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Helicopter Far-Field Acoustic Levels as a Function of Reduced Main-Rotor Advancing Blade-Tip Mach Number

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Page 10 - Words were inadvertently omitted from the end of a sentence. Replace page 10 of the report with the attached corrected page.

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ABSTRACT

During the design of a helicopter, the weight, engine, rotor speed, and rotor geometry are given significant attention when considering the specific operations for which the helicopter will be used. However, the noise radiated from the helicopter and its relationship to the design variables is currently not well modeled with only a limited set of full-scale field test data to study. In general, limited field data have shown that reduced main-rotor advancing blade-tip Mach numbers result in reduced far-field noise levels. This paper will review the status of a recent helicopter noise research project designed to provide flight experimental data which may be used to further understand helicopter main-rotor advancing blade-tip Mach number effects on far-field acoustic levels. Preliminary results will be presented relative to tests conducted with a Sikorsky Aircraft Corporation S-76A helicopter operating with both the rotor speed and the flight speed as the control variable. The rotor speed was operated within the range of 107 % NR to 90 % NR at nominal forward speeds of 35, 100, and 155 knots.

INTRODUCTION

During the design stage of a helicopter, many variables are governed by the type of operations for which it is to be constructed. Significant considerations must be given to the design weight of the vehicle, its engine type, and rotor speed along with the rotor geometry. However, the relationship between the noise radiated from the helicopter and these variables is not well understood with only a limited set of model and full-scale field test data to study. The previous database (ref. 1) consisted of far-field sound pressure levels which were available for a helicopter flying at reduced rotor speeds for a constant flight speed of 80 knots. In general, these data have shown that reduced rotor speeds, which may be related to the main-rotor advancing blade-tip Mach number, result in reduced far-field noise levels.

This paper will present the results of a recent noise research project which measured the far-field noise levels of a helicopter operating over a range of reduced rotor speeds and flight speeds. The project was designed to provide supplemental experimental flight data which may be used to further study reduced helicopter rotor speed and main-rotor advancing blade-tip Mach number effects on far-field acoustic levels.

Far-field measured noise level results are presented relative to tests conducted with a United Technologies Sikorsky Aircraft, model S-76A helicopter. The aircraft was flown in straight and level flight while operating with both the rotor speed and flight speed as test variables. The rotor speed was varied over the range of 107 % of the main-rotor speed (NR) to 90 % NR and with the forward flight speed varied over the range of 155 to 35 knots. These conditions produced a wide range of advancing blade-tip Mach numbers to which the noise data are related.

OBJECTIVES AND APPROACH

There were several objectives of the research project. The first objective was to study the helicopter far-field noise as a function of reduced advancing blade-tip Mach number. To meet this objective, the test was designed so that the helicopter would fly at many combinations of rotor speeds and forward speeds. A second objective was to study the far-field noise results which would occur as a result of changing the engine speed (and therefore, the main-rotor speed) while maintaining a constant flight speed. A third objective was to use the results obtained from the significantly expanded far-field noise database to study the LaRC helicopter noise prediction program (ROTONET, refs. 2-3), which is an analytical tool designed to permit the use of acoustics as a consideration in the design of helicopters. A final objective was to use the data to study long-range propagation effects and the effects of the reduced advancing blade-tip Mach numbers on the aural detectability of the helicopter. For the purposes of this report, only results relative to the first and second objectives will be presented.

During the flight of the helicopter, acoustics data were obtained with a linear microphone array. Helicopter position tracking data, helicopter speed and systems data, and weather data were also recorded during the flight tests. All data recordings were synchronized in time. The noise and position data were merged together with measured weather data and reduced using Langley Research Center developed techniques.

The project was conducted as a continuation of research begun under a joint NASA/American Helicopter Society (AHS) program, often referred to as the NR program (National Rotorcraft Noise Reduction). This was a technology development program between industry and the U.S. Government initiated to study helicopter noise prediction and reduction. Industry was represented by Boeing Helicopter, Bell Helicopter, Sikorsky Aircraft, and McDonnell Douglas Helicopter Corporation (MDHC). The government was represented by NASA Langley, Ames, and Lewis Research Centers, and by associated U.S. Army Agencies, with Langley Research Center designated as the lead NASA center.

TEST HELICOPTER

The test helicopter used in this project, a Sikorsky S-76A, is shown in figure 1. It is a medium weight helicopter (approximately 4500 kilograms) flown with two pilots and may carry up to 12 passengers. It has a nominal cruising speed of 145 knots at sea level, has a four-bladed main rotor (diameter 13.41 m) and a four-bladed tail rotor (diameter 1.22 m). Rotor tip speeds are approximately 220 meters per second (mps) for each rotor with the engine speed at 107 % NR. Typical rotor speeds at this 107 % NR engine speed are 313 rpm and 1724 rpm for the main and tail rotors. During all flights, instrumentation onboard the helicopter measured and recorded flight altitude, main-rotor rpm, engine torque, airspeed, and outside air temperature. Additionally, onboard instrumentation recorded ground-based position tracking information which was reduced to rectilinear position coordinates of the vehicle. These coordinates were related to a time signal which was synchronized with the recorded far-field acoustic data.

Figure 2 shows the flight track and test area over which the aircraft was flown. The helicopter was flown over the relatively flat swampy marsh-like terrain of southern Florida. Vegetation was generally thick in the swamp areas. Tree height varied from approximately 3 meters to as high as 30 meters, with no obvious pattern to density of trees relative to either the swamp or hard soil terrain. Hard soil composition consisted mainly of sand and a crushed-sea-shell-sand mixture. The figure also indicates the location of two weather sites. These were located along each side of the flight track and were approximately 8 kilometers apart. Wind speed, direction, temperature, and relative humidity were measured at each of these sites by instrumentation attached to a tethered balloon. The balloons were operated in a manner which permitted these weather data to be obtained in 10 meter altitude increments up to an altitude of 200 meters. The purpose of the two sites was to gather independent but simultaneously measured weather data to be used to aid in the understanding of the measured acoustic signals.

Figure 3 shows the helicopter in the vicinity of the location of a sound jury and the acoustic measurement system. The sound jury consisted of a group of persons who were asked to indicate the moment in time when they heard the helicopter. For the purposes of this report, the aural detection results will not be discussed; however, the acoustic data obtained by the microphone array shown in the photo of figure 3 will be presented.

ACOUSTIC MEASUREMENT SYSTEM

Figure 3 shows that the microphone placement at the test site was in the form of a linear array. This array consisted of both a digital and an analog measurement system. The digital system, designed, and fabricated by the Instrumentation Research Division of LaRC, was the primary acoustic system. It consisted of nine channels each with a 1.27 cm diameter condenser microphone fitted with a grid cap and covered by a wind screen. Each microphone was placed on a ground board (1.22 m x 1.22 m x 0.3 cm plywood), and oriented for acoustically grazing incidence angles. The output of each microphone was used as the input to an analog to digital converter. This converter, located a short distance from and in the power supply box of each microphone, sampled acoustic data at a rate of 2344 samples a second. Each data sample taken was initiated by a command sent from a central processing unit located in an instrumentation van. All nine digital microphone channels were commanded to sample at the same time, insuring synchronization between channels. The digital data were transmitted in the form of Manchester code through cables to the instrumentation van located approximately 300 m away. Inside this van, the digital data were recorded in the form of pulse-code-modulated (PCM) data on a direct recording analog tape recorder.

The secondary measurement system consisted of nine 1.27 cm microphones physically configured with the grid cap and wind screen as the digital system. Each microphone was placed approximately 5 cm from and parallel to its digital counterpart. The resulting analog output signals were recorded on an analog wide-band 14-track magnetic tape recorder operating at a tape speed of 38 cm per second in the FM mode. Since the digital system was relatively new and personnel had little field experience with it, the analog system was used as a back-up system. Post test data analysis has shown that the digital system worked well and is a significant improvement over the analog system.

