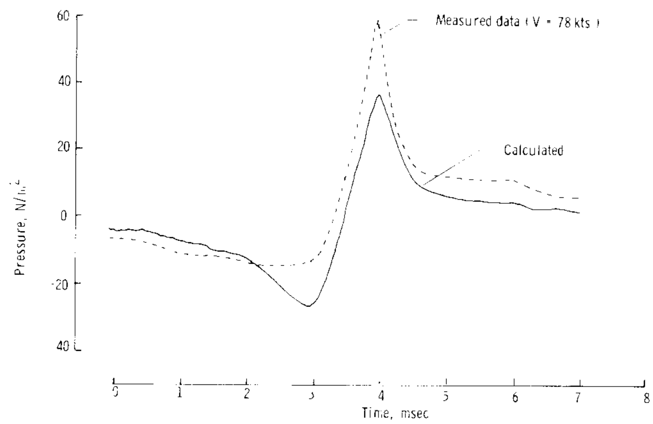

Fig. 7 Comparison of measured and predicted acoustic pressure time histories in the propeller plane at the wing tip

obtained at a flight speed of 78 knots. The agreement shown in Fig. 6 indicates the extent of the prediction modeling capability. Using pressure pulse data similar to those shown in Fig. 6, sound pressure spectra were obtained and are shown in Fig. 7. These spectra represent a noise signal in the propeller plane at the wing tip. Both static and in-flight conditions are presented.

Calculated harmonic levels based on the prediction technique of Reference (8) are superimposed on the measured data as indicated by the dots in Fig. 7. For the flight condition, correlation between the measured and calculated results are in close agreement to the 19th harmonic of blade passage frequency. The comparison obtained under static conditions using only steady loads and thickness in the prediction technique is shown to provide agreement only to the 7th har-

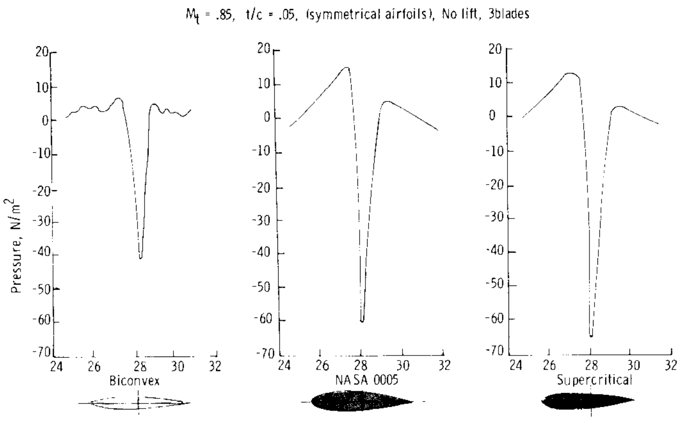

Fig. 8 Effect of airfoil thickness distribution on sound pressure pulse

monic. In the spectrum resulting from static conditions and shown in Fig. 7, unsteady loading must be added to obtain agreement at the higher harmonics. The unsteady loading results were obtained using an assumed overall effective loading law exponent of -2.5 which is used in Reference (5). This fall-off rate provides the best fit with the measured data.

Using the noise prediction theory of Farassat (8) to investigate possible techniques for thickness noise reduction; the effect of airfoil thickness distribution on radiated sound pressure is shown in Fig. 8 for a tip Mach number of 0.85. Pressure signatures were calculated for three rectangular planform blades operating at the same flight conditions with three different airfoil sections. The airfoil sections are a biconvex parabolic arc, a NASA 4-digit symmetrical airfoil, and a symmetrical supercritical airfoil all with a 5 percent thickness ratio. From this figure, it is obvious that a reduced sound pressure has been achieved with the biconvex airfoil section. Acoustic spectra based on the calculated pressure pulses for each airfoil section are shown in Fig. 9. Harmonic levels for the biconvex airfoil are lower than those of the other two sections. Even though the fundamental harmonic levels are approximately the same for the NASA 0005 and the supercritical airfoils, the midfrequency range for the NASA 0005 is lower than that for supercritical airfoil. Camber shape does not enter into the analysis of thickness noise but does govern airfoil lift characteristics; therefore, one can theoretically obtain suitable aerodynamic characteristics and reduced noise levels by controlling the airfoil thickness distribution.

