Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-70-TR–2002/135 December 2002

Signatures Directorate

Technical Report

An Acoustic Procedure for Measuring Blade-Frequency Forces Generated by Model Ship Propellers

by

M. Strasberg

UNITED STATES NAVY

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Reprinted from the Proceedings of the
Symposium on Aero- and Hydroacoustic Facilities...
2001 ASME International Mechanical Engineering Congress
November 11-16, 2001; New York, NY

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
1-Dec-2002

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
-

4. TITLE AND SUBTITLE
An Acoustic Procedure for Measuring Blade-Frequency Forces Generated by Model Ship Propellers

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
M. Strasberg

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)

Naval Surface Warfare Center
Carderock Division .
9500 Macarthur Boulevard
West Bethesda, MD 20817-5700

8. PERFORMING ORGANIZATION REPORT NUMBER

NSWCCD-70-TR-2002/135

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			M. Strasberg
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	8	**19b. TELEPHONE NUMBER** *(include area code)* 301-227-1389

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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Proceedings of IMECE2001
2001 ASME International Mechanical Engineering Congress and Exposition
Symposium on Aero- and Hydroacoustic Facilities...
November 11-16, 2001; New York, NY

IMECE2001/NCA-23500

AN ACOUSTIC PROCEDURE FOR MEASURING BLADE-FREQUENCY FORCES GENERATED BY MODEL SHIP PROPELLERS

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ABSTRACT

An acoustic procedure is described for measuring the blade-frequency fluctuating forces developed by a powered model propeller operating behind a model of a ship's hull or a wake generator in the anechoic test section of a wind tunnel. The sound pressure radiated by the propeller in a given direction is measured and its magnitude inserted into a simple theoretical relation to determine the alternating force developed by the propeller in that direction. Although the procedure was developed years ago, the details and limitations have not previously been described in the literature. Restrictions are discussed on the size of the propeller, location of the measurement point, measurement frequency, and the wind speed. Measurements determining the validity of the procedure are described, including comparisons of the magnitude of forces determined by this acoustic procedure with direct measurements made with a force dynamometer in a water tunnel.

1. INTRODUCTION

"Vibration is a subject of continual interest to naval architects, ship builders, marine engineers, and shipowners. Its presence can ruin the reputation of a passenger ship and seriously impair the fighting efficiency of a warship, and its avoidance should be one of the aims present in any designer's mind when planning a new ship... With the increased complexity of equipment on modern ships and its susceptibility to the effects of vibration, the problem of avoiding excessive vibration seems to be getting more rather than less difficult, despite the research devoted to the subject over the years."

The above is a quotation from one[1] of many textbooks reviewing the entire subject of ship vibration. But only one aspect of the vibration problem will be discussed in this paper, namely, the blade-frequency fluctuating forces generated by ships' propellers which excite the hull vibration and, more specifically, a description of a procedure for estimating the magnitude of the fluctuating components of these forces using measurements made in an anechoic wind tunnel of the sound pressure radiated by a powered model of the propeller rotating behind a model ship's hull or other wake generator. Although the procedure was developed in the 1960s, a complete description of the conditions limiting its validity and verification of its accuracy has previously not been published.

A propeller operating behind a ship's hull develops fluctuating components of force superimposed on the much larger steady thrust. These fluctuations occur because the rotating propeller blades move through regions of varying inflow velocity in the non-uniform wake behind the hull. This results in variations of the angle of attack of each blade relative to the inflow to the blade, causing fluctuations in the lift force developed by each blade. Since the blades rotate through essentially the same velocity variations each revolution, the fluctuations on each blade are periodic at shaft frequency. However, if all the blades are identical, with equal angular spacing between them, the fluctuating forces on the individual blades combine to produce net fluctuating thrust and side forces only at frequencies equal to the fundamental "blade frequency," i.e., the shaft rotation frequency multiplied by the number of blades, plus integral multiples (or harmonics) of this frequency. For example, the fluctuating force developed by a 5-bladed propeller rotating at 60 RPM (1 rev/sec) has a fundamental blade frequency of 5 Hz. On large ships, the fluctuations at the blade frequency and its harmonics typically may range from 5 to 50 Hertz. The fundamental magnitude can exceed 10,000 pounds on a large ship.

