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# RESEARCH MEMORANDUM

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
May 8, 1951

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## SUMMARY

Sound measurements at static conditions have been made for a two-blade, 47-inch-diameter propeller in the tip Mach number range 0.75 to 1.30. For comparison, spectrums have been obtained at both subsonic and supersonic tip speeds. In addition, the measured data are compared with calculations by the theory of Gutin which has previously been found adequate for predicting the sound at subsonic tip speeds.

At supersonic tip speeds, the sound pressures are lower than an extrapolation of the subsonic data would indicate. For a constant power, the over-all measured sound pressures are essentially independent of tip speed for the supersonic tip-speed range of the tests. The spectrums have a high harmonic content with some of the higher harmonics being more intense than the fundamental frequency. For the supersonic tip-speed range of the tests, the measured intensities were a maximum in the plane of rotation. The theory of Gutin is found to be adequate for predicting intensities of the lower harmonics for the tip Mach number range of the tests but overestimates the intensities of the higher ones at supersonic tip speeds.

Curves are presented from which the maximum over-all noise levels in free space may be estimated if the power, tip Mach number, and distance are known.

## INTRODUCTION

Propeller noise has been a problem even at subsonic tip speeds, hence the proposed use of propellers operating at supersonic tip speeds has caused some concern as to the severity of the associated noise problem. Very little information has been published which would allow the prediction of noise levels associated with the operation of these propellers. Since airplane design and airplane operation may be affected by noise considerations, there is considerable interest in data of this type.

There exists considerable information on the subsonic noise problem and the work of Gutin has allowed its unification. Gutin, in reference 1, gives a theoretical expression for the sound produced by a propeller in static operation, as a function of tip speed, number of blades, thrust and torque, and the dimensions of the propeller. Because of simplifying assumptions, these relations are valid only at distances large compared to the propeller diameter. These theoretical results were checked experimentally by Deming (reference 2) for two-blade propellers, and in reference 3 the checks have been extended to multiblade configurations. These two experimental investigations indicated good agreement with theory, for the lower harmonics, in the tip Mach number range 0.50 to 0.90.

The oscillating pressures produced by a propeller are recognized as sound when observed at large distances and references 1, 2, and 3, as well as the present paper, are primarily concerned with propeller sound. There is also interest in the oscillating pressure field at positions near the propeller both from the standpoint of sound and structural vibrations. Reference 4 presents an analysis whereby the oscillating pressures may be calculated at any point in space for static conditions. This analysis is based on the work of Gutin without simplifying assumptions of distance. Good experimental agreement was obtained for the lower harmonics up to a tip Mach number of 1.00 which was the highest reached in the test. Because of its complexity, the analysis of reference 4 is most useful near the propeller where the assumptions of reference 1 regarding distance are not valid.

The present paper is concerned primarily with sound measurements at distances large enough so that the theory of reference 1 would be applicable. Comparisons with the theory of reference 1 are extended to a tip Mach number of 1.30. Frequency spectrums and the corresponding wave forms for a two-blade propeller at both subsonic and supersonic tip Mach numbers (0.75 to 1.30) were recorded and are presented for comparison. Data are also presented which make possible the estimation of the maximum over-all sound intensities at given conditions of power and distance for the supersonic tip Mach number range of the tests.

## SYMBOLS

$b$ blade chord, feet

$D$ propeller diameter, feet

| | |
|---|---|
| $h$ | blade-section maximum thickness, feet |
| $h/b$ | blade-thickness ratio |
| $b/D$ | blade-width ratio |
| $r$ | blade-section radius, feet |
| $R$ | propeller-tip radius, feet |
| $\beta$ | blade angle, degrees |
| $\beta_{0.75}$ | blade angle at $r = 0.75R$, degrees |
| $M_t$ | tip Mach number |
| $\theta$ | angle from axis of propeller rotation ($0^{\circ}$ in front) |
| $S$ | distance from propeller, feet |
| $m$ | order of the harmonic |
| $B$ | number of blades |
| $P_o$ | disk power loading, horsepower per square foot of disk area |
| $p$ | root-mean-square sound pressure of a given harmonic |
| $\overline{p}$ | over-all root-mean-square sound pressure |
| $p'$ | over-all peak sound pressure |
| $A$ | propeller disk area, square feet |
| $P_H$ | horsepower to propeller |
| $T$ | thrust of propeller, pounds |
| $J_{mB}(x)$ | Bessel function of order $mB$ and argument $x = 0.80M_t mB \sin \theta$ |

## APPARATUS AND METHODS

Tests at static conditions were conducted for the purpose of measurement and analysis of the sound from a propeller operating at tip Mach numbers greater than unity. The propeller used for these tests was a two-blade configuration, 47 inches in diameter, incorporating (5)(08)-03 blade sections. The blade-form curves for this propeller are given in figure 1.

The drive unit consisted of two 200-horsepower, water-cooled, variable-speed electric motors operating in tandem as shown in figure 2. The total power input to the motors was recorded by means of a wattmeter. Power delivered to the propeller was determined from measured values by taking account of motor efficiency.

The propeller and motor were located in an open field, approximately 6 feet from the ground surface and about 70 feet from the nearest obstruction which might give other appreciable reflections. A heavy-gage safety fence placed around the installation did not appreciably affect the sound measurements.

Thrust data for use in the calculations were obtained from a total-pressure survey at one position in the wake at a distance of 4 inches behind the propeller plane. The approximate values obtained, as shown in table I, are not intended as performance data but are considered adequate for the sound calculations.

Sound pressures were measured by means of a Massa Laboratories model GA-1002 sound measurement system and a Panoramic Sonic Analyzer. This equipment is calibrated to indicate sound pressures either in decibel units or dynes per square centimeter, at the convenience of the operator, and provides essentially a flat frequency response between 20 and 20,000 cycles per second. The viewing screen of the Panoramic Sonic Analyzer was photographed, thus a permanent record of the frequency analysis at each test condition was obtained. Simultaneously, a photographic record was made of the wave shape of the over-all signal as it appeared on the viewing screen of a cathode-ray oscillograph. These latter records were useful in computing the peak pressure values. The sound detecting and measuring equipment is shown in figure 3.

The microphone was placed at ground level to insure the maximum pickup of all frequencies. The ground is assumed to be a perfect reflecting surface and the measured sound pressures are divided by 2 to convert them to free-space values. The data presented in this paper are for free space since ground-reflection corrections have been applied in all cases. All data are in root-mean-square (rms) values unless otherwise noted and decibels are referred always to a reference level of 0.0002 dyne per square centimeter.

## RESULTS AND DISCUSSION

### Experimental Results

This paper gives results of noise tests of a propeller operating at both subsonic and supersonic tip Mach numbers. The terms "noise, sound, and sound pressure" are used synonymously throughout the text. Data were taken for the tip Mach number range 0.75 to 1.30 and at various azimuth angles from $0^\circ$ to $165^\circ$. Most of the testing was at $\beta_{0.75} = 15^\circ$ which corresponds to a maximum power absorption at a tip Mach number of 1.20. A limited number of tests were run, however, at $\beta_{0.75} = 13^\circ$ in order to extend the tip Mach number range to 1.30.

Frequency spectrums.- Figure 4 shows typical spectrums of the propeller noise for tip Mach numbers from 0.75 to 1.30 at three azimuth angles, $\theta$, of $60^\circ$, $90^\circ$, and $120^\circ$, representing, respectively, positions ahead of the plane of rotation, in the plane, and behind it. These spectrums were recorded with the aid of a Panoramic Sonic Analyzer. Frequency is indicated on the horizontal scale and free-space intensity in decibels is indicated on the vertical scale. It should be noted that the ordinate scales are not the same in every case and therefore direct comparisons of amplitudes may not be valid. The intensities and frequencies of the various components of the complex noise signal are indicated by the height and position of the corresponding pips. The pip on the left in each case represents the fundamental frequency of rotational noise (the blade passage frequency) and the others are integral multiples of the fundamental.

