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A Review of Propeller Noise Prediction Methodology 1919-1994

F. Bruce Metzger
Metzger Technology Services, Simsbury, Connecticut

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National Aeronautics and
Space Administration
Langley Research Center
Hampton, Virginia 23681-0001

1.0 INTRODUCTION

Since 1919 attempts have been made to predict the noise of propellers. Early work was hampered by a lack of computers for processing the complex calculations of theoretical formulations of complete prediction methods. Also, these early efforts were hampered by limitations in experimental equipment for measuring noise. Some progress was made in the time period up the early 1950's but the advent of computers at that time led to the development of methods which addressed a significant portion of the propeller noise generation process. Between the 1950's and early 1970's some progress was made in refining the prediction methods. Empirical methods were also developed in this time period that provided an indication of the effects on noise of many operating and geometric parameters without having to use computer calculations.

Since the early 1970's there has been a renewal of interest in propeller noise prediction. this has been driven first by interest in the control of noise of General Aviation and commuter airplane propellers and second (in 1980's) by interest in the control of the noise of the Propfan advanced high cruise speed turboprop. Both empirical and theoretical methods were developed in this time period. The empirical methods were generally refinements of earlier methods but some also used regression analysis of propeller aircraft data bases to define improvements. Most of the theoretical methods have been based on the acoustic analogy proposed by Lighthill in 1952[1.1]. However some attempts have been made to use numerical technologies based on the Euler equation to predict noise at high cruise speed for the Propfan.

In this report, the emphasis is on review of methods that exist in a form that they can be used for propeller noise prediction. However, many theoretical developments have been reported that describe improved equations for predicting noise but in many cases the computer program is not available for use of the method. Some of these theoretical developments are discussed as the findings reported may be of interest to researchers who are attempting to make further improvements in existing propeller noise prediction tools.

The empirical methods discussed in this report exist in graphical, equation or computer program form. The early methods exist primarily as graphs or equations. The most recent methods have been converted to computer or hand calculator programs to speed up the prediction process, particularly for preliminary design studies where the effect of many design variables on noise produced is being studied.

The organization of the remaining sections of this report are as follows:

2.0 PROPELLER GEOMETRY, NOISE SOURCES, AND THE CHARACTER OF SOUND PRODUCED

SECTION 1.0 References

1.1 Lighthill, M. J. "On Sound Generated Aerodynamically- I. General Theory." Proceedings of the Royal Society (London) A 211, pp 564-587, 1952.

2.0 PROPELLER GEOMETRY, NOISE SOURCES, AND THE CHARACTER OF THE NOISE PRODUCED

As a framework for discussion later in this report, some general information is provided in this section which it is hoped will give physical meaning to the concepts being modeled in propeller noise prediction methods.

First the differences in propeller configurations should be considered. Figure 2.1 shows examples of the various propeller configurations which exist. The most common configuration is shown in Figure 2.1a. This two blade configuration is most often used on small piston engine powered General Aviation airplanes. The four-blade configuration of Figure 2.1b is typical of the propeller used on larger turbine powered commuter airplanes. Figures 2.1c and 2.1d show two versions of the Propfan, an experimental concept designed as a fuel efficient way to power large, high cruise speed transport aircraft. The single- rotation configuration of Figure 2.1c was the initial focus of the research on this concept. The counter-rotation configuration of Figure 2.1d was investigated because it offered even higher propulsive efficiency than the single rotation Propfan of Figure 2.1c. It should be noted that an intermediate step between the single and counter-rotation Propfan has also been evaluated. This configuration had a set of stationary vanes downstream of a single upstream rotating stage. These stationary vanes were designed to improve propulsive efficiency by recovering swirl in a manner similar to the downstream blade row of the counter rotation Propfan. Figure 2.1e is a single example of the many unusual propeller configurations that have been considered in an effort to reduce propeller noise. Figure 2.1e is an example of the use of unequal circumferential and axial blade spacing for noise reduction. Proplets at the propeller blade tips (very much like winglets on a wing tip) have also been considered. For the Prop-Fans of Figures 2.1, swept blades were used to reduce noise and enhance performance. Also, in the counter- rotation Propfan, the front and rear rotors sometimes incorporated different blade count and different diameter to reduce noise. From this it can be seen that propeller noise prediction methods must vary in their complexity depending on the degree of complexity found in various propeller designs.

Next the character of sound produced by propellers should be considered. The typical propeller is characterized as having a tone dominated character (see the upper curve of Figure 2.2). The noise spectrum of a propeller or Propfan in flight is dominated by harmonics of blade passage frequency (an integer times number of blades times RPM divided by 60). At low flight speeds a lightly loaded propeller operating at low tip speed will produce lower tone noise and the broadband noise floor between the propeller tones (see the upper curve of Figure 2.2) will be a more significant part of the noise produced. When a propeller is operated statically (no forward motion) the noise spectrum is still tone-like but listeners note that it has a more random quality. The spectrum has a character like that at the bottom of Figure 2.2. There are peaks at harmonic frequencies but there is broadening of these peaks indicating that they are not the pure tones seen in propellers operating at high speed taxi or in forward flight.

In propeller noise prediction, the operating conditions, the propagation path of the sound, and the environment of the measuring microphone have a significant effect on the measured noise level. The four scenarios of Figure 2.3 are typical in predicting propeller noise. The first depicted in Figure 2.3a is a far field measurement of a takeoff, climb or low level flyover. For this scenario the prediction procedure must account for the presence of the ground around a microphone mounted flush with the ground surface or, if the microphone is at a height of 4 ft from the ground (as in certification), the procedure must address the effect of interference between the sound propagating directly from the airplane and that which is reflected from the ground to the microphone. Any averaging or frequency weighting circuits used in the processing of the measured sound must also be included if the predictions are to agree with measurements.

Figure 2.3b shows an unusual scenario where the propeller is operated statically (as in a runup test), is taxing to or from the terminal, is accelerating to liftoff, or is in very low altitude flight. Here there is an excess absorption above that which exists due to the normal atmosphere. It is believed to be due to propagation of sound near the ground. The third scenario (see Figure 2.3c), where noise is measured on the ground as an airplane flies over at a fairly high altitude, has basic elements like those of the takeoff/climb/level flyover scenario of Figure 2.3a. However, an accurate prediction in the scenario of 2.3c must include detailed effects of propagation through an inhomogeneous atmosphere. Measurements also indicate that levels include instabilities which are probably due to scattering of sound by atmospheric turbulence.

The fourth scenario, Figure 2.3d, is propagation between the propeller and fuselage surface of an airplane. In this case the fuselage is close to the propeller so a prediction procedure must include the complexity of the airplane flow field . Also, in order to predict the levels of noise measured on the fuselage surface, the effects of scattering and shielding of the fuselage must be included. At high cruise speeds the effects of refraction of sound propagating fore and aft from the propeller through the fuselage boundary layer must be predicted. Accurate predictions in this scenario are needed for evaluation of the effects of the fuselage noise transmission to the interior of the airplane.

Noise prediction methods must accurately address the noise sources that produce the tones, narrow band random, and broadband noise making up the propeller noise spectrum.
In single-rotation propellers operating in level flight, the dominant tone noise sources are the result of the propeller blades (1) physically displacing air as they pass through (thickness noise) and (2) producing the thrust which drives the airplane through the

air (loading noise). At moderate blade velocities relative to the flight velocities the thickness and loading sources are linear and act on the blade surfaces. However, at transonic blade relative velocities, non-linear effects occur that are modeled as quadrupole sources in the volume surrounding the blades. This has the effect of enhancing the thickness and loading sources particularly for unswept, highly loaded Propfans/propellers.

Periodic changes in loading or velocity of the propeller blades is also a source of tone noise. This is most commonly found as a result of non-uniform inflow to the propeller during climb conditions. Figure 2.4 shows schematically how the blade loading and relative velocity change as the propeller rotates through the non-uniform inflow during aircraft climb. As the upper left sketch of Figure 2.4 shows, the flow enters the propeller plane of rotation at an angle during climb conditions. This is true for single-engine General Aviation airplanes as well as multi-engine airplanes with wing-mounted engines. For the wing mounted engines an additional source of non-uniform flow is the wing circulation. This non-uniformity exists even when the airplane is in level flight.

In the front view of the propeller of Figure 2.4,(the sketch at the upper right) four blade locations are identified. Location A is halfway between the vertical blade locations for the up-going blade. The two B locations are at the top and bottom of rotation. Location C is halfway between the vertical blade location for the down-going blade.

The table of Figure 2.4 shows the relative velocity, angle of attack and loading for the four blade locations. Vector diagrams of the velocities occurring during blade rotation are included. At location A the lowest relative velocity, lowest angle of attack and lowest blade loading is experienced. Therefore the lowest noise is produced. Furthermore, since the noise produced by a propeller blade is in the direction of blade motion, this lower noise occurs above the airplane and the noise below the airplane due to the blade at this location is very low. At the B locations the relative velocity, angle of attack and loading are fairly neutral. At location C the downgoing blade experiences the highest relative velocity, highest angle of attack and highest loading so the noise below the airplane is high due to these effects.

It should be noted in reviewing the vector diagrams in the table of Figure 2.4, that the inflow velocity, rotational velocity, and blade angle relative to the rotational velocity vector are constant. Only the inflow vector angle is causing the change in the relative velocity vector and angle or attack.

Tones due to unsteady velocity or loading experienced by a propeller blade can also be caused by struts upstream or downstream of a rotating blade. This is a significant source of noise in counter-rotation Propfans/propellers, particularly at takeoff conditions. Here the wakes from the front rotor are convected downstream and interact with the downstream rotor to produce noise. The potential field of the downstream rotor, caused by unsteady flow from the upstream rotor, is also felt by the upstream rotor and produces additional tone noise.

Broadband noise, which is found between the tones of the noise spectrum, is caused by (1) interaction of the propeller blade leading edge with inflow turbulence, (2) interaction of the propeller blade trailing edge with the turbulent boundary layer developed by the blade, or (3) interaction of the trailing edge of the blade tips with turbulence in the core of the tip vortex. For typical full-scale propellers, broadband noise is not a significant contributor relative to the tone noise components.

Under static or nearly static conditions, narrow band random noise can occur. This is due to the nearly periodic loading of the blades caused by ingestion of naturally occurring atmospheric turbulence or a vortex originating on the ground or on the fuselage ahead of the propeller.

3.0 EARLY PROPELLER TONE NOISE PREDICTION METHODS

The earliest attempt to develop a noise prediction method appears to be that of Lynam and Webb [3.1], which was published in 1919. Their work was inspired by "the great importance of silencing aircraft for successful operation over enemy territory." Their work followed the suggestion of Lancester in unpublished reports that propeller noise "is due to the movement of pressure centers of constant or nearly constant magnitude in a circular orbit." In their derivation they model the propeller as a ring of sources and sinks very much like later method developers. They also simplify the analysis by positioning the rings of sources and sinks at 3/4 radius as in the effective radius approach adopted in later analyses. At the time when this work was done there was no measurement equipment so the work was in the form of hypothetical assumptions. The authors hoped to get experimental confirmation of their theory shortly after the report was published.

Bryan in 1920 published further theoretical work on propeller noise [3.2]. Apparently this work was prompted by discussions with Lynam and Webb. They had apparently proceeded with their plans, noted above, to conduct experiments on propellers with different numbers of blades. Bryan notes that tests were conducted with 2, 3, and 4-blade propellers "driven electrically on a spinning tower at known speeds." It was found that the fundamental tones near the plane of rotation were proportional to the number of blades and that the propellers operating at sonic tip speed produced a "crackling effect producing a very painful psychological sensation." According to Morfey [3.3], in his excellent review of the progress in rotating blade noise theory up to 1973, the work of Bryan was an interesting though unsuccessful example of the retarded time approach used in modern propeller noise theories. Also Morfey notes that "neither Lynam and Webb or Bryan predicted the absolute magnitude of the radiated sound" of a propeller.

Gutin was the first to develop a theory for propeller noise that correctly addressed the noise generation process[3.4]. In his paper he points out that Lynam and Webb based their theoretical developments on hypotheses which lead to predicted directional characteristics which are not in agreement with experiments. Gutin shows that even though Hart[3.5] attempted to develop a theory free of arbitrary assumptions he used one of the Lynam and Webb hypotheses and therefore got the same results.

Gutin's theory represented aerodynamic forces on the propeller blades by a ring of dipoles in the disc swept out by rotation of the propeller blades. Gutin began from basic aerodynamic principles of a wing in developing his method. He recognized that each spanwise element of a propeller produces thrust and drag very much like that of a wing. The addition of all these thrust and drag increments for the full span and number of blades of the propeller is the thrust and drag of the propeller. His analysis assumed that the propeller was stationary with air flowing past it (like a propeller in a wind tunnel). Using an effective radius approximation to simplify the calculations, Gutin showed that the predicted directivity was in good agreement with measurements of a 2-blade propeller. This is shown in Figure 3.1.

Deming in 1937 and 1938 was the first to provide a theory for noise due to blade thickness[3.6,3.7]. In his 1937 report he followed Gutin's approach distributing a ring of sources to represent the propeller blade. In his 1938 report he developed the theory to address the noise of the full propeller blade. His theory addressed the noise of a propeller blade with symmetrical airfoil sections with no blade angle of attack and operating at static conditions. Comparisons of measured and predicted noise showed remarkably good agreement in the harmonics (up to the fifth) and good agreement in polar directivity patterns. Figure 3.2 shows the comparison of polar directivity patterns for the first four harmonics of the 2-blade test propeller. While the agreement is not perfect, it is more likely that the differences seen in Figure 3.2 are due to measurement anomalies. Deming commented that "the peak just ahead of the 90° position shown by the experimental curves for the fundamental and second harmonic may be due to a slight twist of the blades."

In 1940 Deming published his theoretical work on propeller rotation noise due to torque and thrust.[3.8] He followed the approach of Gutin but included the full distribution of torque and thrust over the disk swept out by rotation of the propeller blades. He used an algebraic equation for the spanwise distribution of torque and thrust that approximates the actual aerodynamic loading. With these assumptions he was able to use Gutin's equations to derive an algebraic equation for noise due to torque and thrust. Deming compares his results with Gutin's and shows good agreement. He then shows comparisons between measured and predicted polar directivity patterns for a 2-blade propeller operating at 423 ft/sec tip speed. The polar directivity pattern of Figure 3.3 for the first harmonic shows that Gutin's and Deming's calculations are in close agreement. Also the measured directivity pattern generally confirms the predicted directivity pattern.

Deming in reference [3.8] also provides the first evaluation of the effect of number of blades on sound pressure at harmonics of blade passage frequency. Curves are included based on Gutin's and Deming's equations for sound pressure as a function of blade passage frequency and blade tip Mach number at a directivity angle of 110° from the inflow axis. These curves clearly show that increasing the number of blades at a given tip Mach number reduces the harmonic sound pressure level.

Ernsthausen in 1941[3.9] published comparisons between measurement and a theory that included blade thrust and thickness. Morfey states that the "theory is unsatisfactory in that a harmonic spectrum envelope was assumed, rather than deduced from the chordwise distributions of blade thickness and loading."

In 1942 Gutin extended his work of 1936 to include the effects of blade thickness [3.10]. It was not until 1946 that the effect of forward flight on propeller noise was addressed in published noise prediction methods. At that time the translation of the German reports on Modern Aeronautical Acoustics became available. A paper in this report[3.11] by Merbt and Billing describes the theoretical development. This work was also published in 1949[3.12]. Morfey[3.3] comments that they "considered the propeller blades to have finite section areas and lift but neglected the radiation from the force component in the drag direction."

Garrick and Watkins, in 1953, extended the work of Gutin on noise due to thrust and torque to include the effects of subsonic forward flight [3.13]. The derivations are fairly complete and address the near field as well as the far field where simplifying assumptions are discussed. Equations are provided which allow integration over the full disk as well as those involving an effective ring (radius) approximation for simplicity. For the effective ring approximation, the entire thrust and torque is assumed concentrated on the ring. The authors recognized that the effective radius of this ring was somewhat variable and noted that Deming had shown that an effective radius of 0.8 of the propeller radius was acceptable for initial calculations for a static propeller. The authors were aware that the noise produced by a propeller would be affected if the inflow was not axial as in the climb case. This is an early recognition of the importance of including the geometry of the inflow to the propeller for accurate noise predictions.

In 1954 several members of the Research Department of United Aircraft Corporation began to work on propeller noise prediction methods. According to Metzger et. al . [3.14] the work was:

> "aimed at extending the work of Garrick and Watkins. They synthesized the field using a line source moving uniformly at subsonic speeds. The sound field is expressed by integration over the propeller disc and also includes the assumption of integration over an effective ring, to give expressions for both near and far field noise. Kemp and Arnoldi [3.15] adapted the work of Garrick and Watkins to machine computation with modifications to account for variable chordwise loading. Thickness noise was not included in this work. Shashady and Kemp [3.16] examined the usefulness of effective radius in sound field calculations. Also Shashady[3.17] used the machine computation procedure to calculate free field sound pressure levels for a typical propeller under typical operating conditions. These computed values show that harmonics increase in importance as forward speed increases. Arnoldi [3.18, 3.19] also worked on a method of machine computation of thickness noise. Comparisons of computed and measured levels for an aircraft in flight indicate that the trends observed in the measurements, namely, the forward shift of the

sound field and the increase in noise level, can be attributed to thickness noise rather than thrust and torque noise."

Arnoldi comments [3.19] that his equations for thickness noise should now be equivalent to those developed by Garrick and Watkins for loading noise. It should be noted that this was the time (1956) when computers were becoming available for complex calculations. Arnoldi's initial calculations were limited to the far field due to the complexity of the near field equations. His work was later computerized and loading and thickness noise methods of this time period were the basis of noise prediction methods in common use until the methods based on Lighthill's Acoustic Analogy [1.1] were developed beginning in the mid 1970's.

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4.0 MORE RECENT METHODS OF TONE NOISE PREDICTION BASED ON EARLIER THEORY

Between the mid-1960's and mid-1970's there was an interest in vertical and short takeoff and landing (V/STOL) aircraft. The tilt wing Ling-Temco-Vought XC142 VTOL aircraft and deHavilland Dash 7 STOL aircraft shown in Figure 4.1 are examples of such aircraft. Also, there was an interest in quiet propeller driven reconnaissance airplanes. Four methods were developed at the time for predicting noise of these aircraft. They were based on earlier theory which has been discussed in the previous section of this report. These methods are discussed below.

Healy, 1968 - This method [4.1] follows the approach of Gutin and of Garrick and Watkins to predict harmonic noise due to thrust and torque. The method is limited to predictions with constant chord blades. Unlike the earlier theories, this method allowed the propeller/rotor to be tilted relative to the direction of flight. The method allows input of time varying blade loading in both the radial and circumferential directions. Calculations can be done with only power and thrust values. An external aerodynamic program for input of loading information is not required. The author states that this is a desirable feature for preliminary design studies. A program for use on a mainframe computer was developed. Comparisons with Gutin's and with Garrick and Watkin's calculations show good agreement.

Barry and Magliozzi, 1971 - A prediction method for low tip speed propeller noise was published by these authors in 1971 in two volumes: a theoretical and experimental discussion in the first volume [4.2] and a computer program user's manual in the second volume [4.3]. The objective was to establish accurate methods for the design of quiet propellers that could be used on airplanes for military reconnaissance operations. Here the designs were to be optimized to reduce detectability. The loading noise formulation was based on Garrick and Watkins [3.13] and the thickness noise formulation was based on Arnoldi [3.18]. A significant effort was made to improve the accuracy of broadband propeller noise as the low tip speed operation of propellers for quiet reconnaissance operations were expected to minimize the tones due to loading and thickness sources.

Griffith and Revell, 1973 - These authors report on an extensive analytical and experimental program to develop methods for designing low noise propellers and to confirm the accuracy of the methods [4.4]. These methods were intended as a guide in designing propellers for minimum detectability in reconnaissance missions. The method resulting from this work was an empirically adjusted version of the method of Barry and Magliozzi [4.2,4.3]. The method of reference 4.4 is empirically tailored to the configuration of the quiet reconnaissance airplane in Figure 4.2. Therefore it is not appropriate for general use in predicting propeller noise. There are, however, some features that may be of interest to researchers investigating the reduction of noise of propeller driven airplanes. First, the flyover noise did not continue to decrease as the tip speed of the propeller was reduced. This is shown in Figure 4.3. Here it can be seen that minimum noise occurs at about 0.3 tip helical Mach number and noise increases at either higher or lower speeds. The authors suggest that this is caused by two effects: 1) as tip speed is reduced, the flight speed is reduced so the airplane tends to pitch up causing the propeller to operate at an increasing degree of non-uniform inflow and thus produce more noise at the ground, and 2) the wakes from the propeller interact with the wings to produce noise like that of rotor-stator interaction in turbofans. Based on the empirically adjusted method, reference 4.4 includes design charts for 2, 3, and 6 blade propellers operating at 0.2 to 0.4 tip helical Mach number.

Magliozzi, 1976-1982 - This method [4.5-4.7] for predicting the noise of V/STOL propulsion systems was published initially in 1976. It is a comprehensive method in that it predicts noise of not only unshrouded propellers but also includes shrouded propellers, variable and fixed pitch fans, helicopter rotors and lift fans.

The initial report of 1976 [4.5] only allowed predictions of loading noise since it was expected that V/STOL propellers that satisfied environmental constraints would be highly loaded and operate at low tip speed. In this operating regime, loading noise was expected to be dominant. In the report of 1979 [4.6] the predictions using the 1976 method were compared with measurements of propellers in forward flight. As a result of this work it was recommended that thickness noise and ground reflection effects be added to the method. This was done for the third report published in 1982 [4.7].

In this method the loading noise is calculated using the procedure of Garrick and Watkins[3.13]. This is an effective radius method with the loading assumed to occur at 80% of the tip radius. The method is "stand-alone" in that only thrust or horsepower is needed as an input for loading noise. The method used to generate the required thrust from a given power or the resultant thrust for a given power is based on a simplified version of the Generalized Method of Propeller Performance Estimation[4.8]. This method requires the propeller design parameters (diameter, blade number, solidity) and operating conditions (thrust or power, tip speed, flight speed).

The thickness noise predictions are based on the method developed by Arnoldi [3.18]. The method of Arnoldi assumes a spanwise distribution of sources to represent thickness noise. At each radial station there is only one source. At high tip speeds this produces high levels of high frequency noise that does not represent the action of a real propeller blade. Therefore, in the V/STOL method, a chordwise non-compact formulation developed by Hanson[5.49] is used. The method assumes the airfoils are NACA Series 16. Although other airfoil shapes are used in many propeller designs, the differences are not expected to produce significant errors.

A unique feature of the method is the manner of defining the blade planform and thickness. As Figure 4.4 shows, there are pre-defined planform and thickness distributions included in the method. A user simply selects a blade chord at 80% radius or the activity factor(a parameter proportional to blade area) for the blade. This then defines the blade planform and thickness distribution for the calculation.

This method also includes atmospheric absorption for propagation effects and the influence of interference when the microphone is mounted 4 ft. above the ground for certification.

5.0 MORE RECENT METHODS OF TONE NOISE PREDICTION BASED ON THE ACOUSTIC ANALOGY

Many of the recent advances in propeller noise theory are based on the acoustic analogy proposed by Lighthill in 1952 [1.1] Goldstein in his derivations of Lighthill's equations[5.1] states that "Lighthill's approach allowed calculation of acoustic radiation from small regions of turbulent flow embedded in an infinite homogeneous fluid in which the speed of sound and density are constant. Upon realizing that the density fluctuations at large distances from the turbulent region ought behave like acoustic waves in such flows, Lighthill arranged the exact equations of continuity and momentum so they reduce to the homogenous acoustic wave equation at large distances from the turbulent flow."

In 1955 Curle [5.2] extended Lighthill's theory by pointing out that fixed boundaries in the flow in the analogy can be replaced by surface force distributions. Then in 1969 Ffowcs Williams and Hawkings [5.3] developed the equations, based on Lighthill's acoustic analogy, which are the basis for many of the recent theoretical methods.

The Ffowcs Williiams and Hawkings equations show that propeller noise is due to thickness and loading in a manner very similar the early theories. In addition, a non-linear (quadrupole) term is included which appears to be important for conventional propellers with blades having unswept planforms and operating at transonic tip speeds. Many of the prediction methods described below delete the quadrupole term from the analysis because the Propfans of interest in the late 1980's had thin bladed airfoils with swept blade planform to alleviate transonic effects.

In organizing this section, the work of two researchers, Farassat and Hanson stand out for their many technical papers that explored the capabilities of the acoustic analogy approach to predict the noise of single-rotation and counter- rotation propellers/Propfans. Their work will be described first followed by discussion of the work of many other researchers who made technical contributions between the late 1970's and 1994.

Farassat (1975 - 1992) - Between 1975 and 1992 Farassat published many papers as a sole author or with co-authors. From his earliest papers Farassat has used the time domain approach for his theoretical development. His first papers in 1975 and 1976 [5.4,5.5] described a basic approach to the prediction of noise of helicopter rotors based on equations derived from the Ffowcs Williams and Hawkings equations. Then, in his paper co-authored with Brown [5.6] in 1977, he further developed the theory presented in 1975 and 1976 and indicated its value for predicting propeller noise in forward flight.

In 1977, Farassat as co-author with Pegg and Magliozzi, presented a paper summarizing experimental and analytical work on the effects of forward flight on propeller noise [5.7]. The test results used in the paper were obtained from a light STOL twin engine transport. Measurements of noise were obtained from wing- tip- mounted microphones. Blade surface pressures were measured with pressure transducers. Important results from the test program were the documentation of the reduction in high frequency tone-like noise as the propeller operation changed from static to forward flight. This is shown in Figure 5.1. The change in measured blade surface pressure spectra from static to forward flight is shown in Figure 5.2. The reduction of high frequency harmonics is seen to be quite dramatic. the reason for the reduction in surface pressure and noise harmonics is postulated on the basis of Hanson's work to the be the result of changes in inflow turbulence. This is shown conceptually in Figure 5.3. Under static conditions the patches of naturally occurring atmospheric turbulence are attracted by the propeller in sink-like flow. In this process the eddies are stretched and contracted in cross section. When the propeller "chops" these eddies, tone-like noise is produced. A ground vortex or a vortex originating on the fuselage surface of a twin engine airplane could produce the same result. Under flight conditions the eddies are not contracted and stretched so the related noise is believed to be substantially lower and noise due to steady loading and thickness sources are dominant.

Farassat used the method of reference 5.4 to calculate the noise at static and forward flight conditions. Normally reference 5.4 includes only the effects of steady loading of the blade plus the thickness noise. The quadrupole non-linear term in the basic equation of Ffowcs Williams-Hawkings is not included. For the predictions of reference 5.7, shown in Figure 5.4 an additional calculation for noise due to unsteady loading caused by inflow turbulence interaction was included. This calculation uses the approach of Lowson and Ollerhead [5.8] to define the higher order airload harmonics on the basis of the measured blade surface pressure such as those shown in Figure 5.2. It can be seen in Figure 5.4 that the predicted noise, which includes steady loads alone, agrees well with the measured spectra obtained in flight. Under static conditions the predictions with steady loads alone are considerably lower than measured noise above the seventh harmonic. When the unsteady loads are included in the predictions, good agreement with measurements is shown.

In 1977 Farassat also published his paper on discontinuities in aerodynamics and aeroacoustics [5.9]. This is the basis for some of his later developments in propeller noise theory.

In 1979, Farassat applied his theory to prediction of single rotation Propfan noise [5.10]. This was Farassat's first application of his theory to the highly loaded supersonic tip speed Propfan.

In 1980, a paper on time domain methods was published [5.11] by Farassat and Succi. This paper also provides an excellent review of propeller noise prediction methods from the first method of Gutin to the time of publication of the paper. In this paper the authors clearly recognize the effect of forward flight on propeller noise and that propellers operating statically produce more noise than those operating with some forward speed. They also recognized that propeller noise can be generated by periodic loads due to asymmetry of the airflow into the propeller due to flow around engine nacelles, wings and fuselage.

Two prediction methods are described in reference 5.11. Both are time domain methods based on the Ffowcs Williams-Hawkings equation. One is called the MIT program and the other called the Langley program. The MIT program is for General Aviation propellers operating at subsonic tip speed. The Langley program can handle advanced propellers such as the Propfan operating at supersonic tip speed. Both programs address blade sweep but the Langley program is more complete. Both programs can handle a moving or stationary observer. The Langley program is more complex than the MIT program and takes longer to execute a case on the computer.

The following information is needed to run either the MIT or Langley programs:

1. Blade Geometry: planform, thickness and twist such as that shown in Figure 5.5.

2. Airfoil section description as a function of radial location on the blade.

3. Observer mode of motion i.e. stationary observer or observer moving with the propeller.

4. Aerodynamic Data: blade surface pressure and skin friction coefficient distribution.

5. Operating Data: Propeller RPM and forward speed.

Items 1 and 2 above are available from physical measurements of propeller blades. Item 3 is defined on the basis of the test configuration. For example, the General Aviation propeller test used to evaluate the accuracy of the MIT program was obtained using microphones mounted on the wing tip while the airplane was in flight. If an airplane flyover for certification purposes is to be predicted, then a stationary microphone is specified in the prediction.

Both methods require that the aerodynamic data be supplied by a code that is not part of the method. For test cases included in reference 5.11 the aerodynamic information is obtained from reference 5.12. This is a vortex theory where the propeller is assumed to be operating with a minimum induced loss. The authors comment that the aerodynamic predictions from this method appear reasonable but a more accurate estimate of propeller loading is necessary for greater accuracy in noise prediction. The source of the aerodynamic input for the Propfan test cases in reference 5.11 is not specified.