The linearity, sensitivity, distortion, and noise floor of each acoustic system was calibrated in the laboratory and documented to be linear to within 1 dB before it was placed in the field. The frequency range of calibration was 5 Hz to 10 kHz. A piston phone operating at 250 Hz, 124 dB sound pressure level (SPL), was used in the field for calibration at the beginning and end of each day. Also, at the beginning and conclusion of data acquisition for each flight test, ambient noise levels were recorded.

POSITION TRACKING SYSTEM

In order to correlate helicopter speed and position data to the acoustics data, a microwave tracking system was used. This system uses microwave receivers and transmitters operating on different frequencies to accurately track the helicopter. A receiver/transmitter, installed in the helicopter, was connected to an antenna mounted external to the helicopter and in a position which minimized interference of the helicopter with the tracking signals. Two other receiver/transmitters were precisely located in the area around the test range. The transmitter onboard the helicopter radiated a signal to the receiver/transmitters located in the surrounding area. These units then relayed the transmitted signal to the receiver onboard the helicopter which recorded the delay times associated with these microwave signals. Measurements of these transmission delay times were then used in conjunction with the known positions of the ground-based receiver/transmitters to determine the range to the helicopter.

TEST VARIABLES

Helicopter acoustics data were measured for constant level flight. The test variables are listed in table 1. Data were measured for different combinations of rotor speed (NR = 107%, 104%, 102%, 97%, and 90%), forward speed (nominally constant 155, 150, 100, and 35 knots indicateed air speed), and altitude (nominally 30 and 152 meters). The gross weight of the aircraft was approximately 4500 kilograms. Data to be discussed in this paper will relate to the main-rotor advancing blade-tip Mach number as computed from the test rotor speeds, main-rotor diameter of aircraft, test indicated air speeds, and air temperatures associated with the test flights. The advancing tip Mach number M is given by:

$$M = \frac{V + v}{a}$$

where V is the main-rotor tip speed, v is the indicated air speed of the helicopter, and a is the speed of sound in the air at the air temperature outside of the aircraft. Table 2 presents the test matrix for which far-field acoustic data were obtained. Indicated are the helicopter's advancing blade-tip Mach numbers which were obtained and their relationship to the indicated air speed and main-rotor speed in percent NR. As noted, six runs were obtained for each test condition. At the 102% NR engine speed, it is noted that data were obtained for two different altitudes; however, only data obtained at the 152 meter altitude will be presented herein.

SOURCES OF ROTOR NOISE, DIRECTIVITY, AND NOISE TRENDS

The sources of rotor noise, directivity, and the trend of the noise levels as a function of advancing rotor blade-tip Mach number are shown in figure 4 (refs. 4-6). Blade thickness and shock noise tend to have directivity patterns in the plane of the rotor and noise levels which tend to decrease with a reduction in advancing blade-tip Mach number. Once the advancing blade-tip Mach number reaches the speed at which shock cells no longer form on the blade, this noise source ceases to exist. Both loading of the rotor blade and interactions of one rotor blade with vortices shed from another blade passing through the air (blade/vortex interaction or BVI) tend to have directivity patterns which occur beneath the rotor plane. Noise levels associated with these sources tend to occur from about 10 or 15 degrees to 60 degrees or more beneath the plane of the rotor. BVI noise generally decreases as the rotor speed increases because at the higher rotor speeds the vortices do not have time to mature before an advancing blade cuts a vortex. Broadband noise sources result from turbulence shed from the trailing edge of the rotor. Radiation of this noise principally occurs at angles perpendicular to the plane of the rotor tip. Data presented in this paper were obtained approximately in the plane of the main and tail rotors and are associated with the thickness noise source. Shock noise is not a contributor to the noise levels since blade-tip speeds are on the order of 220 mps, much below the approximate sound speed of 342 mps.

THEORETICAL FAR-FIELD ACOUSTIC PULSE SHAPE

Figure 5 presents a schematic representation of the far-field acoustic results of air flow over a helicopter rotor (ref. 7). The volume of air flowing across the airfoil, fig. 5a, may be modeled mathematically as a distribution of "sources and sinks" of mass flow, as sketched in fig. 5b. It has been shown (ref. 8) that most of the acoustic radiation is generated at the outer tip of the rotor. The fundamental governing equation used to derive the far-field acoustic thickness noise from a rotor is presented in fig. 5c. This equation is the result of considering only the linear term of the general Ffowcs Williams-Hawkings equation describing the acoustic pressure radiated by the helicopter rotor blade. The sources and sinks must be summed over the surface area of the rotor blade outer tip with consideration given to the retarded times between when they occur and the time required for propagation to the observer in the far-field. Time differentiation of the double integral results in the theoretical pressure distribution sketched in figure 5d. This pulse has a characteristically small positive pressure and a much larger negative pressure.

EXPERIMENTALLY MEASURED FAR-FIELD ACOUSTIC PULSE SHAPE

Experimental pressure pulses measured in the far-field of the rotor plane by a single microphone are presented in figure 6. This figure shows the pressure plotted as a function of time, all on the same scale, for the rotor speeds of 107%, 102%, and 90% NR which corresponds to advancing blade-tip Mach numbers of 0.875, 0.756, and 0.586. These data were measured when the helicopter flew at nominal speeds of 155, 100, and 35 knots-indicated-air-speed (KIAS) at an altitude of 152 meters. The noise emission angle is approximately 3.5 degrees. The data show shapes typical of the theoretical pressure shape, exhibiting the small positive and large negative pressure pulses. Additionally, it is observed that as the advancing blade-tip Mach numbers decrease, the magnitudes of the pressures decrease with the largest change occurring in the negative pressure. These data have been transformed from the time domain to the frequency domain using Fourier transforms. Representative narrowband spectral results are shown in the next figure.

MEASURED RELATIVE NARROWBAND SPECTRA

Figure 7 presents the relative narrowband spectrum measured for each of the advancing blade-tip Mach numbers shown in figure 6. For comparison, the mean ambient noise spectrum is shown as the bottom curve. The data have been made relative to the largest sound pressure level measured, which occurred at the highest combination of engine speed and flight speed (noted in table 2 as an advancing blade-tip Mach number of 0.875). Table 3 presents the relative measured overall and narrowband sound pressure levels. Relative amplitudes are at the Doppler-shifted frequencies, which are listed in the table for both the main- and tail-rotor fundamental tones. The data in figures 6 and 7 suggest that as the advancing blade-tip Mach number is reduced, the noise levels and the acoustic frequencies of both the main and tail rotor are reduced.

FAR-FIELD NOISE AS A FUNCTION OF REDUCED ADVANCING BLADE-TIP MACH NUMBER

The effects of reducing the advancing blade-tip Mach numbers on the relative overall and narrowband sound pressure levels are presented in figure 8. The narrowband sound pressure levels are measured in a 1 Hz bandwidth at the Doppler-received main-rotor fundamental frequency. Amplitudes of the sound pressure levels were made relative to the largest measured sound pressure level at 107 % NR (table 2). The data show that reducing the advancing blade-tip Mach number from 0.875 to 0.586 significantly reduced the overall sound levels, as well as those at the fundamental frequency of the main rotor. It is noted that reducing the advancing blade-tip Mach number by approximately 20 percent, from 0.875 to 0.689, results in approximately 13 dB of reduced overall noise and that a "point of diminishing return" appears to be reached beyond which no further reductions appear. It is also noted that at three advancing blade-tip Mach numbers (0.843, 0.800, and 0.684), the overall levels increased slightly as compared to the previous data point. These increases may be due to either an increase in the ambient noise or in the operation of the helicopter. The same trend of decreasing noise levels as the advancing blade-tip Mach number decreases is also evident for the narrowband sound pressure levels. An exception is that a point of "diminishing return" is not as obvious for the narrowband results as for the overall data.

