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NOTATION

A_{xs}	blade cross sectional area
c	blade chord
c_s	speed of sound
C_T/σ	rotor thrust coefficient to solidity ratio
$M_{1,90}$	advancing tip Mach number, $(V + \Omega R)/c_s$
N	number of blades
p	sound pressure
p_m	m-th harmonic periodic rotor noise
r	blade radial coordinate, from 0 at root to R at tip
R	rotor radius
s_o	observer range from rotor hub
t	time
V	air speed
x	blade chordwise coordinate, from x_{le} at leading edge to x_{te} at trailing edge
α_{tpp}	tip-path plane incidence angle, positive aft
θ_o	observer elevation angle, positive above tip-path plane
ρ	air density
ψ_o	observer azimuth angle, positive from downstream in rotor rotation direction
Ω	rotor rotational speed

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SUMMARY

A theory for helicopter rotor thickness noise is described. Two full-scale rotors tested in a wind tunnel with several tips involving changes in chord, thickness, and sweep are described. The impulsive noise data reduction procedures are described. Finally, the calculated and measured impulsive noise peak pressures as a function of advancing tip Mach number are compared, showing good correlation for all six rotors considered.

INTRODUCTION

Blade slap is a periodic, impulsive sound pressure disturbance produced by helicopter rotors in certain flight conditions. When it occurs, blade slap is the dominant noise component of the rotor.[1] Blade slap has been attributed to a number of aerodynamic sources, including vortex/blade interactions,[1,2,3] shock formation on the advancing tip,[1,4] retreating blade stall,[5] and compressibility effects on the drag of the advancing tip.[3,5] Recently attention has been focused on thickness noise as the source of rotor blade slap.[6,7,8] Prediction of measured rotor impulsive noise using a thickness noise theory has been attempted for only a few cases, with varying degrees of success.[7,9,10] The present investigation was undertaken to establish whether thickness noise is a principal source of helicopter blade slap, by comparing the predicted and measured noise pressure pulses for several full-scale helicopter rotors tested in a wind tunnel.

The rotor impulsive noise will be examined in terms of the sound pressure time history. Looking at the harmonics can be misleading for impulsive noise, particularly if only the spectrum magnitude is used. The advantage of working with wind tunnel noise measurements is that the critical parameters are well known: the location of the microphone relative to the rotor hub, the air speed and the tip-path plane angle-of-attack, the rotor rotational speed, and the air density and speed of sound. The principal disadvantages of noise tests in a conventional wind tunnel -- the presence of background noise and reflections -- are not important for rotor impulsive noise in the time domain. By averaging the sound pressure signal in the time domain, the random background noise can be removed from the periodic component of the rotor noise. Moreover, at high speeds the pulse peak will be much higher than the background noise pressure level. The reflections will not mask the direct pressure pulse if the difference between the arrival times of the direct signal and the first reflection is greater than the pulse width.

THICKNESS NOISE THEORY

Thickness noise theory was first developed by Deming[11,12] for a propeller at zero thrust. He represented the blade by a distribution of source doublets over the disk, nonrotating but periodically varying in time to produce pressure disturbances equivalent to the rotating blade. Thickness noise has long been recognized as a noise source with propellers, but it is less than the thrust-generated rotational noise at the usual tip Mach numbers of subsonic propellers. The role of thickness noise in helicopter acoustics has generally been ignored until recently, particularly in connection with blade slap.[13,14] Consequently while the theories for helicopter thrust and torque-generated rotational noise were being extended to the cases of time-varying blade loading and forward flight, the comparable extensions of the thickness noise theory were ignored.

Johnson[15] has used the acoustic equations of Lowson[16] and Farassat[17] for bodies in arbitrary motion, to derive a thickness noise theory for the rotating blades of a helicopter in vertical or forward flight. Consider a helicopter rotor moving with forward speed $V_x = M_x c_s$ and vertical speed $V_z = M_z c_s$ (where V_x and V_z are the velocity components relative to the tip-path plane axes). The sound is required at an observer station moving with the rotor. The observer position relative to the rotor hub is defined by the range s_o, the azimuth angle ψ_o (measured from downstream, in the direction of rotation of the rotor), and the elevation angle θ_o from the tip-path plane (positive above the rotor disk). The sound pressure p is periodic with fundamental frequency equal to the blade passage frequency $N\Omega$ (where N is the number of blades, and Ω is the rotor rotational speed), so it can be written as a Fourier series with harmonics p_m:

$$p = \sum_{m=-\infty}^{\infty} p_m e^{imN\Omega t}$$

In the far field, the following expression is obtained[15] for the thickness noise harmonics:

$$p_m = - \frac{(mN\Omega)^2 N \rho}{4\pi} \frac{\sigma_o}{S_o^2} e^{-imN\Omega\sigma_o/c_s} \sum_{n=-1}^{1} \left(1 - \frac{n}{mN}\right)$$

$$e^{-i(mN-n)(\Psi_r - \pi/2)} \int_0^R A_{xs} a_{mN-n} V_n J_{mN-n} \, dr$$

where the argument of the Bessel function J_{mN-n} is

$$\frac{mN\Omega r}{c_s} \frac{1}{S_o} \sqrt{(x_o - M_x \sigma_o)^2 + y_o^2}$$

and $V_0 = 1$, $V_1 = -iV_x/(2\Omega r)$, $V_{-1} = iV_x/(2\Omega r)$,

$$x_o = s_o \cos\theta_o \cos\Psi_o$$

$$y_o = s_o \cos\theta_o \sin\Psi_o$$

$$z_o = s_o \sin\theta_o$$

$$\beta^2 = 1 - M_x^2 - M_z^2$$

$$S_o^2 = \beta^2 s_o^2 + (M_x x_o - M_z z_o)^2$$

$$\sigma_o = \frac{1}{\beta^2}(S_o - M_x x_o + M_z z_o)$$

$$\Psi_r = \tan^{-1} y_o/(x_o - M_x \sigma_o)$$

Here A_{xs} is the area of the blade cross section, and a_n is a factor accounting for the chordwise distribution of the blade thickness:

$$a_n = \frac{1}{A_{xs}} \int_{x_{le}}^{x_{te}} t(x) \, e^{-inx/r} \, dx$$

where $t(x)$ is the blade thickness. For the present calculations, the thickness distribution of NACA 4-digit and 5-digit airfoil series was used.[18] This thickness noise theory involves two major assumptions. A high aspect ratio of the blade has been assumed, in order to separate the integral over the chordwise variable x. A far-field observer point has been assumed in order to analytically solve for the retarded time and evaluate the integral over the rotor azimuth.

The integrals were evaluated numerically using 10 chordwise steps, and up to 500 radial steps at high speed. Up to 500 harmonics were evaluated at high speed, and the time history of the sound pressure was evaluated at up to 500 points over the period to define the pulse peak.