The rotational noise is that component due to the steady aerodynamic forces on the blades and the frequencies are multiples of the rotational speed. There may also be a vortex component of noise for some conditions of the tests. The vortex noise is due to the oscillatory forces on the blades associated with vortices in the wake. It consists of a random spectrum distributed over a wide band of frequencies.

The data of figure 4 illustrate marked differences in the high-speed and low-speed spectrums. At low tip speeds, the spectrums are noted to consist primarily of a limited number of rotational noise harmonics of which the lower ones are the most intense. In contrast, the high-tip-speed spectrum appears to contain significant harmonics up to approximately the fiftieth order, and some of them are more intense than the fundamental frequency. This result confirms the findings of reference 2 wherein the higher harmonics were found to increase in intensity at a faster rate as a function of tip speed than do the lower ones. The entire range of frequencies recorded on the records of figure 4 are believed to consist primarily of rotational rather than vortex components because of the excellent repeatability obtained for successive analyzer records. Past experience has shown that, because of the random nature of vortex noise, successive records of vortex noise would differ considerably. The above result agrees with observations of reference 3 wherein it is noted that the vortex component is an appreciable part of the total only at low-subsonic tip Mach numbers. Previous tests have also indicated that vortex noise is a maximum along the axis of rotation and is a minimum at $\theta = 90^{\circ}$ where some of the data of figure 4 were obtained. There is apparently a trend for a larger amount of energy to appear in the higher-order harmonics as the tip speed increases and for these higher-order frequencies to be strongest in and ahead of the plane of rotation. It is significant that at supersonic tip speeds the highest over-all intensities were recorded in the plane of rotation.

Wave forms.- Simultaneously with the recording of the spectrums of figure 4, records were made of the corresponding wave forms of the over-all noise signal. These wave forms, shown in figure 5 by the solid line, were obtained by photographing the screen of a cathode-ray oscillograph. These are essentially time histories of the sound-pressure pulses for one or two blade passages with time increasing from left to right. Positive pressure is indicated downward and negative pressure, upward. Various attenuation factors were necessary to keep the deflections within practical limits, and, for this reason, the multiplying factors (MF) applicable to each wave form are given in order to make amplitude comparisons possible. A reference is also indicated in each case by the dashed line. It is seen from figures 4 and 5 that the sharply peaked wave forms are generally associated with spectrums which have a large high-frequency content. A brief discussion of the measurement of nonsinusoidal wave forms is given in the appendix.

Polar distribution.- Figures 6(a) and 6(b) illustrate the variation of root-mean-square and peak sound pressures as a function of azimuth angles for two different tip Mach numbers. At subsonic tip speeds the root-mean-square and peak pressures are generally noted to be a maximum slightly behind the plane of rotation as shown by the curves of figure 6(a). At supersonic tip speeds the maximum root-mean-square and peak sound pressures occur in the plane of rotation as indicated by the curves of figure 6(b). Gutin, in reference 1, shows the sound distribution in space to be a function of the torque and thrust. The torque noise is a maximum in the plane of rotation, hence the maximum intensities will occur in that direction when the torque is large compared to the thrust. This latter condition is not necessarily associated with supersonic tip Mach numbers but may also occur at subsonic tip Mach numbers for the stall condition.

Effect of tip Mach number.- The variation of sound pressure as a function of tip Mach number, at a constant power, is shown in figure 7. Over-all sound pressures were measured by means of a voltmeter and, in addition, were computed by summing up the component harmonics as in reference 3. Both sets of data were adjusted to equality at $M_t = 0.75$ and all values have been adjusted to a power absorption by the propeller of 30 horsepower per square foot of disk area. The same trends are indicated by both sets of data. At subsonic tip speeds, the sound pressures increase at a rapid rate as the tip Mach number increases. For the supersonic tip-speed range and the conditions of these tests the sound pressures at a constant power loading are essentially independent of tip Mach number.

Effect of distance.- The effect of distance on the over-all sound pressures is shown in figure 8 for a two-blade propeller at a tip Mach number of 1.20. Distance is defined in terms of the propeller diameter and is measured from the center of rotation. Measurements were made at the two distances shown by the data points and the curve has been estimated on the basis of data presented in reference 4. At distances of several diameters the sound pressure varies inversely as the distance. This corresponds to a reduction of 6 decibels when the distance is increased by a factor of 2. At points close to the propeller, however, the sound is known to decrease at a faster rate, as indicated by the curve.

Even though figure 8 was prepared from data for a tip Mach number of 1.20 it is believed to apply for the whole supersonic tip Mach number range of the tests. On the basis of data presented in figure 7, the curve of figure 8 is representative of two-blade propellers operating at supersonic tip speeds for a power loading of 30 horsepower per square foot of disk area. Since the sound pressures in the plane of rotation are directly proportional to the power loading, 6 decibels would be added to the sound-pressure values of figure 8 if the power loading were doubled. Thus figure 8 allows the rapid estimation of free-space sound pressures in or near the plane of rotation where they are a maximum, provided the power and distance are known.

Effect of number of blades.- Sound reduction by increasing the number of blades has been found effective at subsonic tip Mach numbers, as reported in reference 3. This sound reduction results from a cancellation of certain frequencies in the propeller disk thus preventing them from radiating into space. For instance, in the spectrums of figure 4 the odd harmonics would disappear for a four-blade propeller. Thus, for given operating conditions, a larger number of blades would generally produce lower over-all sound intensities. The reductions thus obtained would tend to be much greater at subsonic tip Mach numbers, where the fundamental frequency is predominant, than at supersonic tip Mach numbers, where some of the higher-order harmonics are more intense than the fundamental. It is believed that the curve of figure 8 would then also apply approximately to multiblade propellers in the given supersonic tip-speed range.

## Comparison with Theory

It is of interest to make a comparison of the measured results with the theory of reference 1 which has been found satisfactory for the subsonic tip Mach number range as reported in references 2 and 3. The basic equation of Gutin, in a form convenient for engineering use, from reference 3 is

$$p = 169.3 \frac{M_t R m B}{SA}\left(\frac{0.76 P_H}{{M_t}^2} - T \cos \theta\right) J_{mB}(x)$$

where free-space pressure is given in dynes per square centimeter when all quantities are in English units. It is seen that the quantities $m$ and $B$ always occur as a product. Thus the equation predicts the same sound pressure for the fundamental of a four-blade propeller as for the second harmonic of a two-blade propeller. This concept, which has been confirmed experimentally in reference 5, may be applied in interpreting data presented in figures 9 and 10.

The variation of the sound pressure as a function of the product $mB$ is given in figures 9(a) and 9(b) for a station in the plane of rotation for a subsonic and a supersonic tip Mach number. At a tip Mach number of 0.75 the agreement is shown to be good for the range of harmonics recorded. It should be noted that the theory predicts decreasing intensity as the order of the harmonic increases. At a tip Mach number of 1.20 the theory predicts increasing intensities as the order of the harmonic increases. The experimental results exhibit the same trend but fall off rapidly in intensity after the third harmonic. Thus, it can be seen that, at supersonic tip speeds, the theory overestimates the intensity of the higher harmonics ($mB > 8$).