As earlier noted, the second objective of this research was to study the effects on the far-field noise by reducing the engine speed while maintaining a nominally constant flight speed. Nominally constant flight speeds of 100 KIAS and 150 KIAS were flown while engine speeds were changed. Table 3 shows that there were two separate advancing blade-tip Mach number data sets associated with each of the engine speeds. Those associated with the 100 KIAS flight speed were 90% NR and 102% NR. Those associated with the 150 KIAS were 97% NR and 104% NR. The averaged noise results (for each of the two associated data sets at each of the advancing blade-tip Mach numbers) for the reductions in engine speed are presented in figure 9. The noise levels are referenced to the largest sound level measured at the 150 KIAS 104% NR. The figure shows that at both of the nominally constant flight speeds the noise levels were reduced. The largest reductions, approximately 4 dB as compared to approximately 1 dB, occurred at the slower flight speed. It is noted that at this slower speed the change in the average of the two associated advancing tip Mach numbers (0.755 to 0.686) is approximately 9%, whereas the change is 5% for the average of the advancing tip Mach numbers associated with the faster flight speed (0.844 to 0.802).

COMPARISON OF PREDICTED AND MEASURED FAR-FIELD SOUND PRESSURE LEVELS

Figure 10 presents the results of a comparison of the predicted far-field sound pressure levels to those measured at three advancing blade-tip Mach numbers. The predicted results were obtained from the analytical program ROTONET (refs. 2-3). This program is composed of numerous modules which vary in sophistication and consideration of sources of noise associated with the helicopter during its operations in flight. Often, it is necessary to run the program in a less complex form (called "Phase I") than the more complex ("Phase II") form. Predicted data presented are based on results obtained from the "Phase I" form of ROTONET and are for advancing blade-tip Mach number computed values of 0.88, 0.69, and 0.61. Measured values presented are for advancing blade-tip Mach numbers of 0.875, 0.689, and 0.588. The noise data are made relative to the largest measured sound pressure level obtained at the advancing blade-tip Mach number of 0.875. The noise data were measured at a slant range of 2.5 Km. The figure shows the predicted values are approximately 5 dB greater than those measured, with the least difference (3dB) occurring at the largest advancing blade-tip Mach number. These predicted values are believed to be in good agreement with the measured values, and it is further believed that a better predicted result will occur when the "Phase II" form of ROTONET is used. Table 4 presents a comparison of the previous noise database available as a function of advancing blade-tip Mach number (ref.1) to that herein reported. This significantly expanded database may be used to further evaluate the "Phase II" form of ROTONET.

CONCLUDING REMARKS

Far-field noise measurements were made for a Sikorsky S-76A model helicopter operating in level flight over a range of engine speeds from 90% NR to 107% NR and flight speeds of 35 KIAS to 155 KIAS. This produced a wide range of advancing blade-tip Mach numbers. Test design included helicopter operations with the main-rotor speed as the control variable at nominal flight speeds of 100 KIAS and 150 KIAS. A reduction of the advancing blade-tip Mach number by 20% produced a corresponding far-field overall noise reduction of approximately 13 dB. Additionally, a point of diminishing return appeared to be reached where further reductions of advancing blade-tip Mach numbers did not result in further reductions in the overall noise levels. The narrowband sound pressure levels followed the same trend as did the overall noise levels; however, the point of diminishing return for reduced levels as the advancing blade-tip Mach number was reduced was not as obvious as it was for the overall levels. It was noted that at a nominally constant flight speed of 100 KIAS, reducing the main-rotor speed from

102% NR to 90% NR resulted in noise reductions of approximately 4 dB (a reduction of about 9% in advancing blade-tip Mach number). This was several dB larger than the results obtained when the aircraft was operated at 150 KIAS with the main-rotor speed reduced from 104% NR to 97% NR (a commensurate reduction of about 4% in advancing blade-tip Mach number). ROTONET PHASE I predicted far-field noise values at three advancing blade-tip Mach numbers favorably compared to the measured values. Further study of ROTONET prediction capability is now possible with the availability of the significantly expanded far-field noise database obtained from these tests.

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Table 1. Nominal Values of Test Variables for the Sikorsky S-76A Helicopter

- Rotor Speed

	RPM Main Rotor	RPM Tail Rotor
107% NR	314	1724
104% NR	305	1675
102% NR	299	1643
97% NR	284	1563
90% NR	264	1450

- Forward Speed, KIAS
  155, 150, 100, 35

- Weight, kilograms
  4500

- Altitude,meters
  30, 152

Table 2. S-76A Reduced Rotor Speed Test Matrix for Advancing Blade-Tip Mach Number

Air Speed Kts	Main Rotor Speed % NR				
	90%	97%	102%	104%	107%
35	0.586 & 0.588	--------	--------	--------	--------
100	0.684 & 0.689	--------	0.753 & 0.756 0.752 & 0.760*	--------	--------
150	--------	0.800 & 0.803	--------	0.843 & 0.845	--------
155	--------	--------	--------	--------	0.875

Six repeat runs per condition at altitudes 152 meters

*Altitudes of both 152 and 30 meters

Table 3. Nominal Values of Measured Sound Pressure Levels for Slowed Rotor Noise Tests Using the Sikorsky S-76A Helicopter

Acoustic Fundamental Frequency at 100% NR

Main Rotor 19.5 Hz — Tail Rotor 107.4 Hz

Altitude, 152 meters
Slant Range, 2.5 kilometers

Engine RPM %NR	Flight Speed KIAS	ATM	Relative Overall Sound Pressure Level dB	Calculated Doppler Shifted Frequency, Hz		Relative Narrowband Sound Pressure Level, dB	
				Main Rotor	Tail Rotor	Main Rotor	Tail Rotor
107%	155	0.875	00.0	27.2	149.6	-5.4	-21.9
104%	150	0.845	-1.3	26.9	147.9	-4.3	-25.8
104%	150	0.843	00.0	26.2	144.1	-5.8	-25.2
102%	100	0.756	-4.1	23.8	130.9	-7.9	-23.8
102%	100	0.753	-8.4	23.4	128.8	-13.9	-34.4
97%	150	0.803	-3.8	24.9	136.9	-8.0	30.5
97%	150	0.800	00.0	24.4	134.1	-3.4	-26.0
90%	100	0.689	-12.5	21.2	116.6	-15.8	-34.2
90%	100	0.684	-8.4	20.7	113.8	-13.0	-33.0
90%	35	0.588	-12.1	19.1	105.1	-19.5	-38.5
90%	35	0.586	-11.9	18.7	102.8	-18.1	-32.0

Table 4. Variable Rotor-Speed Database

Advancing Tip Mach Number	Helicopter	
	500E	S-76A
0.572	X	
0.586		X
0.588		X
0.618	X	
0.663	X	
0.684		X
0.689		X
0.730	X	
0.752		*
0.753		X
0.756		X
0.760		X*
0.800		X
0.803		X
0.843		X
0.845		X
0.875		X