FULL SCALE WIND TUNNEL TESTS

A 6.7m radius four-bladed rotor constructed by Sikorsky Aircraft was tested in the NASA-Ames 40- by 80-ft Wind Tunnel in 1977; and a 7.3m radius two-bladed rotor constructed by Bell Helicopter Company was tested in 1974. In both cases a number of tip shapes were tested (figure 1), involving changes in the blade chord, thickness, and sweep. The corresponding radial distributions of the cross section area are shown in figure 2. The Sikorsky rotor blades had a constant chord and 9.5% thickness ratio airfoil inboard of 95% radius. The rectangular tip maintained the chord out to 100% radius. The trapezoidal tip was tapered to 60% of the baseline chord at the tip, with a constant thickness ratio and an unswept quarter chord line. The swept tip had constant chord with 20° sweepback. The swept-tapered tip had 35° sweep of the leading edge and 10° sweep of the trailing edge, giving a tapered blade with constant thickness ratio. The Bell rotor blades had a constant chord with a NACA 0012 airfoil section inboard of 80% radius. The thin tip tapered in thickness to 6% thickness ratio at the tip, with constant chord. The single-swept tip had 51° sweepback of the leading edge from 96% radius; its thickness ratio varied from 12% at 0.8R to 10.5% at 0.88R, was constant to 0.96R, and then increased to 11% at the tip.

The principal parameters of the rotors and tests are presented in Table 1. The rotor was operated by setting collective pitch and shaft angle, and adjusting the cyclic pitch controls to achieve zero cyclic flapping. Hence the shaft angle-of-attack also gives the tip-path plane incidence angle (α_{tpp}, positive for aft tilt). The noise data presented here are for a 5° forward tilt of the tip-path plane, over a small range of rotor thrust around $C_T/\sigma = 0.07$ (the thickness noise prediction does not depend on the rotor forces, and no dependence on thrust over this range was observed in the measurements either). The tunnel airspeed and rotor rotational speed were set to vary the advancing tip Mach number $M_{1,90} = (V + \Omega R)/c_s$ at a constant value of $V/\Omega R$. The resulting rotor speed was around 320 rpm for both rotors, giving a 1/rev frequency around 5 Hz. The microphone was located upstream of the rotor, slightly below the tip-path plane. There were minor variations in the air density and speed of sound for the test points considered (the range is shown in Table 1, but the actual measured values were used in the thickness noise calculations).

NOISE DATA REDUCTION

The microphone signal was recorded on an FM tape recorder (center frequency 27 kHz, bandwidth 5 kHz). The sound pressure signals were played back into a time series analyzer for digital processing. The noise signal was sampled at a rate of 5120/sec for 0.2 sec, beginning when the rotor azimuth angle was zero. The resulting frequency resolution was 5 Hz with a Nyquist frequency of 2.06 kHz; a 2 kHz anti-aliasing filter was used. An example of the raw noise signal is given in figure 3a. The noise signal was averaged 50 times to eliminate the background noise and the rotor broadband noise (figure 3b). Finally, the noise signal was processed by a 25 Hz high-pass filter to eliminate the mean, and the first blade passage harmonic of the thrust-generated rotational noise. (The filtering was accomplished by calculating the Fourier transform of the signal, dropping all spectral lines below 25 Hz, and then calculating the inverse Fourier transform. By this means any magnitude or phase distortion of the harmonics above 25 Hz was avoided. As figure 3c shows, there was no observable change in the pulse shape or amplitude using this procedure.)

A key element of the data reduction is converting the recorded signal to pressure units (N/m^2). The microphone was calibrated using a B&K Pistonphone, which produces a 124 dB (re 0.00002 N/m^2) rms acoustic signal at 250 Hz:

$$124 = 20 \log \frac{p_{rms}}{p_{ref}}$$

Now $p_{rms} = K V_{rms} = K V_{amp}/\sqrt{2}$, where K is the conversion factor from volts to N/m^2, and V_{amp} is the amplitude of the calibration signal in volts. Then

$$K = \frac{10^{6.2}\, p_{ref} \sqrt{2}}{V_{amp}} = \frac{44.83}{V_{amp}} \quad \frac{N/m^2}{Volt}$$

When the rotor noise was recorded with a different amplifier setting than was used for the calibration (by ±10 dB or ±20 dB typically, in order to keep the signal within the best working range of the tape recorder), it was also necessary to account for this difference in the factor K. Lee[19,20] gives additional details of the measurement and data reduction process.

For the test configuration considered here, it was verified experimentally that the first reflection (from the wind tunnel floor) arrives about 4 msec after the direct wave, and the sound pressure pulse width was found to be much less than 4 msec, particularly at high speed. Actually, there was little evidence of impulsive noise reflections in the measured sound pressure signals (see figure 3). A probable factor in the absence of observed reflections is the location of the microphone nearly in the rotor tip-path plane, where the impulsive noise directivity is greatest. Hence pulses reflected off the tunnel floor or ceiling have smaller magnitude than the pulse traveling directly from the rotor to the microphone.

COMPARISON OF MEASURED AND CALCULATED NOISE

Time histories of the measured impulsive noise are shown in figure 4 for the Sikorsky 6.7 m rotor with trapezoidal tips, at three advancing tip Mach numbers. Similar waveforms were observed by in-flight measurements of the noise produced by a UH-1 helicopter,[21] which identified the negative pressure pulse increasing in amplitude with Mach number so that it dominates the sound pressure signal at high speed; and found at very high speeds a positive pressure spike closely following the negative pulse so that the waveform becomes unsymmetric. Figure 4 also shows the impulsive sound pressure calculated using the thickness noise theory described above. Clearly there is more to the periodic rotor noise than just the thickness noise component, but the impulse is well accounted for by the thickness noise. Lee[19,20] gives the rotor sound pressure time histories for additional cases.

Figures 5 to 10 compare the measured and calculated peak impulsive noise pressures for the Sikorsky 6.7 m rotor with four different tips and the Bell 7.3 m rotor with two different tips, at constant $V/\Omega R$ as a function of advancing tip Mach number. The overall correlation is quite good. It is also seen in both the measured and calculated data that the impulsive noise can be reduced by decreasing the cross sectional area of the blade tip. For example, compare the noise produced by the Sikorsky 6.7 m rotor with trapezoidal and rectangular tips (figures 5 and 7), which differ in cross sectional area as shown in figure 2. Sweeping the blade tip without changing the chord or thickness has little influence on the thickness noise (compare figures 5 and 6 for the Sikorsky 6.7 m rotor with trapezoidal and swept-tapered tips).

CONCLUSIONS

It is concluded from this comparison of measured and calculated rotor impulsive noise that high speed blade slap is dominated by the thickness noise, which can be predicted well using existing theories. A complete prediction of helicopter noise will require an accurate treatment of the positive pressure spike following the thickness noise negative pulse at very high advancing tip Mach number; the blade lift- and drag-generated rotational noise, including the impulses due to blade/vortex interaction, and the rotor broadband noise. The ability to predict blade thickness-generated impulsive noise however does much to allow the confident design of quieter helicopter rotors at high speed.