For calculations with the MIT program, the chordwise mesh size must be selected and the chordwise loading distribution must be specified. A mesh with 5 divisions at the blade tip and 1 division at the blade root was considered adequate. A chordwise loading distribution that peaks at the leading edge of the blade was considered more realistic than a uniform chordwise loading. Unsteady loading was also included in the calculations based on the flight test results. Agreement between predicted and measured noise spectra using wing tip microphones was very good. The authors state that "on the whole, it can be said that the in-flight propeller noise of General Aviation aircraft can be predicted with reliable precision."

The comparisons between predictions using the Langley method and data from a Propfan model were less successful than the General Aviation propeller predictions using the MIT method. This was attributed to the use of a parabolic chordwise blade loading distribution and the possibility that a non-linear flow effect existed in the test results which was not included in the method. It should be noted that the Propfan configuration used for these comparisons was one of the earliest swept blade designs, so non-linear effects, which were suppressed in later more advanced designs, could indeed explain the discrepancies.

In 1980 Nystrom and Farassat published another version of Farassat's methods for predicting advanced high speed propeller/Propfan noise [5.13]. The method described in this report is a basic building block for the methods developed later by Farassat. In later work it was used successfully for predicting noise of propellers operating at subsonic tip speed. However, in the 1980 report it was used for calculation of Propfan cases with supersonic tip speed. These comparisons were not satisfactory due to jaggedness of the acoustic waveform caused by numerical integration problems inherent in the method. These deficiencies were corrected in later formulations. However, the method is an important beginning for the extensive theoretical propeller prediction developments of Farassat which are described below.

In 1981, Farassat published a paper which used a unified approach to derive the helicopter rotor and propeller discrete frequency noise prediction equations of many other researchers[5.14]. Only linear acoustic formulas are addressed (the non-linear quadrupole term is not included). Both compact and non-compact formulations are addressed. The derivations presented are based on the Ffowcs Williams-Hawkings equation method without the quadrupole source term. In concluding this excellent review of the many approaches used to predict propeller noise, Farassat states that "it is not possible to select one particular formulation which can be used for all rotating blade noise problems." The method used should be selected to address the specific predictions required and approximations should be used wherever appropriate to reduce the time and cost of predictions.

In Farassat's paper of 1982 [5.15] he derives a new formulation for predicting noise of propellers operating at supersonic tip speed. He calls this formulation 2. This time domain approach requires that the propeller have thin blades that operate at constant RPM and flight speed. Non-uniform inflow effects are not included. This formulation is superior to the earlier formulation by Farassat which produced high frequency oscillations in the acoustic pressure waveform because of numerical integration problems. The acoustic pressure signatures predicted with the new formulation were much smoother and agreed better with test data.

This was followed in 1983 by three papers; a joint paper with Succi addressing helicopter rotor noise [5.16], a paper discussing the evolution of time domain methods [5.17] and a paper providing new theoretical results [5.18]. In reference 5.18 the formulation of reference 5.15 is used as the starting point for a formulation with the objective of removing some of the restrictions. The new formulation required blade surface geometrical properties and blade surface pressure information only. This new formulation can also be used as the basis for predicting aerodynamic pressure. It was expected that the use of this formulation would reduce computing time for noise predictions by 50% relative to predictions made with earlier formulations. The computer program, incorporating the new formulation, used the earlier formulation for parts of the blade operating subsonically and the new formulation for the parts of the blade operating transonically or supersonically.

In 1984 five papers were published by Farassat; one basic paper on the solution of the wave equation [5.19], one discussing a unified approach to predicting aerodynamics and acoustics [5.20], one discussing a new formulation for noise prediction [5.21], one discussing the development of a computer code for propeller noise prediction using recent theoretical formulations [5.22], and one summarizing progress in predicting advanced propellers using time domain formulations [5.23].

The information in reference 5.23 appeared initially as a technical meeting preprint in 1984 and appeared in 1986 as a journal article. It is of interest because it demonstrates the progress made from early days of Farassat's theoretical development to the time when the paper was first presented. The implementation of the theoretical formulations in computer codes for Propfan noise prediction is discussed. In making a noise prediction, the propeller blade geometry, surface pressure and motion are specified. The blade surface is then divided into spanwise and chordwise panels. The Mach number of each panel is then calculated. If the panel is operating subsonically, then formulation 1A is used to predict the noise contribution of that panel. If the panel is operating transonically or supersonically, then formulation 3 or 3M (mean surface formulation) is used to predict the noise contribution of that panel. The main output of the code is the acoustic pressure waveform which is then Fourier analyzed to produce the harmonic spectrum. Reference 5.23 shows several examples of acoustic pressure waveforms. One comparison demonstrates that the new formulation has reduced the oscillations that lead to errors in predicted harmonic spectra. Another comparison shows good agreement between a measured spectrum and predictions made with the mean surface formulation.

A paper dealing with aerodynamics and acoustics similar to that of reference 5.18 was also published in 1985 [5.24]. Also in 1985 Farassat and Myers published a paper on thickness and loading noise predictions [5.25].

In 1986 a review of the various theoretical formulations developed by Farassat was published [5.26]. Formulation 1 was derived in reference 5.4. It was applicable to both subsonic and supersonic rotating blades. It was, however, time consuming for high speed blades when implemented in a computer program. Also the results were sensitive to numerical errors of time differentiation which caused high frequency oscillations in waveforms. Formulation 1-A which was closely related to formulation 1 was derived for use in subsonic blade predictions. The formulation also includes a blade mean surface approximation which reduces calculation time. Formulation 2 was derived for supersonic blades. Three assumptions were required for use of this formulation: 1) the blades have thin airfoil sections and lie on the helicoidal surface swept out by the propeller blade in flight; 2) uniform RPM and flight speed; and 3) steady blade surface pressure (no non-uniform inflow). The predictions made with this formulation were faster and more accurate. Formulation 3 was derived for supersonic blades and is applicable to the actual blade surface rather than the thin blade approximation. It is intended for use on that portion of the blade that runs above sonic speed. For the portion of the blade that runs subsonically formulation 1-A is used. Aerodynamic formulations are also discussed in the paper.

Three papers were published in 1987 with Farassat as sole or first author. The first [5.27] is a review of the developments using the acoustic analogy for helicopter rotor noise. It is of interest for the discussion included regarding quadrupole noise. The second [5.28] is the result of a workshop where the status of Propfan noise prediction was discussed by many of the world's leading theoretical aeroacousticians. Most of the material presented can be found in other references. However, Farassat did include a noise prediction of a model of the General Electric counter-rotation unducted fan. Good agreement in level and directivity was shown at the fundamental frequency. For the sixth harmonic the forward part of the directivity was well predicted but the aft part of the directivity curve was significantly under-predicted. It is noted, in the information presented, that the aerodynamic input for the calculations was obtained from an Euler code.

In the third paper of 1987 [5.29] Farassat et. al. provides a fairly extensive review of the capability of the computer code for advanced propeller noise prediction which was developed at NASA-Langley Research Center. This code uses formulations 1-A and 3, (which have been discussed earlier), as the basis of the method. At the time of publication of reference 5.28 the code discussed was a stand-alone program that differed from the discrete frequency model in the Aircraft Noise Prediction Program (ANOPP). In using the code, the blade is divided chordwise and spanwise into panels. The paper reviews the selection of panel size that provides the highest accuracy consistent with computer run time. For noise predictions, the blade is initially divided into coarse panels. The three coarse grid systems used in the grid size study of reference 5.29 are shown in Figure 5.6. The flow at each coarse panel is evaluated to establish whether the subsonic formulation (1-A) or supersonic formulation (3) is required to predict the noise contribution of the panel. If it is found that formulation 3 is required, then the coarse panels are further subdivided and the noise contributions are calculated.

Blade surface pressures required as input are obtained from other codes. In this reference the surface pressures were obtained from a computational fluid dynamics code. The studies in this paper showed that coarse grid B of Figure 5.6 was the desirable compromise for acceptable noise prediction accuracy and minimum computer run time. The fine grid found to be the best compromise divided each panel by 10 in each direction.

Figure 5.7 shows a comparison between the acoustic pressure waveforms and the related spectra obtained from the new code and those obtained using the earlier method of Nystrom and Farassat [5.13]. It can be seen that the high frequency oscillations of reference 5.13 caused by numerical errors have been eliminated in the latest calculations. This leads to smoother harmonic spectra as shown at the right of Figure 5.7.

Comparisons of predictions and measurements were made for microphones on a boom above a Propfan model mounted above the fuselage on a test bed aircraft. The microphone arrangement is shown at the left of figure 5.8. Comparisons of predicted and measured noise spectra are shown at the right of Figure 5.8 for the three microphone locations on the boom. It can be seen that the predicted levels agree quite well with measured levels at the low frequency harmonics at all microphones. At higher frequencies the agreement is excellent at microphone 4 but shows progressively worse agreement at microphones 3 and 1. The reason for discrepancies at microphones 3 and 1 is not known. The authors of reference 5.29 suggest that some effects of the installation on the test airplane may have affected the data. One possibility explored in the paper is the reflection of the Propfan noise from the fuselage of the test bed aircraft.

A further evaluation of the code discussed in reference 5.29 of the previous paragraphs is contained in reference 5.30 which was first presented in 1990. This paper compares predicted noise to measurements made on the test airplane shown in Figure 5.9. Measurements on the fuselage surface and on the microphone boom of Figure 5.9 were used in the comparisons. This report is a thorough evaluation of the Propfan noise prediction capability using the best codes developed by NASA. The Propfan blade deformation by aerodynamic and centrifugal forces was predicted using the NASTRAN code. The Adamczyk computational fluid dynamics code [5.31,5.32] was used for aerodynamic input to the predictions. The DFP-ATP, code discussed in the previous paragraphs, was used for the noise calculations. The influence of the fuselage boundary layer on noise reaching the fuselage surface and the scattering effects of the circular fuselage surface were calculated using the code developed by McAninch and Rawls [5.33].

Figure 5.10 shows how the predictions and measurements compare for the boom microphone locations. For this case the Propfan was operating at 3000 shaft horsepower at a flight Mach number of 0.808 and a tip helical Mach number of 1.107. It can be seen that the agreement for all of the directivity points for three harmonics is quite good. This and other comparisons in the reference show that the level of the peak directivity point of the first harmonic tends to be over predicted. For the higher harmonics this over prediction is less. The authors attribute the differences between predictions and measurements to inflow effects and reflections from the nacelle, wing, and fuselage of the test aircraft.

Figure 5.11 shows how the predictions and measurements compare for the fuselage surface microphone locations. For this case the Propfan was operating at 3029 shaft horsepower at a flight Mach number of 0.814 and a tip helical Mach number of 1.150. It can be seen that the general character the measured noise contours is predicted. The peak level of the first and second harmonic is well predicted. The peak level of the third harmonic is significantly over predicted. Also, for all harmonics, the predicted noise levels fall off in the forward direction more rapidly than the measured levels. The authors attribute this to the calculation's use of a laminar boundary layer profile rather than the turbulent boundary layer profile which actually exists on the test aircraft.

In 1992 a technical note was published by Farassat which addresses the effects of non-uniform inflow on propeller noise [5.34]. The prediction method is a modification of the DFP-ATP code used earlier. The new code is now called Advanced Subsonic and Supersonic Propeller Induced Noise (ASSPIN). The comparisons of predicted and measured first harmonic levels at one location near the peak noise directivity point are shown in Figure 5.12. This figure shows that the effect of inflow angle is under-predicted. A limited number of additional comparisons shows very good agreement at higher harmonics at one microphone but poor agreement for some higher harmonics at a second microphone. The poor agreement was attributed to the destructive interference between thickness and loading noise predicted at this particular location by ASSPIN.

With the improvements included in ASSPIN, Farassat considered that the code was complete. However, he warned that the effects of acoustic phenomena such as reflections from wing, nacelle, and fuselage must be included in any comparisons of predictions and measurements.

In closing this discussion of Farassat's contributions, it seems appropriate to review the prediction methods that have been developed based on his theories. The first of these is described in reference 5.35, the theoretical manual for the Aircraft Noise Prediction Program (ANOPP). The noise prediction section of this report is a review of that found in reference 5.36. In this method, the Farassat theory, used for subsonic portions of the propeller blade, is found in reference 5.4 published in 1975. The noise produced by transonic portions of the blade uses the Nystrom Farassat method of reference 5.13. A modification to the method is included to reduce spurious jaggedness of predicted acoustic waveforms based on reference 5.18. Broadband noise due to blade trailing edge effects is predicted based on the work of Schlinker and Amiet reported in reference 8.14. Scattering of noise by the presence of a nearby fuselage, refraction of noise by propagation through a fuselage boundary layer, atmospheric attenuation, and ground reflection interference are included in the method.

Earlier in 1984 Padula and Block [5.37] published the prediction methods for use in the NASA Generalized Advanced Propeller Analysis System (GAPAS) [5.38]. These methods were based on Farassat's theories discussed above, which were in the process of being incorporated in the Aircraft Noise Prediction Program (ANOPP). The evaluation of the methods recommended in reference 5.37 showed that measurements agreed well with predictions if correct thrust was used as the input to calculations.

In 1984 and 1985 Padula and Block [5.39] used the prediction techniques of ANOPP to explore the effects of changes in angle of attack of the axis of propeller rotation. They based their analysis on the methods used in the NASA Generalized Advanced Propeller Analysis System (GAPAS) [5.37]. The simplifying assumption of the GAPAS method (that the propeller moves in a direction parallel to its axis of rotation) had to be changed for the work in reference 5.39.

In 1986, in addition to the publication of the theoretical manual for propeller aerodynamics and noise for ANOPP by Zorumski and Weir[5.34], Brentner published a computer program, called WOPWOP, for helicopter discrete frequency noise prediction based on Farassat's formulation 1A for subsonic tip speed operation [5.40]. This method, like that of Padula and Block [5.39], can be used to simulate propeller operation correctly in asymmetric flight conditions. Atmospheric propagation and ground reflection effects are also included. Outputs are the acoustic time history pressure pulses, narrowband spectra, 1/3 octave band frequency spectra and various versions of weighted and unweighted overall noise levels.

In 1988 a version of ANOPP for predicting propeller noise alone, on an IBM-PC, was developed. Reference 5.41 is the user's manual for this program called ANOPP-PAS. The program predicts propeller noise as measured in a wind tunnel or in a flyover. A performance prediction program is included which matches computed power coefficient to the measured power coefficient. Only cases where the tip helical mach number is subsonic can be calculated using ANOPP-PAS. The method incudes a full surface version of the solution of the Ffowcs Williams-Hawkings equation as presented in reference 5.35. Broadband noise due to interaction of the blade turbulent boundary layer with the blade trailing edge is also predicted.

The user's manual for the DFP-ATP computer code for predicting high speed propeller noise [5.42] was published in 1989 by Dunn and Tarkenton. As discussed earlier, this code uses formulation 1A to compute the noise contribution of subsonic portions of the propeller blade and formulation 3 to compute the contribution of transonic and supersonic portions of the blade.

In 1990 Weir published a review of the method of Reference 5.40[5.43] . His review included comparisons of predictions and measurements for a two blade General Aviation propeller that was tested in the DNW wind tunnel and also tested in flight on a Piper Lance single engine airplane. In general, the comparisons showed fairly good agreement. However, the angle of attack comparisons using the DNW wind tunnel data showed poor agreement when the propeller axis was in a dive attitude. Also, there appeared to be a systematic error in predicting the effect of ground reflection in the comparisons of measured and predicted airplane flyover data. Further evaluation of the method appears warranted to discover the reasons for the observed discrepancies since this code has great potential for use in all types of General Aviation propeller noise prediction.

The latest improvements to ANOPP and ANOPP-PAS were published by Nguyen in reference 5.44. Comparisons of predictions and measurements were made in this report. A sample comparison for data taken in the DNW tunnel with three different angles of attack for the axis of rotation is shown in Figure 5.13. Here it can be seen that the agreement of predicted and measured spectra are excellent at a simulated climb of 7.4° (propeller shaft at -7.4° in the figure) and in level flight (propeller shaft at 0° in the figure). At a "dive" angle of 7.3° the data is under-predicted. The reason for this is not known.

<u>Hanson 1976-1992</u> - Between 1976 and 1992 Hanson published many papers as a sole author or with co-authors. His first paper published in 1976 [5.45] described a theory for predicting near field noise of single rotation propellers in flight. The non-linear quadrupole term was neglected in this theoretical development as it was considered small relative to the thickness term of the Ffowcs Williams- Hawkings equation. The thickness formulation used the approximation that volume displacements for both surfaces of the blade act on the chord line. This method is a

time domain approach where the waveform of the acoustic pulse of a passing blade is predicted. Comparisons were made to data obtained by Hubbard and Regier [5.46] on a 2-blade 4 ft diameter propeller run statically at tip mach numbers up to 1.00. Figure 5.14 shows the comparisons for the 0.75 and 1.00 tip mach number cases. It can be seen that the predicted and measured waveforms are in good agreement thus confirming that this method captures the mechanisms that generate the measured noise.

In 1978 Hanson and Fink [5.47] addressed the quadrupole non-linear source in the Ffowcs Williams-Hawkings equation. As opposed to the surface sources which are volume displacement (thickness) and blade surface forces (loading), the quadrupole is a volume source that represents shear stress in the air. This paper shows that the quadrupole source is only important above the critical Mach number of an airfoil (the airfoil relative velocity where the speed of sound is reached somewhere on the airfoil surface) and below a Mach number of 1.0. This is plotted in Figure 5.15. The increase of almost 6 dB of quadrupole noise relative to thickness noise shown in Figure 5.15 is significant. The improvement in predicted noise due to addition of the quadrupole source is shown in Figure 5.16. Here the predictions are compared to data obtained on a Propfan model with eight blades but no tip sweep. The authors comment that "quadrupole radiation should be reduced to the negligible point if the blades are swept or their Mach number is subcritical."

In 1979 Hanson presented his paper on a helicoidal surface theory for harmonic noise in the far field [5.48]. In this theory the noise sources are distributed on a helicoidal surface defined by the passage of the propeller blades in forward flight. The quadrupole term is calculated using a transonic airfoil analysis code. The strength of the dominant quadrupole element around an airfoil from this paper is shown in Figure 5.17. It can be seen that the source is reasonable localized around the airfoil surface.

In 1979 Hanson also presented a very general paper [5.49] discussing the influence of many important design parameters on far field noise of propellers in flight. Also the effects of noncompactness in thickness and loading components are demonstrated for different classes of propeller/Propfan driven airplanes at different operating conditions of interest to a designer. The Propfan at cruise is shown to be the most affected by noncompactness assumptions . The effect of chordwise loading assumptions is shown to be very significant. The lowest noise associated with loading noise is shown to be achieved for a uniform chordwise loading. A loading that peaks near the leading edge of the airfoil produces substantially higher noise levels, particularly at higher frequencies.

This paper demonstrates, by graphical means, the effects of blade sweep on noise. Figure 5.18 shows the planform of a swept blade. The noise produced by the blade is shown to be the result of adding the contributions from small chordwise slices of the blade. If these contributions are added in amplitude and phase then the total blade noise is the result. This is demonstrated graphically in the vector plot of Figure 5.18. It can be seen that adding sweep causes the vectors to produce the smallest resultant noise. Although not shown, the sweep of the tip is most important as the noise associated with the blade tip dominates that produced by the inner sections of the blade. The vector plots and resultant noise directivity plots for a straight and swept blade of a Propfan at cruise are shown in Figure 5.19. it can be seen that sweep significantly reduces the peak noise. At lower flight speeds the phase cancellation benefits of sweep are shown to be much less effective.

In reference 5.50 Hanson reviews the general results of his analysis work and shows comparisons with test data up to the time of the paper. Of interest is the information of Figure 5.20 which shows significant reduction in near field Propfan noise at helical tip Mach numbers from 0.7 to 1.2.

In 1983 Hanson published a paper [5.51] on a compressible helicoidal lifting surface theory which is applicable to both propeller aerodynamics and noise. This paper brought together the earlier results of many researchers as special cases of the general theory presented and identified areas where further theoretical development could occur. The paper includes equations for acoustics, unstalled flutter, and steady performance of unshrouded propellers.

Hanson, in 1983, presented a paper on a near field frequency domain theory for propeller noise prediction. This was later published in 1985 [5.52]. This theory is based on the helicoidal lifting surface theory discussed in the previous paragraph. A comparison of predictions and measurements for a swept blade Propfan is shown in Figure 5.21. Agreement is shown to be quite good over a range of tip helical Mach numbers even without the inclusion of the quadrupole sources, which are weak for highly swept blades.

Although not a complete propeller noise prediction method, the reports by Hanson in 1981 [5.53] and 1984 [5.54] and that of Hanson and Magliozzi in 1983 [5.55] and 1985 [5.56], which present methods for predicting the effects of fuselage boundary layer shielding on tone noise from a nearby propeller, are of interest. An accurate method of this kind is needed to predict the distribution of propeller noise on the surface of a fuselage as the starting point for fuselage noise reduction and cabin noise studies. This work was inspired by flight test results from a model Propfan mounted above the fuselage of a Jet Star test bed aircraft driven by four aft mounted jet engines. The initial results showed the measurements on the fuselage surface to be considerably lower than expected based on theoretical calculations and other test experience. The prediction procedure described in references 5.53 - 5.56 models the refraction process shown in Figure 5.22. It can be seen that the refracted path of an acoustic ray emanating forward from a propeller toward the fuselage surface travels farther than a ray traveling in a straight line. Furthermore, if the ray is traveling at far forward angles, the boundary layer refraction would prevent the sound from reaching the surface. Comparisons of predictions with Propfan measurements on the fuselage surface of the Jetstar at high cruise speed showed fairly good agreement.

In 1984 Hanson published his first theory for noise of counter rotation propellers[5.57]. This was later published in 1985. It provided analytical models for aerodynamic unsteady interaction between the rotors of a counter-rotation propeller and for the noise caused by unsteady blade loads. The aerodynamic interactions included were assumed to be due to viscous wakes, trailing potential waves and bound potential effects. In the evaluation of this work, comparisons were made with the noise data from the Fairey Gannet which had a single nose mounted counter-rotation propeller with four blades on each blade row. The predicted levels agreed well with the measurements for the first four harmonics. However, the noise due to unsteady loading associated with the counter-rotation configuration was so low that it was off the scale of the graphs. Noise at forward directivity points at higher frequencies was not as well predicted. Hanson states that this "suggests that the aerodynamic interference model needs to be refined". As a side note, the publication of an engineering note in 1985 deserves some comment for readers who are working on counter-rotation propeller noise. In this note [5.58] Hanson and McColgan show how the level of interaction noise of a counter-rotation propeller can be identified by running the two blade rows at slightly different RPM's. They show that the interaction noise appears as tones between the harmonics of the two blade rows. The example of Figure 5.23 from the Gannet test shows that there is no tone between the first blade passage frequency harmonics. At the second harmonic an interaction harmonic appears. At higher harmonics more interaction noise harmonics appear. Using this technique, the level of interaction noise can be identified in a counter rotation test.

In 1986 Hanson published his theory for noise caused by blade tip radial forces[5.59]. This noise is caused by air flowing from the pressure surface of a propeller blade around the tip to the other surface. This theory explains the underprediction of an unswept Propfan at takeoff conditions. This additional noise source radiates in phase with thickness noise and is expected to be more important for unswept blades than swept blades.

In 1987 Hanson participated in a workshop "Prop-Fan Aeroacoustics - Understanding /Application."[5.60] The reader may find this summary of his important theoretical developments of interest. Many of these are discussed in previous paragraphs of this report.

In 1989 Hanson published his theory for predicting sound power and wave drag for a propeller in flight [5.61]. Hanson concludes that the acoustic power is somewhat less than 1% of the shaft power for a well designed Propfan with swept blades. However, for a configuration without swept blades the acoustic losses could have a significant impact on performance.

In 1990 Hanson addressed the effect of angular inflow on propeller loading sources [5.62]. His theory predicts the increase in noise caused by unsteady loading and angular inflow as the axis of propeller rotation is tilted relative to the flow. Only the loading effects are dealt with in detail. However, comments are included regarding its application to thickness noise. A calculation of the effects of angular inflow on a typical 4 blade commuter propeller are shown in Figure 5.24. The figure shows that the unsteady loading associated with the tilted axis of rotation increases the noise relative to the levels for steady loading in axial flow by a small amount. Adding the angular inflow has a much larger effect. The maximum level is higher and the directivity is shifted forward. These effects are shown in Figure 5.24 to occur for both the blade passage frequency fundamental (mB=4) and the third harmonic (mB=12).

In 1991 Hanson and others published the NASA contractor's reports [5.63-5.67] that summarized the results of an extensive development of methods for Propfan aerodynamics and noise. Volume I summarizes the theory for blade loading, blade wakes, and noise. Volume II summarizes the work on wing shielding. Volume III summarizes the application of the theory of the earlier volumes. Volume IV is the computer program user's manual and Volume V summarizes the work on boundary layer propagation. These volumes bring together much of the work reported by Hanson in earlier reports which have been discussed in previous paragraphs.

In 1992 Hanson published a technical note describing the theory for noise due to angular inflow[5.68]. This theory accounts directly for effects such as tilt of the propeller axis of rotation, unsteady thickness and unsteady loading with the placement of the noise sources on the propeller blade's actual camber surface. Using the new theory, predictions were compared with near field noise measurements on the Propeller Test Assessment aircraft, where a large scale single-rotation was mounted on the wing. These showed fairly good agreement with fore and aft directivity.

In 1992 Hanson and Parzych presented the next paper on angular inflow effects [5.69]. The information was also published as a NASA report [5.70]. The NASA report describes the computer program for angular inflow noise prediction developed from the theory. Only the linear source terms are included (the quadrupole is not addressed). The importance of including both the tilt angle and unsteady loads in a propeller noise prediction is shown in Figure 5.25. Here, predictions were made for a 4-blade commuter propeller operating at takeoff conditions at a 10° angle of attack. The figure shows that:

1. with unsteady loads but 0° inflow assumed, the lower harmonics increased more than the higher harmonics;

2. with steady loads but 10°inflow assumed, the higher harmonics increased more than the lower harmonics;

3. both the unsteady loads and 10° inflow are required to show the increased noise at all harmonics.

The accuracy of directivity predictions with this method is shown in Figure 5.26. Here the measurements on a 2-blade General Aviation propeller tested under controlled conditions in the DNW tunnel are compared with predictions. It can be seen that agreement is excellent both in directivity and level for the five harmonics calculated.

Although not authored by Hanson, the NASA report by Culver and McColgan [5.71] describing a unified computer program for counter rotation propeller noise prediction was based on the NASA reports for single-rotation propeller of 1991, which are discussed above. Most of this report deals with the aerodynamics of counter rotation including steady aerodynamics, unsteady aerodynamics and wake modeling. It does however include the ability to predict noise with the aerodynamic calculations as inputs. The accuracy and capabilities of this method have not yet been fully documented.

Dokuchaev, 1964-1970 - Between 1964 and 1970 Dokuchaev published three papers dealing with the basic theory for propeller noise. These were originally published in the Russian Acoustic Journal and their translations were published in Soviet Physics-Acoustics. In all of the papers, the problem is treated in a very theoretical way which only briefly mentions propellers. Instead of propellers these reports deal with "bodies moving in helical lines" or "a body moving in a circle" or "a harmonic monopole in circular motion." The first paper [5.72] presents the theory for simple bodies spinning in a circular path whose radius is much larger than the body. Then a vane spinning in a circular path is simulated as a series of bodies spinning on the same circular path on the same radius line. the theory is presented for far field noise generated for subsonic motion of the bodies. The second paper adds helical motion of the bodies due to flow parallel to the axis of rotation [5.73]. The third paper provides the theory for a pulsating monopole in circular motion[5.74]. The author suggests that this theory is appropriate for analyzing cavitation noise of ship propellers.

Heinig, 1971 - In this paper [5.75] the general theory of helicopter rotor or propeller noise due to thickness, thrust, drag and radial force is briefly discussed, and an empirical procedure for predicting higher harmonics of rotation noise due to unsteady loading is presented.

Hawkings and Lowson, 1972-1974 - In 1972 Hawkings and Lowson published their theory for supersonic (tip speed) rotor noise [5.76]. This was later published as reference 5.77. The theory is based on Lighthill's acoustic analogy. In developing the theory, two assumptions were made: (1) the blades are thin, and (2) only steady sources are important. A linear theory is described with a modification based on the Witham weak shock theory [5.78] to modify the acoustic waveform generated by the propeller blade as the sound propagates from the near to the far field. Comparisons between measurements and predictions using the non-linear theory are shown in Figure 5.27 Two sets of test data are used: the first from a test by Hubbard and Lassiter at NACA in 1952 for a 2-blade 47 inch diameter propeller at a distance of 30 ft and the second from a test by Kurbjun at NACA in 1947 for a 3-blade 10 ft diameter propeller at a distance of 100 ft. All data and comparisons of Figure 5.27 are in the plane of propeller rotation. It can be seen that the linear theory shows major discrepancies with the test data while the non-linear theory shows substantial agreement in both level and spectrum shape.

Woan and Gregorek, 1978 - This method [5.79] is based on the Ffowcs Williams-Hawkings work published in 1969. It calculates noise due to blade thickness and steady surface pressure. It is valid for subsonic propeller tip helical Mach number. The non-linear quadrupole term is also neglected in this method. Program inputs for blade surface pressures are obtained from an external procedure. Output of the program is the time history pulse made up of thickness and loading contributions. A sample prediction from reference 5.79 is shown in Figure 5.28. These predictions for a 3-blade propeller show fairly good agreement with measurements obtained in flight on a twin engine General Aviation airplane with a microphone mounted on the wing tip. The predictions in Figure 5.28 also show good agreement with those of Farassat and Brown [5.6].

Hawkings, 1979 - This reference [5.80] describes an alternate approach to the use of the Lighthill acoustic analogy to deal with transonic rotor noise. It is based on the non-linear equation of transonic flow around a rotating blade. A method of calculating far field noise is described that avoids the pitfall of the acoustic analogy. The theory presented deals only with the simplest case of a stationary non-thrusting rotor. Predictions were said to be within 4 to 5 dB of experimental results.