X=Data for altitude 152 meters

*For altitude 30 meters

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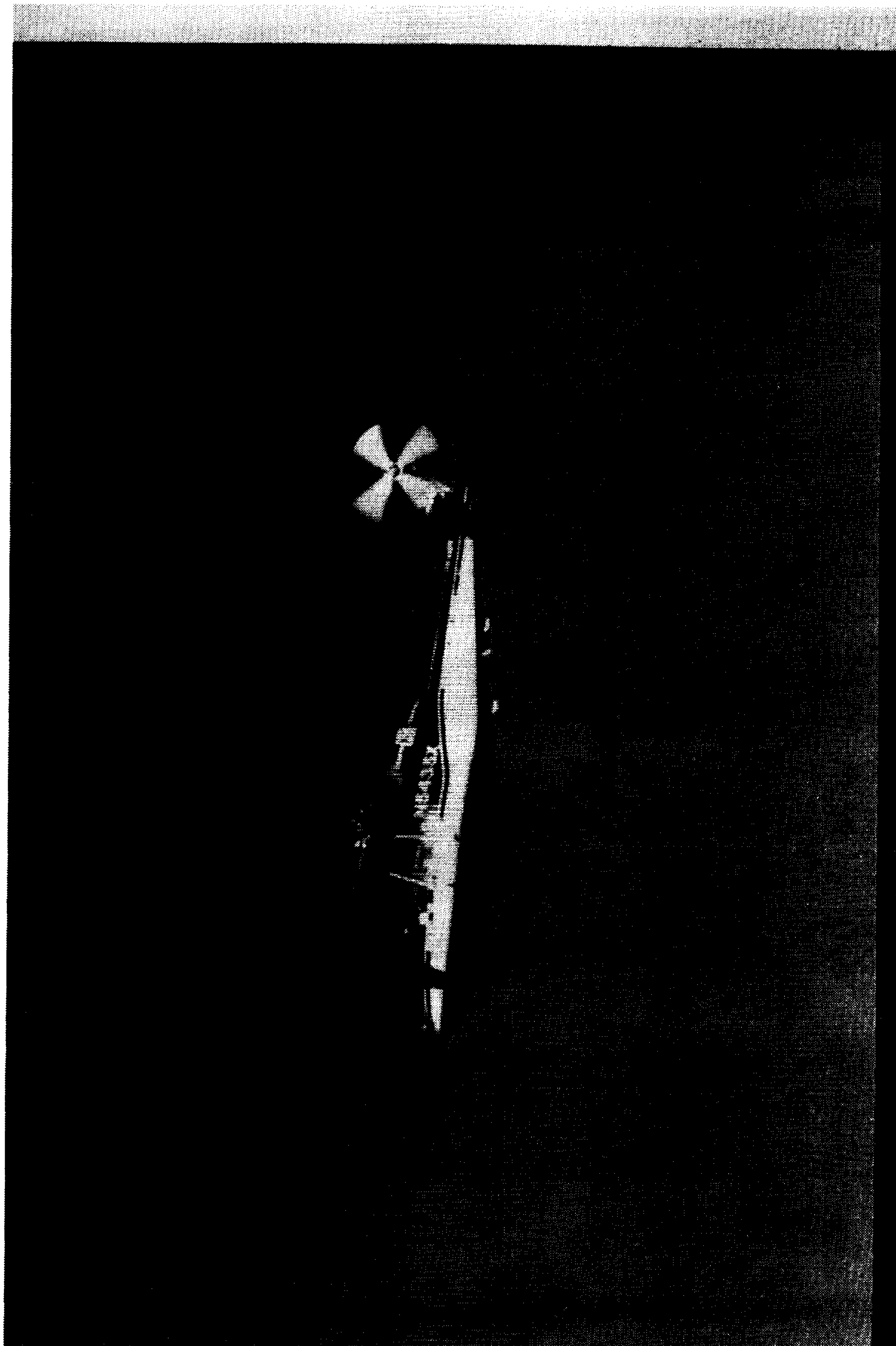