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Table 1 **Rotor and Test Parameters**

	Sikorsky 6.7 m rotor	Bell 7.3 m rotor
Number of blades, N	4	2
Rotor radius, R (m)	6.71	7.32
Blade chord, c (m)	0.394	0.533
Blade thickness ratio	0.095	0.12
Microphone position		
range, s_o (m)	19.66	21.40
azimuth, ψ_o	180°	180°
elevation, θ_o	-7.4°	-7.4°
Rotor operating condition		
C_T/σ	0.065 to 0.075	0.065 to 0.075
$V/\Omega R$	0.375	0.300
α_{tpp}	-5°	-5°
Air density ρ (kg/m^3)	1.12 to 1.15	1.13 to 1.17
Speed of sound c_s (m/sec)	341 to 346	345 to 349

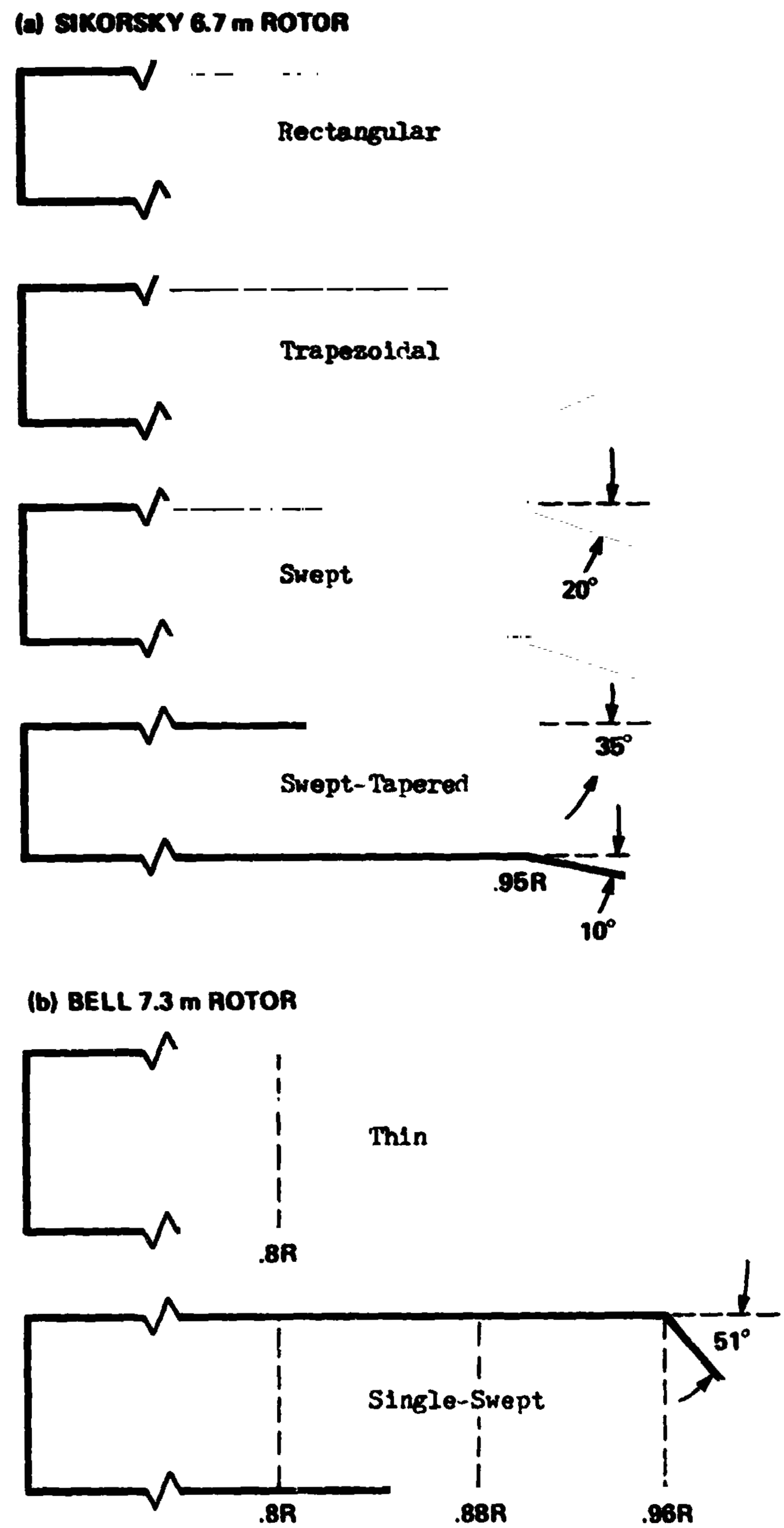

Figure 1 Tip shapes of the full scale rotors tested

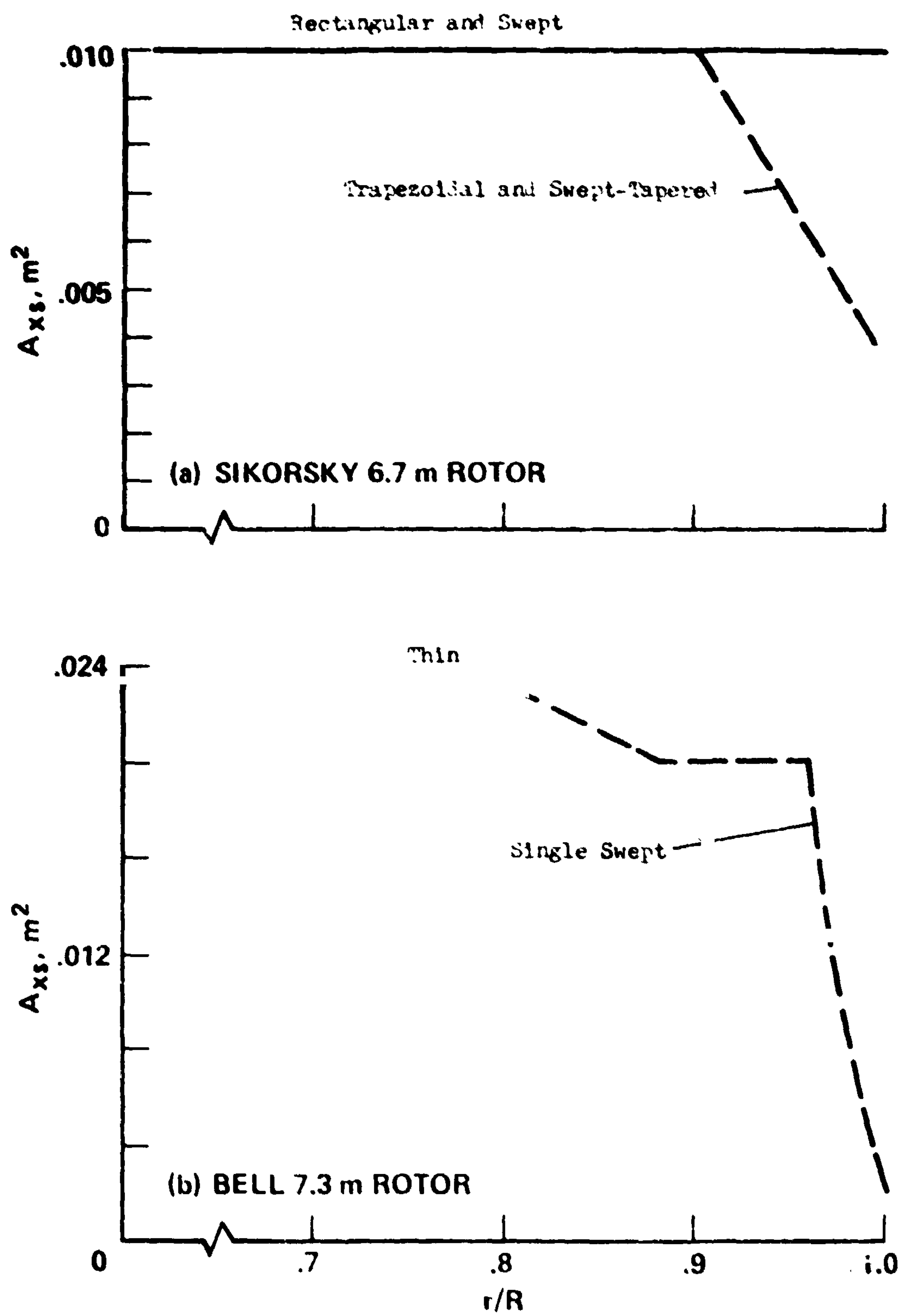

Figure 2 Blade cross-section area distributions

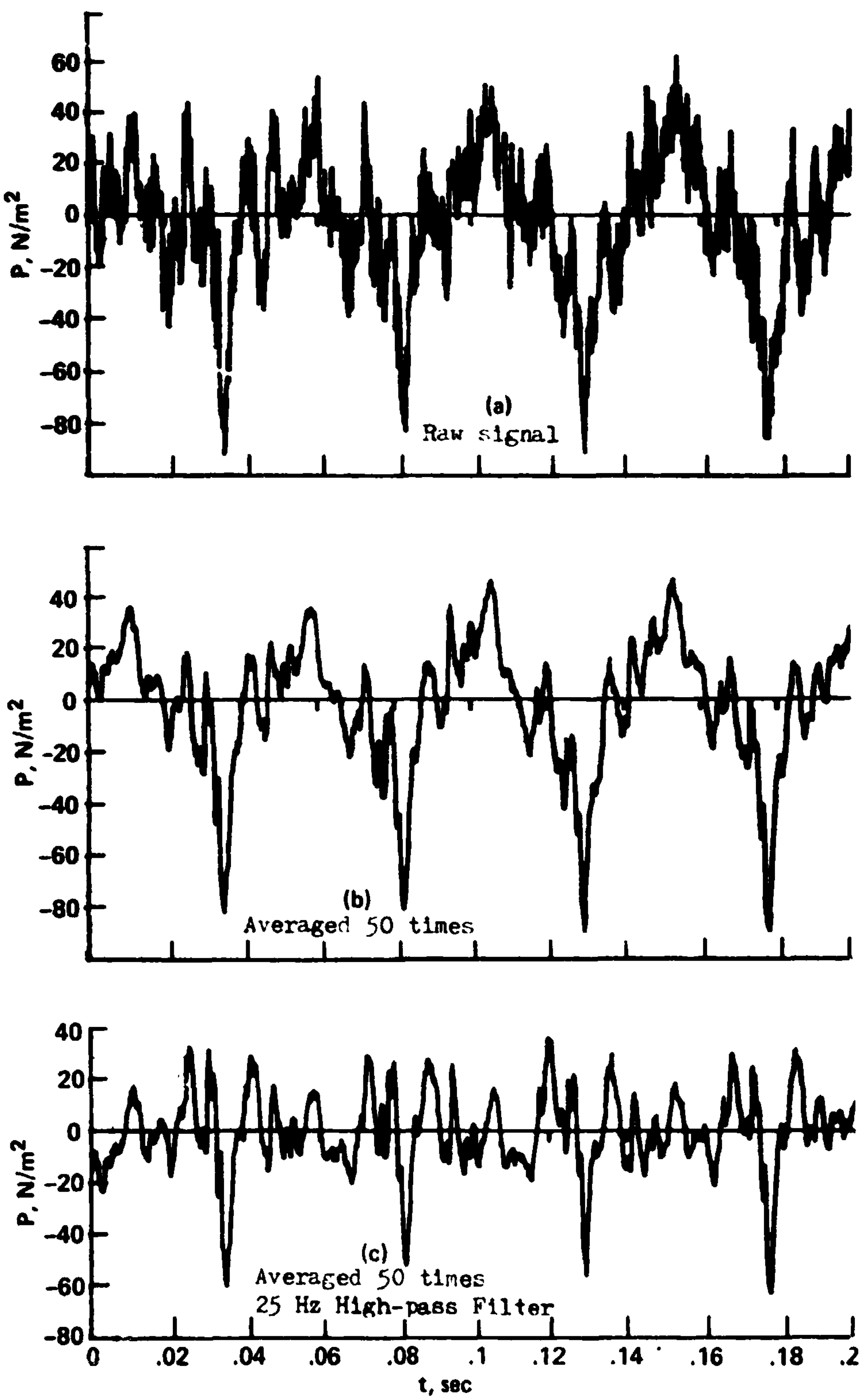

Figure 3 Example of the noise signal processing (Sikorsky 6.7 m rotor with trapezoidal tips, at $M_{1,90}$ = 0.896 and $V/\Omega R$ = 0.375)