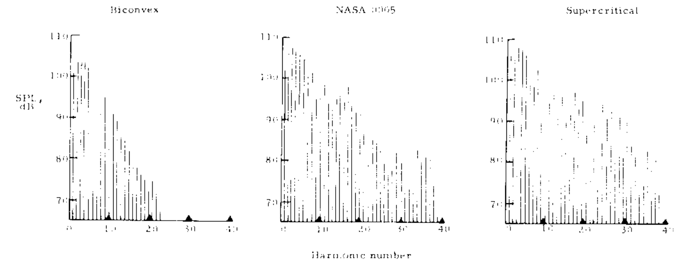

Fig. 9 Acoustic spectra of three different airfoil shapes having a 5 percent thickness

CONCLUDING REMARKS

The results of a program where the noise of an unshrouded propeller was measured under static and forward flight conditions and a comparison of measurements with theory have been reported. This test program confirmed that lower propeller noise levels are produced in forward flight than under static conditions and that the most significant reductions occur at the midfrequencies which dominate perceived and A-weighted noise levels. Analytical techniques have been used to predict the observed experimental trends and to provide further insight into the noise generating mechanisms. Predictions which include only steady loads and a thickness component agree with experimental data at low frequencies at static conditions and at all frequencies in forward flight. The effect of unsteady load components must be considered to obtain agreement at high frequencies under static conditions. It is tentatively concluded that propeller tone noise generation in flight is primarily due to steady loads and thickness. The mechanisms of noise generation at higher frequencies dominated by broadband noise are not yet fully understood. Under static conditions, the principal noise is related to the unsteady loading associated with the interaction of the propeller with persistent turbulent eddies passing through the propeller disk. Through the use of existing prediction techniques, it was shown that changes in the geometry such as different airfoil thickness distribution can affect the radiated acoustic pressure signatures.

REFERENCES

1 Metzger, F. B., Magliozzi, B., and Pegg, R. J., "Progress Report on Propeller Aircraft Flyover Noise Research," SAE Business Aircraft Meeting, Wichita, Kansas, April 1976.

2 Trillo, R. L., "An Empirical Study of Hovercraft Propeller Noise," Hovering Craft and

Hydrofoil, Vol. 5, No. 3 and 4, Dec.-Jan. 1965-1966.

3 Metzger, F. B. and Magliozzi, B., "New Directions in Aircraft Propulsor Noise Research," SAE Business Aircraft Meeting, Wichita, Kansas, April 1975.

4 Hanson, D. B., "Study of Noise Sources in a Subsonic Fan Using Measured Blade Pressures and Acoustic Theory," NASA CR-2574, Washington, D. C., Aug. 1975.

5 Lowson, M. V. and Ollerhead, J. B., "Studies of Helicopter Rotor Noise," U. S. Army Aviation Material Laboratories, Fort Eustis, Va., TR-68-60, Jan. 1969.

6 Brown, D. and Ollerhead, J. B., "Propeller Noise at Low Speeds," Technical Report AFAPL-TR-71-55, Air Force Flight Dynamics Laboratory, Sept. 1971.

7 Hanson, D. B., "Near Field Noise of High Tip Speed Propellers in Forward Flight," 3rd AIAA Aeroacoustics Conference, Palo Alto, Calif., AIAA No. 76-565, July 1976.

8 Farassat, F., "Theory of Noise Generation from Moving Bodies with Application to Helicopter Rotors," NASA TR-451, Washington, D. C., Dec. 1975.

9 Ffowcs Williams, J. E. and Hawkings, D. L., "Sound Generation by Turbulence and Surfaces in Arbitrary Motion," Philosophical Transactions of the Royal Society London, Series A., Vol. 264, May 8, 1969, pp. 321-342.

10 Magliozzi, B., "The Influence of Forward Flight on Propeller Noise," NASA CR-145105, 1977.