Gounet and Lewy, 1982-1986 - Between 1982 and 1986 Gounet, as sole author and in collaboration with Lewy, published several papers on propeller and Propfan noise. In 1982 Gounet and Lewy published the first paper [5.81] on theoretical and experimental work on propeller noise. Their work emphasized General Aviation propeller noise but also considered transonic tip speed advanced propellers. Their theoretical work references that of Farassat, Hanson, and Fink so their initial methods are based on the Lighthill acoustic analogy.

In 1982 Gounet published her thesis on light propeller noise [5.82]. Both theoretical and empirical methods are discussed in this thesis as well as experimental work. She concludes that the dominant noise of General Aviation propellers is mainly due to the mean load on the blades. However, tip rotation Mach number is the parameter having the greatest effect on noise produced. Gounet's prediction method appears to follow the frequency domain methods developed by Hanson. Reference 5.82 also compares theoretical predictions with the early version of the Society of Automotive Engineers empirical propeller noise prediction method .

In 1983 Gounet published a summary of the main results from her studies of light propeller airplane noise [5.83]. She concluded that rotational tip speed is the most important parameter for noise generation.

In 1986 and 1988 Gounet and Lewy published French and English versions of a report on prediction of single rotation Propfan noise [5.84,5.85]. The far field method of these reports was in the frequency domain and based on the acoustic analogy. A near field method using 3D Euler code results directly was also included. Predictions of far field noise compared with measurements published by NASA for the SR-I Propfan showed the ONERA method to under-predict the measurements below a relative tip mach number of 1.06 and over-predict the measurements above a relative tip mach number of 1.06. This is shown in Figure 5.29.
No comparisons of the 3D Euler code results relative to measurements are shown.

Miller, 1984 - In 1984 Miller's doctoral thesis was published on optimizing propeller performance with noise as a constraining variable [5.86]. The noise method was a compact source formulation based on Lowson [5.87] which predicts loading and thickness noise. Since this thesis investigates proplets as a means of reducing noise, Lowson's work is extended to allow prediction of noise due to radial forces.

Schulten, 1984-1993 - In 1984 Schulten published a paper describing a theory for propeller noise in non-axisymmetric flow[5.88]. This is based on the Ffowcs Williams-Hawkings equation. The quadrupole term is not included in the analysis. Predictions are compared with measurements and show fairly good agreement with data measured on the fuselage of a twin engine model scale aircraft in a wind tunnel. All predictions were done assuming axisymmetric inflow since Schulten had no way of generating the unsteady surface pressures on the blades in the non-axisymmetric case.

In 1993 Schulten published his doctoral Thesis on a lifting surface theory for sound generated by propellers and ducted fans[5.89]. Although propeller noise is included in Schulten's theoretical development, most of the thesis applies to ducted fans.

Boyd, Crighton, Parry, and Peake, 1988-1993 - These authors, in various combinations, published papers on approximate methods for predicting propeller noise which do not involve numerical integration or the evaluation of Bessel functions but retain the accuracy needed for evaluating the influence of various parameters. The earliest of these papers by Parry and Crighton [5.90,5.91] described the theory as applied to subsonic single rotation propellers. It was originally presented in 1986 and then published in 1989. These papers discuss the major concepts of the asymptotic theory used in all of the papers of these authors. The basic idea is that the equations for propeller noise and its characteristics can be approximated with reasonable accuracy if the number of blades in the propeller is large. The authors suggest that even with as few as 4 blades this approach is useful, and for the Propfan with 8 or more blades, it can produce fairly accurate predictions.

The equations used to begin the theoretical development of reference 5.91 are based on Hanson's frequency domain theory which is discussed elsewhere. Thickness and loading sources are included but the quadruple source is neglected because it is of importance only at transonic tip speeds. In this paper the non-compactness in the chordwise direction is also neglected because it is said to be more important at high subsonic and supersonic speeds. Comparisons were shown between asymptotic and full numerical predictions. The asymptotic predictions took, at the most, 5% of the time taken for full numerical predictions. For a 12-blade propeller, the comparisons showed good agreement up to 0.75 tip rotational Mach number (the maximum evaluated). For a 4-blade propeller the agreement was not as good at the first harmonic but was fairly good at the second harmonic.

The authors comment on several features of the asymptotic theory which explain experimental findings on propeller noise. The first is that noise at higher tip speeds (but still subsonic) has a spectrum with higher harmonic content than that for a lower tip speed. The second is that reducing the tip loading reduces noise. A finding in the subsonic asymptotic theory is that most of the noise is generated near the blade tip so reducing the loading there reduces the noise generated.

Blade sweep is also addressed in reference 5.91 and 5.92. Although the benefits of blade sweep are overestimated for lower harmonics, the trends with tip rotational Mach number are reasonable and agreement at higher harmonics is good. For a Propfan with 8 or more blades the authors conclude that the asymptotic approach provides an indication of the benefit of sweep to reduce perceived noise where the higher harmonics tend to be dominant.

In 1987 Crighton participated in a workshop on Propfan Acoustics [5.93]. In 1988 Parry's thesis on counter-rotation propeller noise was published [5.94]. Then in 1989 Parry and Crighton presented a paper on counter-rotation propeller noise [5.95]. These all deal, to some extent, with the application of the asymptotic theory to counter-rotation propellers. The basic concepts of the asymptotic theory are as described above. However references 5.93, 5.94 and 5.95 extend the theory to address the viscous wake and potential flow interaction of the two blade rows of a counter-rotation propeller. Comparisons with far field test data from the Fairey Gannet showed quite satisfying agreement in the blade row interaction tones. Furthermore these comparisons demonstrated that the potential field interaction noise significantly dominated the viscous wake interaction noise of the Fairey Gannet propeller.

In 1989 the asymptotic theory for supersonic single rotation propellers was first presented and then published by Crighton and Parry [5.96]. In contrast to the subsonic theory where the noise source is primarily at the tip, the supersonic theory shows that the dominant source is located at the blade radius that approaches the observer at precisely the speed of sound. Reference 5.96 also includes the effects of chordwise non-compactness which becomes important for accurate predictions at high subsonic speeds and supersonic speeds.

In 1992 a refinement of the theory for supersonic single-rotation propellers of reference 5.96 was published [5.97]. In this publication a second order term was added to the earlier theory that brings the results quite close to those obtained by full numerical calculations. This second order term showed that radiation from the blade tip is the most important source after the dominant source at the sonic radius. Again these theoretical developments are based on Hanson's frequency domain equations. The work in reference 5.97 does not, however, deal with chordwise non-compactness or blade sweep. Comparisons with full numerical calculations for a propeller with 12 straight blades operating at supersonic tip speed showed quite good agreement for the first and second harmonic over a range of tip helical Mach number from 0.7 to 0.9. Also included in this report are the expressions for the continuous transition through the condition where the Mach radius and blade tip coincide. This is the area where the subsonic formulations are highly inaccurate.

Peake and Crighton in 1991 [5.98] and Peake and Boyd in 1993 [5.99] extended the earlier work on asymptotic techniques to allow the derivation of far field noise estimates based on near field estimates in a wind tunnel or the derivation of near field estimates based on far field predictions. In the former case this allows near field measurements in confined wind tunnels to be used to estimate community noise early in the development of a new propeller. In the latter case it allows far field predictions, that can be done at lower computing cost, to be used as the basis for estimating near field noise for cabin noise or acoustic fatigue studies. The authors show that their methods are generally effective in making the correction from near to far field and vice versa.

Tam et al, 1986-1988 - In 1986 Tam and Salikuddin published their theory for noise produced by Propfans operating at supersonic helical tip speed [5.100]. They applied the Witham weak shock theory to propagation of sound from blades moving supersonically. Comparison of the theory with measurements from a Propfan model operating at high cruise speed showed improved agreement relative to the linear theory. The comparisons indicate that, at low cruise Mach number, weakly non-linear propagation is not very important in the near field but at high cruise Mach number non-linear propagation effects lead to formation of shocks and a strong distortion of the waveform.

In 1988 Tam, Salikuddin and Hanson published a paper on acoustic interference of counter-rotation propellers[5.101]. They provided a theory for counter-rotation propellers where the front and rear blade rows must have the same number of blades and be nearly identical in geometry. However, loadings of the two blade rows do not have to be the same. Comparison of measured and predicted interference patterns at very low flight Mach number showed excellent agreement. It was shown that there is a significant predicted shift in the position of this pattern at high flight Mach number that must be considered.

Tam in 1987 presented a summary of the above two publications at a workshop on Prop-Fan noise [5.102]. He suggests that it is appropriate to use a propeller-fixed or fuselage-fixed coordinate system in many propeller acoustics problems.

Dash, 1986 - This paper[5.103] describes a theoretical development that improves on the earlier work of Hawkings and Lowson for noise due to blade loading. It improves prediction accuracy near the axis of rotation when number of blades increases. It appears that his result reduces to that of Gutin as a special case.

Takallu et al, 1986-1987 - In 1986 Takallu published a paper which included the aerodynamic computations needed to predict the unsteady pressure distribution and unsteady lift on a propeller mounted downstream of a pylon [5.104] This is the configuration considered in airplane designs with the propulsion system mounted on both sides of the fuselage near the tail. In 1987 Takallu and Block [5.105] and Takallu and Spence [5.106] published papers where the analysis of reference 5.104 was coupled to the ANOPP propeller noise theory to predict the effects of pylon wakes on propeller noise. Calculations were done for geometry of a model propeller test. The calculations show that spikes are produced in the predicted time history plots due to the unsteady loads caused by the wake from the upstream pylon. The accuracy of the shape of the spikes in the predictions could not be verified in the tests due to averaging of the test data. However, the amplitude of the spikes appeared to be well predicted. The calculations confirm that noise forward and aft of the propeller plane of rotation are increased by pylon wake interaction with the propeller.

Kroll et al 1987, Lowmann, 1993 - In the first paper [5.107], a lifting surface code for aerodynamics and acoustics is discussed which is based on the linearized Ffowcs Williams-Hawkings equation. It was developed at DLR in Germany and is called the DLR Lifting Surface Code (LBS). It is applicable to subsonic flow, as the non-linear quadruple is not included. The method is equivalent to that of Farassat's subsonic formulation. Predictions were compared with data for a two-blade General Aviation propeller. These show that the time history plots of the noise agree fairly well. Also the overall sound pressure levels are in fairly good agreement. The measured harmonic noise spectra are slightly under- predicted at 0.57 tip helical Mach number condition. At 0.76 tip helical Mach number, the higher frequency harmonics are under-predicted by an increasing amount as the harmonic number increases. The authors attribute the under-prediction to acoustic wave reflections in the test data.

In 1993 Lohmann published a paper[5.108] which uses the LBS method, discussed above, to develop propeller configurations with reduced noise. To accomplish this, the LBS code was coupled with an optimization code. The author shows that blade sweep can be used to reduce noise. Furthermore, he shows that a propeller that has different sweep for each blade can provide further reductions. These reductions are due to interference between the noise generated at different spanwise locations on the blades.

Xiao-feng/Li-xi/Zhou/Weiyang et al 1989-1992 - Four reports summarizing the development of theory for predicting single-rotation and counter-rotation propeller noise have been published by these authors. Xiao-feng et al in 1989 in reference 5.109 discussed a method for predicting counter-rotation noise. This method used a viscous wake model developed earlier for rotor-stator interaction prediction in turbofans. Also in 1989 Li-xi et al published a near field theory for thickness and loading noise of single-rotation propellers based on the Ffowcs Williams-Hawkings equation[5.110]. A similar paper was published by Zhou and Huang in 1991 [5.111]. In 1992 a paper was published by Weyang and Wenlan [5.112] for thickness and steady loading based on the Ffowcs Williams-Hawkings equation. This analysis appears to follow Farassat's time domain approach.

Jou, 1989 - In this paper [5.113] Jou extends the work of Hawkings and Lowson [5.76] on supersonic rotor noise to the forward flight condition. Using his analysis he concludes that there are cones of silence forward and aft of the plane of rotation centered on the axis of rotation. He suggests that his analysis could be useful for planning the position of a propeller with respect to the cabin to minimize noise and acoustic treatment.

Myers and Wydeven, 1989 - In this paper[5.114] the authors develop a supersonic propeller noise theory based on the Ffowcs Williams-Hawkings equation without the quadruple term. An asymptotic approximation for the chord is used to reduce computation time. The waveforms for combined thickness and loading are compared with those obtained using the full numerical DFP-ATP code. Good agreement is shown. Also the corresponding noise spectra are in good agreement. The time required to run cases with this code is 50 - 75% of that required to run the NASA DFP-ATP code.

Whitfield et al, 1989-1990 - A series of four reports was published in 1989 and 1990 authored by Whitfield et al. The first report describes theoretical model development for predicting noise of single-rotation high speed turboprops [5.115]. The second [5.116] contains the computer programs based on the models in reference 5.115. The third describes model development for predicting noise of counter-rotation high speed turboprops [5.117]. The fourth [5.118] contains the computer programs based on the models in reference 5.117.

The single-rotation model of reference 5.115 is based on the Ffowcs Williams-Hawkings equation without the quadrupole term. The basic method is far field in the frequency domain. It follows the work of Hawkings and Lowson [5.76,5.119] and Hanson 5.48. For near field predictions the semi-empirical approach of Sulc, et al [5.120] for conventional propellers is used. In this approach the source to observer distance is replaced by the distance between the observer and an equivalent near field source.

An alternate near field approach was also considered where aerodynamic Euler code calculations were used to estimate the pressure distribution on a cylindrical surface surrounding the propeller. This was abandoned due to the cost of obtaining Euler code solutions with a sufficient number of grid points in the blade-to-blade direction to guarantee adequate resolution for acoustic calculations.

Loading distributions as an input to the noise calculations for the method of reference 5.115 were obtained from three-dimensional non-linear aerodynamic Euler code flow solutions.

Installation effects due to propeller angle of attack, the effect of wing induced flow, and the effect of flow induced by a nearby fuselage are also calculated by the method in reference 5.115. Both unsteady loading and unsteady thickness noise due to installation effects are considered. The effects of scattering of propeller noise by the fuselage and the effects of boundary layer refraction are included as well.

Comparisons of predictions, using the methods of reference 5.115, with various measurements were made. Good agreement with free field data taken on a model Propfan in high speed forward flight was found. Moderate agreement was found with propeller noise data measured on the surface of a fuselage or in a wind tunnel. The check on the accuracy of the installation effects method showed encouraging agreement. The fuselage scattering and boundary layer refraction model is said by the authors to be in agreement with observed trends.

Reference 5.117 summarizes the model development and evaluation of the counter-rotation propeller noise prediction method by Whitfield et al. This method includes steady loading and thickness noise sources for the two rotors, unsteady loading noise of the downstream rotor resulting from interaction with the wakes and vortices shed from the upstream rotor, and unsteady loading and thickness noise of both rotors due to installation effects. The theory in this report is, in general, an extension of the single-rotation theory of reference 5.115.

One significant change in reference 5.117 is the approach to predicting noise due to installation effects. In this method, the cross flow due to angle of attack is used for predictions rather than the earlier theory of reference 5.115, which assumes that the unsteady sources are immersed in a stream of uniform axial inflow. This theory is described in more detail in reference 5.121. The improvement achieved by this revised method can be seen in Figure 5.30. Here the left figure shows the prediction for the front rotor blade passage frequency of a counter-rotation Propfan model at an angle of attack of 16°. The measured increase and decrease of noise at locations around the circumference of the Propfan is significantly under-predicted by the earlier method. The plot at the right of Figure 5.30 shows the significant improvement achieved by use of the new model in reference 5.117.

Other comparisons between predictions and measurements showed good agreement. The plots at the right of Figure 5.31 show the fore and aft directivity of blade passage frequency, two times Blade Passage Frequency and three times Blade Passage Frequency. The blade planforms for the Propfan used in these comparisons is shown at the left of Figure 5.31. Predictions are compared with data from a NASA wind tunnel and with data from a Boeing wind tunnel (labeled BTWT). It can be seen the predictions are in good agreement with measurements. Reference 5.117 includes many additional comparisons. It addition to the total noise predictions of Figure 5.31 the individual contributions by the two rotors are shown in separate plots. This provides additional insight into the rotor-rotor interaction tones.

Neuworth/Lolgen, 1990-1993 - Three papers have been published by these authors which deal with propeller inflow disturbances or the related interference effects between the rotors of counter-rotating propellers. The first paper [5.122] presents a theory for the increase in noise due to upstream disturbances such as pylons, inflow vanes or a wing. It is part of a modular computer code for predicting impulsive noise of rotors with disturbances in the inflow. Comparisons of predictions with measurements on a low pressure ratio ducted propeller with inflow disturbances showed good agreement. Noise reduction concepts are also discussed. A swept blade platform was the most promising noise reduction concept..

The second paper [5.123] extends the work of the above paper to deal with inflow distortions.
The third paper [5.124] deals with unducted counter-rotation Propfan noise. As in the first two papers, the modular system for predicting propeller noise is used. For this paper, the interaction noise due to (1) the bound potential field of the two blade rows, (2) the tip vortex of the front blade row, and (3) the viscous wake of the front blade row are included. The noise calculation methods is based on the Ffowcs Williams-Hawkings equation without the quadrupole term. Comparison of predictions with measurements at a low flight speed on a Propfan model with 5 blades on the front blade row and 6 blades on the aft blade row showed good agreement. It was found that the noise of this configuration was dominated by the contribution from the aft blade row whose inflow is distorted by the viscous wakes and tip vortices from the front blade row.

Krejsa, 1990 - This paper [5.125] extends the work of Mani [5.121], who included the effect of angle of attack on the radiation of steady loading and thickness noise in addition to that of unsteady loading. It is a frequency domain far field method. Figure 5.32 shows that the addition of the angle of attack effect on source location and loading direction using Krejsa's method dramatically improves the accuracy of the prediction over that where only unsteady loading is included.

Kim and Rho, 1990 - In this paper[5.126] a time domain method is described. Comparisons with predictions published by Farassat and Dunn[5.30] show significantly more high frequency oscillations in the time history waveforms calculated by the method of Kim and Rho..

DeBernardis and Tarica, 1992 - These authors provide some theory for predicting a portion of the quadrupole term in the Ffowcs Williams-Hawkings equation where surface terms appear[5.127]. Three kinds of surfaces are involved: the blade surface, the vortex wake and possible shock waves. The authors of reference 5.117 suggest that the overall quadrupole can be accounted for by including volume and surface quadrupole terms evaluated at the outer edge of the boundary layer. In the evaluation of this idea, they state that in principle the surface denoted as the outer edge of the boundary layer should also include the blade wake. However they include only the portion of the boundary layer surface surrounding the blade up to the trailing edge. Comparisons between the theory and measurements of a 2- blade General Aviation propeller in the DNW tunnel show improved agreement of the acoustic time history waveform at a tip Mach number of 0.772. However, at a higher tip Mach number of 0.874, the quadrupole noise is believed to be dominant and the surface quadrupole does not fully correct the predicted acoustic time history waveform. It is suggested that the sound emission from shocks must be added to obtain good agreement.

Brouwer, 1989-1992 - In 1989 a lifting line method for propeller noise was published by Brouwer [5.128]. This was followed by a more ambitious paper describing a theory for both aerodynamics and noise [5.129]. This work is based on Van Dyke's method of matched asymptotic expansions [5.130,5.131]. The method can be used to predict aerodynamics as well as acoustics of high aspect ratio propellers typical of those in General Aviation or Commuter applications. The comparison of noise predictions to measurements for a 1/5-scale 6-blade commuter propeller in a wind tunnel showed good agreement for the blade passage frequency. It is noted that the computing time for one harmonic at 50 points in the forward and aft direction for a constant distance from the axis of rotation requires 5 minutes using a 386/25 MHz personal computer equipped with a math coprocessor.

Envia, 1991-1994 - This author has dealt with propeller noise prediction in three documents [5.132,5.133,5.134]. In reference 5.133 the effect of angle of attack is dealt with. Of significant interest is the ability to predict the quadrupole contribution in supersonic propeller operation, in addition to the more common loading and thickness contributions . This is done with an asymptotic approximation. As shown in Figure 5.33, the addition of the quadrupole source improves the agreement with test data, particularly the rounded peak near 1.2 tip helical Mach number. Without the quadrupole source, the linear noise in this formulation as well as that predicted by other authors tends to increase with increasing tip helical Mach number while the test results can even show decreases in noise at the highest speeds.

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6.0 MORE RECENT TONE NOISE PREDICTION METHODS BASED ON COMPUTATIONAL AEROACOUSTICS

The most recent approach to propeller and Propfan noise prediction makes direct use of computational fluid dynamics codes. This approach is most appropriate for high cruise speed, high tip speed, and near field noise. It can be considerably more computer intensive than the other approaches based on the Acoustic Analogy or classical prediction approaches. It is, however, appealing for analyzing the installed near field noise distribution, particularly for the study of fuselage surface noise that is the cause of cabin noise.

Korkan et al. 1986-1990 - Three papers were authored or co-authored by Korkan regarding advanced propeller noise prediction by direct computational aeroacoustics methods. In the first paper [6.1] the flow field near a Propfan was predicted using and Euler code. This information was used to derive the overall sound pressure level and blade passage frequency harmonics of the noise near the plane of rotation. From 0.863 to 1.21 helical tip Mach number the agreement in overall sound pressure level was within 2.6 dB. At 1.14 and 1.21 helical tip Mach number the agreement was within 5.6 dB. These calculations were made at two radial distances from the axis of rotation: 3.93 tip radii and 2.95 tip radii. The reason for the greater discrepancy at higher Mach number is not discussed by the authors. Further work is suggested including evaluating the effect of numerical damping and the dependence of the predictions on the numerical grid.

The second publication [6.2] is from the proceedings of a workshop on Propfan Acoustics held in 1987 and includes a summary of reference 6.1 plus additional developments. The additional developments include the effects of changes in 1) the numerical damping, 2)the Euler code, and 3) the numerical grid. It is shown that the amount of numerical damping must be carefully selected to predict accurate noise levels. An Euler code with non-reflecting boundaries is shown to improve the accuracy of predictions. Increasing the grid density also improves the accuracy of predictions. The author shows that, when using the Euler code method for predictions, it is important to establish the damping and grid density based on comparisons with test data to insure accuracy and minimize computing cost.

Also, in reference 6.2, the concept for predicting far field noise using Euler results is discussed. Direct use of Euler results is not possible because of the high cost of the fine grid needed in the far field and the fact that numerical damping leads to errors in predictions. An alternative approach is to calculate near field noise on a cylindrical control surface using the Euler code and the propagation to the far field by the use of a Ffowcs Williams-Hawkings approach. Korkan shows the general results of using this approach but does not show comparisons with measurements. The results do appear reasonable. This far field approach is further discussed in reference 6.3 published in 1990.

Linblad/Meijer et al. 1990-1994 - In four publications [6.4-6.7] these authors have explored the use of an Euler code prediction of the flow field at a Kirchoff surface close to a transonically operating propeller coupled with a linear calculation in order to predict noise at greater distances. The Kirchoff surface used is a cylinder centered on the propeller axis of rotation. The radius of the cylinder for most calculations was 1.155 blade radii and the length of the cylinder was 0.95 blade radii. A total of 20,680 panels was used on one quarter cylinder. The Euler code used has non-reflective boundaries. The flow variables are determined in the Euler grid and then interpolated to the Kirchoff surface. This method shows remarkably improved accuracy, over linear methods, for predicting the maximum level of the first three harmonics of an advanced propeller operating up 1.079 tip helical Mach number. This is shown in Figure 6.1.

Sankar, 1994 - This information [6.8] was presented in a workshop on propeller noise. It describes a unified numerical technique for predicting aerodynamic and aeroacoustic characteristics of high tip speed propellers by use of computational fluid dynamics codes. The acoustic calculations use an Euler code with non-reflective boundaries. It is found that near field predictions agree well with measurements for a Propfan at high cruise speed. Sankar states that computational aeroacoustic simulations can only predict accurate sound pressure levels up to a distance of about two propeller diameters.

Hall, 1994 - In this presentation [6.9], the objective is to predict noise on the surface of an aircraft in high speed flight. This information is of importance in the control of airplane interior cabin noise. A computational fluid dynamics code is used to predict the time-dependent static pressure field and calculate the resultant noise levels. Parallel processing using multiple computers is used to provide sufficient computing power to predict noise over the airplane surface. Non-axial inflow as found in the actual airplane environment is simulated in the predictions. Comparisons with near field wind tunnel data show good agreement. Comparisons with noise data on the fuselage surface show good agreement for one case but worse agreement for another case where unusual effects occur which may be due to flow separation, shocks or installed aerodynamic effects. The ability to predict the distribution of noise over the surface of the fuselage such as that shown in Figure 6.2 is very valuable for cabin noise studies.

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7.0 EMPIRICAL PROPELLER NOISE PREDICTION METHODS

Empirical prediction methods based on observations or measurements on propellers have been developed since the early days of propeller noise research. Since these methods are based only on observed noise levels, they do not provide insight into the noise generation mechanisms that can be found by theoretical methods. Also, these methods do not include the details of theoretical methods. They rely on gross parameters such as flight speed, rotation speed, power absorbed, and number of blades. The advantage of these methods is that predictions of flyover nose for conventional propeller designs can be made with reasonable accuracy using hand calculations. The accuracy of these methods has not been found to be as good in the near field (on a fuselage surface) because the influence of the airplane flow field is complex and not amendable to an empirical approach. In the following paragraphs the various empirical methods developed over the past 40 years are discussed.

Bolt, Beranek, and Newman, 1952 - This method [7.1] predicts overall (unweighted) propeller noise level in the far field under static conditions. Prediction of both subsonic and supersonic tip speed operation is included. An evaluation of this method showed that predictions were accurate to ±5 dB for overall noise and ±7 dB for octave band levels.

Franken, Kerwin and the Staff of Bolt, Beranek, and Newman, 1958 - This method[7.2] added the capability for predicting harmonic levels and octave band levels of broadband noise in the propeller near field for static and forward flight operating conditions. A limited evaluation of this method showed an accuracy of ±5 dB for near field predictions.

Trillo, 1965 - This method [7.3] was developed to fill the need for predictions of hovercraft propeller noise. An accuracy of ±2.5 is claimed for predictions of the maximum noise at a distance up to 500 ft.

Magliozzi, 1966-1971 - In 1966 a method was published for prediction of near field noise of propellers for Vertical Takeoff and Landing aircraft [7.4]. the method was a refined version of the Franken, Kerwin et al method discussed above. Predictions were generally accurate to ±3 dB. This method was revised several times between 1967 and 1971 as more test data became available for correlation with predictions [7.5]. Prediction of A-Weighted and Perceived Noise levels which are of interest for aircraft noise certification were added in the later versions. Changes were also incorporated to improve the accuracy of predictions for medium tip speed propellers used on commuter transport aircraft. In the last revision in 1971 [7.6], the spectrum shape of propeller noise was changed on the basis for airplane flyover data. Magliozzi in reference 7.5 states that "the latest revision (1971 Revision D) [7.6] was compared to flyover measurements and found to have a 2 sigma (95% confidence) limit of ±3 dB for near field overall noise, ± 6 dB for far field overall noise and ±4.5 dB for far field Perceived Noise."

ESDU, 1976 - This method [7.7] predicts the level of the first four blade passage frequency harmonics of propellers or helicopter rotors operating statically or at forward flight speeds of less than 40 knots. Only the maximum level at a given distance from the propeller or rotor is predicted(directivity information is not included). The basis for the prediction is the work of Gutin for the first harmonic with test information used to develop the prediction procedure for higher harmonics. The stated accuracy of the method is ±3 dB for 75% of the available data for the first harmonic. For the higher harmonics the stated accuracy is ±10 dB for 93% of the data.

SAE, 1977 - In 1977 the Society of Automotive Engineers published a method [7.8] for near and far field propeller noise prediction which was essentially the same as that developed by Magliozzi in 1971[7.6]. This has received fairly wide use in industry for preliminary design studies and has been used by certification authorities to evaluate acoustic changes relating to retrofit of new propellers on existing airplanes.

Smith, 1981 - This method [7.9] is based on A-Weighted sound level data obtained during certification tests. Data from 30 single engine and 28 twin engine airplanes were used to develop this method. Regression analysis was first used to establish the most important parameters for noise prediction. Then an equation was developed that used the most important parameters. It should be noted that this method is in the form of an equation. Many of the earlier methods discussed above are graphical techniques where partial levels, which are a function of geometrical or operating parameters, are obtained from a graph and the total level is obtained by arithmetic sum of the partial levels. In contrast, Smith's result is an equation which lends itself to easy calculations using a hand held calculator or personal computer. Subsequent empirical methods followed the same approach of developing an equation rather than graphs for noise prediction.

Most empirical methods require power, RPM, number of blades, and flight speed as an input. Smith adds twist at the blade tip and blade thickness divided by chord at the 95% station. Based on noise theory these two parameters should enhance the accuracy of Smith's method. The thickness divided by chord affects the thickness noise, which is significant for high tip speed propellers. The tip twist affects the spanwise (blade root to blade tip) loading distribution. Higher tip twist means more power is absorbed by the tip than the root so more noise is generated.

This method, measured against the data used in its construction, was reported to have a 2 sigma confidence of ±2.2 dBA for far field flyover noise.

Rathgeber 1981 - Rathgeber developed an alternate equation [7.10] on the same basis as Smith but excluded the two turboprops in the data set. His equation predicts A-Weighted level flyover noise at 1000 ft as a function of power and tip helical Mach number with corrections for number of blades, turbocharged engine and number of engines. Although his equation does not include thickness divided by chord or tip twist, the accuracy is only slightly worse than the equation of Smith. A 2 sigma accuracy of ±3 dB was found for predicting the data base levels used in generating the method.

Galloway, 1982 - In this report [7.11] Galloway reviews some of the methods discussed above and also recommends his own equations for predicting A-Weighted Perceived Noise and Effective Perceived Noise Levels of single engine and twin engine airplanes. A check of his single engine prediction method relative to Smith's 30 samples of single engine noise shows the method to overpredict by 2.3 dB with a standard deviation of 1.9 dB.