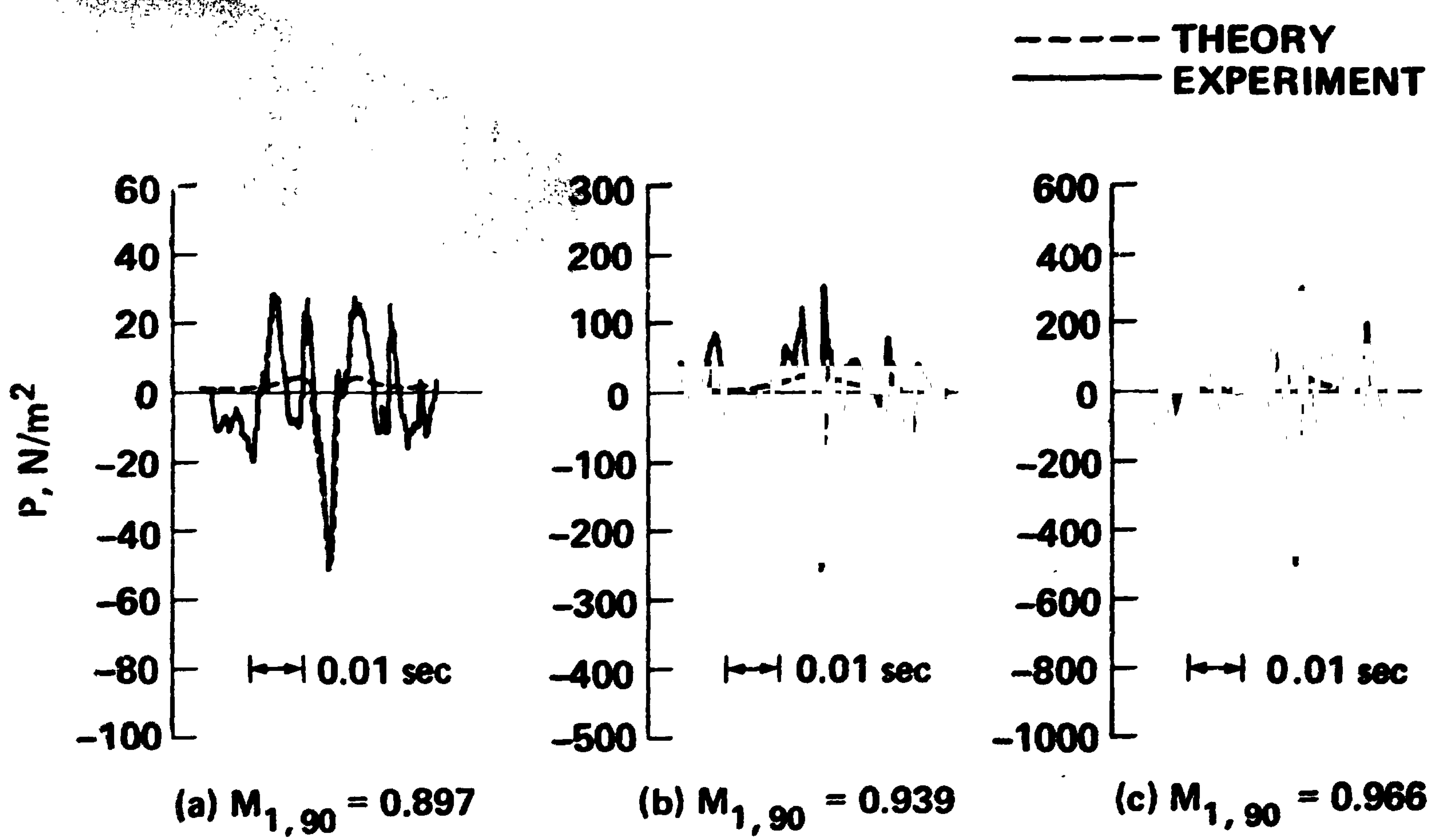

Figure 4 Comparison of the measured and calculated thickness noise time histories for the Sikorsky 6.7 m rotor with trapezoidal tips, at $V/\Omega R = 0.375$ and several advancing tip Mach numbers

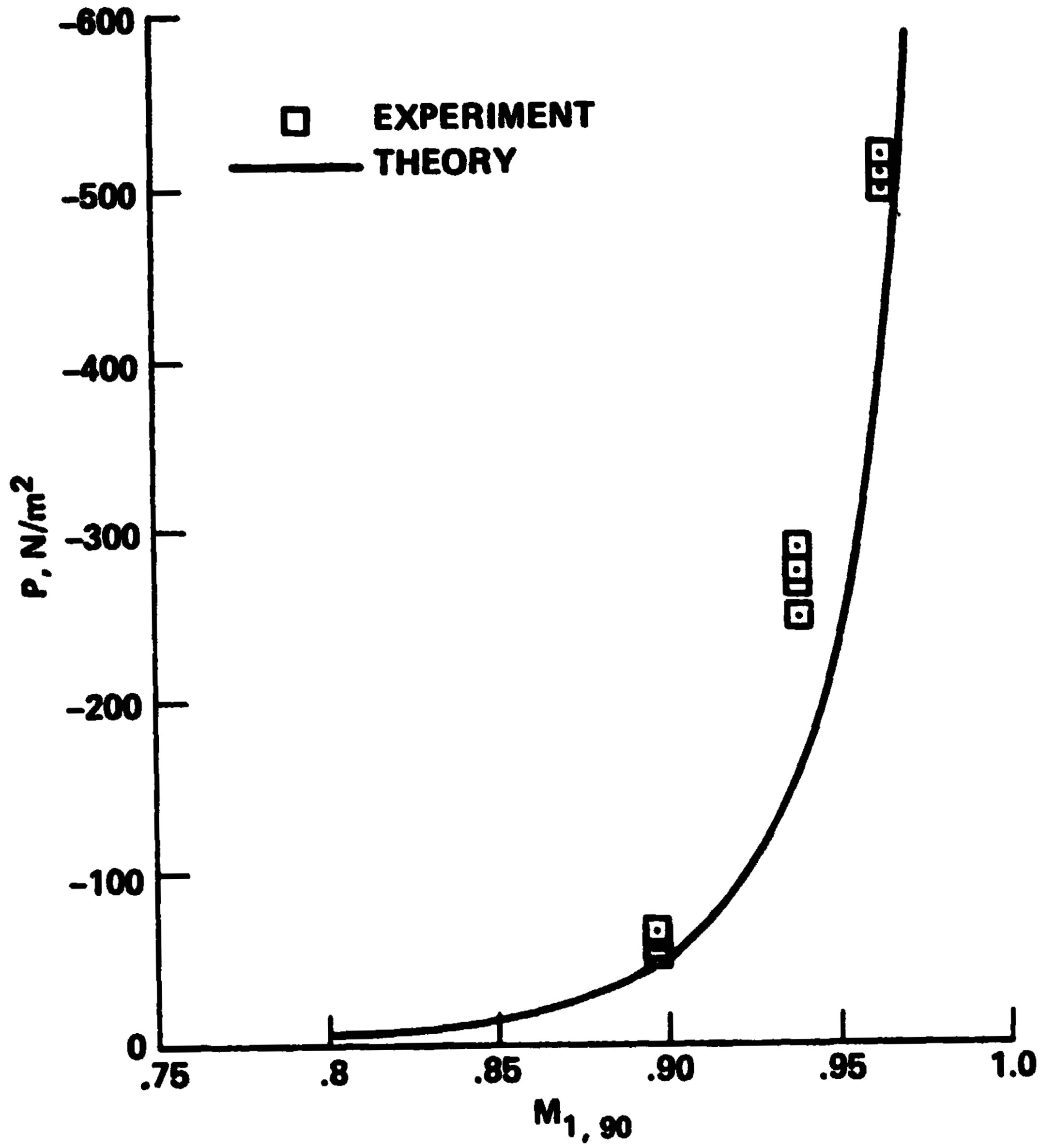

Figure 5 Comparison of measured and calculated impulsive noise peak pressures for the Sikorsky 6.7 m rotor with trapezoidal tips ($V/\Omega R = 0.375$)