Figure 1.- Sikorsky S-76A helicopter

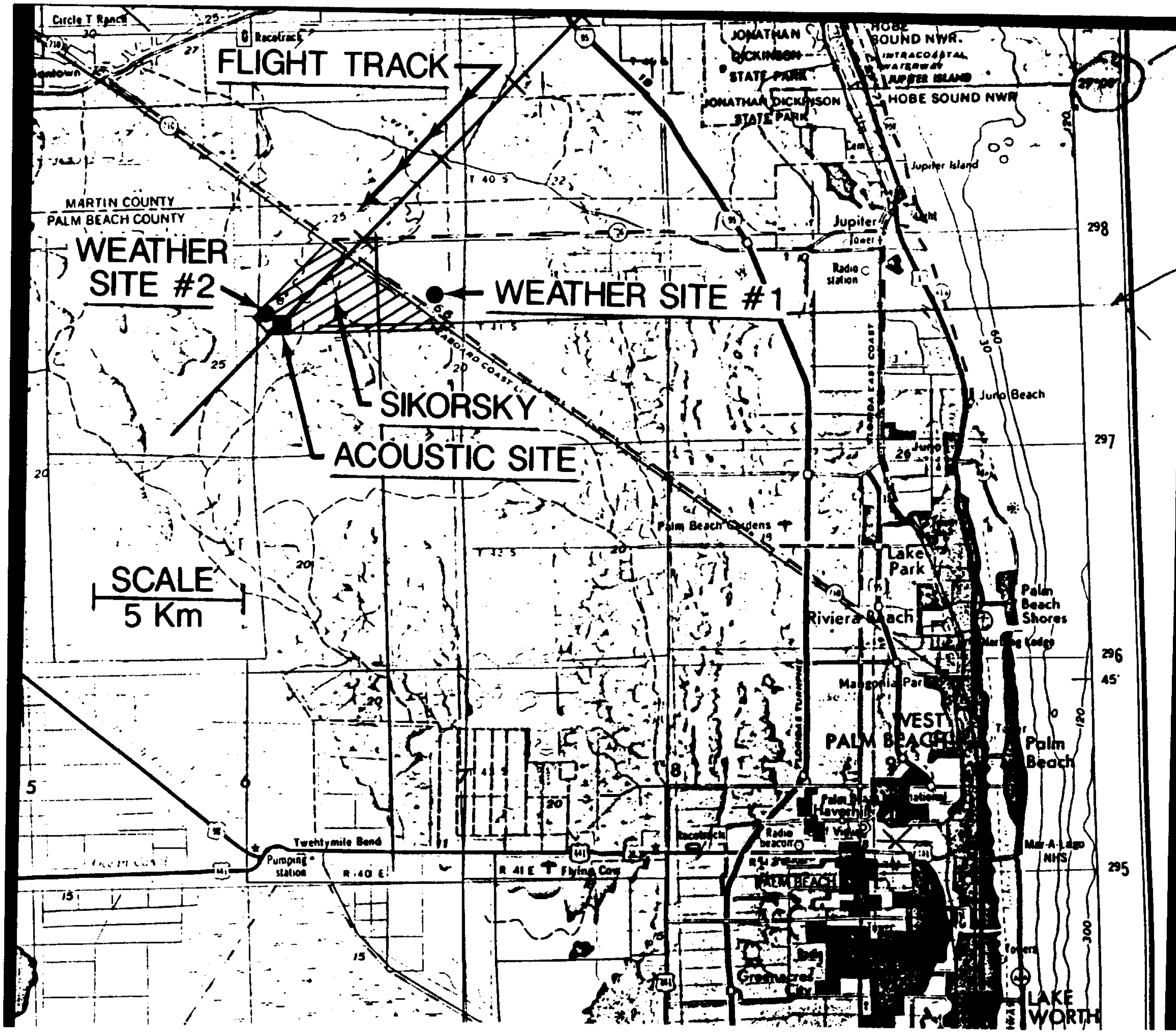


Figure 2.- West Palm Beach S-76A flight test area

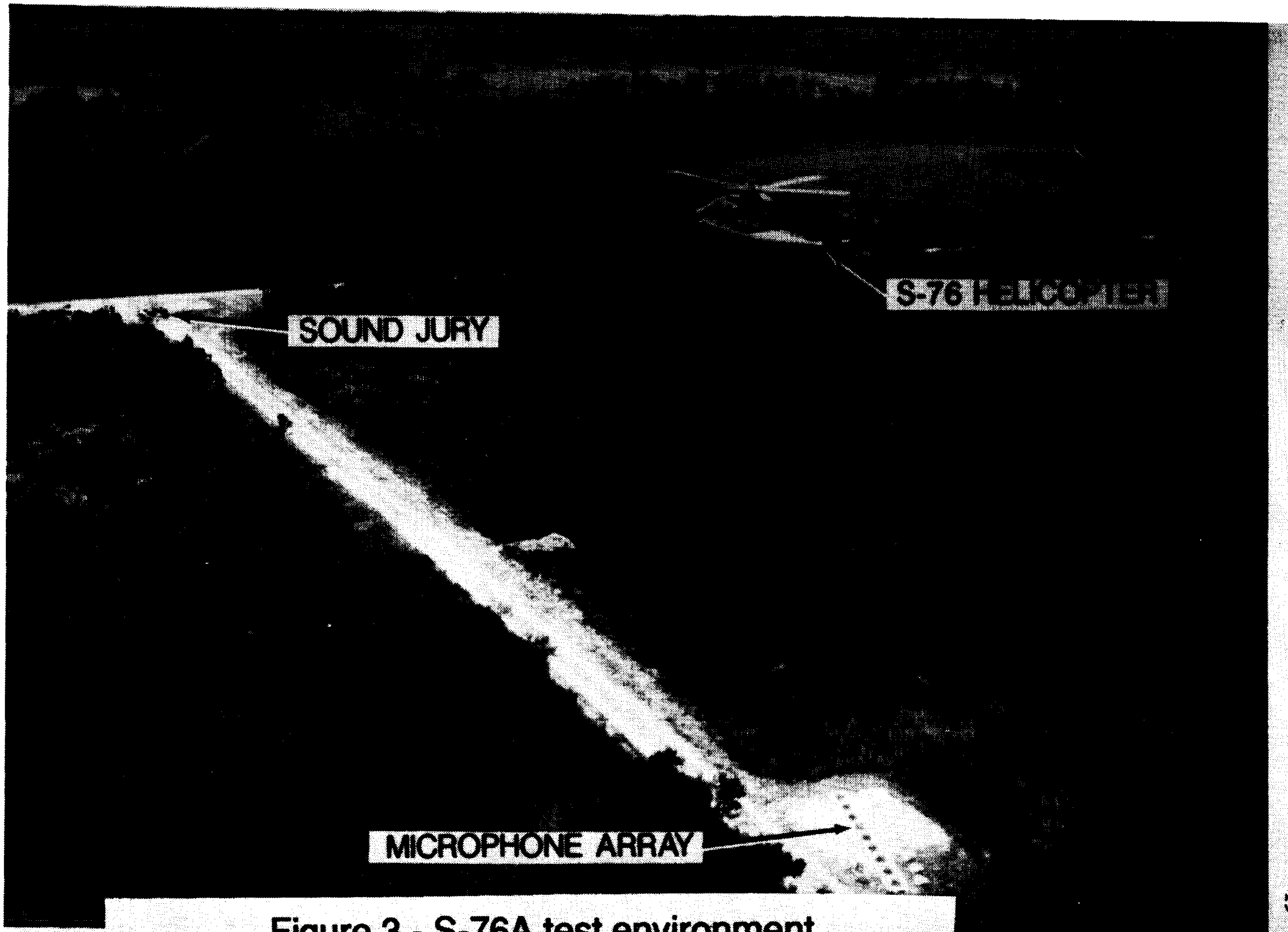


Figure 3.- S-76A test environment

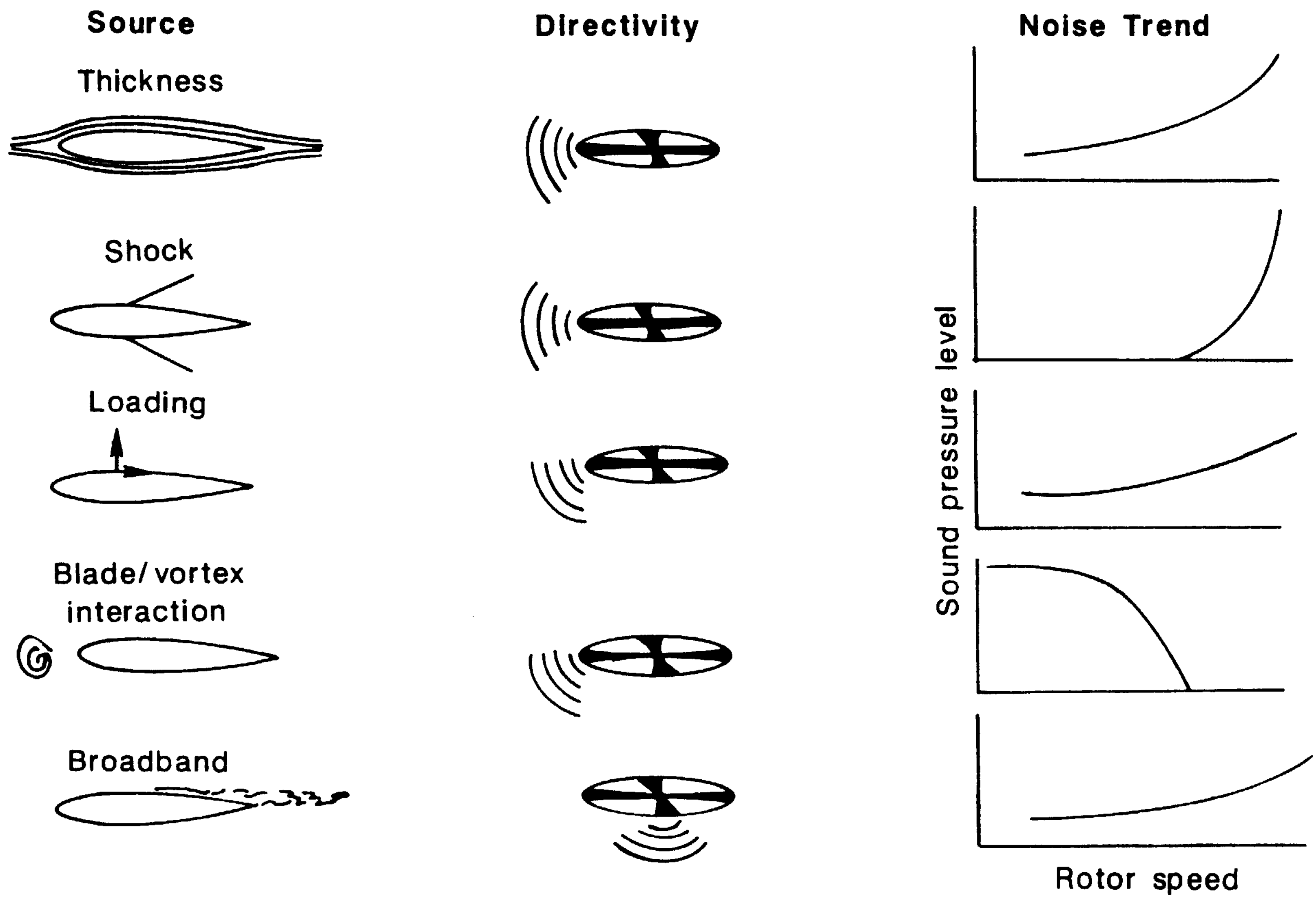
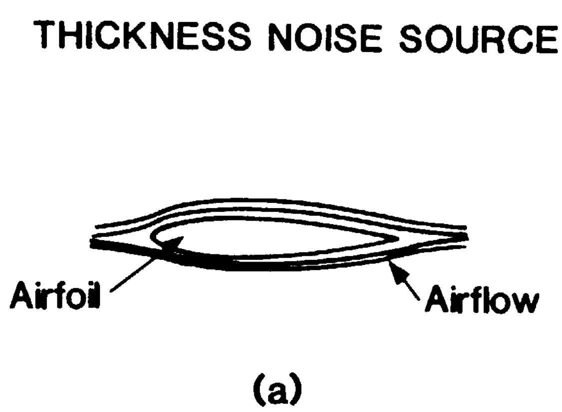
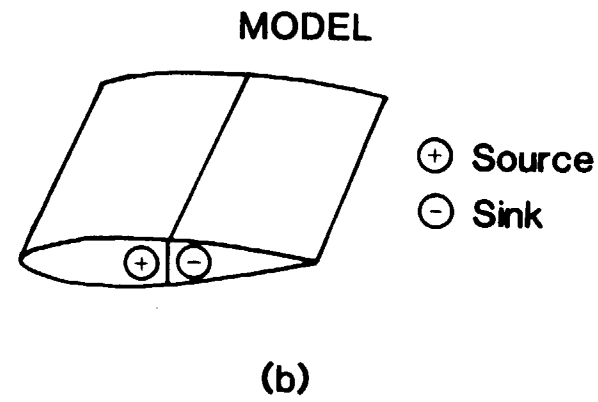