Galloway's equation for twin-engine airplane noise does include thickness divided by chord as a parameter since he found that many twin-engine propeller have very thick tips. This is because these propellers are made by cutting off the tips of larger diameter propellers. A check of his twin-engine prediction method relative to Smith's data set shows an average overprediction of 6.9 dB with a standard deviation of 2.2 dB.

SAE, 1994 - In 1994 the fourth draft [7.12] of a method for predicting far field propeller flyover noise was circulated for comments prior to being published as an SAE Aerospace Recommended Practice. This method, like other recently developed empirical methods, has equations for predictions rather than graphs. This method replaces the 1977 SAE procedure described above. While the 1977 method predicts near field noise as well as far field noise, the 1994 method only predicts far field noise. The SAE Propeller Noise Subcommittee of the SAE A-21 Aircraft Noise Committee, who developed the method, found that near field predictions were much more complex than far field predictions so a new near field method was not included in the 1994 method. The accuracy of the method was evaluated relative to the data used to develop the method. It was found that the standard deviation of Effective Perceived Noise Level was 3.007 dB for 49 airplane samples. For 417 other samples, the standard deviation for A-Weighted Noise Level was 3.842 dB.

Dobrzynski, 1994 - This method [7.13] is not completely empirical in nature since it relies on noise prediction done with a theoretical method. The starting point for developing the method was to run the theoretical method for a fixed blade geometry, radial blade loading distribution and typical blade lift and drag coefficient. The resulting method was then checked against flight measurements for a variety of airplanes. Finally the calibrated method was simplified for use in predicting A-Weighted far field noise. A feature of this method is the inclusion of an empirical piston engine noise prediction method. This is a desirable inclusion for complete airplane noise estimates, particularly if propeller noise reduction features are included in an airplane design, i.e. reduced tip speed. Reference 7.13 which discusses this method is incomplete. The form of the equations of the method is presented but the values of the constants in the equations are missing. These are expected to be published in the near future.

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8.0 BROADBAND NOISE PREDICTION METHODS

Although broadband noise is not a significant noise source in most conventional propellers, it may be important in the future for propellers designed for low noise. The methods for predicting this noise component have been under development since it was first recognized by Obata et al [8.1] in 1932. In early work, broadband noise was called vortex noise since it was thought to be caused by the turbulent trailing edge vortex shedding of the propeller. Stowell and Deming [8.2] reported measurement of vortex noise of rotating cylindrical rods in 1935. Yudin [8.3] , in 1947, published his theory for vortex noise which was based on a dimensional analysis of flow parameters around rotating rods. Hubbard [8.4] , in 1953, used the experimental data for Stowell and Deming and others to develop an empirical formula for vortex noise.

Curle [8.5] , in 1955, indicated that broadband noise could be produced by interaction of a turbulent inflow with a propeller blade or by turbulent flow at the surface of a propeller blade passing the trailing edge of the blade.

Two approaches have been developed to predict the trailing edge noise. Ffowcs-Williams and Hall [8.6] is an example of the first approach. According to reference 8.7, this relies on Curle [8.5] who showed that the pressure field produced by turbulence can be represented by volume quadrupole sources together with surface monopoles and dipoles to satisfy the boundary condition on the surface. The problem of a quadrupole in the vicinity of a half plane is solved first. Since the surface dipoles induced by the quadrupoles are the main sound-producing sources, the method can be described as a calculation of the surface forces produced by the quadrupoles, followed by the calculation of noise. The method suffers in that distributions of quadrupoles are not known with sufficient accuracy.

The second approach assumes that the surface pressure produced by convective turbulence is known. At the blade trailing edge, the surface pressure is no longer supported so a fluctuating dipole force is produced on the surface that then radiates sound. Chase [8.8] , in 1972, was the first to use this approach. Later in 1976 and 1978 Amiet [8.9,8.10] further extended the approach. Amiet used surface pressure data for a flat plate boundary layer in his calculations. His work can be further refined using references 8.11 and 8.12 to provide the ability to model trailing edge noise if accurate expressions for surface pressure are available. Yu and Joshi [8.13] as well a Schlinker and Amiet [8.14], Brooks and Hodgson [8.15,8.16], and Chou and George [8.17] have all attempted to improve the prediction of trailing edge noise by improving on the curve fitting of measured airfoil surface pressure data.

Another broadband noise prediction method that concentrates on curve fitting of trailing edge noise data was published by Schlinker and Amiet [8.14]. It uses the frequency dependence of reference 8.18 to give a prediction of the broadband noise spectrum in 1/3 octave bands. Kim and George [8.19] and George and Chou [8.20] have also worked with Amiet's approach. This work is discussed in Reference 8.21.

Two other sources of broadband noise have been studied (1) noise due to interaction of inflow turbulence with a propeller/rotor, and (2) interaction of the turbulence in a locally separated region of a blade tip with the tip trailing edge. For propellers under normal flight conditions these sources are not significant. For further discussion see references 8.21, 8.22, and 8.23.

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9.0 CONCLUDING REMARKS

This report demonstrates that there are a large number of propeller noise prediction methods available at the present time. These vary in complexity from simple empirical methods requiring only hand calculations to very sophisticated and complex computer codes that require super computers for their use. All of these codes have a use. While some are less complex than others, they still provide sufficient accuracy for the needs of many users.

In reviewing the literature it was found that many methods had not been sufficiently evaluated relative to test results. This was due in some cases to lack of test data and in others a lack of sufficient funding for thorough evaluation. Also, many methods exist only as research codes without documentation. Therefore a potential user will have difficulty in acquiring the code and understanding its limitations. The unique features of such research codes need to be incorporated into well documented, accessible and user-friendly codes for the benefit of potential users.

In summary, it appears that deficiencies in the accuracy of propeller noise predictions, in many cases, may be related <u>not</u> to the noise methods being used but the accuracy and detail of the aerodynamic inputs to the calculations. It appears that the needs in propeller noise prediction are not <u>more methods</u> but a consolidation of the unique features of the many existing methods. A thorough review of the most promising methods relative to well documented, high quality data is also required to establish accuracy and limitations.

10.0 RECOMMENDATIONS FOR FURTHER WORK TO IMPROVE PREDICTION METHODS

The information presented in earlier sections of this report demonstrate that extensive experimental and analytical work has been conducted over an extended time period to develop methods for accurate prediction of propeller noise. However, the accuracy of the methods is not fully known; in same cases because data for correlation is not available and in other cases the method has not been fully exercised relative to available data. Furthermore, the complexity of some methods make their use impractical for many potential users.

The steps recommended to provide prediction methods that are as accurate and as easy to use as is consistent with the complexity of the predictions are listed below:

1. Identify reliable test data for correlation with prediction methods;
2. Define and conduct experimental test programs to fill gaps in the existing data base;
3. Identify the most promising prediction methods;
4. Evaluate promising prediction methods relative to the data base;
5. Identify and correct the weaknesses in the prediction methods including lack of user friendliness; where appropriate, include features now available only in research codes;
6. Confirm the accuracy of improved prediction methods relative to the data base;
7. Make the methods widely available and provide training in their use as required.

Step 1 is the foundation for successfully developing accurate prediction methods. Although many test programs have been run, over the years, the majority are flawed in terms of providing an acceptable set of data for correlation studies. For example, many tests were run in the early days of propeller noise research under static conditions. It is now known that this data is not consistent with flight data since inflow turbulence or ground vortex interaction with the propeller operating statically is a dominant noise source. Also, because of cost or facility constraints, many propeller noise tests have been done at small scale with results that may be questionable. The requirements for acceptable test data are listed below:

a. Full scale or large scale test hardware;
b. Known and acceptable test environment consistent with test objectives;
c. Known test hardware definition;
d. Accurate data of sufficient detail for correlation studies.

An example of test data that is suitable for correlations studies is that which was obtained in the DNW Tunnel in a joint DFVLR/FAA program. In this program the test hardware is full scale (two different General Aviation propellers), the test environment is known and consistent with the objective of measuring inflight noise, and the noise and other supporting data is catalogued in great detail (narrow band noise spectra, time history plots, etc.).

In Step 2 the deficiencies in available high quality data are filled. For example extending the conventual General Aviation propeller noise data base to high helical tip Mach number where the non-linear quadrupole is of concern is desirable. Also the influence on noise of the wing circulation in multi-engine aircraft should be documented under controlled test conditions. This work should be done with a carefully selected set of variables in the propeller geometry including blade number, planform and thickness distribution.

In identifying the most promising noise prediction methods (Step 2 above) many factors should be considered. These are listed in the following table:

Type of Method

Characteristics	Empirical	Reduced Complexity Theoretical	Detailed Theoretical
Calculation Platform	Graphs or hand held calculators or PC	PC or workstation	Workstation, mainframe or super computer
Input Complexity	Simple	Moderate	Complex
Input Source	Stand alone	Stand alone	External Sources
Output Complexity	Limited to specific requirement	Somewhat limited	Capable of satisfying diverse objectives
Uses	Preliminary design studies, Certification retrofit evaluations, Land use planning	Preliminary design studies, Certification studies including retrofit evaluations	Research programs, Propeller or aircraft design, Near field noise prediction for cabin comfort design or research

As listed in the above table there are three types of prediction methods: empirical, reduced complexity theoretical and detailed theoretical. The Society of Automotive Engineers AIR 1407 is an example of the empirical methods. It is a graphical procedure that can be used without access to a computer. The ANOPP-PAS for PC is an example of the reduced complexity theoretical methods. It runs on a personal computer. The ANOPP is an example of the detailed theoretical methods. It runs on a mainframe computer.

The complexity of inputs needed to run the different types of prediction method varies with the degree of complexity of the calculations performed. The empirical methods require very simple inputs such as power, RPM, flight speed and number of blades. The reduced complexity theoretical methods are stand-alone programs that require somewhat more input than the empirical programs. For example, the geometry of the propeller blade must be defined to run the ANOPP-PAS. The more complex theoretical procedures in may cases rely on external inputs that may be generated by methods as complex or more complex than the noise prediction procedure itself. For example, the ANOPP code in some cases has been run with input generated by computational fluid dynamics codes.

The outputs from the different types of methods also differ. The empirical method outputs are usually very specific and limited. For example, the method developed by Smith only predicts A-Weighted noise of airplane flyovers. The reduced complexity theoretical methods have a somewhat limited output but usually have more general outputs like those of the detailed theoretical methods. For example the V/STOL method provides noise spectra for thickness, loading and broadband noise components at different directivity angles in an airplane flyover. It also provides outputs in dBA, PNdB and EPNdB. The detailed theoretical methods have outputs limited only by the output subroutines included. These can deal with layered atmospheric effects such as sound propagating from an airplane at a high altitude to the ground or sound propagating through a boundary layer from a wing-mounted propeller to a nearby fuselage surface.

As the above table indicates, the empirical methods are often used for preliminary design studies. They are also used by certification authorities to determine whether a proposed propeller retrofit an on existing airplane will have an acoustic impact. This type of method is also useful in land use planning since a common output is dBA, the unit often used in land use planning.

The reduced complexity theoretical methods are also used for preliminary design studies and for certification evaluations. Their added capability makes them more useful for investigating the effects of changes in propeller configuration and operating condition.

The research organization, propeller designer or airplane designer with significant computer resources will use the detailed theoretical methods. These methods are required to make accurate tradeoff studies between noise, performance, structure, weight, and cost. Also the airplane designer needs the ability of these more complex methods to conduct airplane certification noise studies and the fuselage noise reduction studies required to achieve acceptable cabin comfort levels.

In steps 4, 5, and 6 the methods selected as being most promising and useful for the many types of user are evaluated, improved where necessary and then checked to insure that the improved versions are sufficiently accurate. One factor that must be emphasized in any evaluation or improvement is the user-friendliness of the methods. Also, the many research codes that have been developed over the years should be reviewed. Where appropriate, unique features from these codes should be added to the codes selected as being most promising. The objective of this is to improve accuracy, reduce complexity or reduce computing cost.

Finally in Step 7 the methods are made available to users and, where necessary, training for use is provided. Such training is imperative for the more complex methods.

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The information in five reports is acknowledged as the basis for significant insight into various theoretical and empirical methods: 1) Rotating Blades and Aerodynamic Sound by C. L. Morfey[3.3], 2) A Review of Propeller Discrete Frequency Noise Prediction Technology with Emphasis on two Current Methods for Time Domain Calculations by F. Farassat and G. P. Succi[5.11], 3) Linear Acoustic Formulas for Calculation of Rotating Blade Noise by F. Farassat [5.14], 4) The State-of-the-Art in Propeller Noise Prediction by B. Magliozzi[7.5], and 5) Propeller and Propfan Noise by B. Magliozzi, D. B. Hanson, and R. K. Amiet[8.7].

Finally the author gratefully acknowledges the help of J. Preisser and the Library Staff of NASA Langley Research Center for making available many of the reports reviewed.

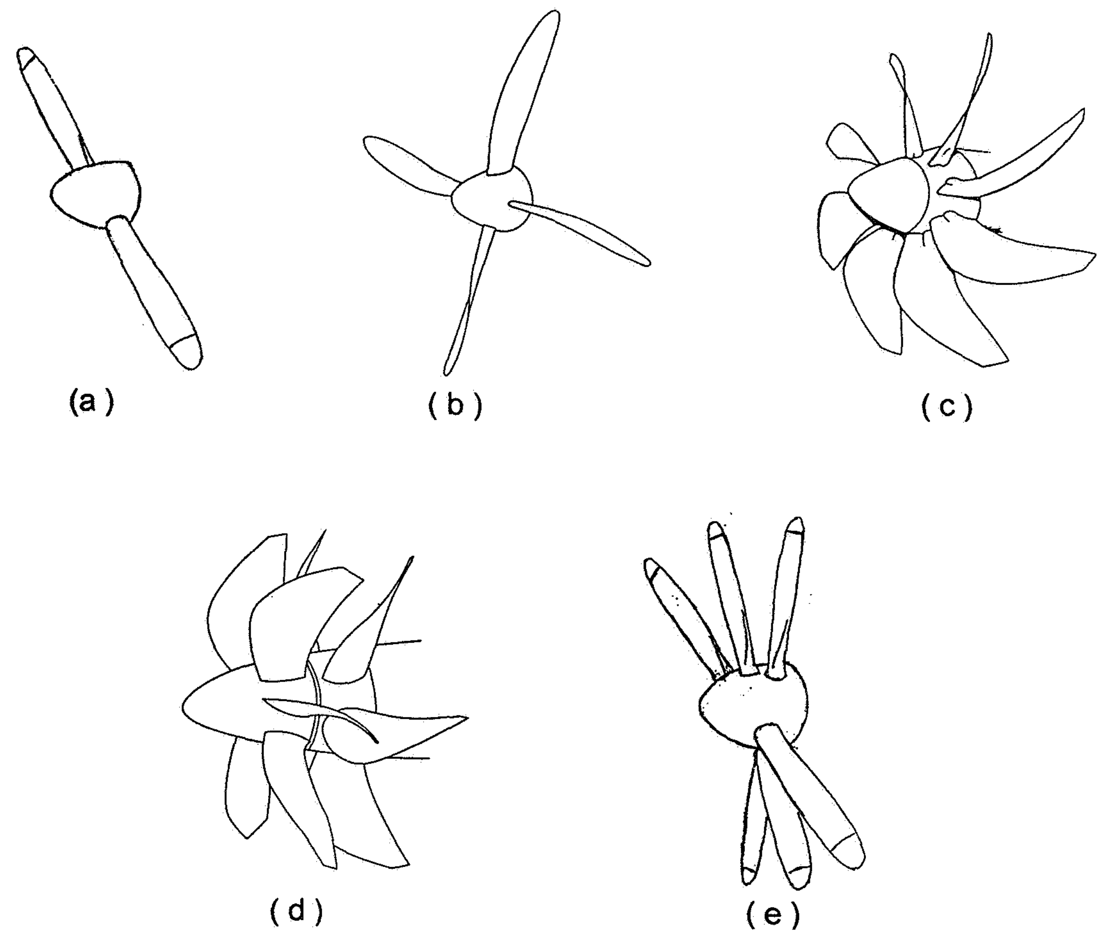


Figure 2.1- Propeller Configurations: (a) General Aviation, (b) Commuter, (c) Single Rotation Propfan, (d) Counter Rotation Propfan, and (e) General Aviation Unequal Blade Spacing

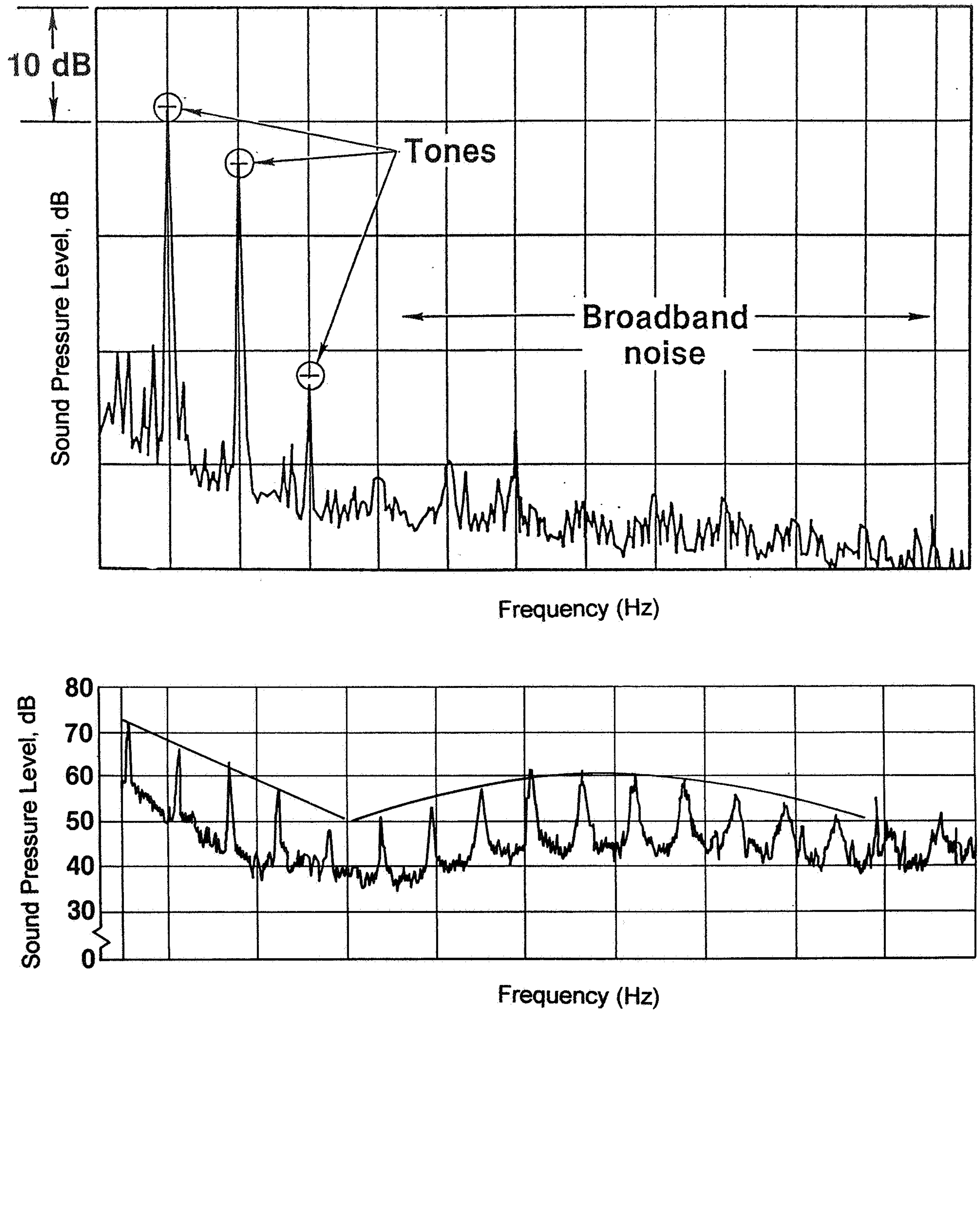


Figure 2.2-Propeller Noise Spectra: In Flight in the Top Figure; Static in the Bottom Figure

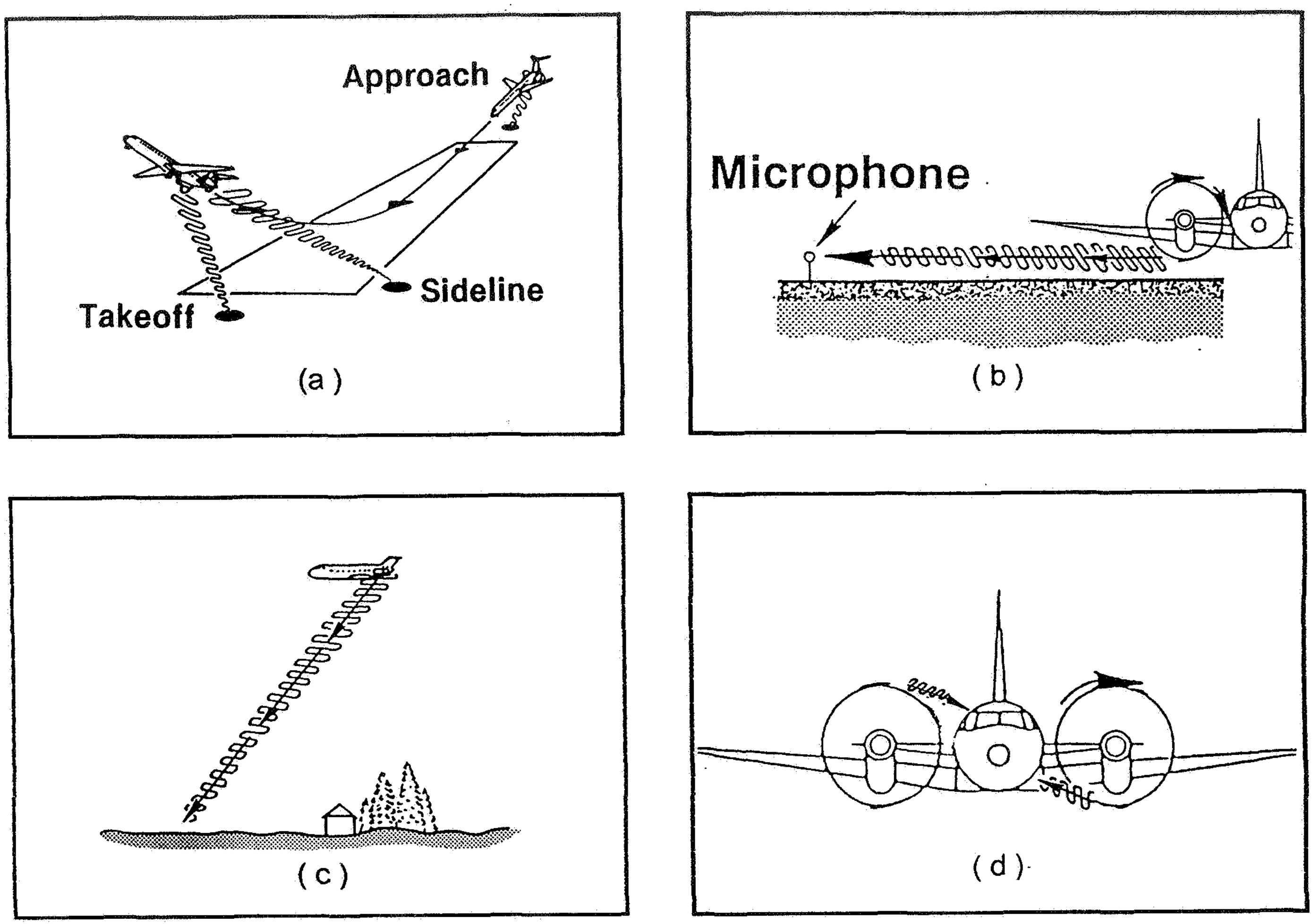
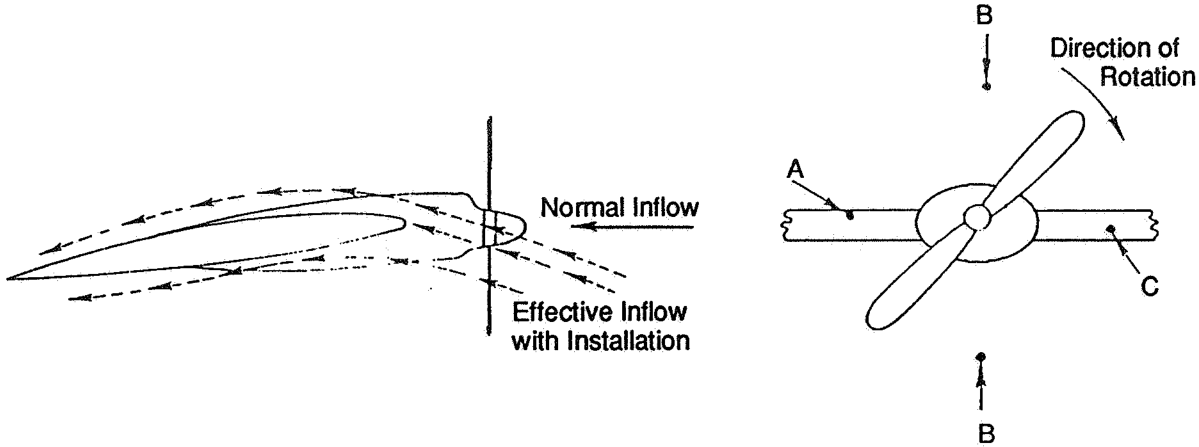


Figure 2.3-Scenarios of Interest for Propeller Noise Prediction:

a. Far Field (Takeoff, Climb, Level Flyover) for Noise Certification
b. Far Field (Static, Taxi, Acceleration to Liftoff) for Airport Noise
c. Far Field (Cruise) for Enroute Noise
d. Near Field (In Flight) for Cabin Noise



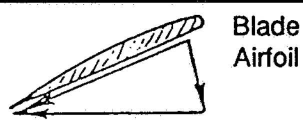
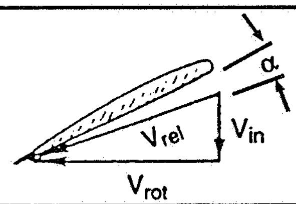
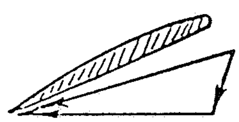
Blade Location	Velocity Vectors Rotation, V_{rot}; Inflow, V_{in}	Relative Velocity V_{rel}	Angle of Attack, α	Blade Loading
A		Lowest	Lowest	Lowest
B		Average	Average	Average
C		Highest	Highest	Highest

Figure 2.4-Effects of Non-Uniform Inflow on Factors Affecting Propeller Noise

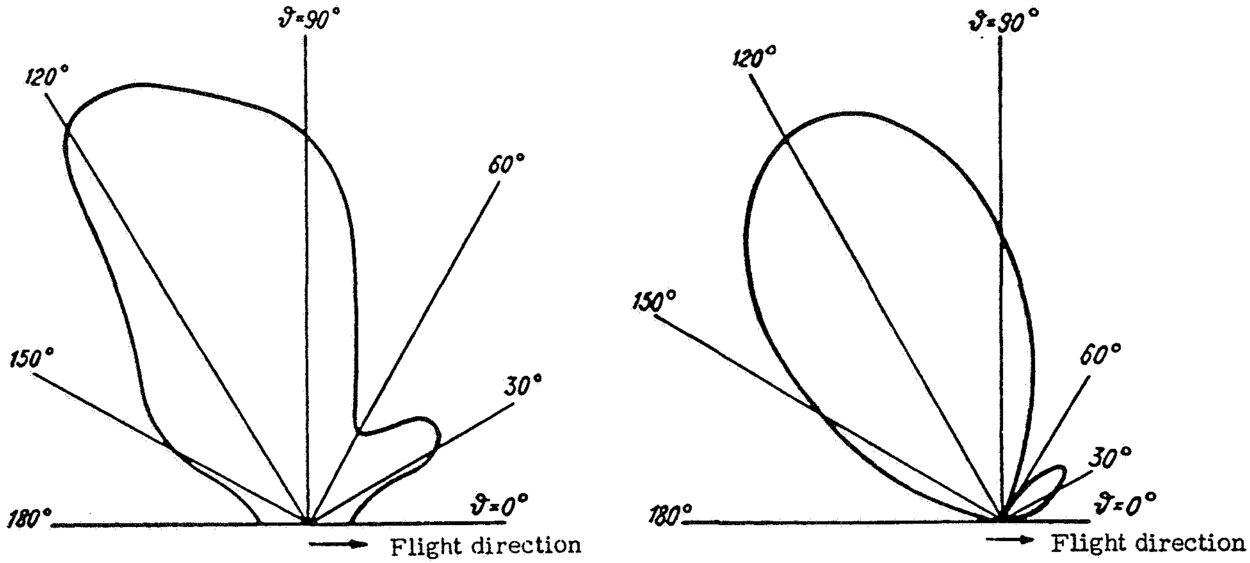


Figure 3.1-Gutin's Comparison of Measured (left) and Theoretical (right) Directivity of the Fundamental Tone of a Two-Blade Propeller (Ref. 3.4)