Figures 10(a), 10(b), and 10(c) show the variation of intensity as a function of tip Mach number for the second, fourth, and sixth harmonics of a two-blade propeller. Good agreement between experiment and theory is found for the range of subsonic tip Mach numbers shown. Likewise, as indicated in figure 9, there is good agreement at all tip Mach numbers for the lower-order harmonics ($mB < 8$). It can be seen from the curves presented that there is a tendency for the measured values of the higher-order harmonics ($mB > 8$) at high tip Mach numbers to be less than the theory predicts.

The data of figures 9 and 10 were recorded at $\theta = 90^{\circ}$ where the maximum sound pressures were measured. Calculations were also made at other azimuth angles to determine the order of agreement of the theory and experiment. At subsonic tip speeds, as indicated in reference 2, good agreement was obtained for the azimuth angles in the vicinity of $90^{\circ}$, but, in general, poor agreement was obtained at points near the axis of rotation. This also applies at supersonic tip speeds except that the region of good agreement is further limited to $mB < 8$. At azimuth angles other than $90^{\circ}$ the calculated values are generally lower than the measured values.

## CONCLUSIONS

Sound measurements were made at static conditions for a two-blade, 47-inch-diameter propeller at supersonic tip Mach numbers up to 1.30 and the results are compared with theory. The following conclusions may be drawn:

1. The over-all sound pressures at supersonic tip speeds are lower than an extrapolation of the subsonic data would indicate. For a constant power the over-all sound pressures increase with increasing tip Mach number in the subsonic range but are essentially independent of tip Mach number in the supersonic range of the tests.

2. Sound spectrums at supersonic tip speeds have a high harmonic content. The higher-order harmonics increase in intensity at a more rapid rate as a function of tip Mach number than the lower ones with the result that several of the harmonics may be more intense than the fundamental frequency. This phenomenon suggests that a much smaller amount of sound reduction is obtainable at supersonic tip speeds than at subsonic tip speeds by an increase in the number of blades.

3. Measured intensities at supersonic tip speeds were a maximum in or near the plane of rotation.

4. For the range of these tests at supersonic tip speeds the theory of Gutin is adequate for predicting the intensities of the lower-order harmonics but overestimates the intensities of the higher harmonics.

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## APPENDIX

## DETERMINATION OF AMPLITUDES OF NONSINUSOIDAL WAVE FORMS

Most commercial sound meters are averaging meters, calibrated to read the true root-mean-square value of a sine wave. For most applications, instruments of this type closely approximate the true root-mean-square values; however, in the case of sharply peaked waves, as encountered in the present tests, they may differ considerably from the true root-mean-square values. Since the ratio of the root-mean-square value to the average value of these peaked waves is larger than the corresponding value of 1.1 for a sine wave, the conventional meters will tend to read less than the true root-mean-square value. Over-all root-mean-square values presented in the figures of the present paper were obtained by a summation of the individual harmonics which were recorded as indicated in figure 4.

The crest factor, a parameter which is defined as the ratio of the peak value to the root-mean-square value of a wave, is descriptive of the type of wave to which it refers. It is a measure of the sharpness of the wave form and is indicative of the strength and phasing of the harmonic content of the wave. The crest factor of a sine wave is $\sqrt{2}$ and, for complex waves that are more sharply peaked, the crest factors are larger. In general, the larger crest factors are associated with waves having a large harmonic content. The data of figure 6 are plotted in a manner which makes possible the rapid estimation of the crest factors. At a tip Mach number of 0.75 the crest factors are approximately equal to 3 while at a tip Mach number of 1.20 they are approximately equal to 7.

It is beyond the scope of this paper to attempt an evaluation of the significance of such highly peaked wave forms in determining ear response; however, it should be noted that a considerable difference between root-mean-square and peak values does exist. This difference may be of importance in establishing loudness criteria for the ear.

## REFERENCES


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2. Deming, Arthur F.: Propeller Rotation Noise Due to Torque and Thrust. NACA TN 747, 1940.
3. Hicks, Chester W., and Hubbard, Harvey H.: Comparison of Sound Emission from Two-Blade, Four-Blade, and Seven-Blade Propellers. NACA TN 1354, 1947.
4. Hubbard, Harvey H., and Regier, Arthur A.: Free-Space Oscillating Pressures near the Tips of Rotating Propellers. NACA Rep 996, 1950.
5. Hubbard, Harvey H.: Sound from Dual-Rotating and Multiple Single-Rotating Propellers. NACA TN 1654, 1948.

TABLE I

THRUST AND TORQUE DATA FOR TEST PROPELLER

| $M_t$ | T (lb) | Q (lb-ft) | $P_H$ (hp) | $P_o$ (hp/sq ft) |
|---|---|---|---|---|
| $\beta_{0.75} = 15^\circ$ | | | | |
| 0.75 | 225 | 114 | 65 | 5.4 |
| .90 | 302 | 140 | 128 | 10.6 |
| 1.00 | 384 | 198 | 188 | 15.6 |
| 1.10 | 496 | 260 | 272 | 22.5 |
| 1.20 | 545 | 310 | 362 | 30 |
| 1.30 | --- | --- | --- | ---- |
| $\beta_{0.75} = 13^\circ$ | | | | |
| 0.75 | --- | 106 | 60.5 | 5 |
| .90 | --- | 130 | 121 | 10 |
| 1.00 | --- | 184 | 181 | 15 |
| 1.10 | --- | 237 | 248 | 20.5 |
| 1.20 | --- | 277 | 335 | 27 |
| 1.30 | --- | 313 | 423 | 35 |

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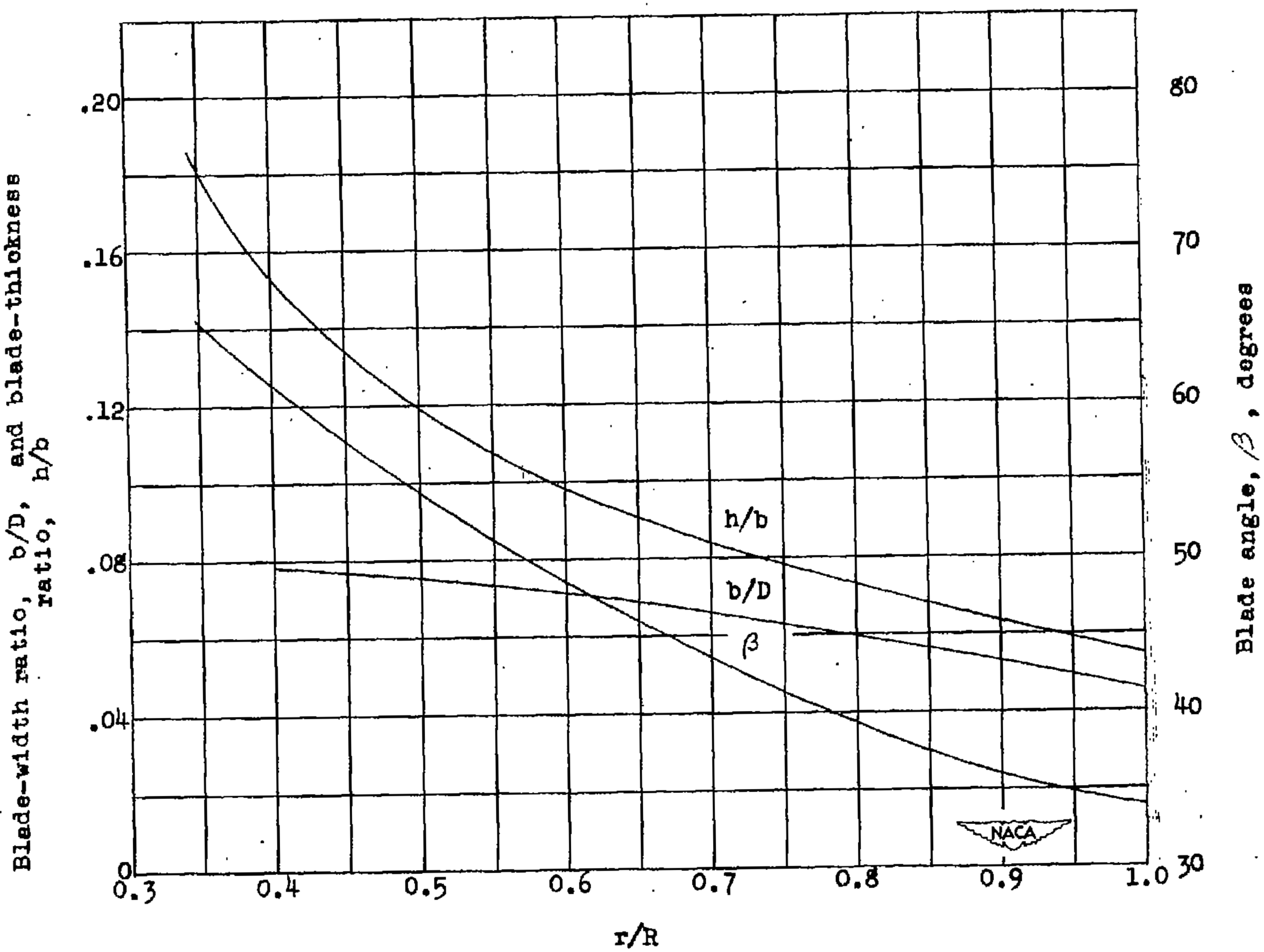