The magnitude of these forces depends on the propeller design and the characteristics of the wake in which the propeller operates. A conventional procedure for estimating the propeller forces for a new ship design is to measure the forces with geometrically scaled models of the propeller and in-water portion of the hull running in a towing basin or water tunnel, and then convert the model data to full scale using conventional scaling rules. It is assumed that the force generated by the propeller is not affected by hull vibration, nor is the hull response influenced by the presence of the propeller. The validity of these assumptions permits use of a scale model hull whose wetted surface is geometrically similar to that of the prototype hull without simulating the vibratory behavior of the prototype. Or, alternatively, measuring model propeller forces in a wake generated artificially by a wake screen.

The earliest measurements of fluctuating propeller forces were probably those made by F.M. Lewis, running a wooden model hull with a powered propeller in the old Experimental Model Basin at the Naval Gun Factory.[2] The forces were determined by first sensing the vibration at the stern of the model running down the towing basin with the propeller rotating at the proper speed to simulate the "self-propelled" condition, and then using a calibrated vibration generator attached to the stern to determine the magnitude of force required to excite the same vibration amplitude. Lewis recognized the need to calibrate the equipment to account for structural resonances that might cause the vibratory response of the stern to depend on the point of application of the exciting force. This was done by applying known oscillatory forces at all frequencies of interest directly to the propeller while it and the hull were in the water,. He also discussed the possibility of errors caused by interactions, or "crosstalk," between different force and response components, e.g., an longitudinal force might excite transverse vibration, and vice versa, because of non-symmetries in the hull. He also suggested using frequency-discriminating devices to reduce the response of the vibration sensor to interfering noises not related to blade-frequencies.

Electronic developments in the intervening years have resulted in force measuring instrumentation of much greater sensitivity, accuracy and sophistication. At our Center, a dynamometer was developed comprising 48 strain-gage elements mounted on the model propeller shaft, arranged to measure all six components of alternating propeller force and torque while minimizing the crosstalk among them.[3] But crosstalk and resonances in the transmission path from propeller to sensors continue to be problems.

The acoustic procedure for measuring propeller blade-frequency forces to be described in this paper was developed simultaneously with the new dynamometer designs. The acoustic procedure has turned out to be faster, more convenient, and perhaps more accurate. It can also provide a check on dynamometer measurements.

2. PRINCIPLE OF THE ACOUSTIC MEASUREMENT OF PROPELLER FORCES

The procedure makes use of the fact that fluctuating pressures occurring on the interface between a surface and a compressible fluid result in radiated sound, even in the absence of any vibration of the surface. The theoretical relation between fluctuating surface forces and the associated radiated sound has been known for some time. It is discussed in the remarkable chapter on "Waves of expansion" in Lamb's classical textbook on Hydrodynamics,[4] and was subsequently used by Gutin to calculate the blade-frequency sound radiated by an airplane propeller.[5] But Gutin's calculation is limited to what is now called "Gutin rotation sound," involving propellers operating in a uniform inflow. In a uniform inflow, the magnitude of the force acting between blades and fluid is constant relative to the blades, but these constant forces radiate sound because their location and direction vary relative to a point fixed in space as they rotate with the blades. In a *nonuniform* inflow, however, the pressure fluctuates on the blades themselves, as described above. It was subsequently recognized that the fluctuating forces developed by fans and propellers operating in non-uniform inflow can radiate more sound than the Gutin sound associated with steady forces in uniform inflow.[6, 7] Both types of blade-frequency sound are considered to be undesirable noise in the papers just cited, but we make use of the sound to estimate the fluctuating forces.

If the entire fluctuating force between a surface and fluid is exerted over a small region on the surface, the force corresponds to an acoustic dipole and the *rms* values of the fluctuating force and the resulting radiated sound pressure $\tilde{p}$ are related by

$$(1) \qquad \tilde{p} = (f\tilde{F}_r/2rc) \, ,$$

where $\tilde{F}_r$ is the component of the fluctuating force at cyclic frequency f in the direction of the measurement point, r the distance to that point, and c the speed of sound in the fluid.[8] In the situation of concern here, however, the blade-frequency fluctuating forces are distributed coherently over the entire surface of all the blades, so the calculation of the total sound pressure requires integration over the entire propeller surface, taking into account phase shifts associated with propagation of the sound from surface sources with varying distances to the measurement point. This integration generally results in a relation between sound pressure and fluctuating force which depends on the details of the force distribution. In this regard, the blade-frequency fluctuations are different from those associated with higher frequency edge forces which generally combine incoherently among the blades.[9]