Figure 4.– Diagrammatic outline of rotor noise sources, directivity and rotor noise trends with tip speed.





GOVERNING EQUATION

$$P\ (\vec{x},t) = \frac{1}{4\pi}\frac{\partial}{\partial t}\iint \left[\frac{\rho_0 \nu_n}{r\left|1-M_r\right|}\right]_{\tau} dS\ (\vec{\eta})$$

(c)

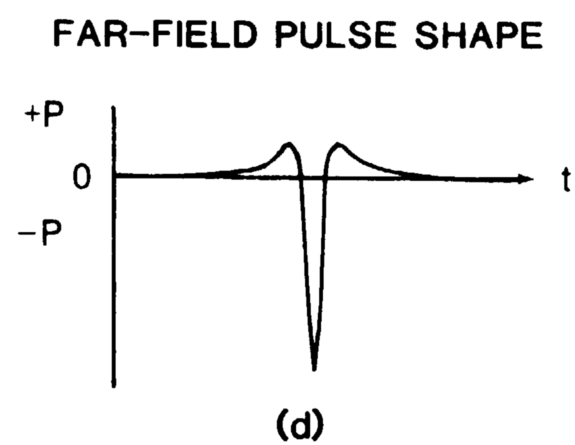


Figure 5.– Diagram showing developement of theoretical far field acoustic pulse shape.

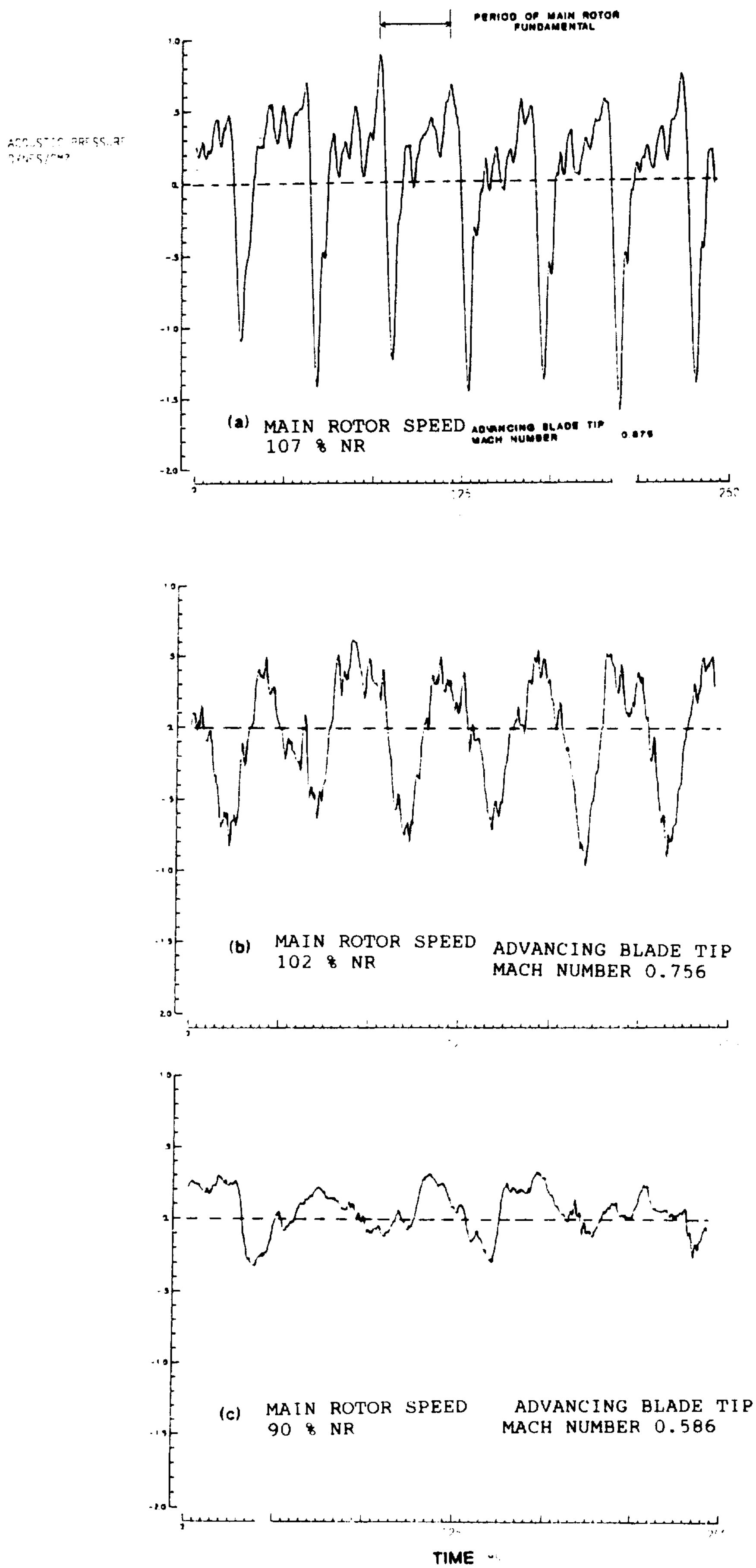


Figure 6.- Experimentally obtained far-field acoustic pulse shapes for three different advancing blade tip Mach numbers for the Sikorsky S-76A helicopter