Figure 1.- Blade-form curves for test propeller.

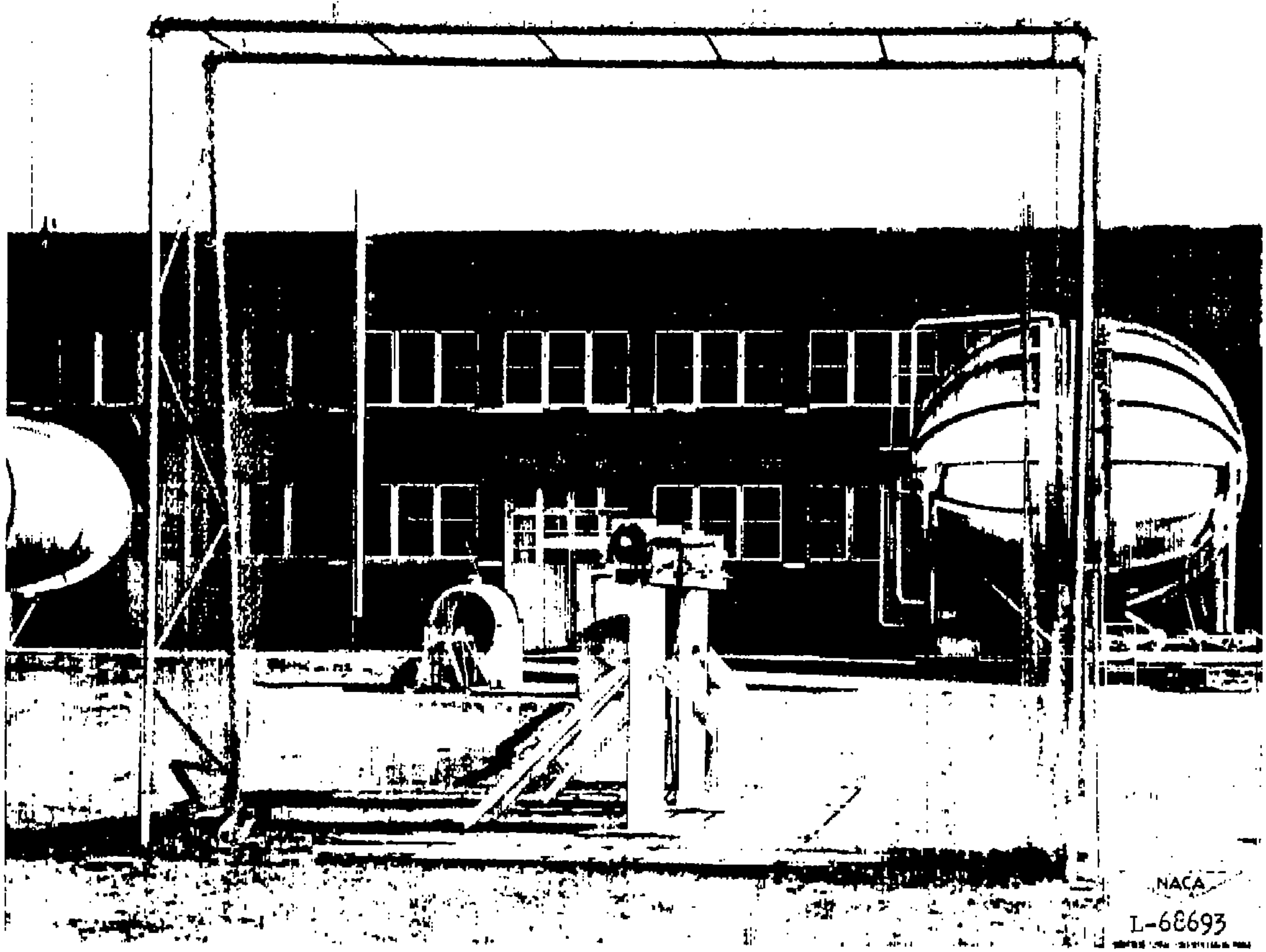



Figure 2.- Propeller test stand.