If a special condition is met, however, the result simplifies to that of Eq. (1) above, even if the force is distributed. The simplifying condition is that the entire region of fluctuating force must be sufficiently small that the *differences* in the distances of all points on the surface to the measurement point is less than one-quarter wavelength of the sound at the frequency of interest. This ensures that the phases of the coherent blade-frequency pressure fluctuations generated on different parts of the blade surfaces do not change appreciably, relative to each other, as they propagate from their points of origin to the measurement point. The test conditions used in our measurements are chosen to satisfy this condition. Note that is not necessary that the radiating region be smaller than a quarter wavelength–only that the *difference* in propagation distances be smaller. This relaxes the limitation on size when the sound is sensed at a position along a line perpendicular to the surface, as is the case for alternating thrust measurements made along the propeller axis.

Fluctuating propeller forces generally have components which are harmonics of blade frequency. If the sound radiation is linear, each frequency component of the sound pressure is related to the corresponding component of fluctuating force in accordance with Eq. (1), with the appropriate frequency inserted for each component. In addition, each frequency component of the force has three vector components. These can be measured independently, in principle, in three orthogonal directions, viz., the alternating thrust along the propeller axis and the vertical and horizontal side forces in the propeller plane

Although Eq. (1) indicates that the sound pressure varies inversely with distance r, as does every well-behaved sound wave, this is so only at distances larger than a wavelength, i.e, for $(fr/c) > 1$. At closer distances, the steady, incompressible pressure fields surrounding each of the Z blades, and rotating with them, are sensed as fluctuating pressures at points fixed in space. Fortunately, their magnitude decreases rapidly with distance from the propeller.[10] Although the steady force on each rotating propeller blade corresponds to a blade-frequency acoustic dipole, the phase differences among the individual blade dipoles results in zero net combined dipole strength (corresponding to the absence of any fluctuating side or axial force when the propeller operates in a uniform inflow).[11] Only a Z-th order multipole remains, so the fluctuating pressure in the incompressible near field falls approximately as $r^{-(Z+1)}$. Accordingly, it is usually only necessary to be at least one wavelength from the propeller in order that the pressure fluctuations associated with steady forces be smaller than those associated with fluctuating forces.

To perform the measurement, a powered model propeller is operated behind an artificial wake generator or model ship hull in the anechoic test section of a quiet wind tunnel, and the radiated sound is measured with a microphone.

3. THE WIND TUNNELS

Our first measurements were made in a subsonic wind tunnel at the University of Maryland. Nowadays we use our Anechoic Flow Facility. The unique feature of both facilities making them suitable for these measurements was their relative quietness

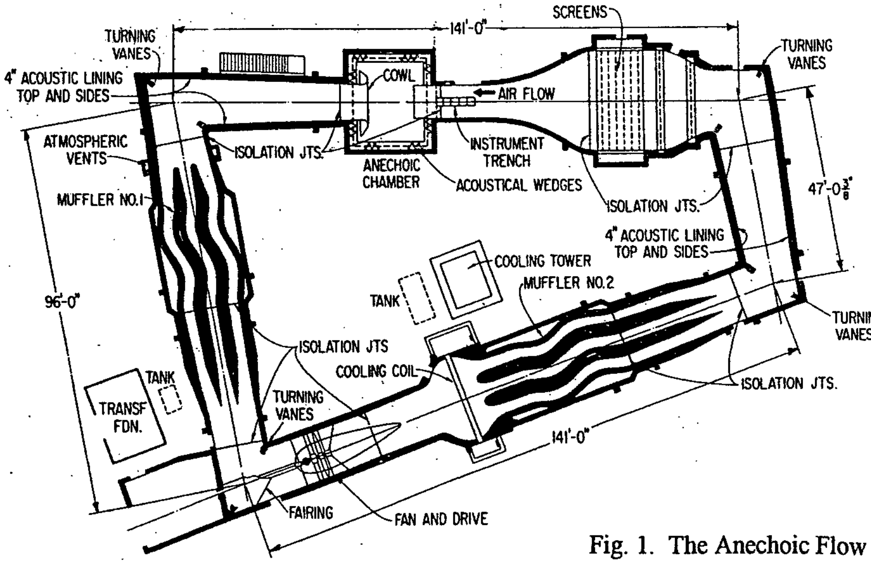

Fig. 1. The Anechoic Flow Facility; cutaway plan view.

when running at wind speeds up to 200 ft/sec. We attributed the quietness of the University of Maryland tunnel to its concrete walls, which did not vibrate and radiate sound in response to the turbulent boundary layer in the wind flowing past them. For our acoustic measurements there, conventional acoustic tiles cemented to plywood panels were attached to the interior walls of the test section to provide a partially anechoic environment.