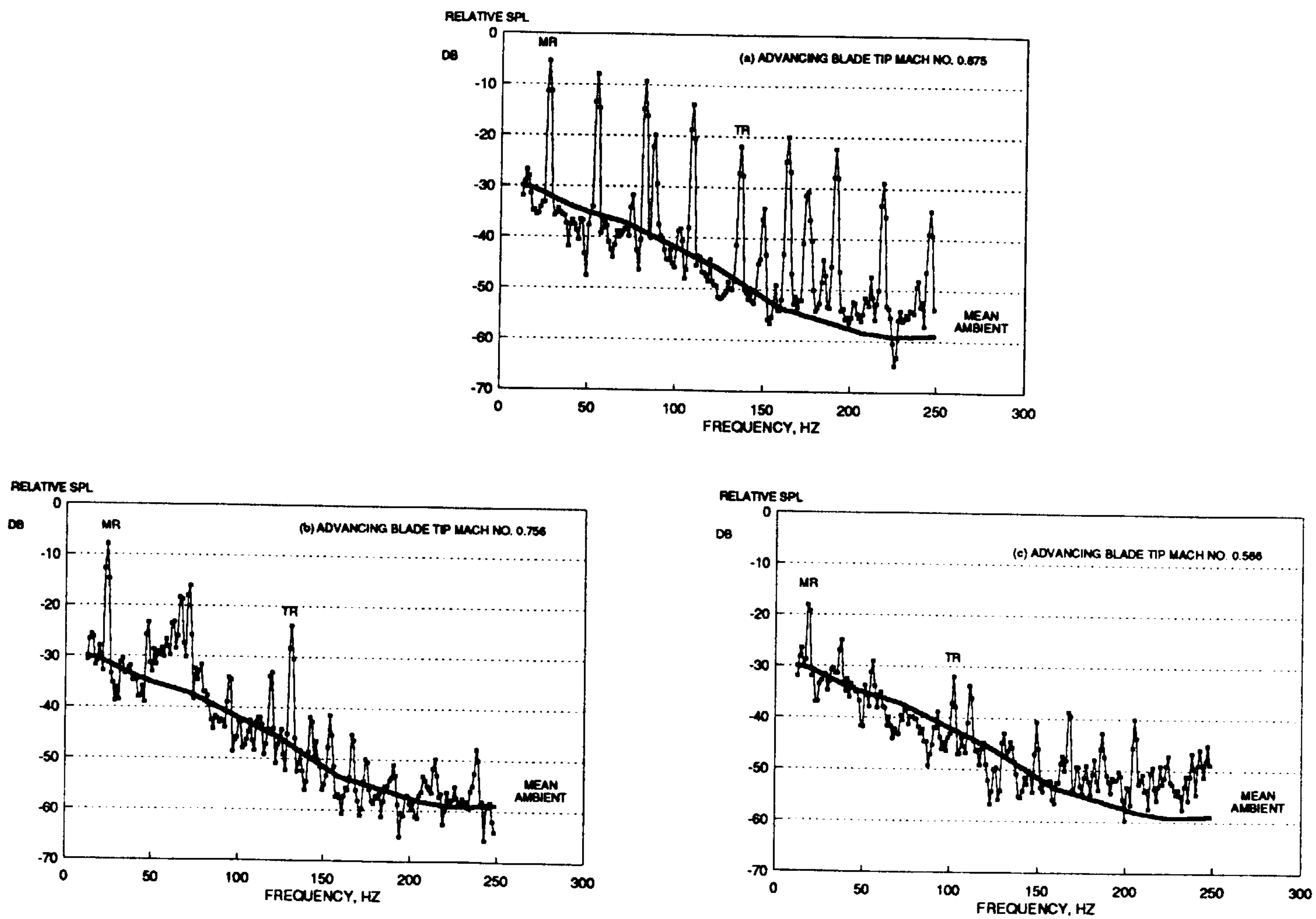


Figure 7.- Typical narrowband spectra for three different advancing blade tip Mach numbers

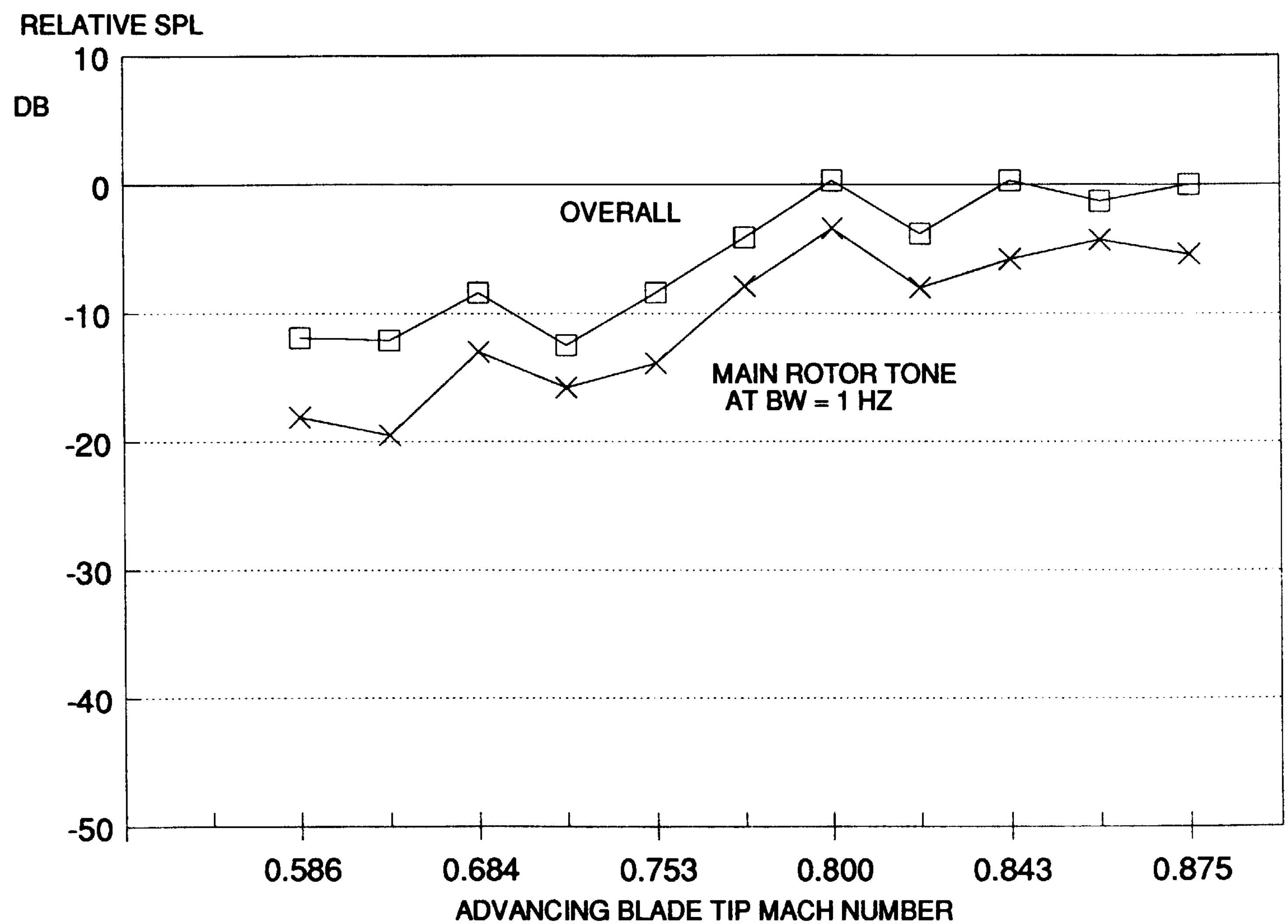


Figure 8.- Effects of reduced advancing blade tip Mach number on far-field sound levels