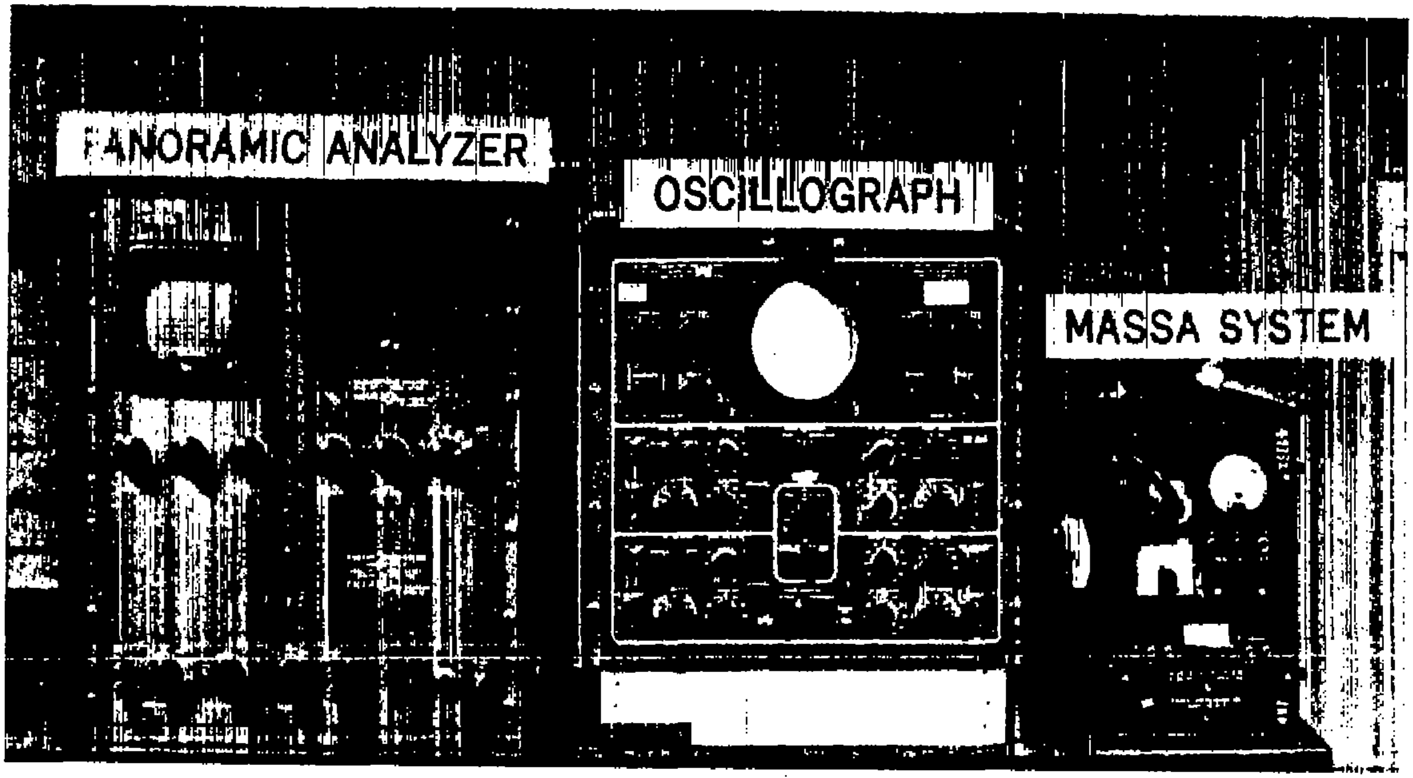
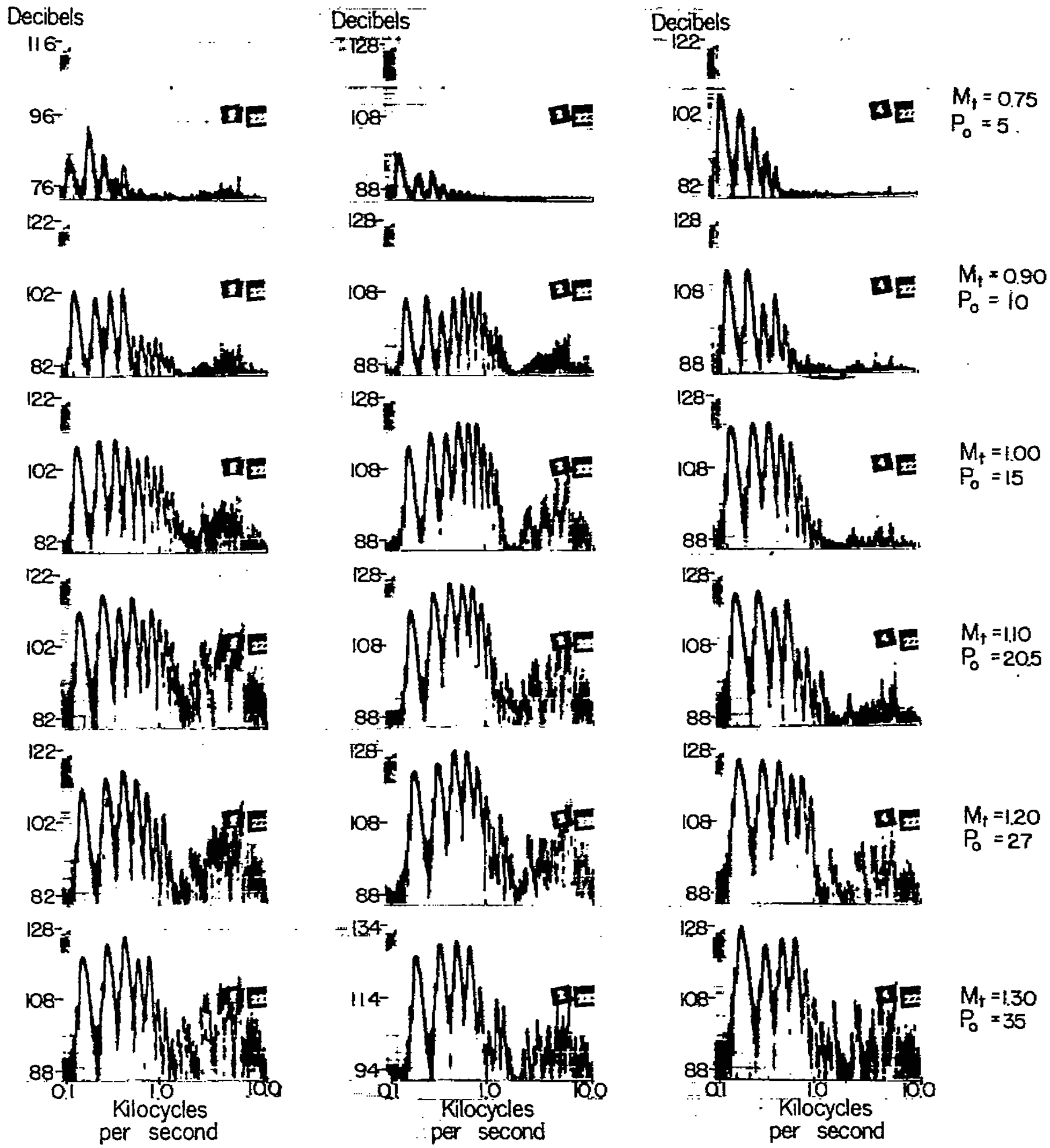
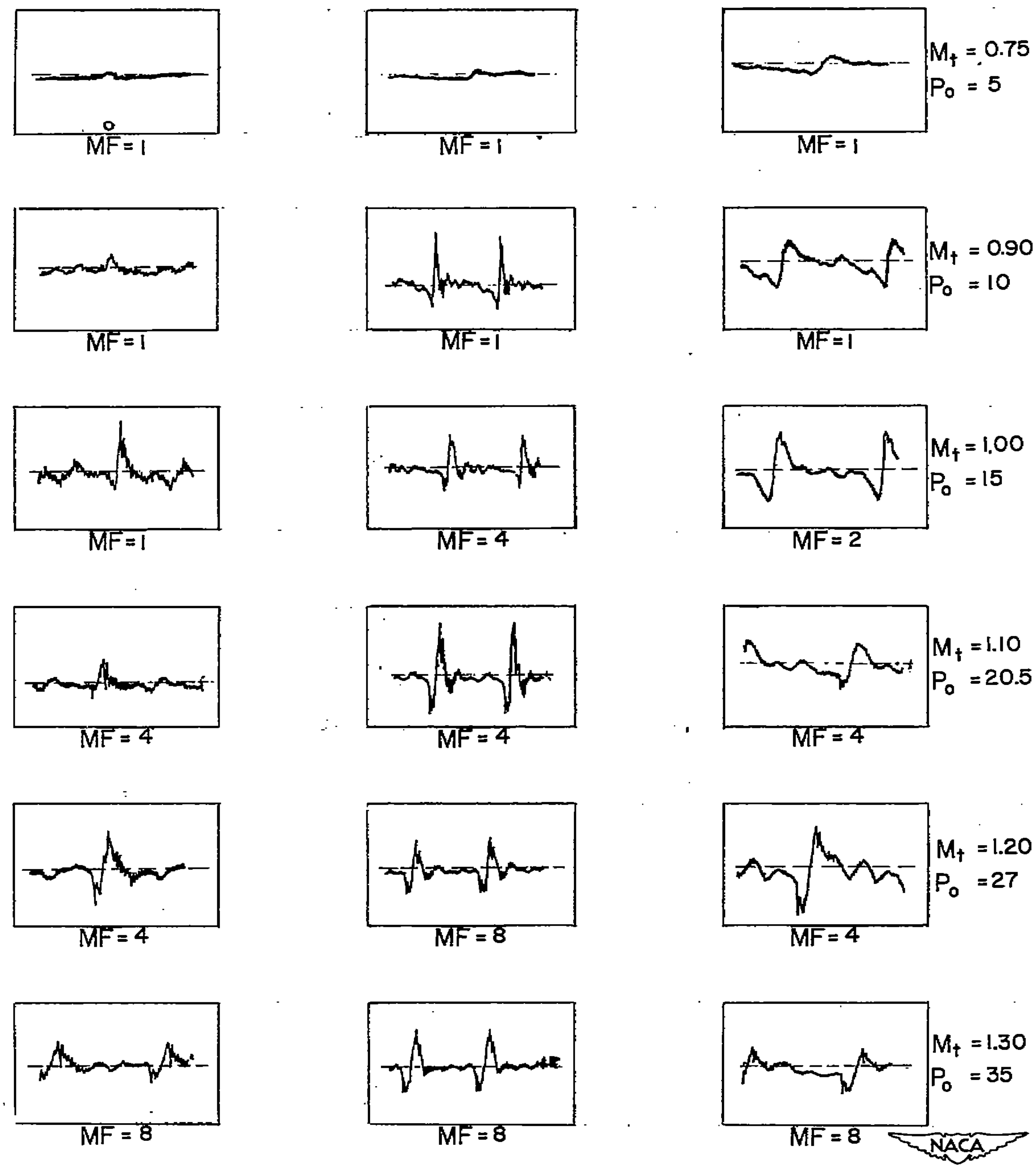