Our Anechoic Test Facility is shown schematically in Figure 1 on the previous page. It is a large, recirculating, subsonic wind tunnel with a closed-jet test section 8-ft (2.4- m) square opening into an open-jet, nearly cubical anechoic test region about 23 ft (7 m) on a side lined with acoustic wedges. Quiet operation is achieved by acoustically isolating the impeller fan from the test section with large mufflers, concrete wall construction, and a large upstream contraction ratio. Details of the facility are described elsewhere.[12, 13]

Figure 2 shows the noise levels measured at several wind speeds at the center of the test section with a ½-inch (1.2 cm) microphone covered with a streamlined nose cone.

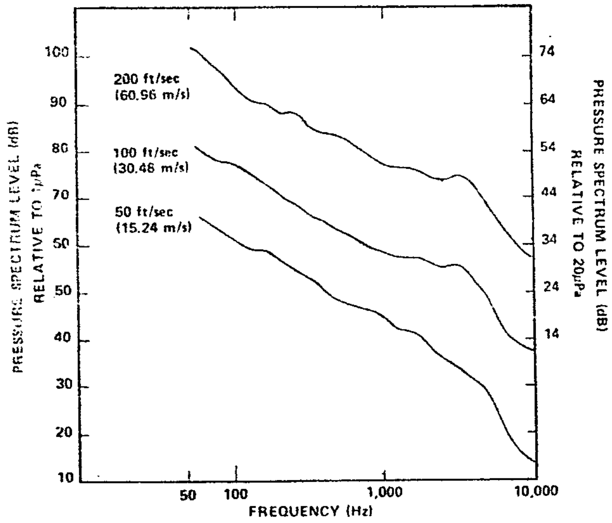

Fig. 2. Noise Levels in the Anechoic Flow facility at three wind speeds (from Ref. 13).

4. TEST PROCEDURE

The measurement procedure was first evaluated by measurements made in the University of Maryland wind tunnel with a three-bladed propeller rotating behind a screen developing a non-uniform wake. The screen had six 60-degree-wide sections of alternating fine and course grids, as shown in Fig. 3, to generate a non-uniform, 3-cycle wake with 120-degree periodicity centered on the propeller axis. The propeller was driven by an electric motor enclosed in a housing downstream of the propeller. The sound was sensed by a microphone fitted with a streamlined nose cone held upstream of the wake screen and propeller on a support capable of rotating in a horizontal plane around the propeller axis.

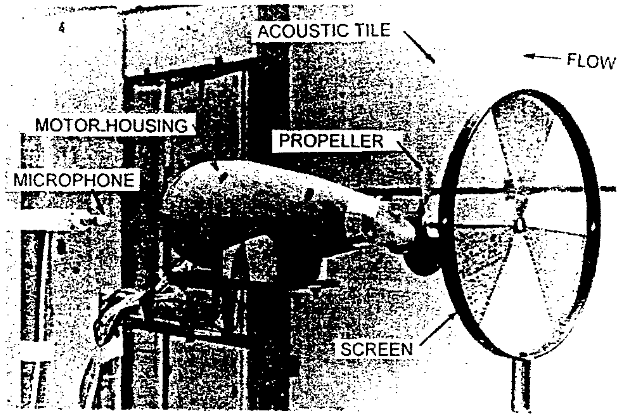

Fig. 3. A 3-bladed propeller behind a three-cycle wake screen in the University of Maryland wind tunnel.