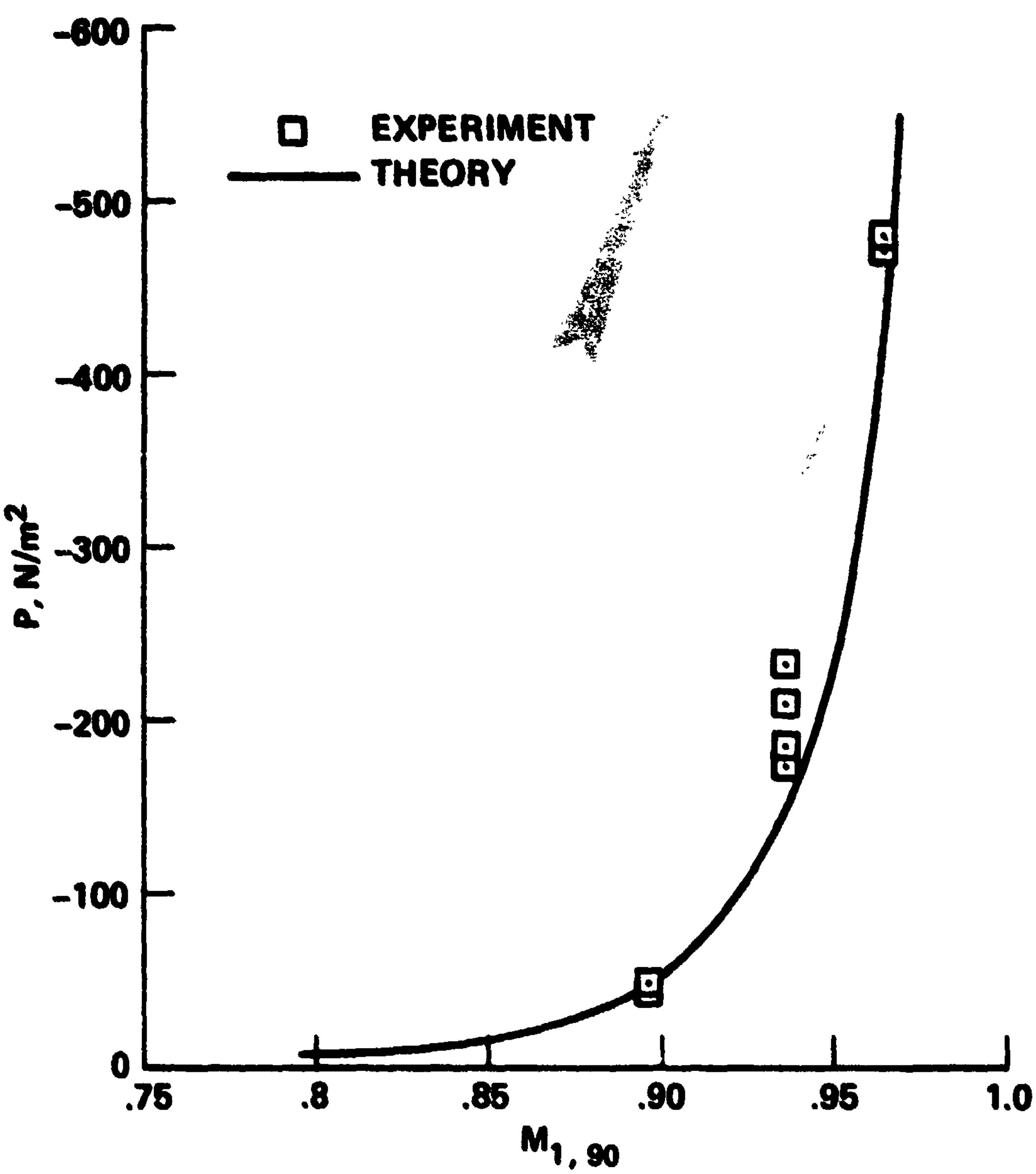

Figure 6 Comparison of measured and calculated impulsive noise peak pressures for the Sikorsky 6.7 m rotor with swept-tapered tips ($V/\Omega R = 0.375$)