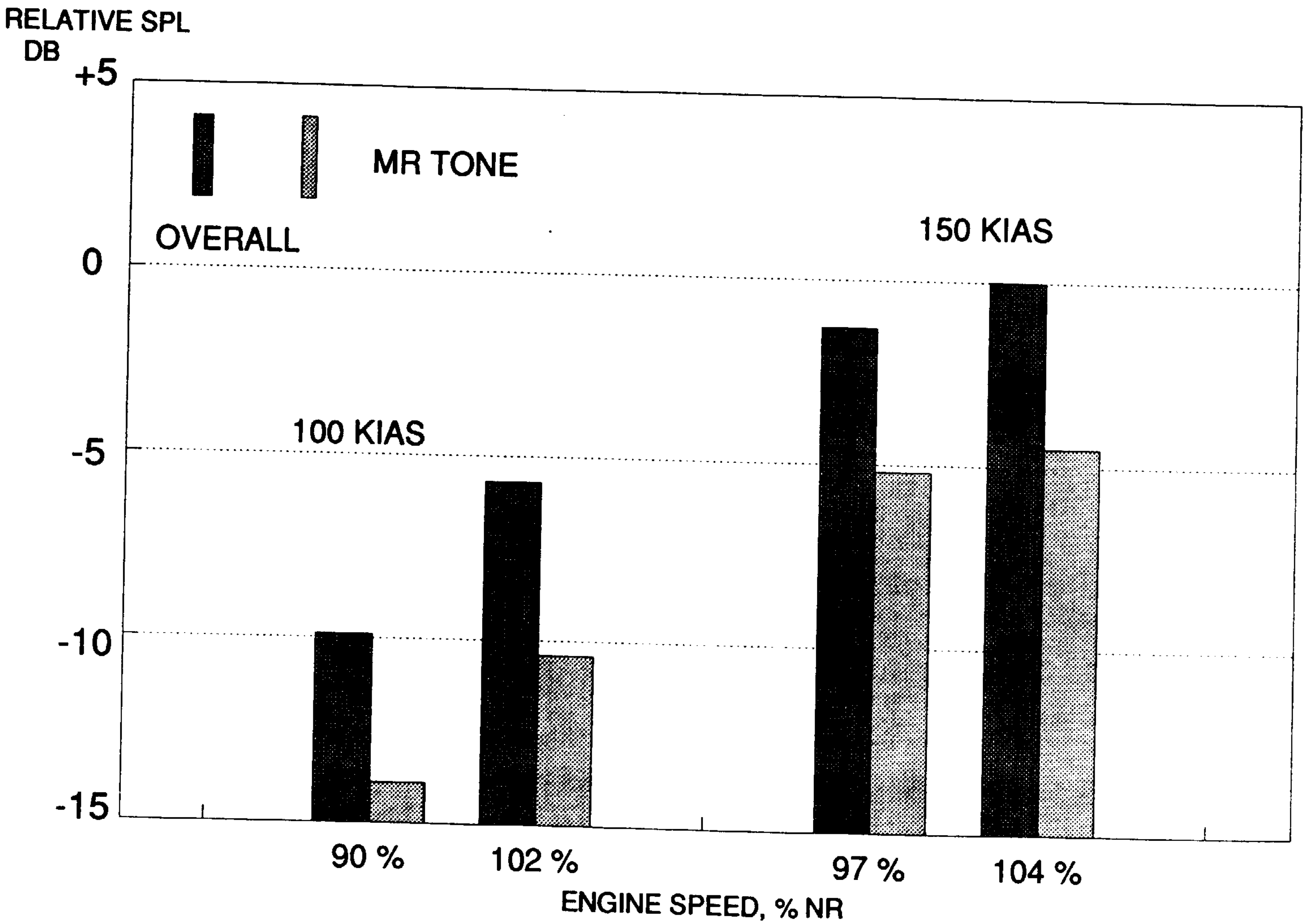


Figure 9.- Comparison of far-field noise effects at reduced rotor speeds for constant flight

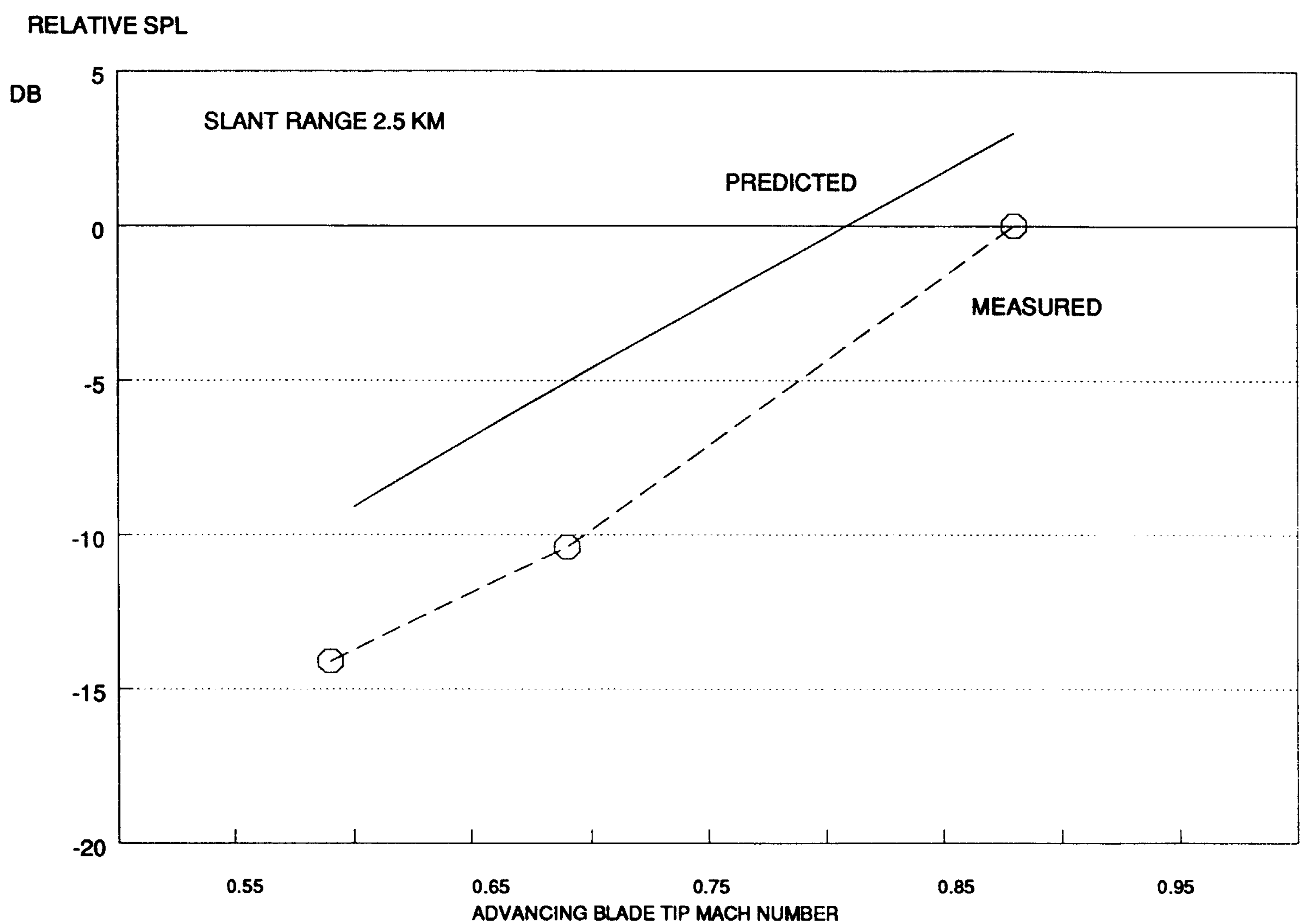


Figure 10.- Comparison of predicted and measured helicopter relative main-rotor narrowband sound pressure levels (re. max measured value)

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16. Abstract

During the design of a helicopter, the weight, engine, rotor speed, and rotor geometry are given significant attention when considering the specific operations for which the helicopter will be used. However, the noise radiated from the helicopter and its relationship to the design variables is currently not well modeled with only a limited set of full-scale field test data to study. In general, limited field data have shown that reduced main-rotor advancing blade-tip Mach numbers result in reduced far-field noise levels.

This paper will review the status of a recent helicopter noise research project designed to provide flight experimental data which may be used to further understand helicopter main-rotor advancing blade-tip Mach number effects on far-field acoustic levels. Preliminary results will be presented relative to tests conducted with a Sikorsky Aircraft Corporation S-76A helicopter operating with both the rotor speed and the flight speed as the control variable. The rotor speed was operated within the range of 107% NR to 90% NR at nominal forward speeds of 35, 100, and 155 knots.

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