If a Fourier series analysis is made of the non-uniform axial inflow velocity in the propeller plane as a function of angle around the propeller axis, the wake produced by a 3-cycle screen with 120-degree periodicity will consist predominantly of the third-harmonic, based on a fundamental period of 360 degrees. Because the fluctuating forces developed on the blades are all coherent with each other, the net fluctuating force developed by a three-bladed propeller operating in a third-harmonic wake will be entirely fluctuating thrust, at a frequency three times the shaft rotation frequency–with no side force at all.[14] Accordingly, the radiated sound pressure should vary with the angle θ relative to the propeller axis as

$$\tilde{p} = (f\tilde{T}/2rc)\cos|\theta| \; ; \qquad (2)$$

an equation similar to Eq. (1) but with $\tilde{F}_r$ replaced by the *rms* alternating thrust $\tilde{T}$ and the frequency f equal to the propeller blade frequency–in this case, three times the propeller rotation frequency.

The acoustic measurement conditions are chosen as a compromise among conflicting requirements. It is desirable to run at a high wind speed because the sound pressure should increase with the cube of speed (18 dB per speed double). This is so because the blade frequency is proportional to speed and the propeller forces are approximately proportional to the square of speed, at fixed propeller operating advance ratio J, so the product of frequency and force in Eq. (2) increases with the cube of speed. ($J = V_0/ND$, with V_0 the mean inflow velocity, N the propeller rotation speed and D its diameter). However, the speed must be limited to about 200 ft/sec (≈60 m/sec) to keep the propeller tip speed sufficiently subsonic to simulate the incompressible flow of water. Unfortunately, the model Reynolds number at 200 ft/sec is much smaller than full scale, leading to the possibility of viscous scale effects. But this is also the case with models in water, since a speed of 200 ft/sec in air has about the same Reynolds number, for the same model dimensions, as a test speed of 14 ft/sec (4.3 m/sec) in water. We usually run over a range of wind speeds from 50 to 200 ft/sec, at constant advance ratio, to determine whether the measured sound pressure does indeed increase with the cube of speed. Within this range, speeds corresponding to mechanical resonances of the propeller blades and drive shaft that are observed as narrow-band peaks in the radiated sound spectrum are avoided.

The choice of measurement distance also involves compromise. It is desirable to have the microphone close to the propeller to increase the directly radiated sound and reduce the interference from tunnel noise and sound reflected by the tunnel walls. However, the microphone must be at least one wavelength away, as discussed previously, to avoid response to the rotating incompressible field. We use a distance of 1 ft (0.3 m)for frequencies above 1 kHz and 2 ft (0.6 m) for lower frequencies.

The requirement that the measurement distance be at least one wavelength is one of the reasons why acoustic measurements of this kind cannot be made in laboratory water facilities. For typical speeds in towing basins and water tunnels, the model blade frequency is below 100 Hz., corresponding to a wavelength of 50 ft (15 m). Even if the facility allowed such a distance, the sound pressure would be too small to be measurable above the facility background noise. Moreover, there are no effective acoustic absorbing materials for these low frequencies in water, so that reverberation and reflections from the walls would interfere with measurement of the direct sound.

For measurements of alternating thrust, the microphone is located upstream of the propeller if a wake screen is used to generate a wake (as in Fig. 3) or downstream when behind a hull. When the microphone is downstream of the propeller, it would be desirable to locate it on the propeller axis to eliminate contributions of side-force components. But this results in excessive noise caused by vortices and turbulence in the propeller wake impinging on the microphone. Accordingly, the microphone is located outside the wake, about 15 degrees off the axis. The reduction in sound pressure associated with alternating thrust is negligible at this angle (cos 15° = 0.97). However some error may occur due to contributions from side forces if they are much larger than the alternating thrust.

Side-force measurements are more restrictive than thrust measurements. For side-force measurements, the microphone is located in the propeller plane, either above or athwartships of the propeller axis. In this location, the difference in the distances of all source points to the measurement point is equal to the propeller diameter. The requirement that this difference be less than one-quarter wavelength seriously restricts the allowable propeller diameter and other conditions for side force measurements.

Figure 4 shows the test setup in our Anechoic Flow Facility, with a 10-ft model submarine hull supported upside down, the propeller behind it, a ½-inch microphone fitted with a streamlined nose cone supported on a movable stand, and the tunnel open test volume lined with acoustic wedges. The propeller is powered by a 10-horsepower, water-cooled electric motor mounted inside the hull. The hull is supported by a strut going through the sail, and stabilized by guy wires attached to the tips of the aft control surfaces. This arrangement keeps the wake developed by the guy wires and the exposed portion of the strut outside the propeller disc.