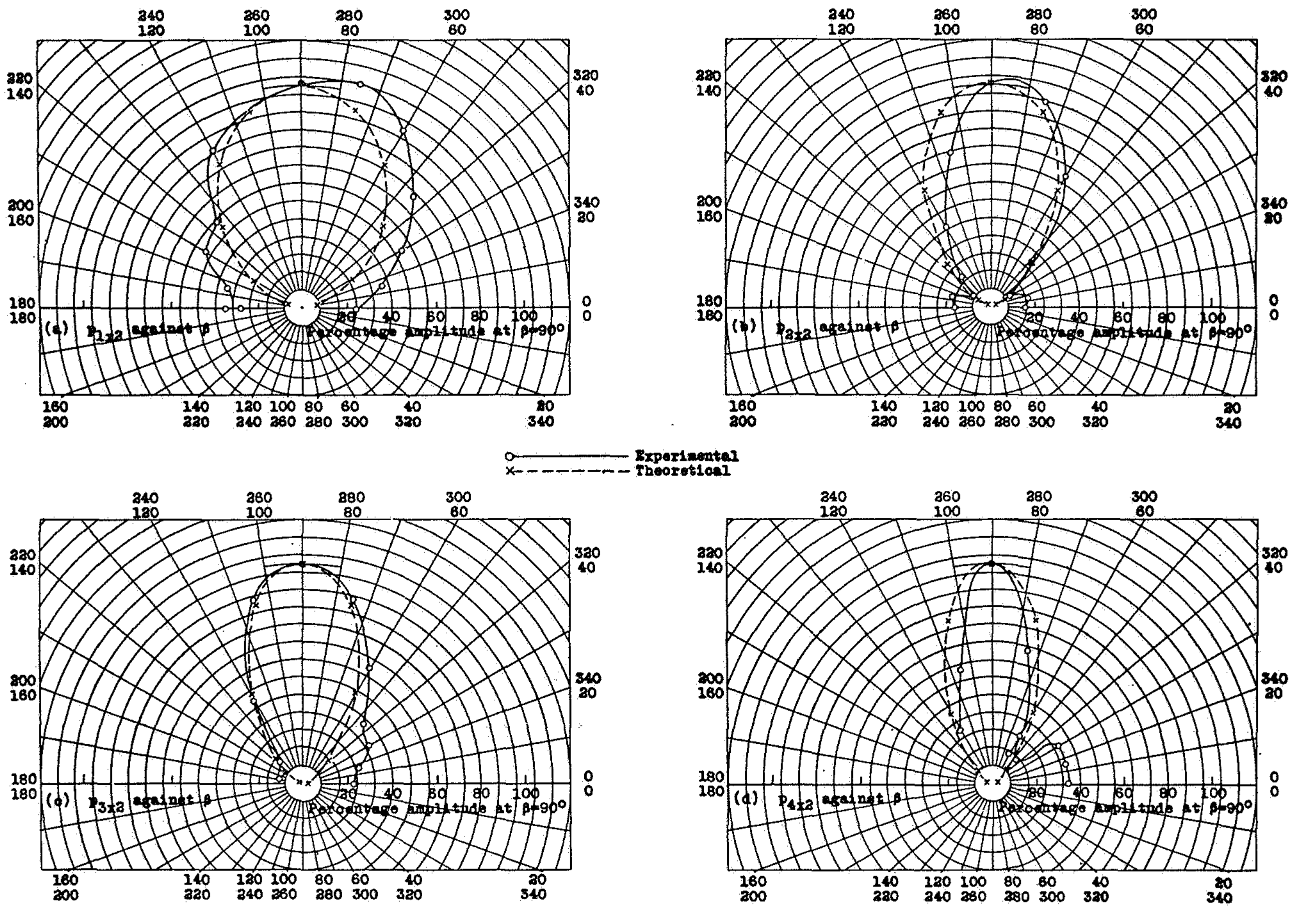


Figure 3.2-Deming's Comparisons of Measured and Predicted Directivities for the First Four Harmonics of a Two-Blade Propeller with Symmetical Airfoil Sections at Zero Blade Angle of Attack (Ref. 3.8)

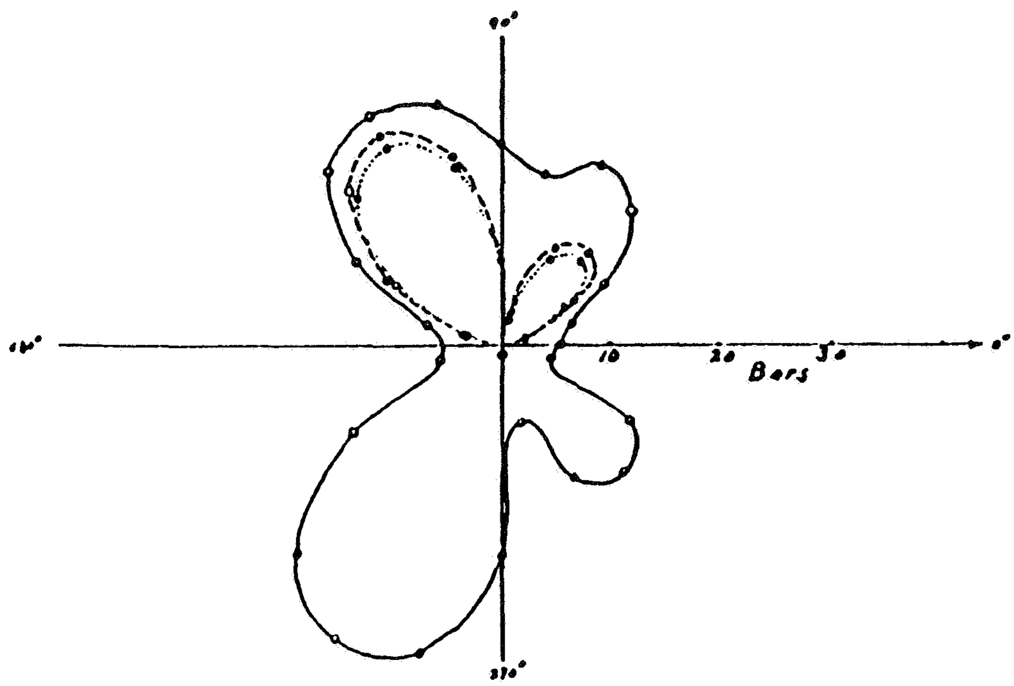


Figure 3.3-Deming's Comparison of Measured (Solid Line) and Theoretical (Dashed Line) Directivities of the Fundamental Tone of a Two-Blade Propeller (Ref. 3.8)

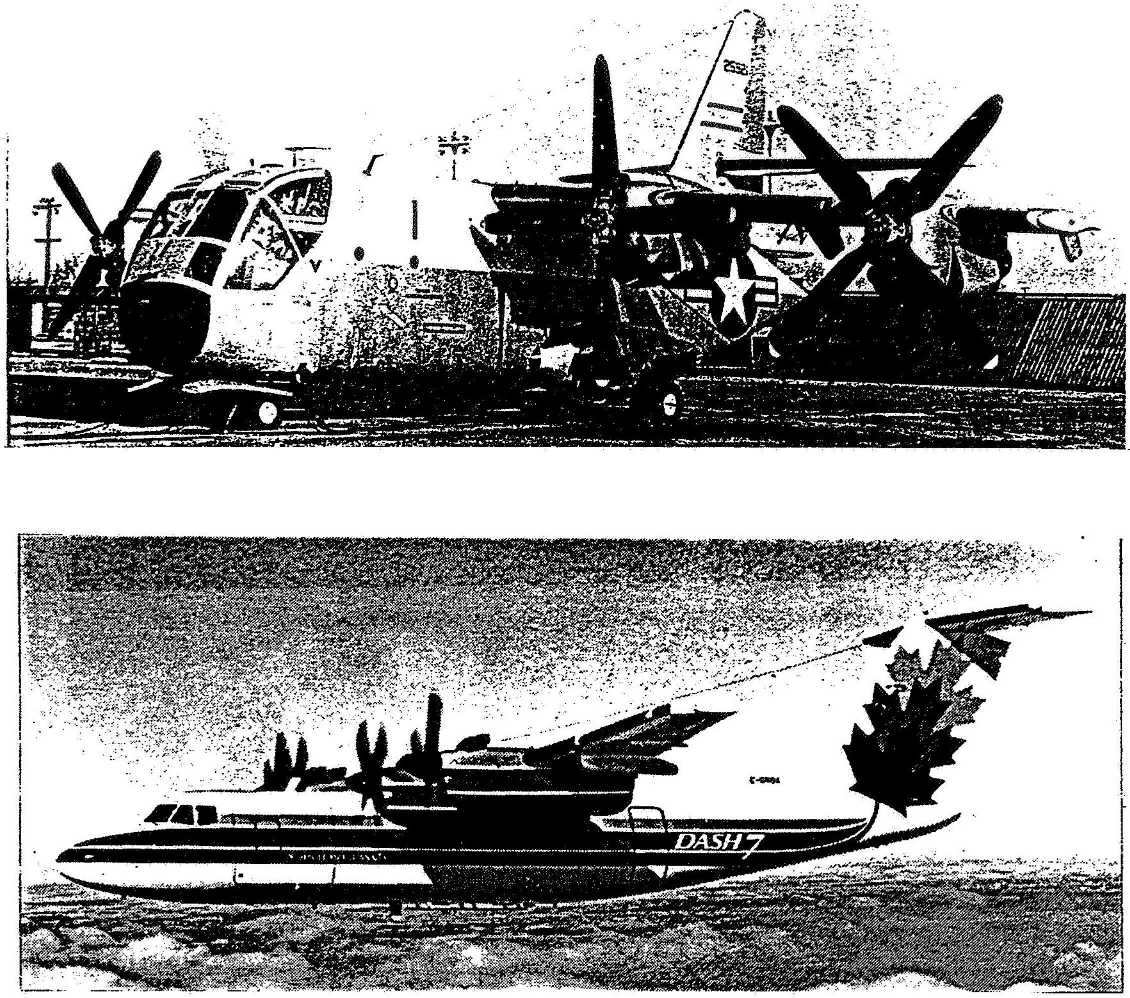


Figure 4.1-Examples of V/STOL Airplanes: Ling Temco Vought XC142 (top) and deHavilland Dash-7 (bottom)

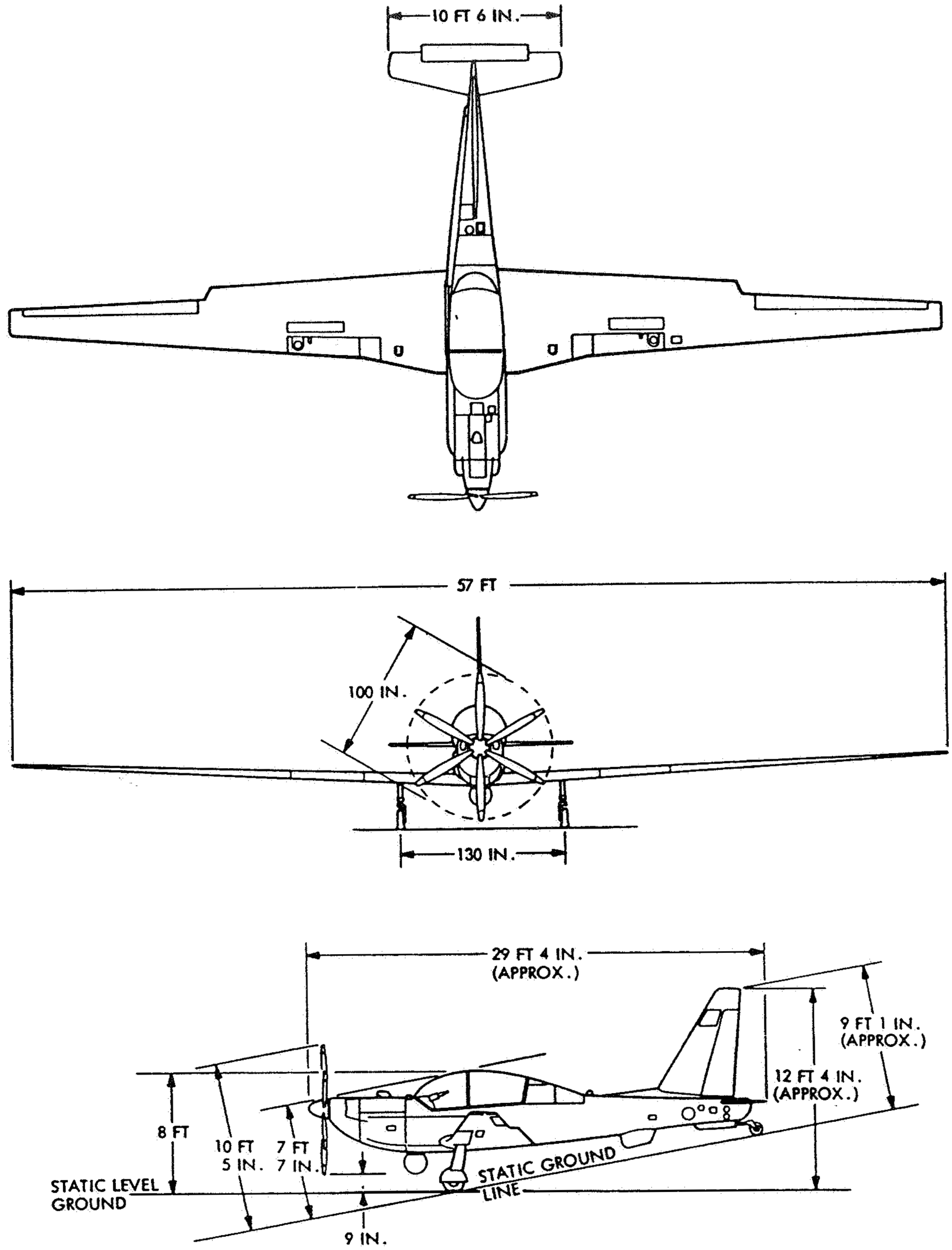
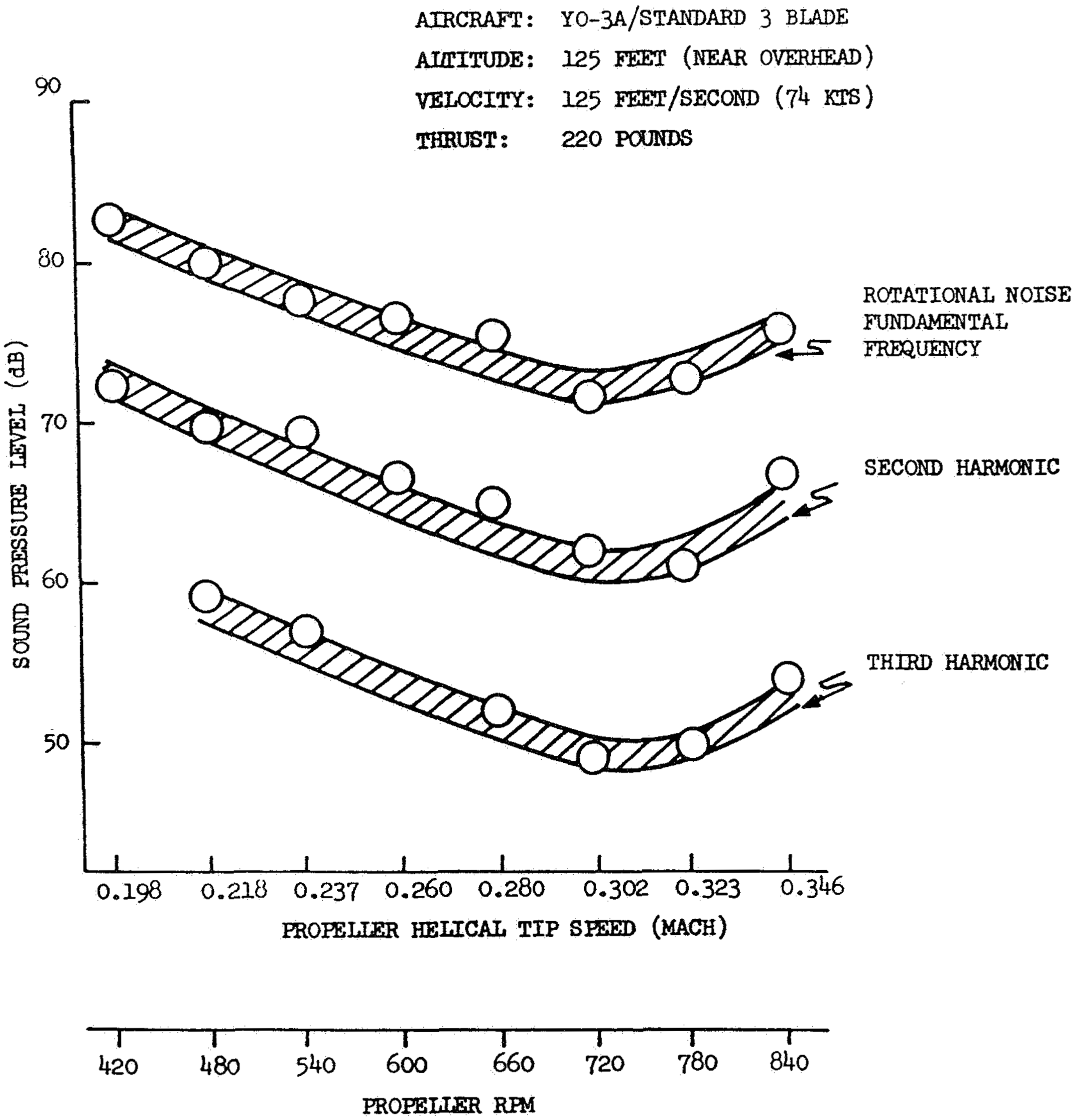


Figure 4.2-YO-3A Quiet Reconnaisance Airplane (Ref. 4.4)



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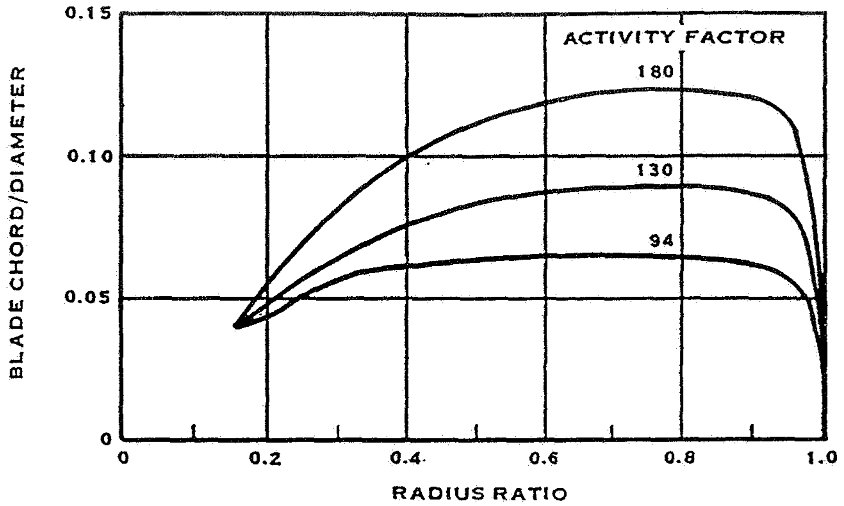
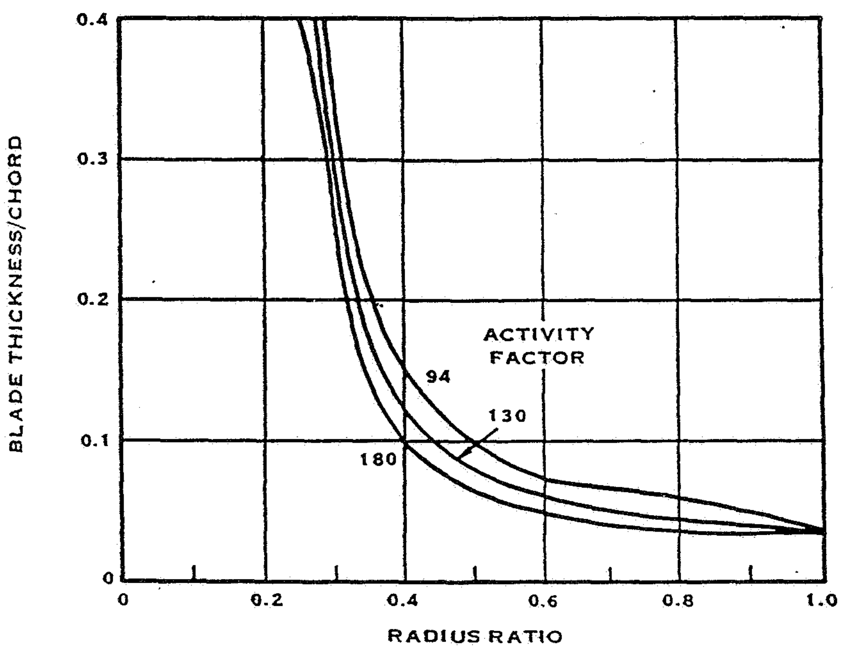


FIGURE 2. GENERALIZED BLADE CHORD DISTRIBUTION



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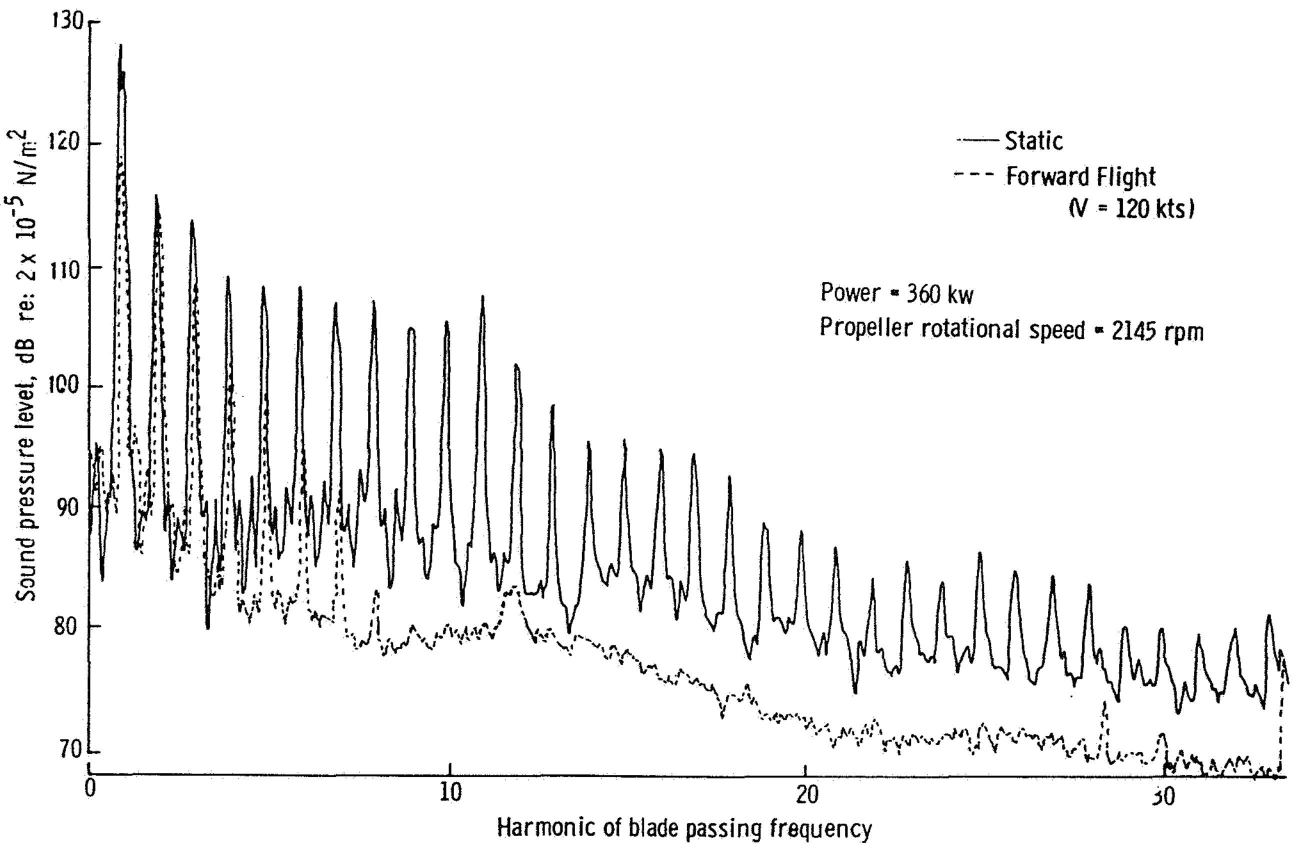

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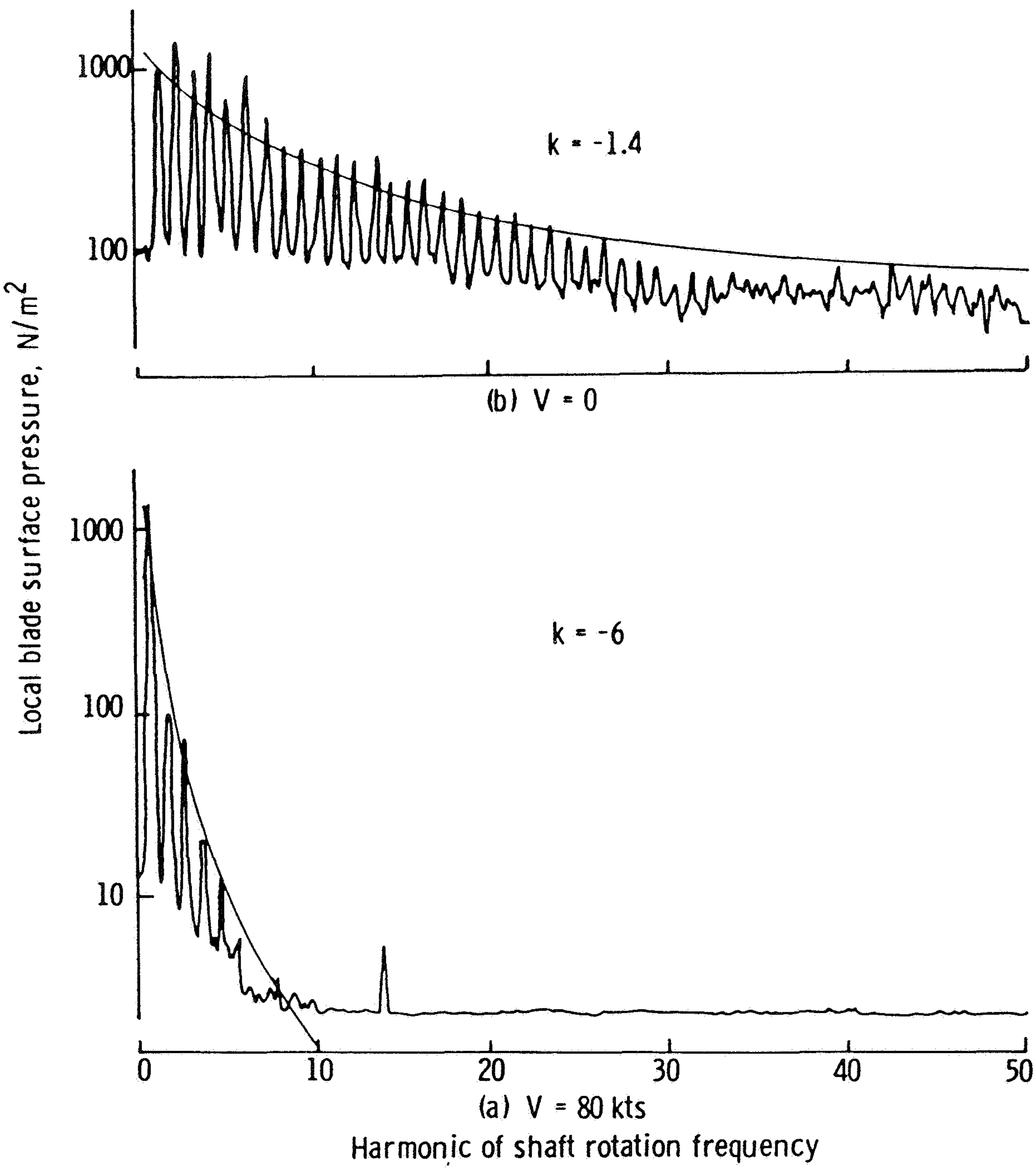

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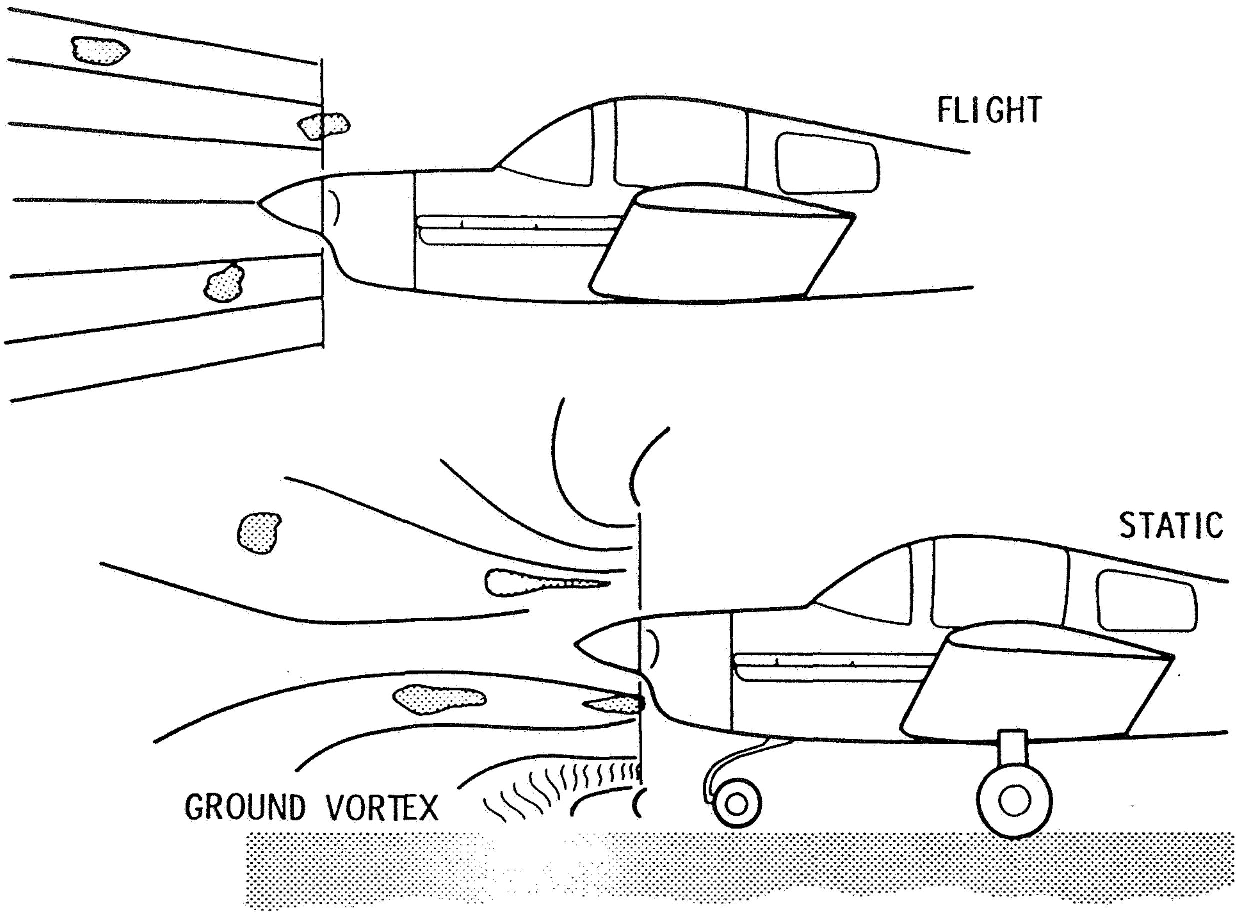