Figure 3.- Sound-pressure measuring equipment. L-68964



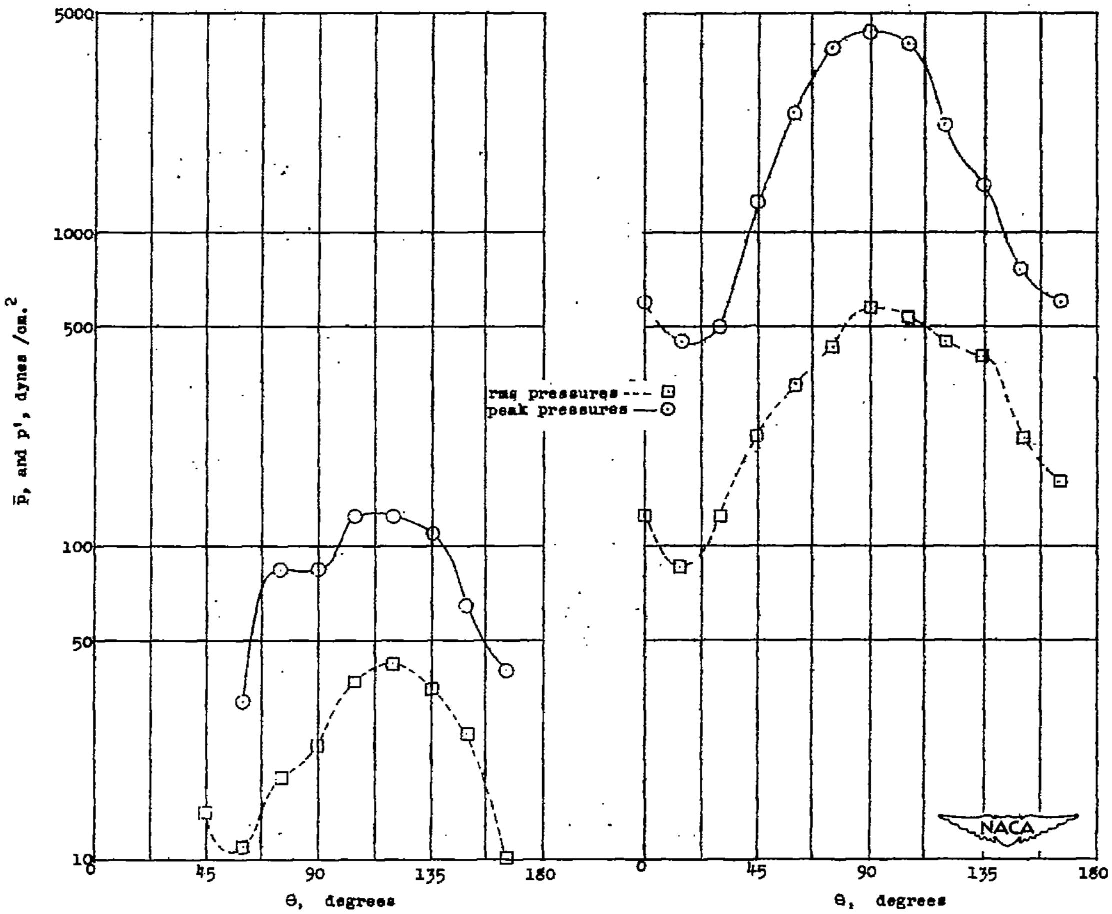

(a) $\theta = 60^\circ$. (b) $\theta = 90^\circ$. (c) $\theta = 120^\circ$.

Figure 4.- Panoramic Frequency Analyzer sound spectrums at various azimuth angles and propeller tip Mach numbers. $\beta_{0.75} = 13^\circ$; S = 30 feet; B = 2. ($P_o$ is defined as horsepower per sq ft of disk area.)




(a) $\theta = 60^\circ$. (b) $\theta = 90^\circ$. (c) $\theta = 120^\circ$.

Figure 5.- Cathode-ray oscillograph pictures of sound-pressure wave forms at various azimuth angles and propeller tip Mach numbers. $\beta_{0.75} = 13^\circ$; S = 30 feet; B = 2.




(a) $M_t = 0.75$. (b) $M_t = 1.20$.

Figure 6.- Root-mean-square and peak sound pressure in dynes per square centimeter as a function of azimuth angle for a two-blade propeller. $\beta_{0.75} = 15^{\circ}$; S = 30 feet.