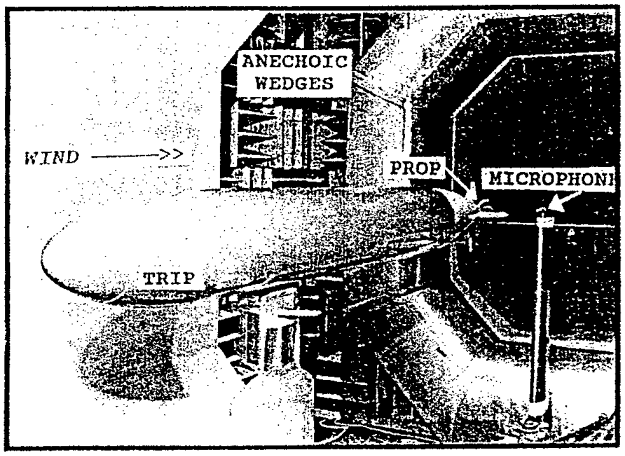

Fig. 4. A model hull in the Anechoic Flow Facility.

The alternating thrust is calculated by inserting the measured sound pressure into Eq. (2) and reversing it to solve for the thrust, viz.,

$$\tilde{T} = 2rc\tilde{p}/f\cos|\theta| \quad , \qquad (3)$$

and a similar equation for side force but with θ the angle relative to the propeller plane.

The result is conventionally expressed as a dimensionless fluctuating thrust coefficient, defined similarly to the steady thrust coefficient, viz.

$$\tilde{k}_T = \tilde{T}/\rho N^2 D^4 \ , \tag{4}$$

except that here $\tilde{T}$ is the *rms* alternating thrust. It is often convenient to express the alternating thrust as a fraction of the steady thrust T_0 , viz., as the ratio $(\tilde{T}/T_0)$. Alternating side-force coefficients can be defined in the same way.

In an attempt to reduce side-force contributions to thrust measurements, we have customarily calculated the alternating thrust as the mean of the two sound pressures measured at ±15°, to take advantage of the fact that the sound pressures associated with side forces are of opposite polarity on diagonally opposite sides of the propeller axis. Although such averaging may reduce the contributions of side forces if they are nearly in phase with the thrust contributions, it has no affect at all if they are in quadrature. (A complete elimination of the contributions of side forces to thrust measurements can be achieved by simultaneously sensing the sound pressures on both sides of the propeller axis and summing the two instantaneous pressures to obtain their instantaneous linear average.)

5. RESULTS

The first test of the procedure was to verify the angular cos θ dependence displayed in Eq. (2) with measurements of the 3-bladed propeller and 3-cycle wake screen previously shown in Figure 3. The measured sound pressure as a function of angle in a horizontal plane including the propeller axis is shown as data points in Fig. 5. A cosine curve is drawn on the plot for comparison. Most of the data follow the cosine reasonably well. However, the sound pressure at ± 90° should be zero ($-\infty$ on a dB scale) because of the supposed absence of side forces. The level actually observed, ≈20 dB below the level at 0°, may be due to several affects: the wake screen may have generated some even wake harmonics resulting in some propeller side force and measurable sound pressure at ± 90°; the measurement point may not have been far enough from the propeller to make the rotating incompressible pressure fields and Gutin sound associated with the large steady propeller forces negligible, or the acoustic tile on the walls of the Maryland U. tunnel may not have reduced the reverberant sound more than 20 dB below the direct sound.

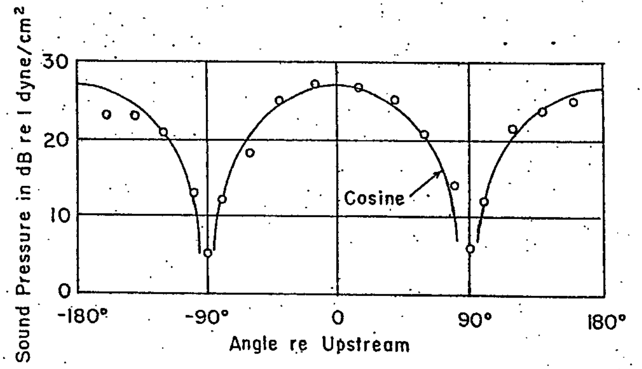

Fig. 5. Variation with angle of the sound pressure radiated by the 3-bladed propeller rotating behind the 3-cycle wake screen.