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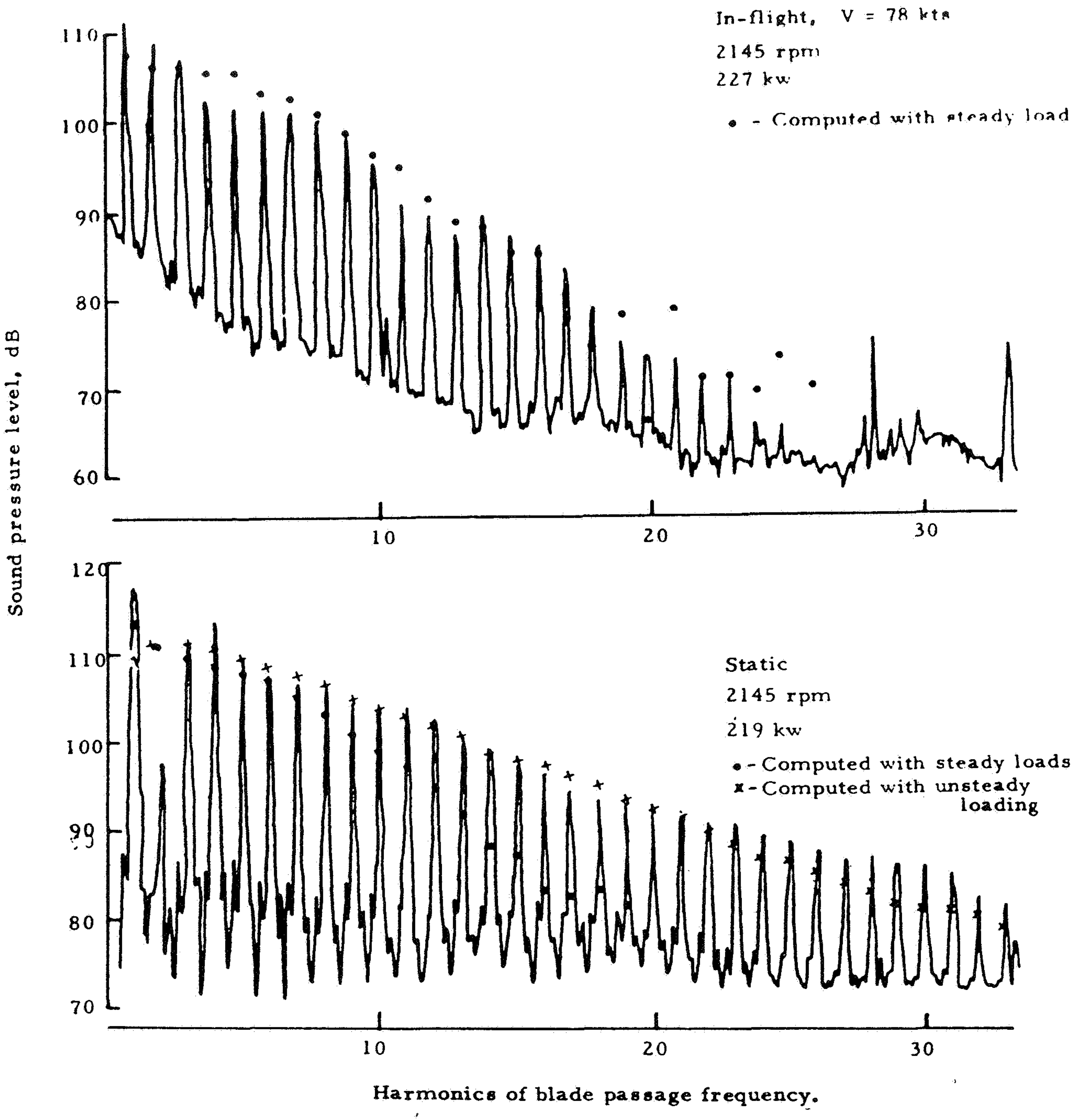

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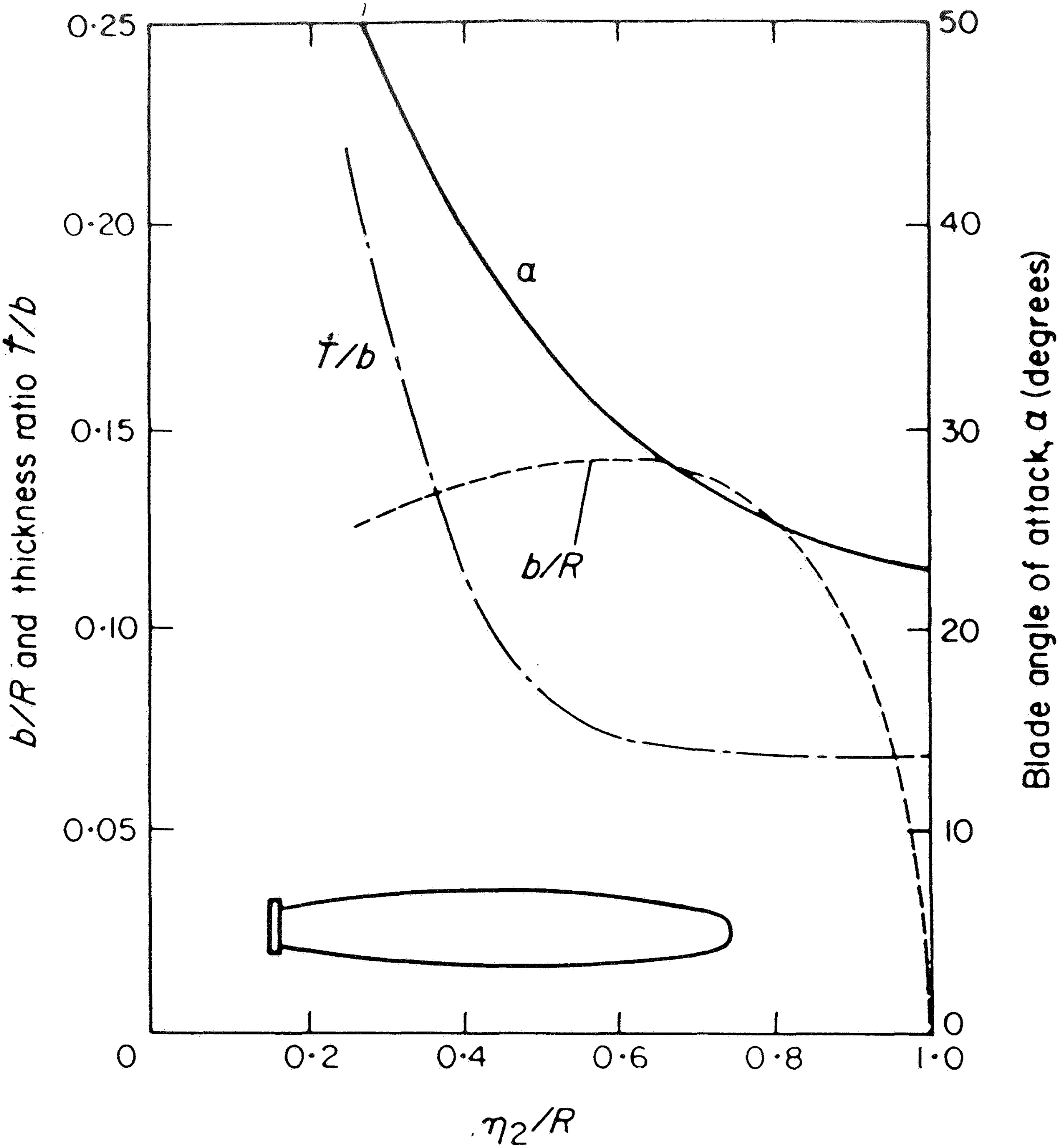

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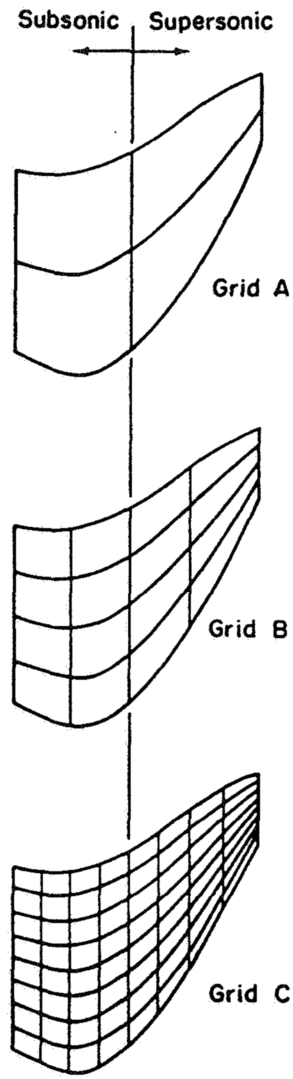

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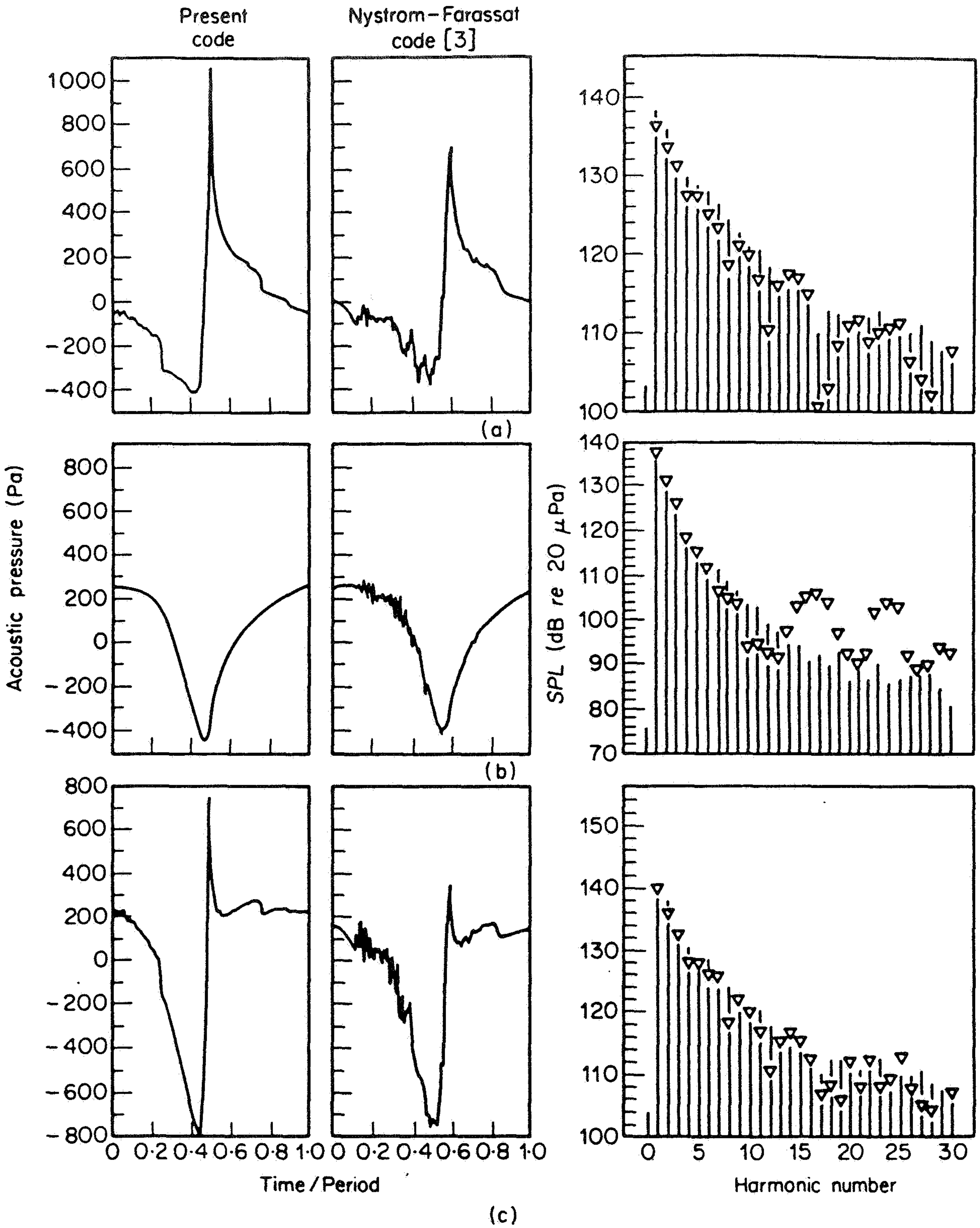

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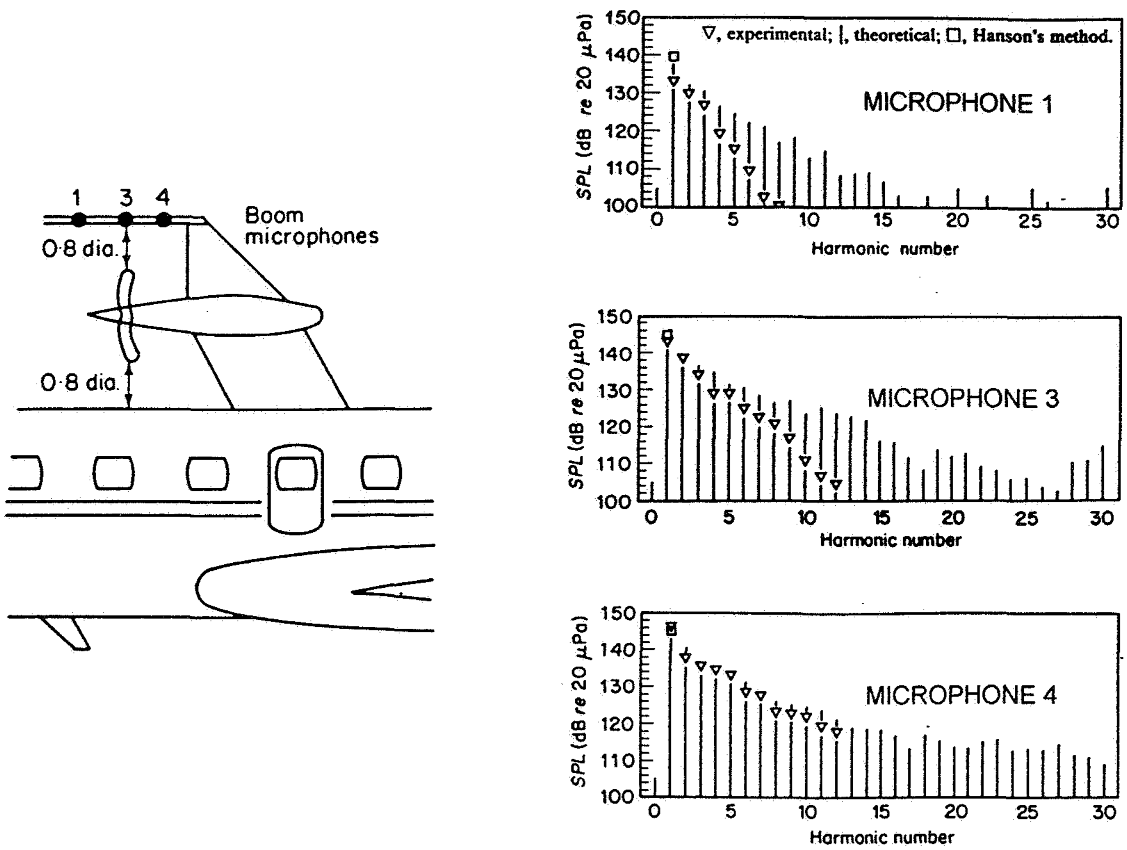

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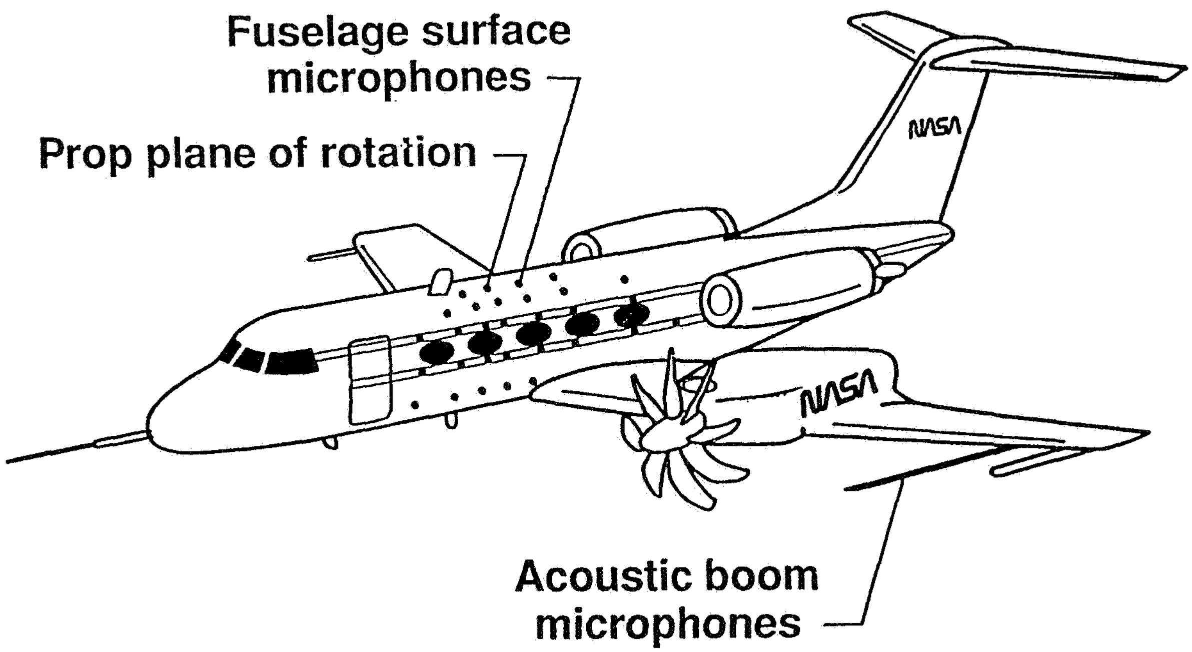

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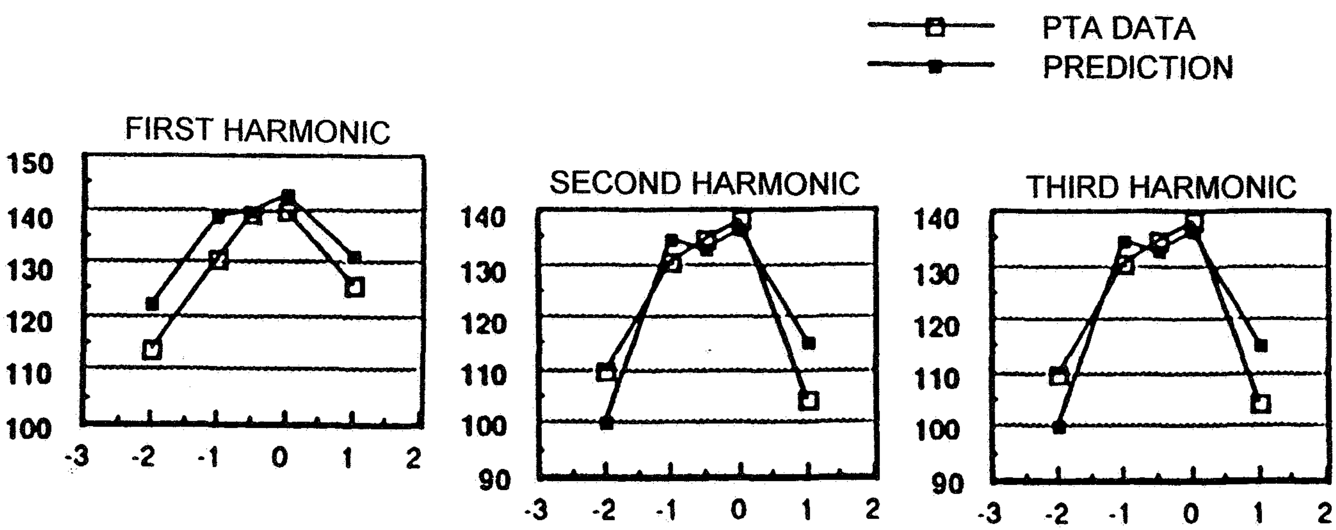

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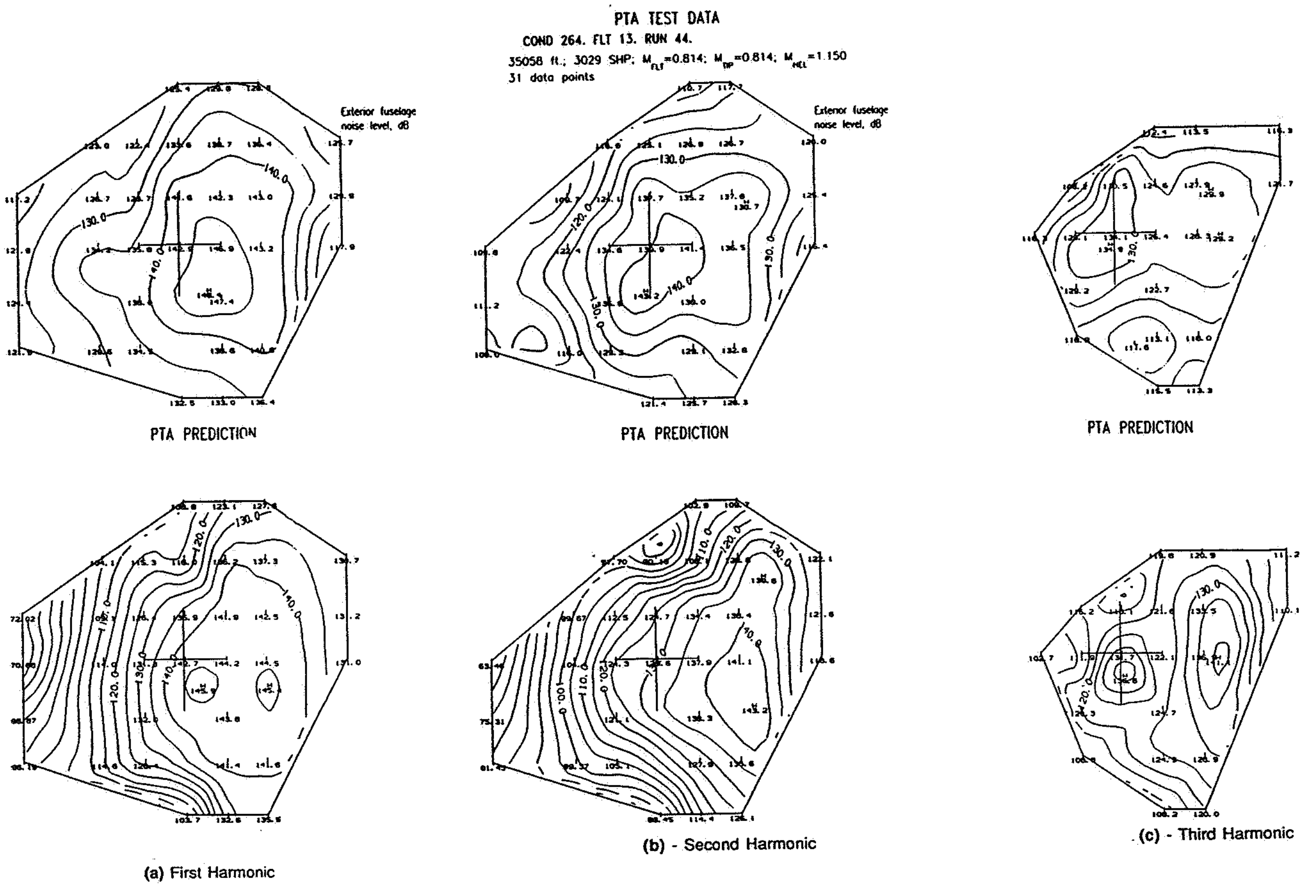

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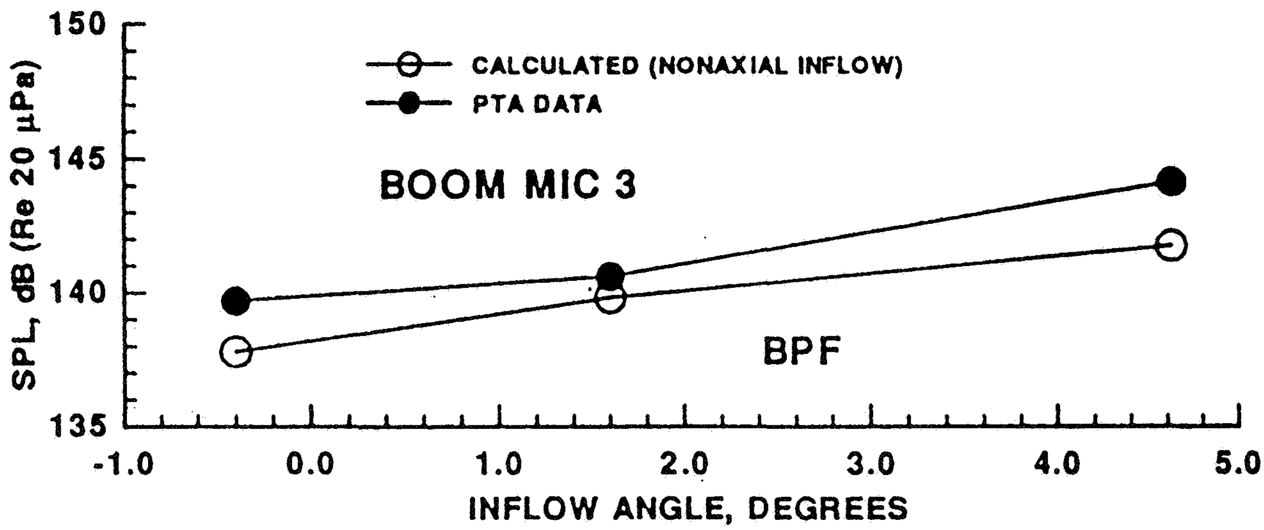

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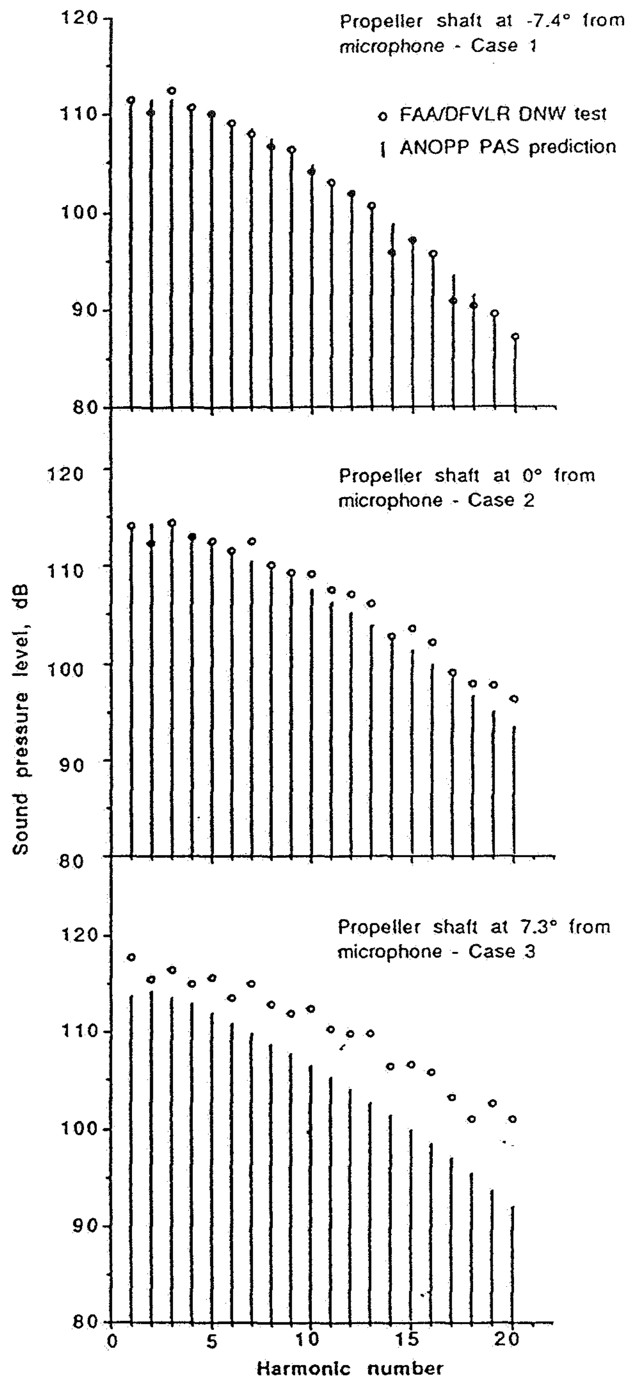