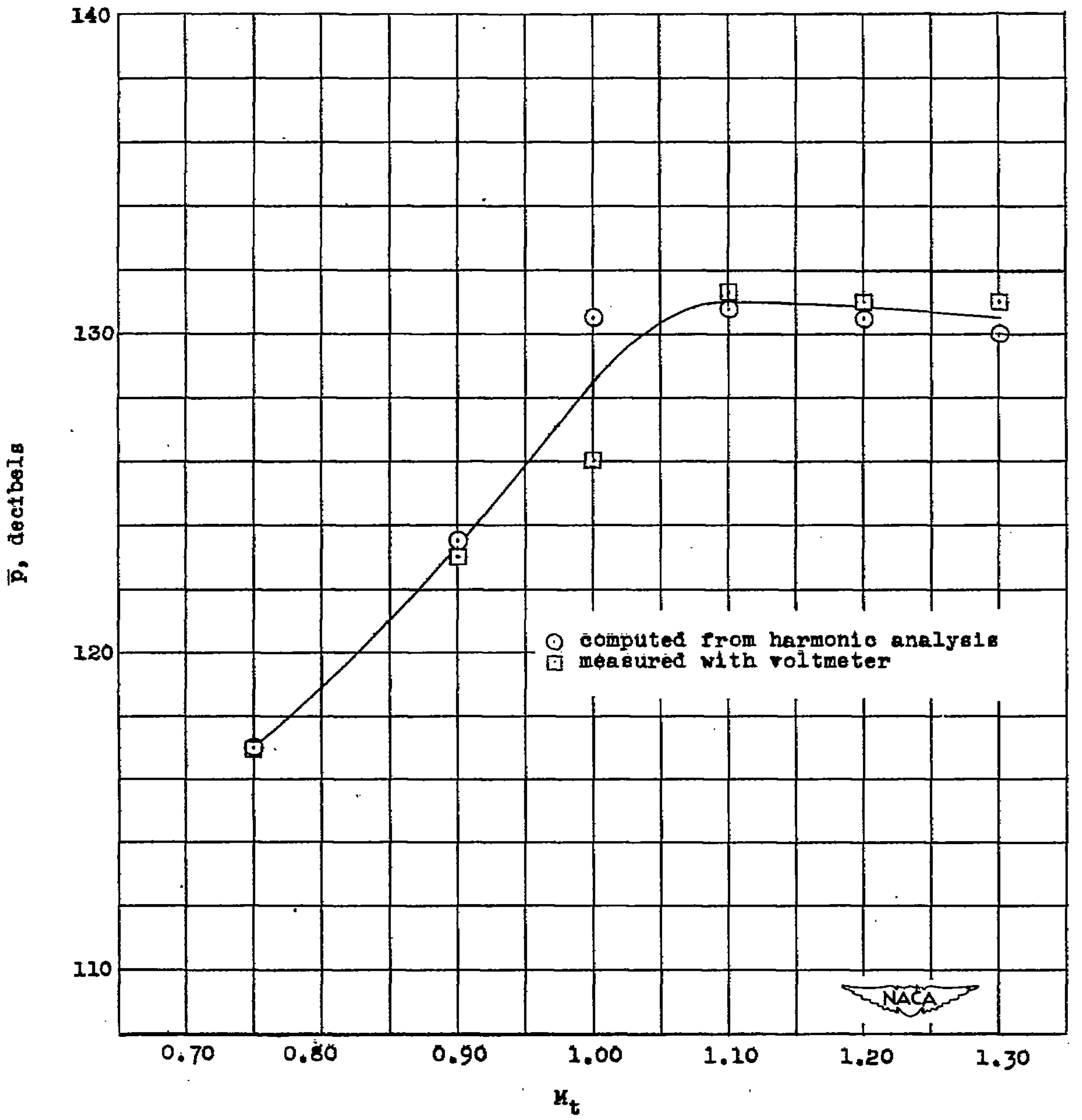



Figure 7.- Effect of tip Mach number at constant power on the over-all sound pressure in decibels. $\theta = 90^{\circ}$; $B = 2$; $P_o = 30$; distance from the center of rotation is equal to 7.5 diameters.

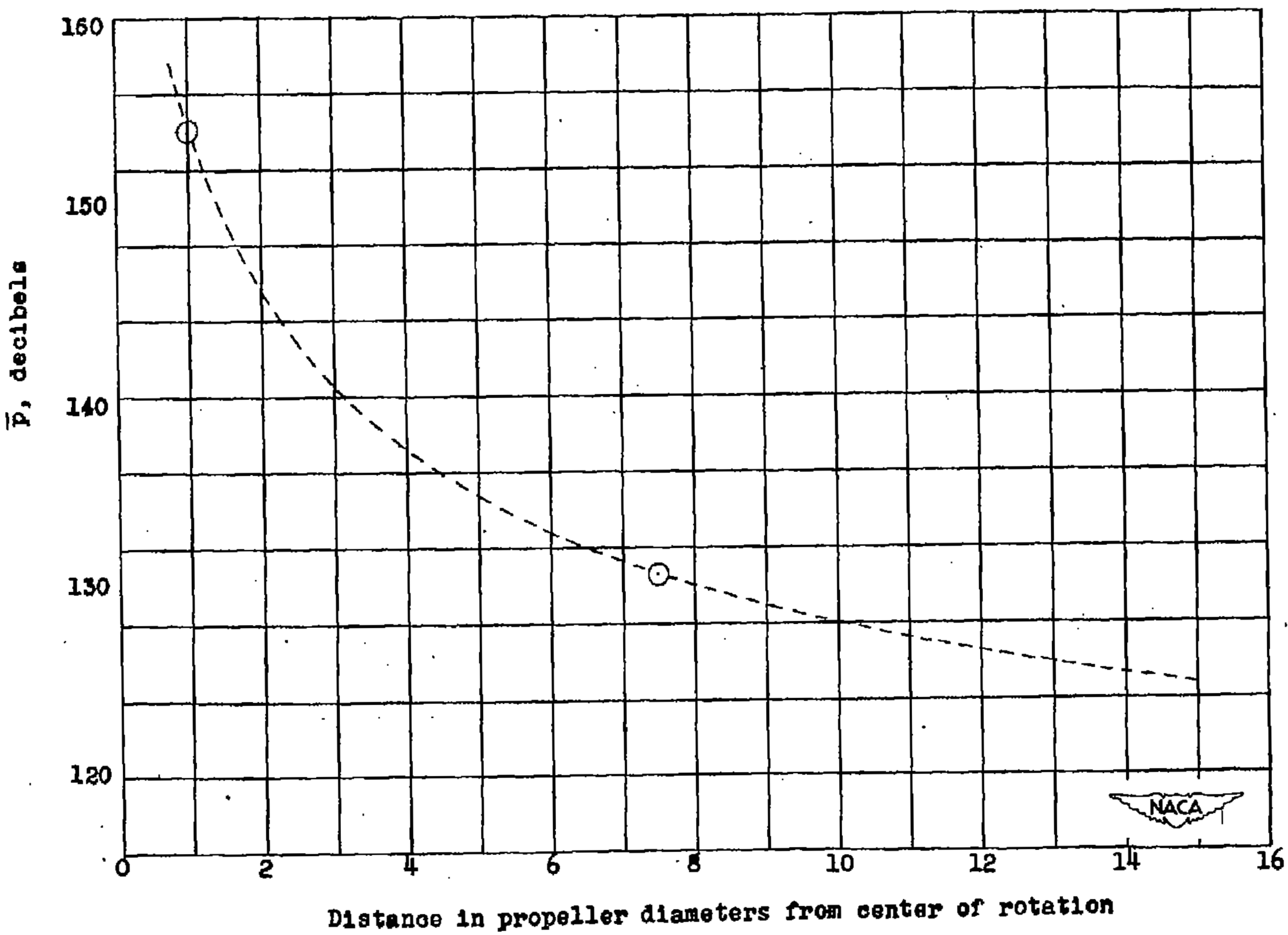
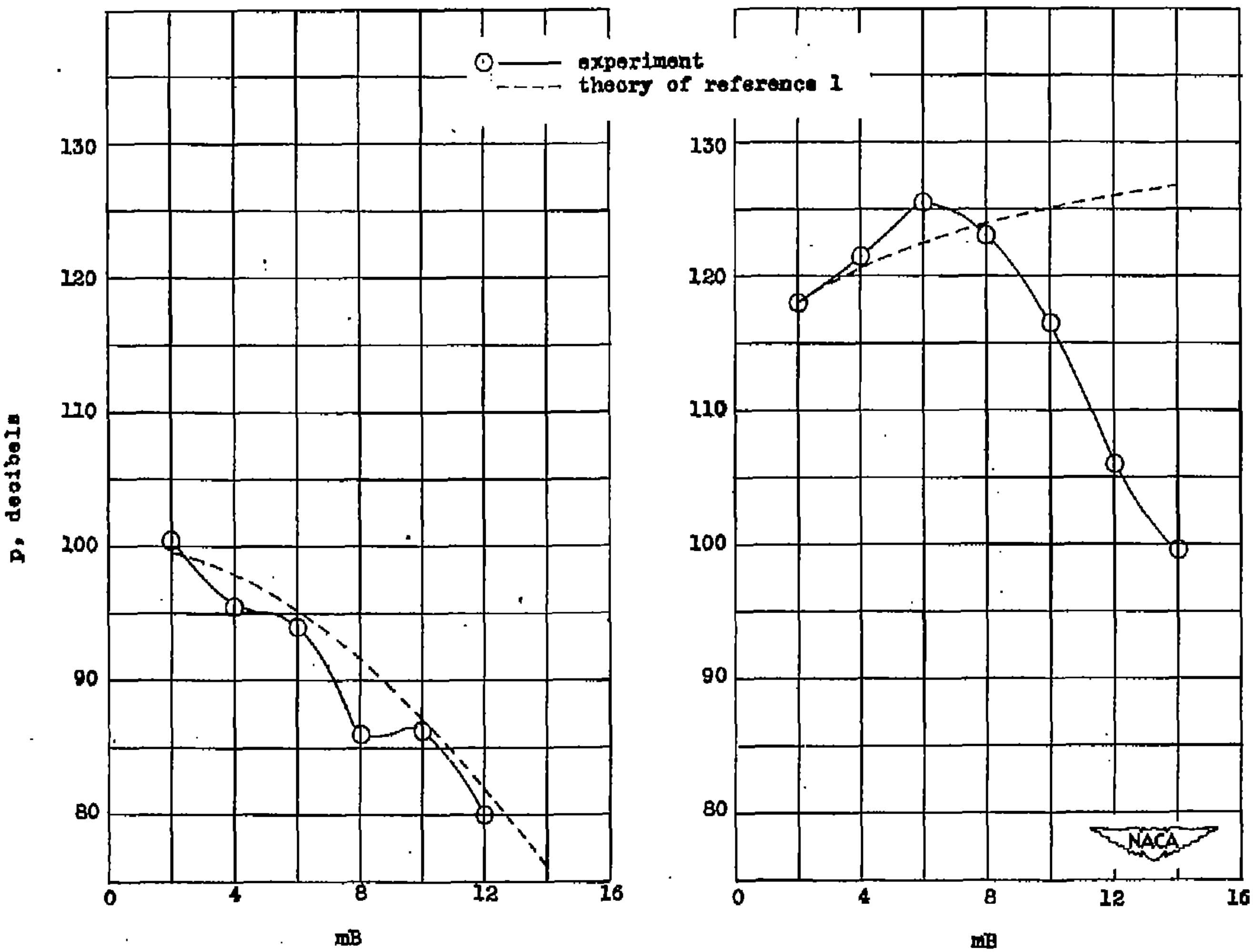