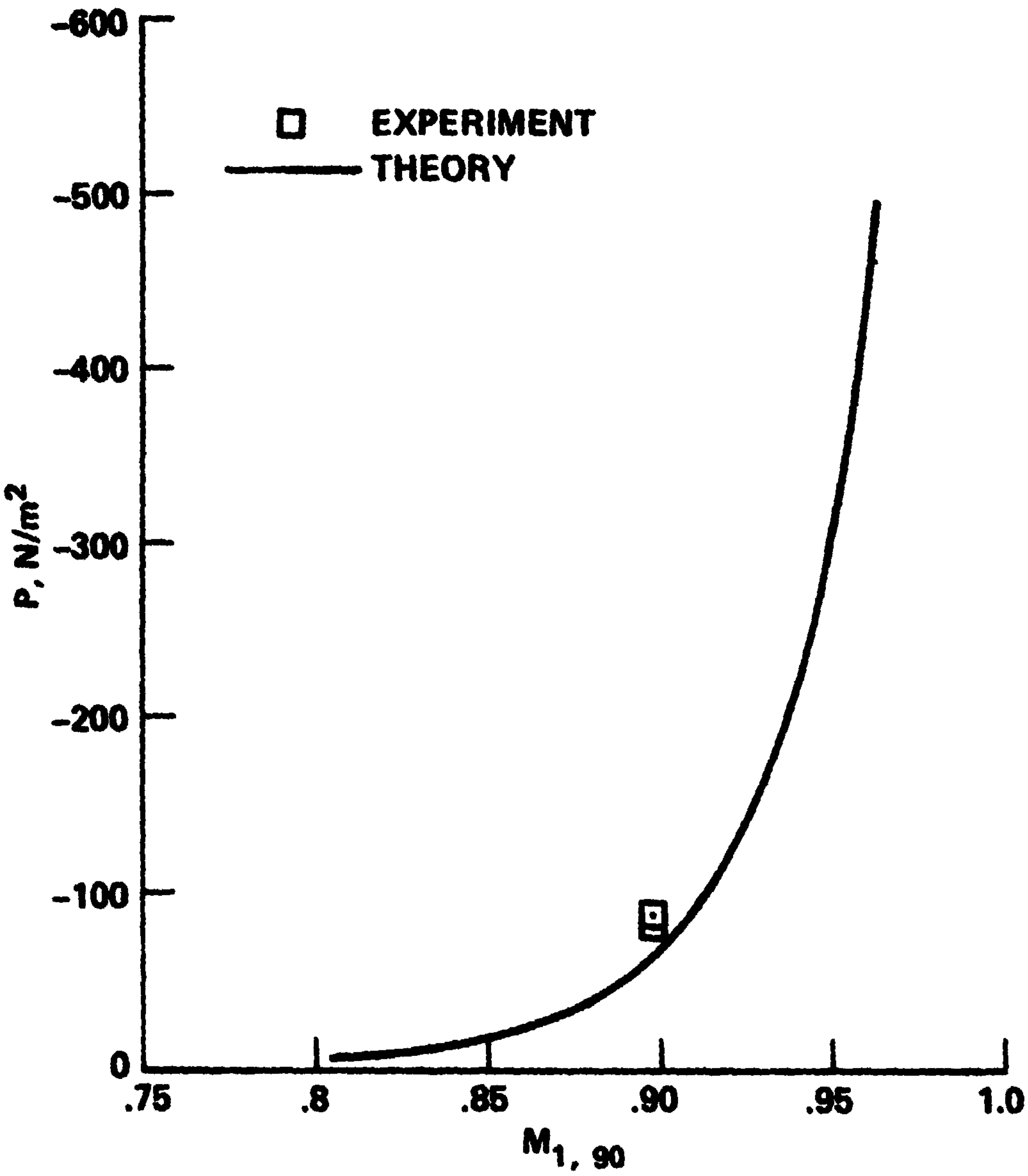

Figure 7 Comparison of measured and calculated impulsive noise peak pressures for the Sikorsky 6.7m rotor with rectangular tips ($V/\Omega R$ = 0.375)

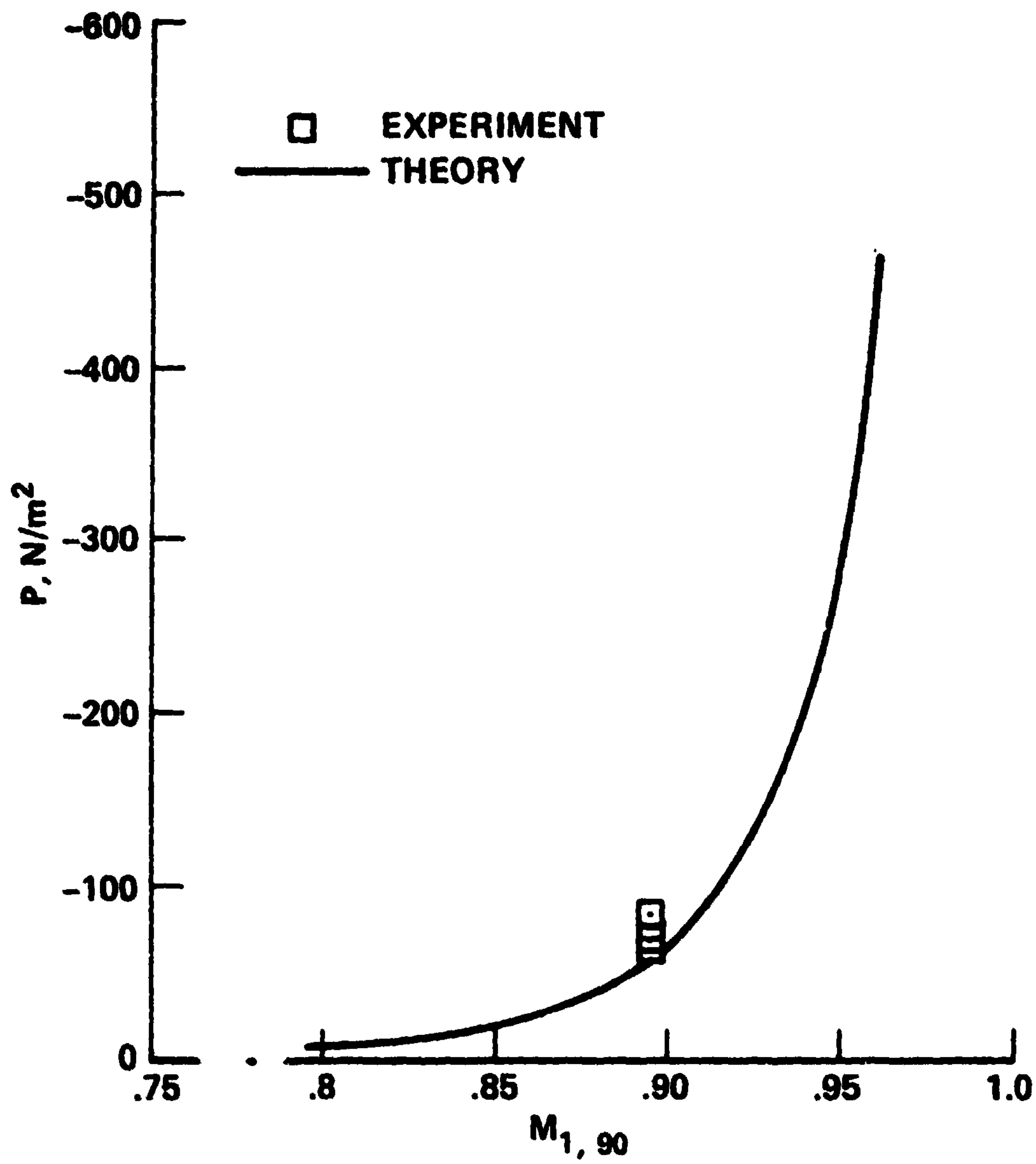

Figure 8 Comparison of measured and calculated impulsive noise peak pressures for the Sikorsky 6.7 m rotor with swept tips ($V/\Omega R$ = 0.375)