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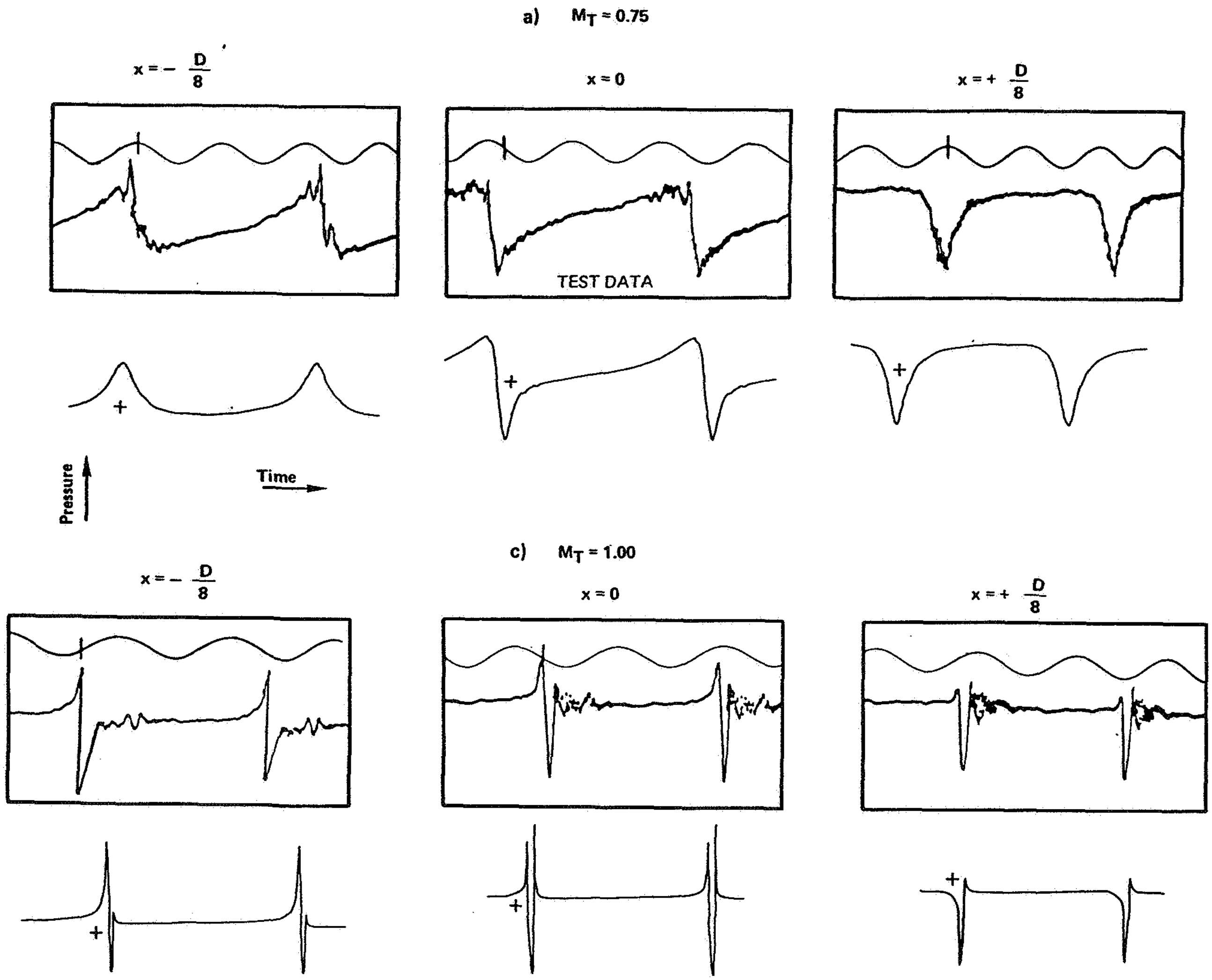

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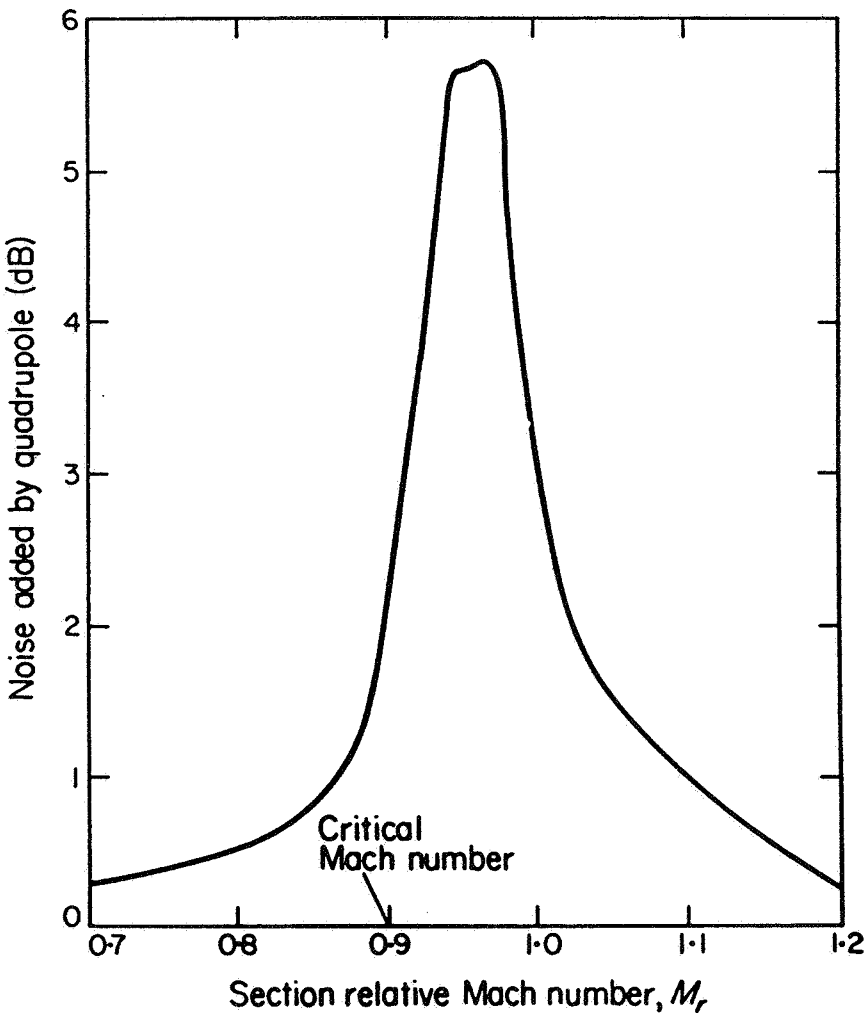

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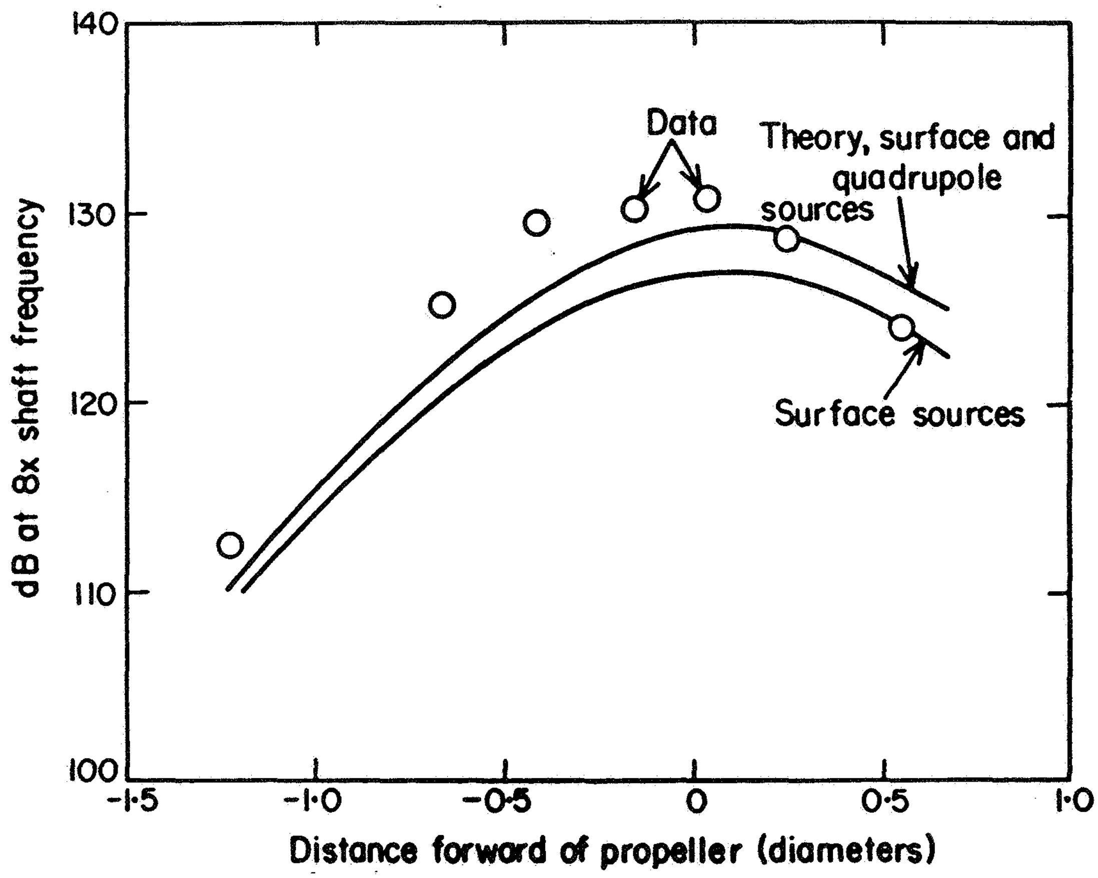

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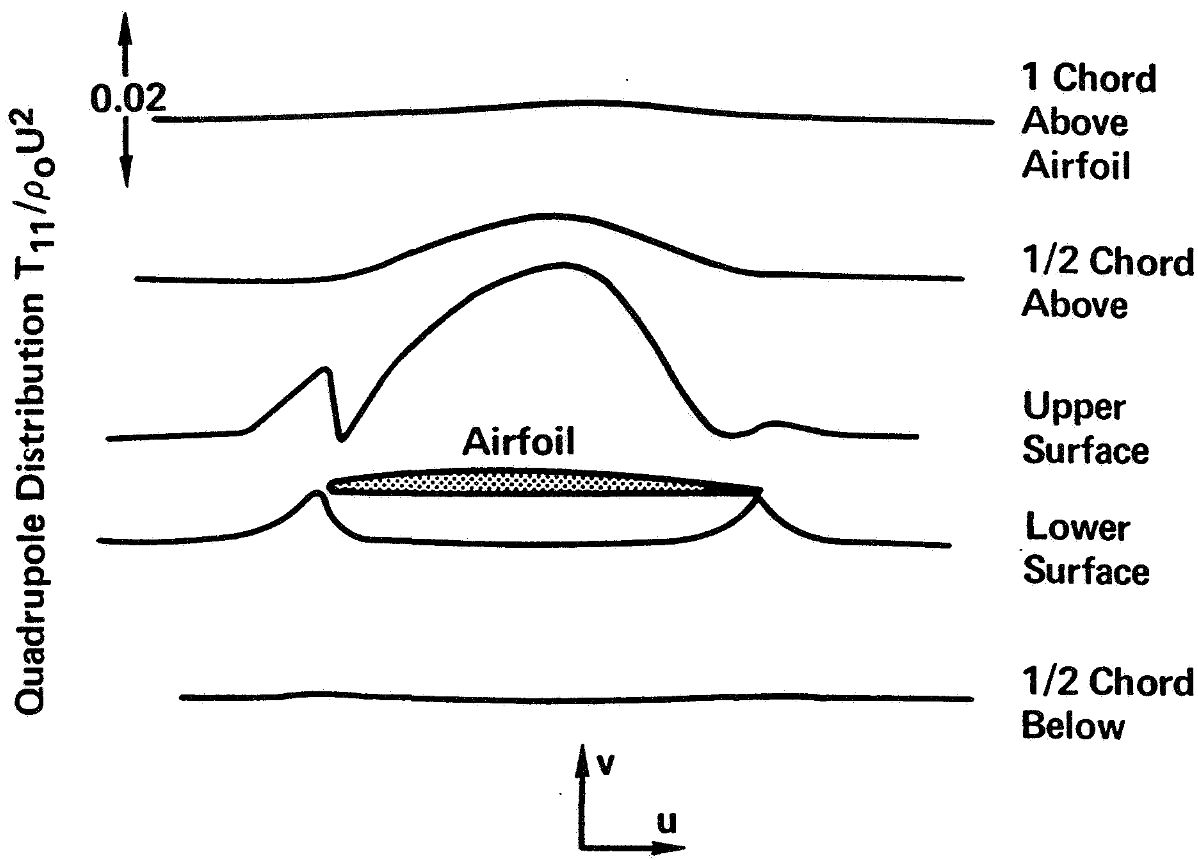

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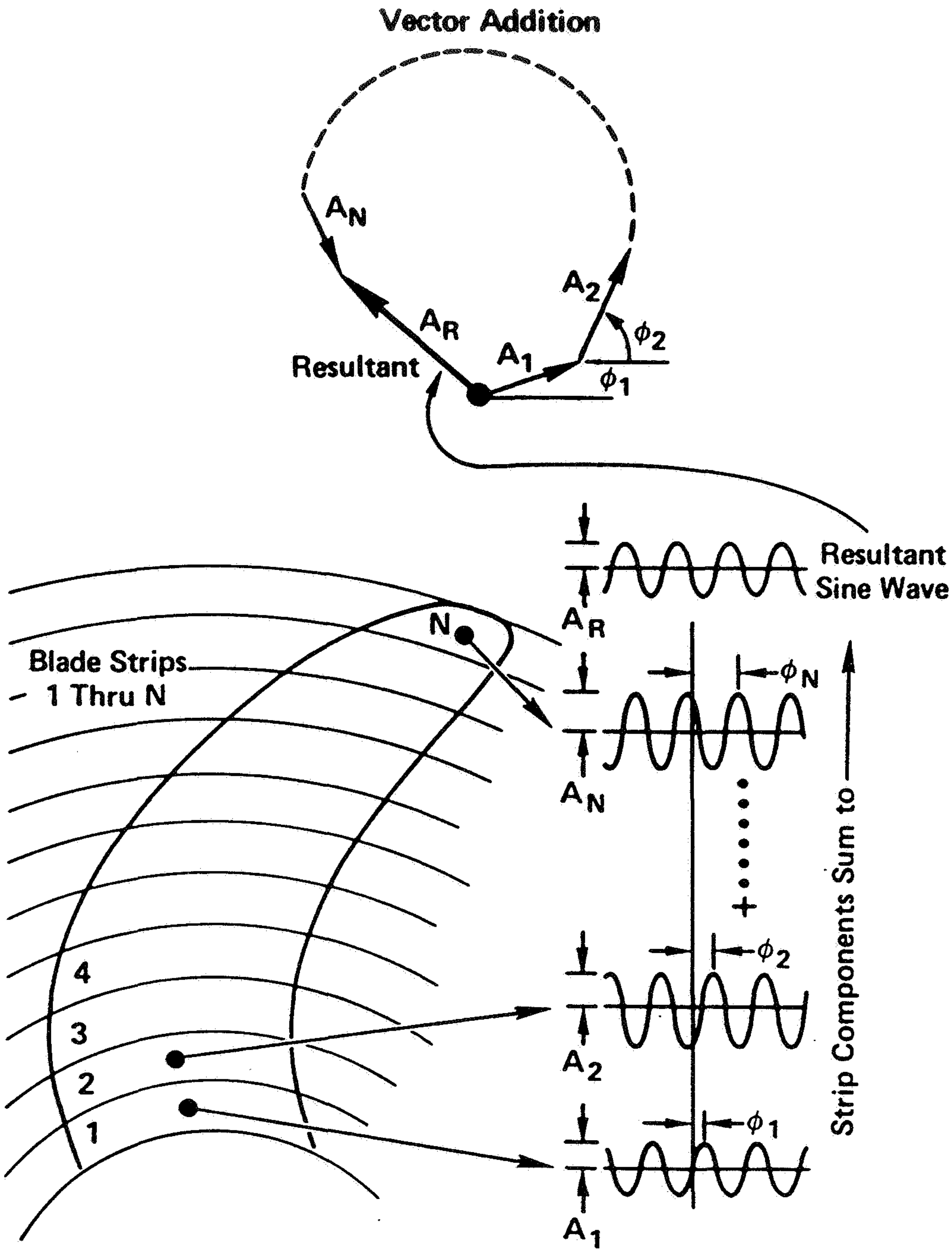

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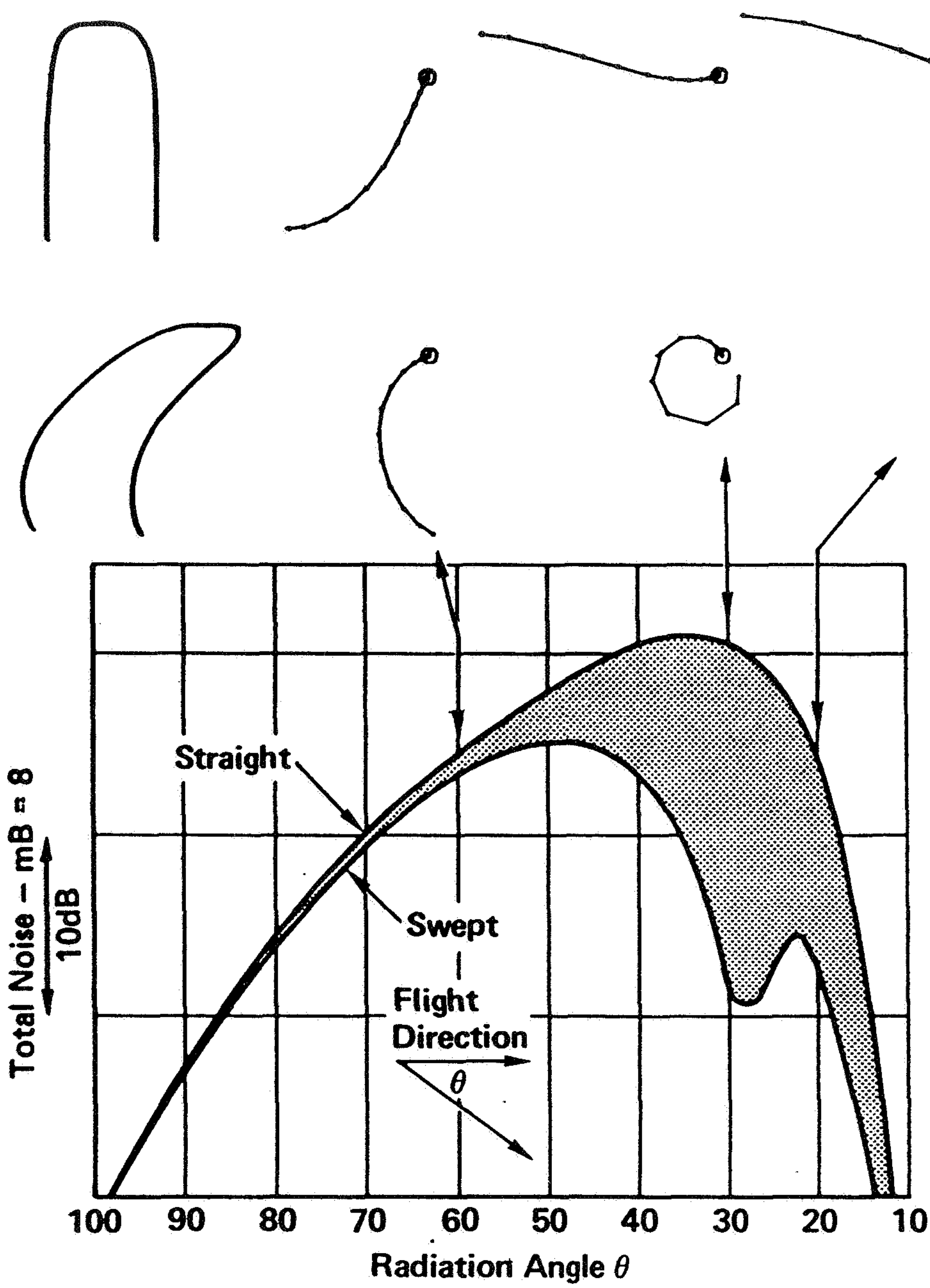

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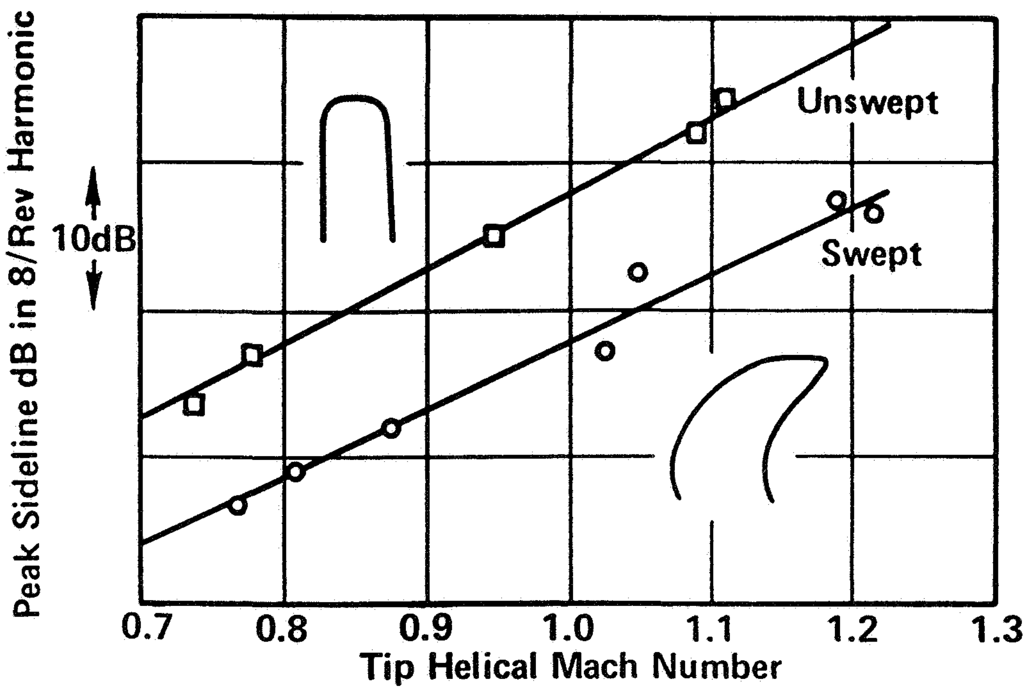

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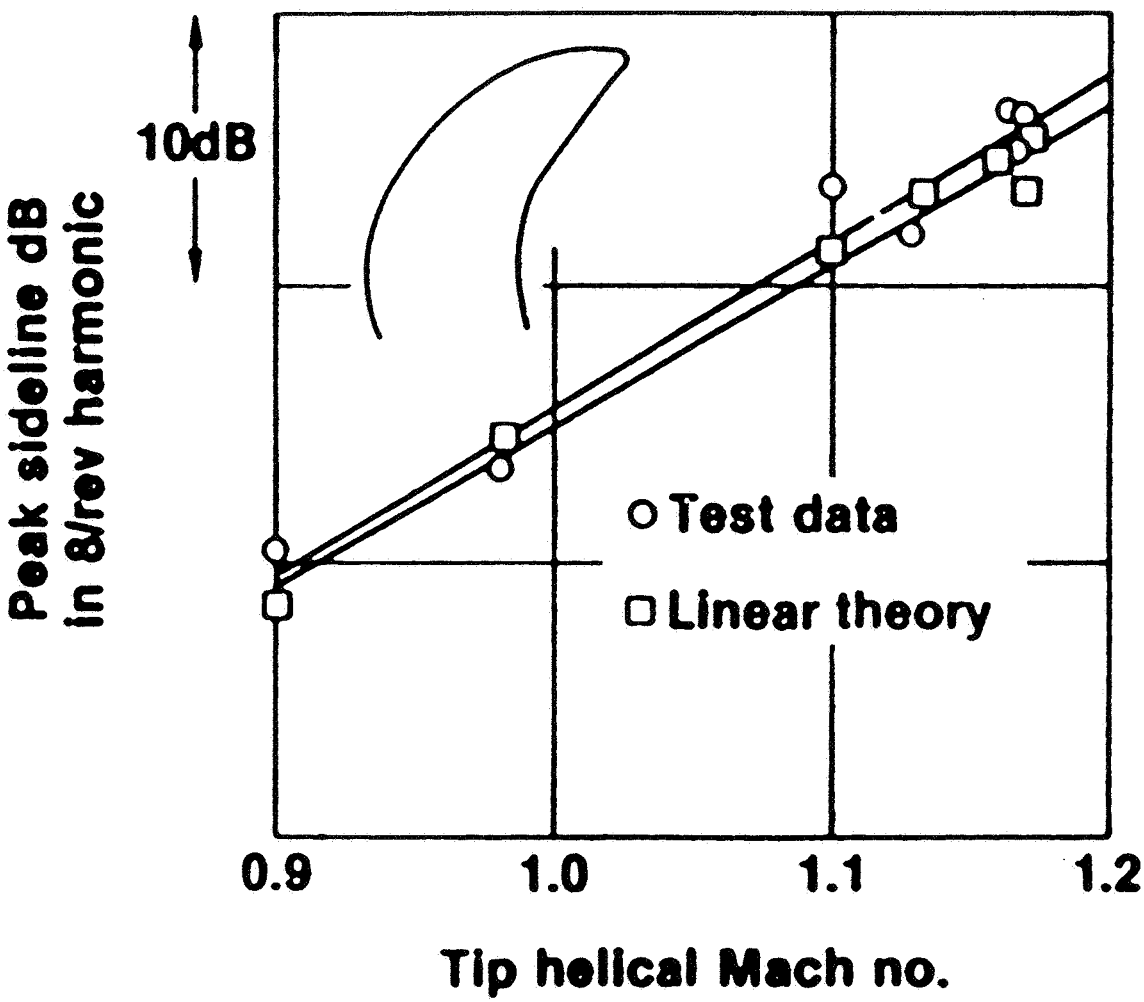

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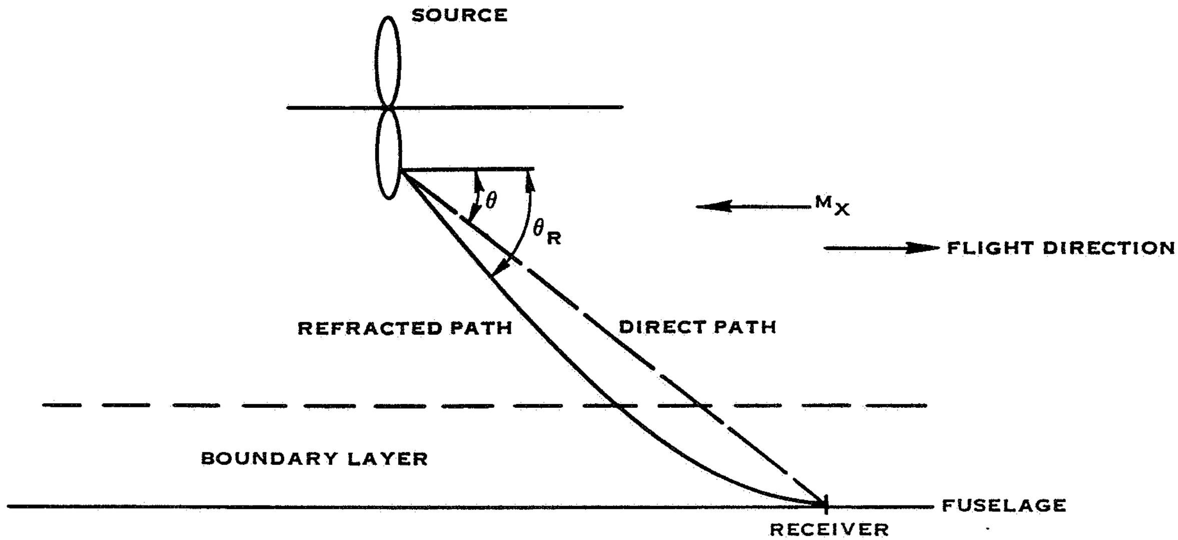