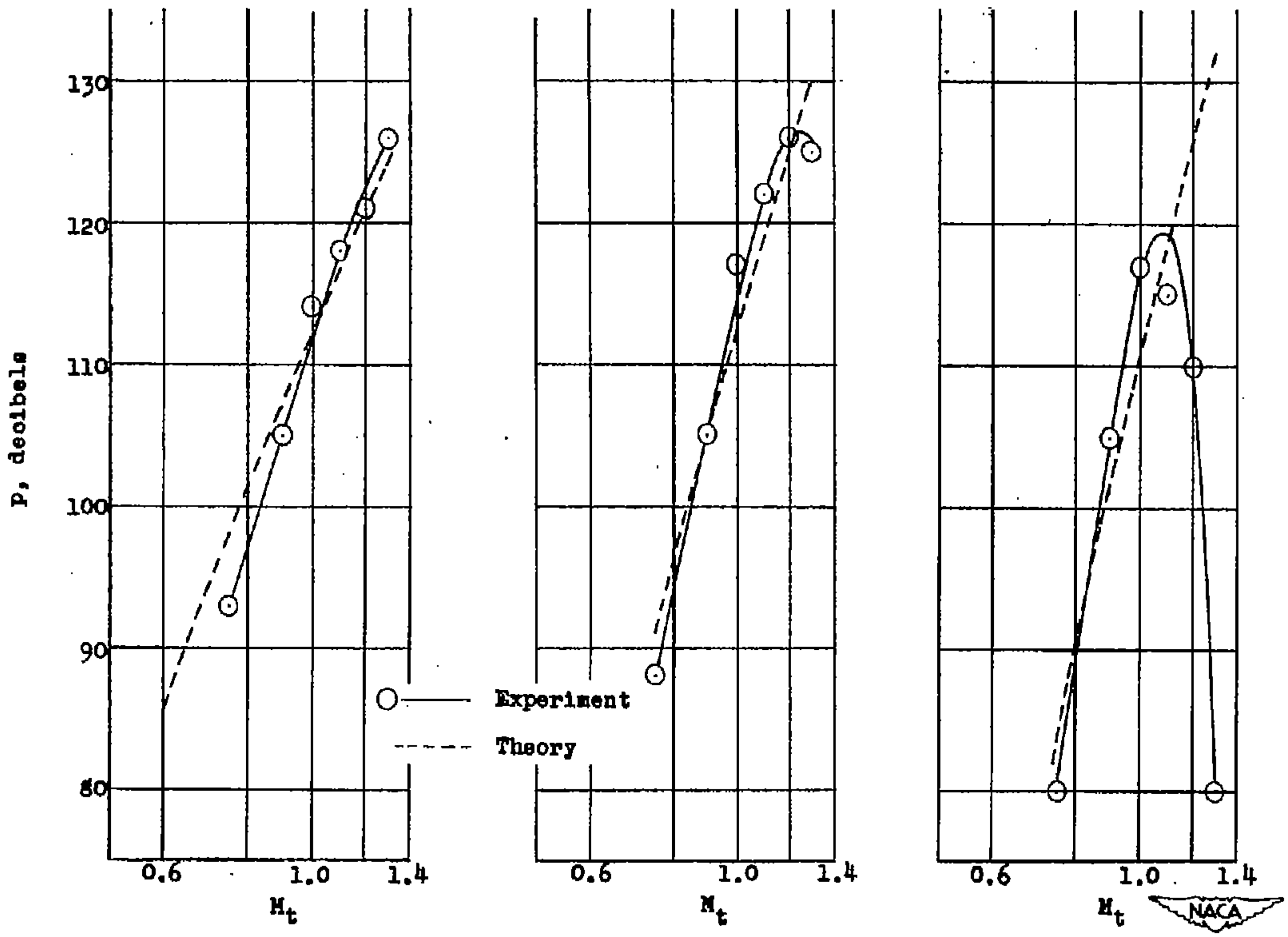

Figure 8.- Sound pressure as a function of distance for a two-blade propeller. $\beta_{0.75} = 15^{\circ}$; $\theta = 90^{\circ}$; $M_t = 1.20$; $P_o = 30$.




(a) $M_t = 0.75$.

(b) $M_t = 1.20$.

Figure 9.- Sound pressure as a function of order of the harmonic. B = 2; S = 30 feet; $\beta_{0.75} = 15^{\circ}$; $\theta = 90^{\circ}$.




(a) mB = 4. (b) mB = 8. (c) mB = 12.

Figure 10.- Sound pressure in decibels as a function of tip Mach number for three harmonics of a two-blade propeller. $\beta_{0.75} = 15^{\circ}$; $\theta = 90^{\circ}$; and S = 30 feet.

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