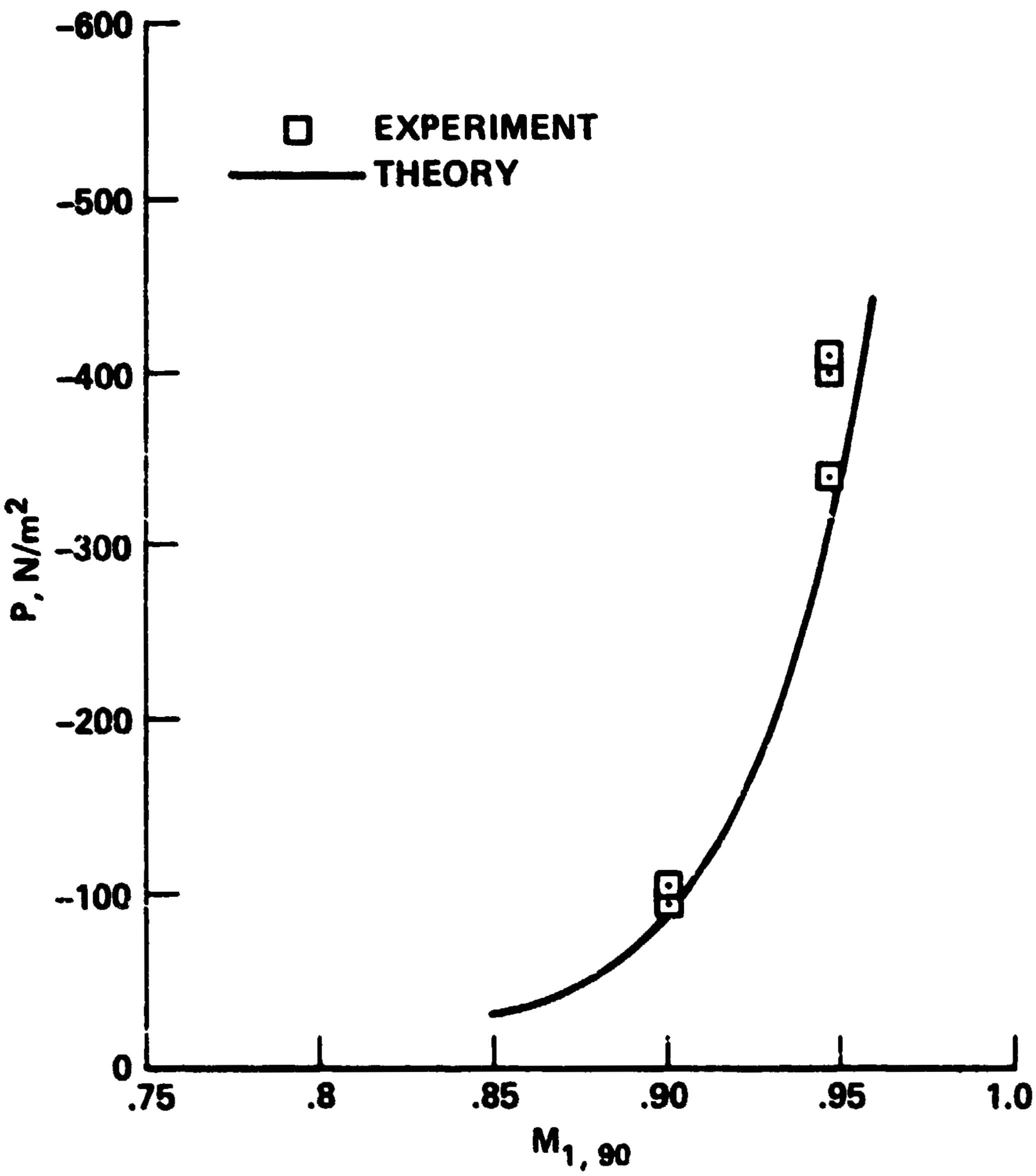

Figure 9 Comparison of measured and calculated impulsive noise peak pressures for the Bell 7.3m rotor with thin tips ($V/\Omega R$ = 0 30)

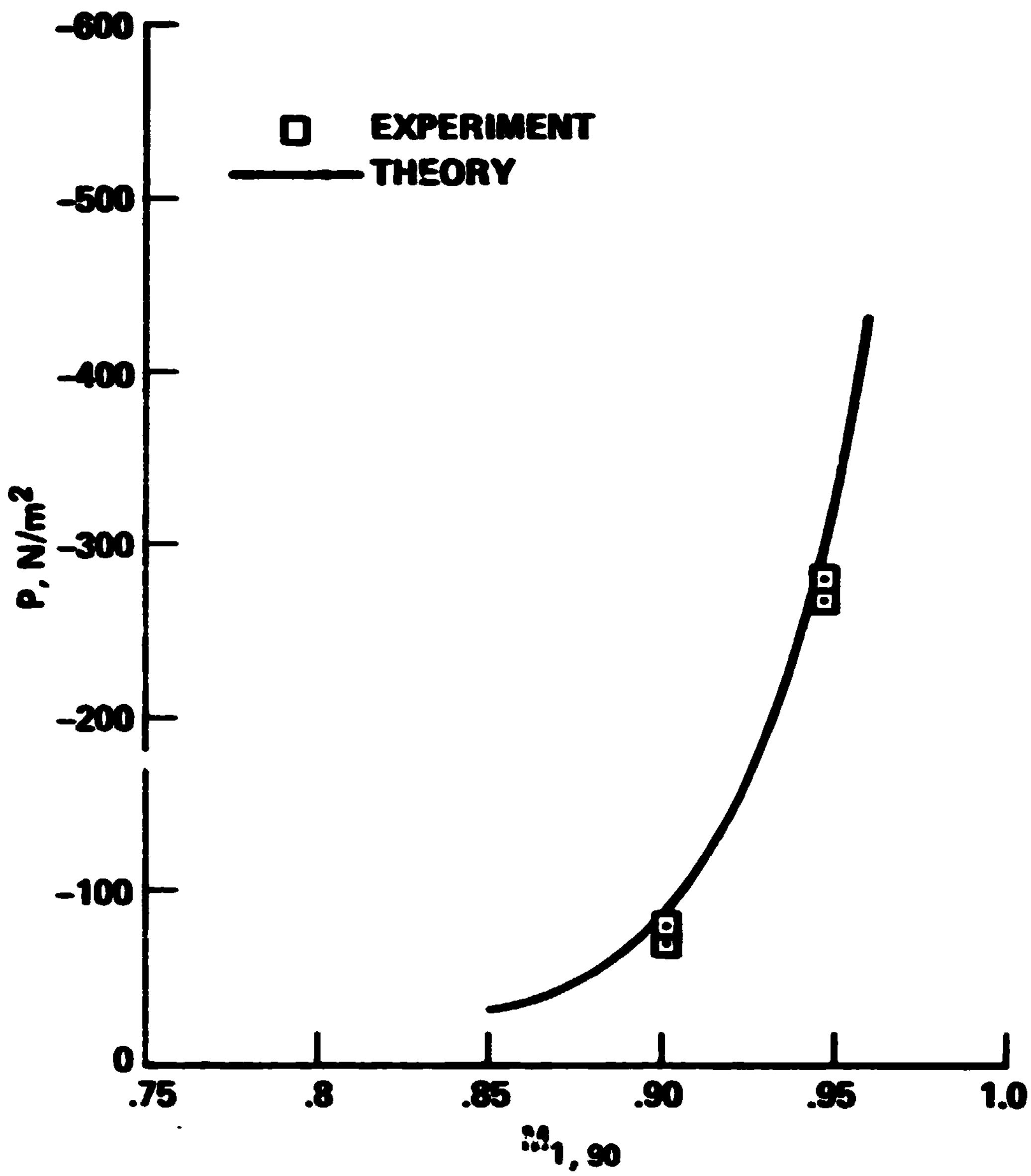

Figure 10 Comparison of measured and calculated impulsive noise peak pressures for the Bell 7.3m rotor with single-swept tips ($V/\Omega R = 0.30$)

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16. Abstract

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