A comparison of the values of alternating thrust measured by this acoustic procedure with measurements made with a similar 3-bladed propeller and wake screen using our BASS alternating-force dynamometer[15] in our 24-inch water tunnel is shown in Table 1 below for several advance ratios V_0/ND . For the comparison, it is necessary to normalize the alternating thrust ratios to take account of the observation that the third harmonic velocities generated by the air and water wake screens were not the same fraction of the mean inflow velocity. Assuming that the alternating thrust is proportional to the magnitude of the wake harmonic, variations in the magnitude of wake harmonics are accounted for by expressing the alternating thrust $\tilde{T}$ as a normalized ratio $(\tilde{T}/T_0)(V_0/V_Z)$, where V_Z is the magnitude of the Z-th wake harmonic associated with alternating thrust.

Table 1
Alternating Thrust with 3-Cycle Wake Screen

Advance Ratio	Normalized Alternating Thrust, $(\tilde{T}/T_0)(V_0/V_3)$		
$J =$ (V_0/ND)	Dynamometer, in Water $V_3/V_0 = 0.21$	Acoustic, in Air $V_3/V_0 = 0.42$	Acoustic, in Air $V_3/V_0 = 0.28$
0.50	1.4	1.1	1.3
0.61	1.6	1.4	1.4
0.83	2.1	2.0	1.9
1.00	2.6	2.3	2.3
1.16	3.1	3.2	2.9

Notation:

T_0 is the steady thrust at $J = 0.83$ and $\tilde{T}_3$ is the alternating thrust at the indicated J;

V_0 is the mean inflow velocity and V_3 is the magnitude of the wake third harmonic at 0.7 of the propeller tip radius.

As shown in the Table, the normalized acoustic wind-tunnel values agree with the dynamometer water tunnel values to within 20 percent (1½ dB), albeit they are consistently smaller. We consider this to be reasonably good agreement for this type of measurement. To be completely candid, however, agreement between dynamometer and acoustic measurements is poorer for measurements made with propellers operating behind model hulls instead of wake screens. The magnitude of the forces measured with dynamometers in water have tended to be 30 to 60 percent larger than those deduced from acoustic measurements in air. This disagreement is not likely to be caused by viscous affects, because the water and air Reynolds numbers do not differ significantly. [The Reynolds number ratio is about 14:1 for the same size model at the same speed in water and air, respectively, so a 20-ft. (6 m) hull in water at a typical towing basin speed of 7 ft/sec (2.1 m/sec) corresponds to about the same Reynolds number as a 10 ft hull in air at 200 ft/sec (61 m/sec).] The cause of the disagreement remains a mystery. We even investigated the possibility that it resulted from reporting air data as *rms* values and water data as single amplitude–but this was not the case. Nevertheless, the air and water data usually gave the same *relative* values for different propeller designs, so they were useful for design comparisons, even though the absolute values had some uncertainty.

This acoustic procedure has also been used to measure propeller forces with models of surface ships. A double-hull model is used, with two identical models of the in-water portions of the hull, as shown in Fig. 6, so that the air flow is entirely longitudinal at the imaginary water line and thus simulates a flat water surface at zero Froude number. Only one propeller is used with the double hull.

For side-force measurements, the microphone is located in the propeller plane. Because of the requirement that the difference in the distances of the closest and farthest points on the propeller to the microphone be less than a quarter of the acoustic wavelength, the propeller diameter must be small and the blade frequency low for side force measurements. For example, if the propeller is six inches in diameter, the measurements must be made at frequencies below 300 Hz. This severely limits the wind speed if the prototype advance ratio is to be maintained.

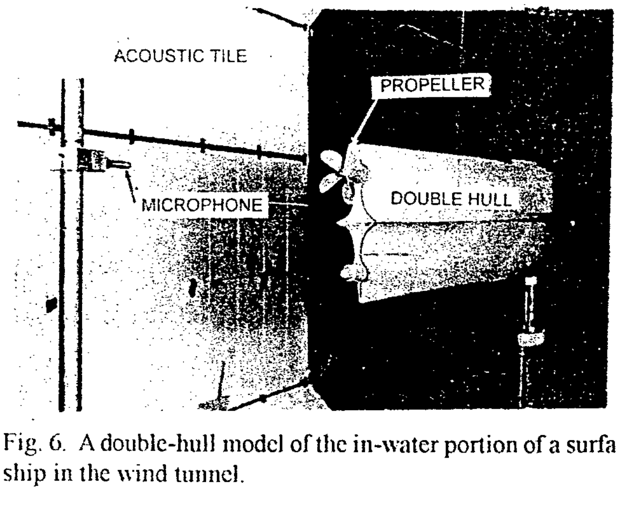

Fig. 6. A double-hull model of the in-water portion of a surface ship in the wind tunnel.

Alternating thrust measurements do not have such severe limitations, because the microphone is located behind the propeller in a direction nearly perpendicular to the propeller plane. Accordingly, speeds corresponding to a blade frequency of 2000 Hz are acceptable for alternating thrust measurements with the same six-inch propeller.

When the propeller is operating in the wake of a hull, the variation of sound level with direction is much more complicated than the simple cosine pattern shown previously in Figure 3. Figure 7 shows the variation of sound level with angle measured with the double-hull model in two perpendicular planes. The solid curve is in the propeller plane, and the dashed curve in a horizontal plane that includes the propeller axis. The patterns are complicated because the sound pressure in any given direction is a vector superposition of axial, vertical, and horizontal force components which may not be in temporal phase with each other and whose magnitudes relative to each other vary with direction.

The lack of symmetry results from the fact that the alternating side-force contributions to the radiated sound, if in phase with the alternating thrust on one side of the hull, will be in opposite phase on the diagonally opposite side. Nevertheless, the sound pressure in any specific direction is directlyproportional to the resultant propeller force in that direction, in accordance with Eq. (1).

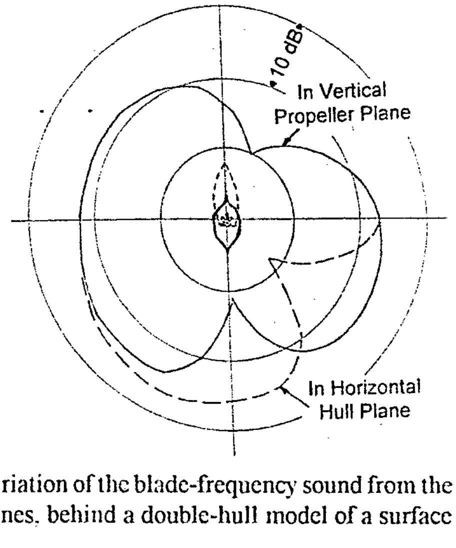

Fig. 7. Variation of the blade-frequency sound from the propeller, in two planes, behind a double-hull model of a surface ship.

All the data described above are for the fundamental blade frequency only. When a propeller is operating behind a hull, the propeller usually develops alternating forces at harmonics of the fundamental blade frequency. A typical spectrum with many harmonics is shown in Figure 8. The force associated with each harmonic is given by Eq. (3) with the appropriate harmonic frequency in the equation, provided the previously discussed limit on frequency is satisfied.

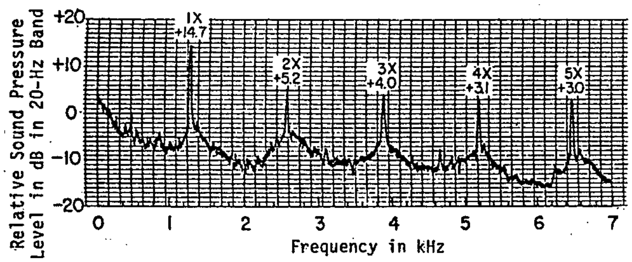

Fig. 8. Typical spectrum of the sound radiated by a propeller rotating behind a hull, showing many harmonics.

6. CONCLUSION AND ACKNOWLEDGMENTS

For measurements of alternating propeller forces of model propellers operating behind wake screens or model ship hulls, this acoustic procedure provides a simple and convenient alternative to measurements in water.

In conclusion, it is appropriate to list those people at the David Taylor Model Basin who contributed to the early development of this procedure. K.E. Schoenherr, then head of the Hydromechanics Laboratory, suggested to me that we investigate some form of acoustic test, and then suggested applying for a patent which issued some years later.[16] P. Leehey, then a Naval officer, provided encouragement and arranged financial support for the experimental work and the construction of the Anechoic Flow Facility. C. Devin, Jr., and J.F. O'Donnell performed the early measurements, and P.J. Granum and T. Mathews continued their work.

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