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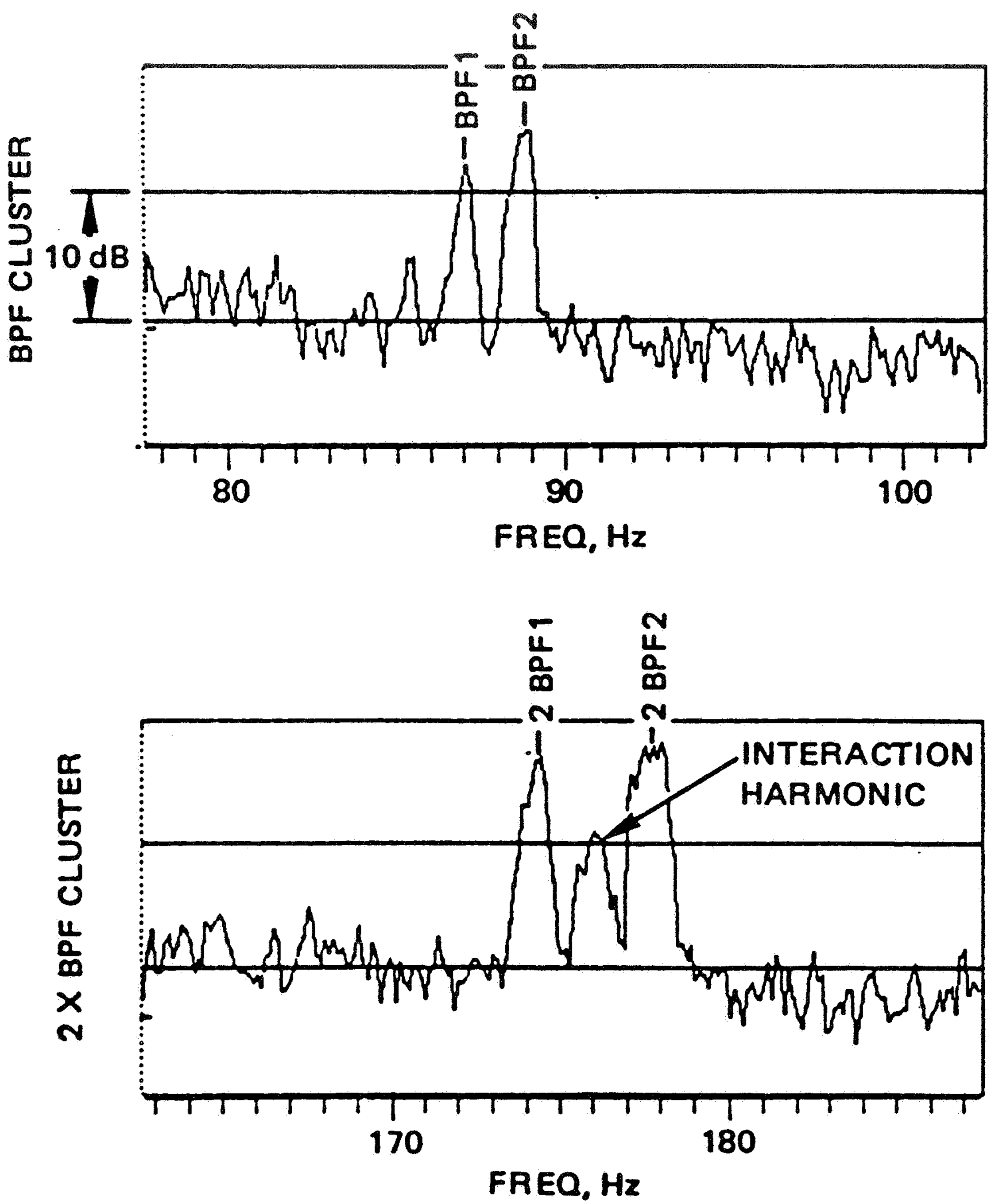

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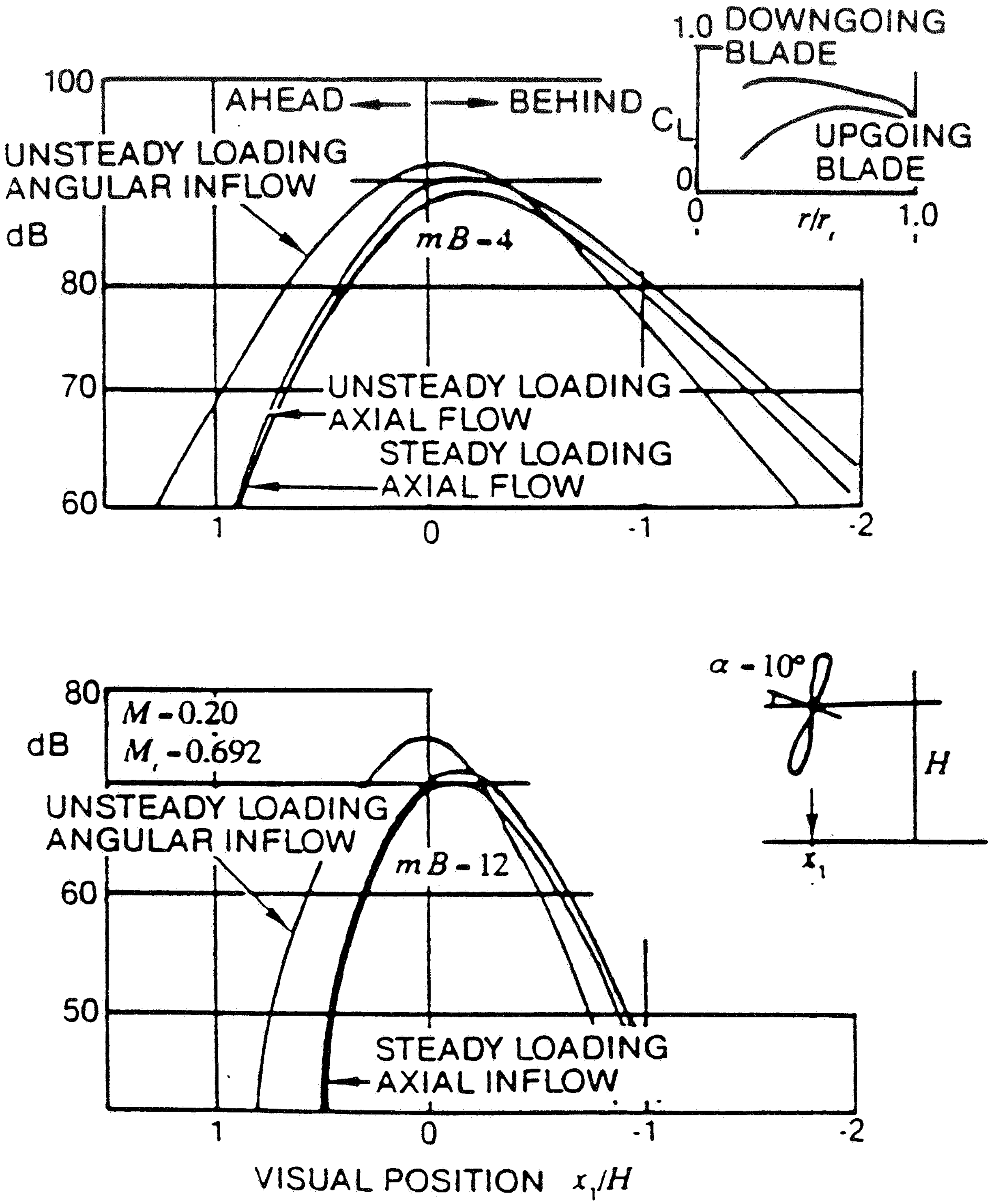

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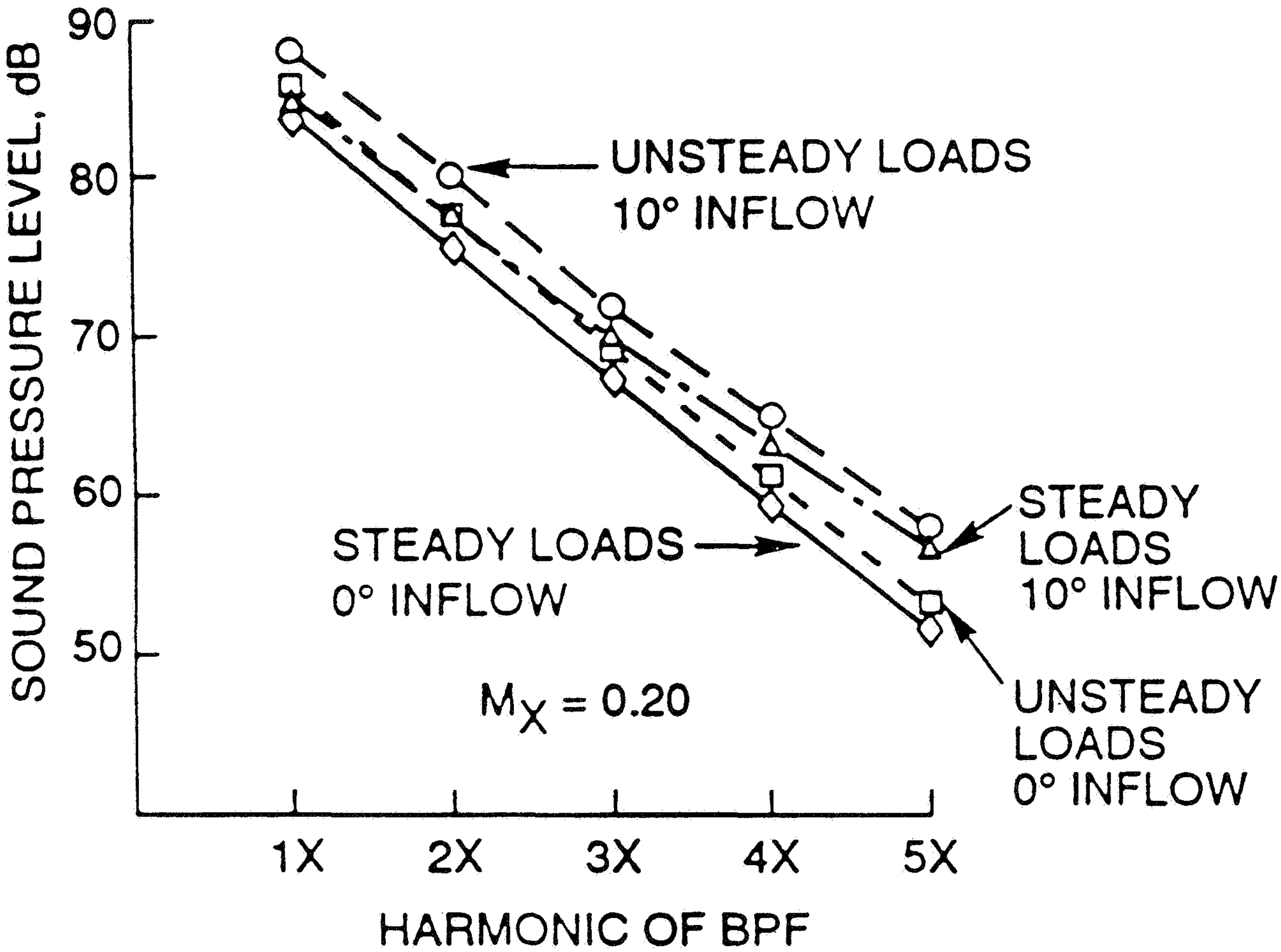

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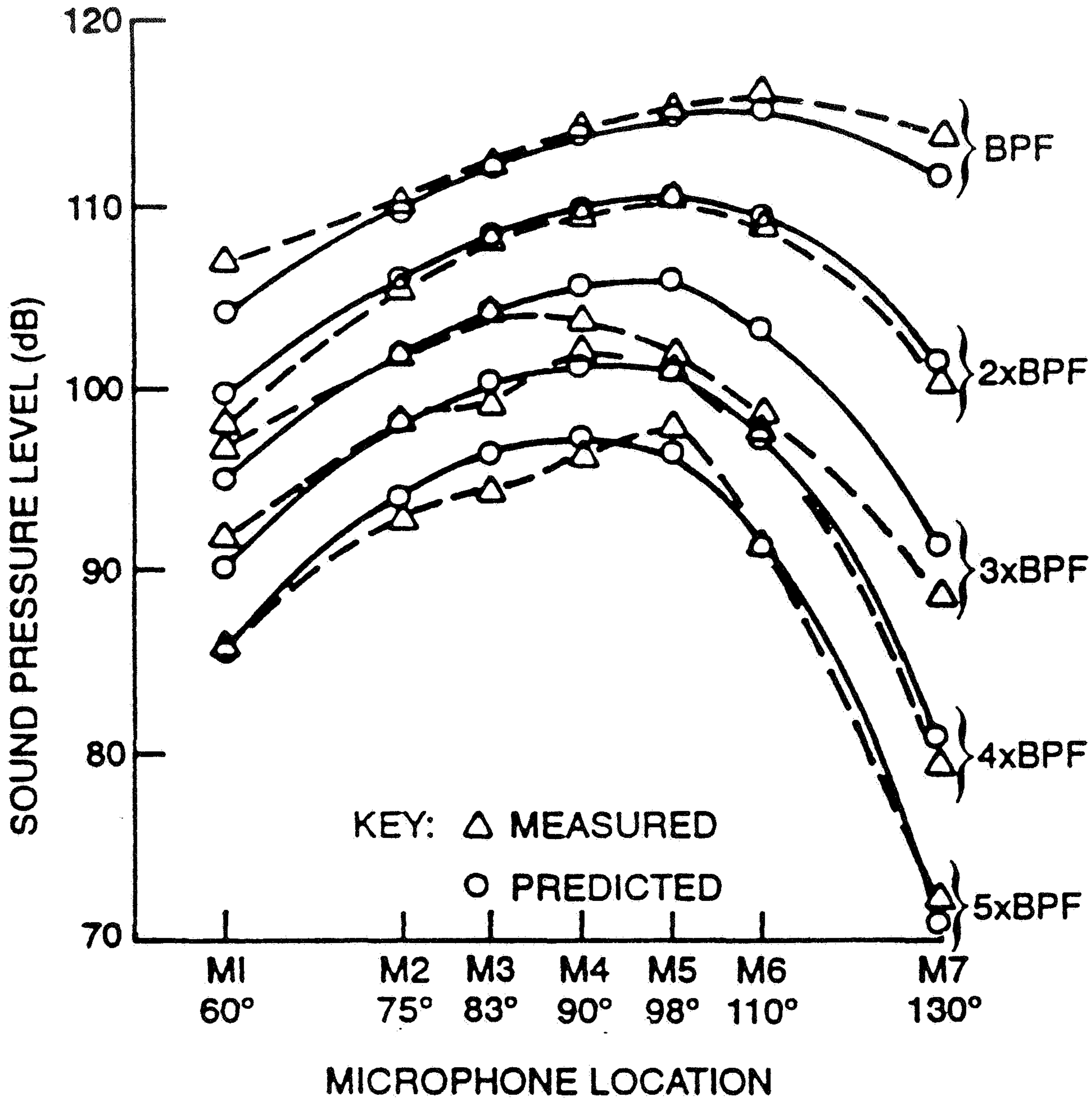

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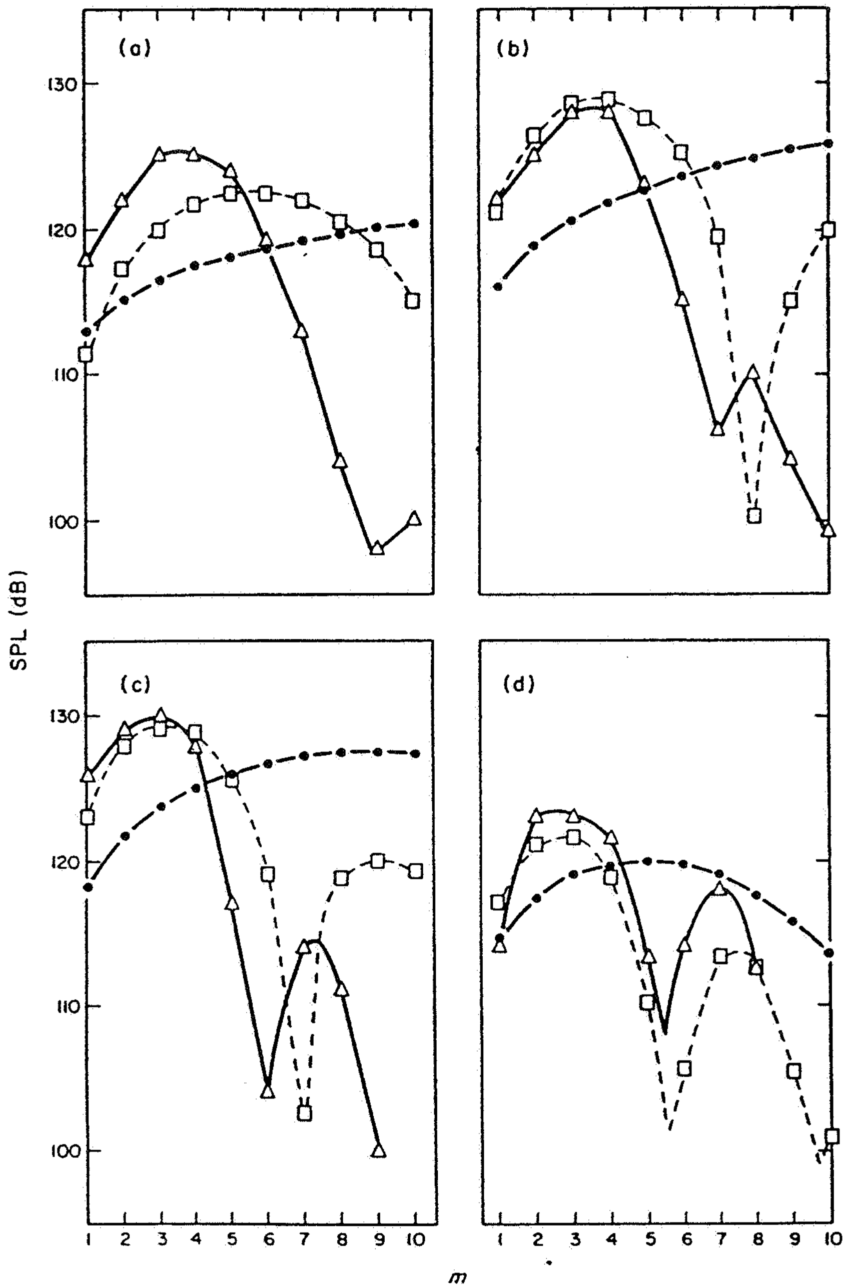

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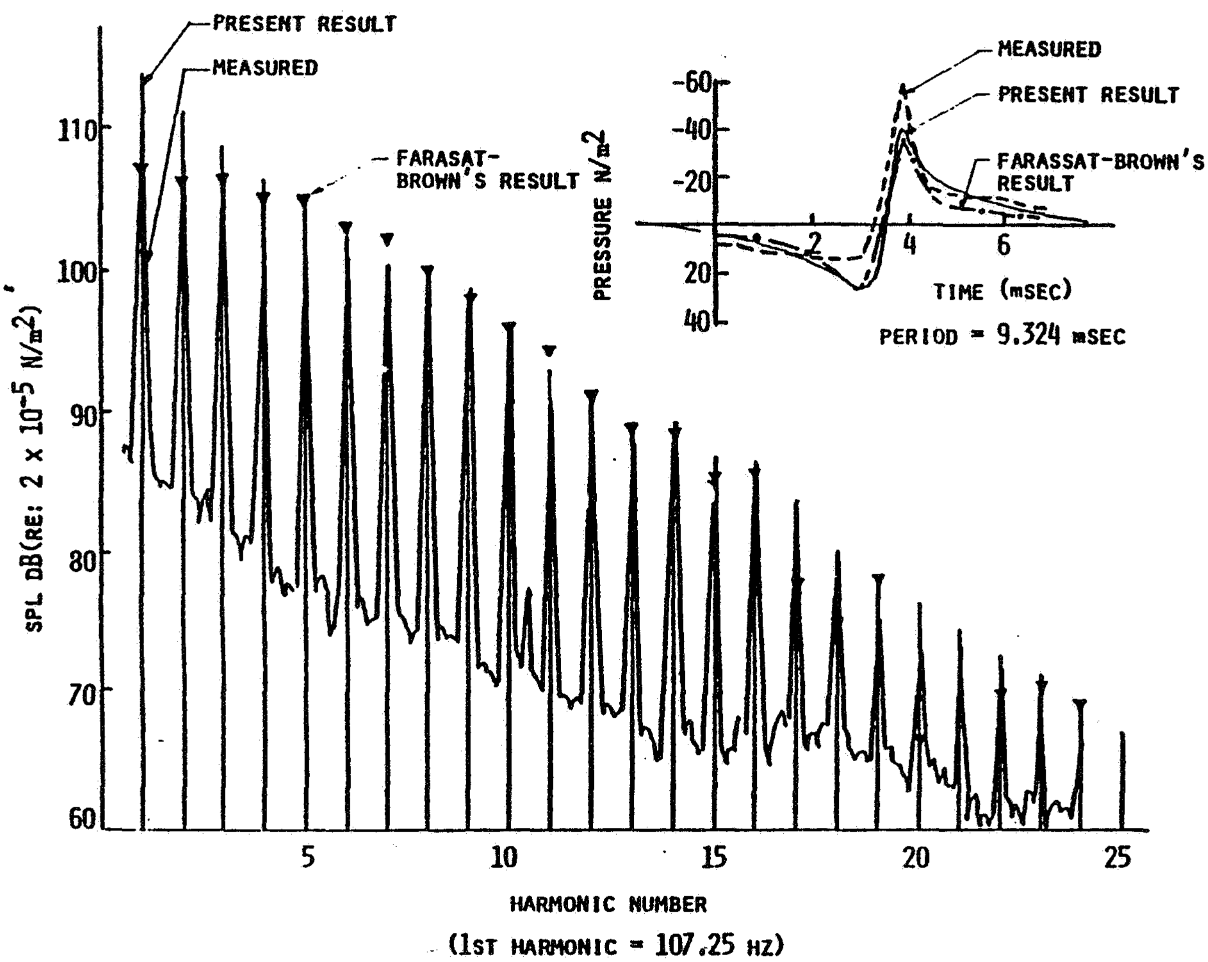

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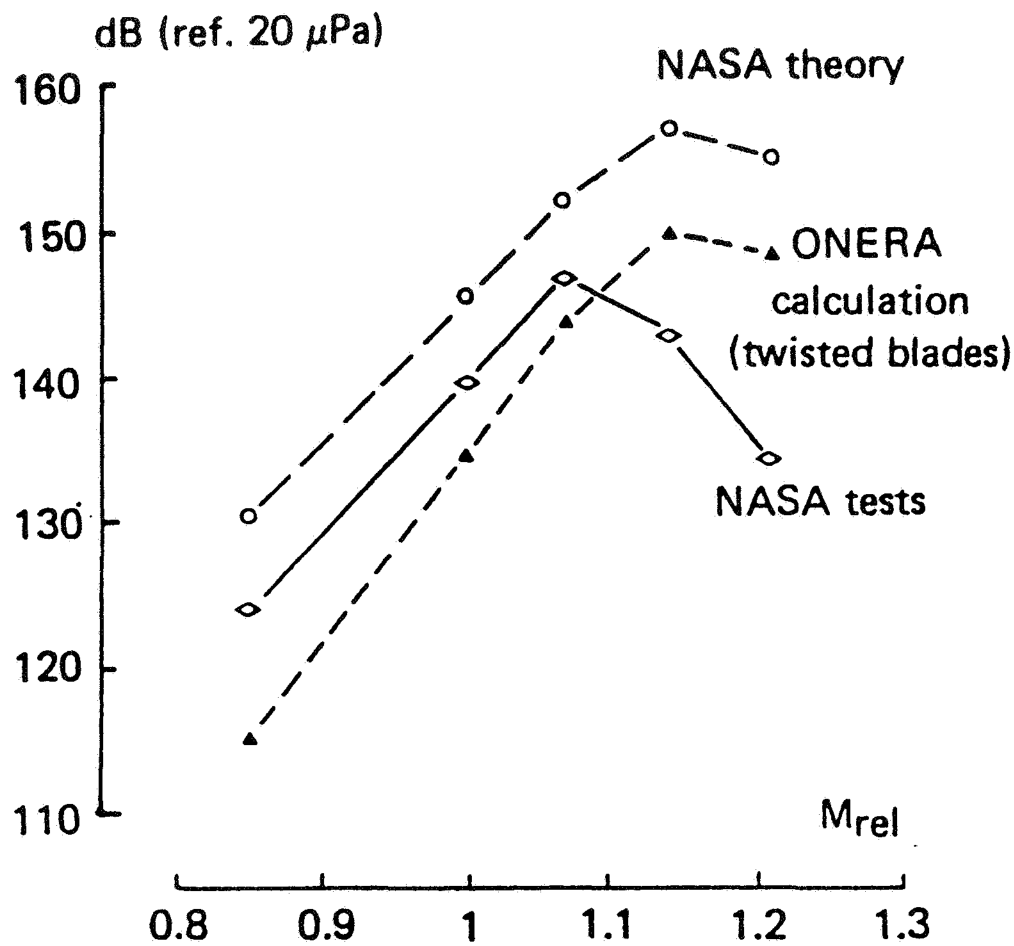

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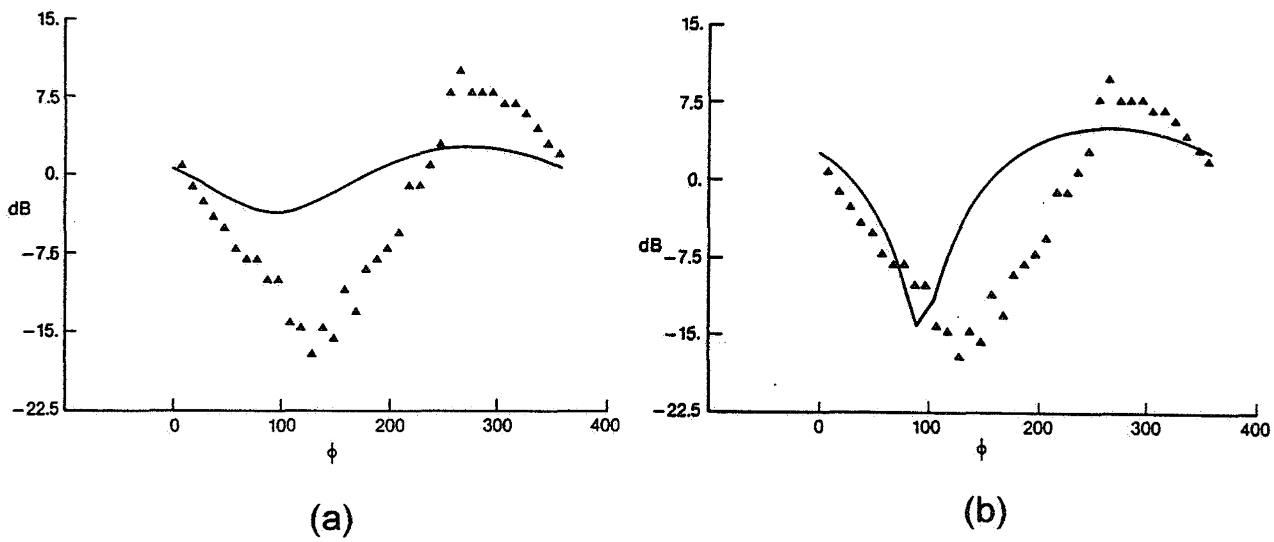

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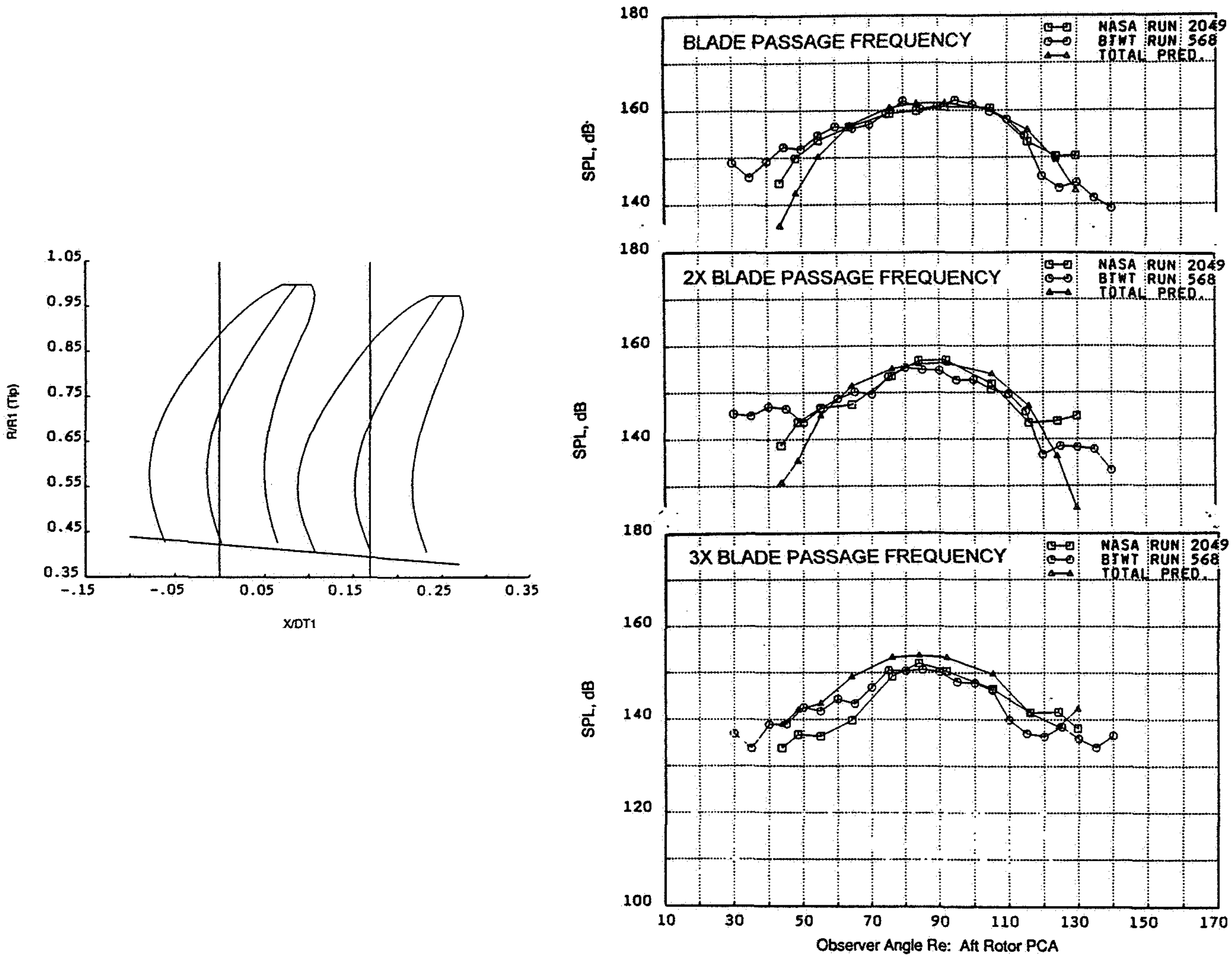

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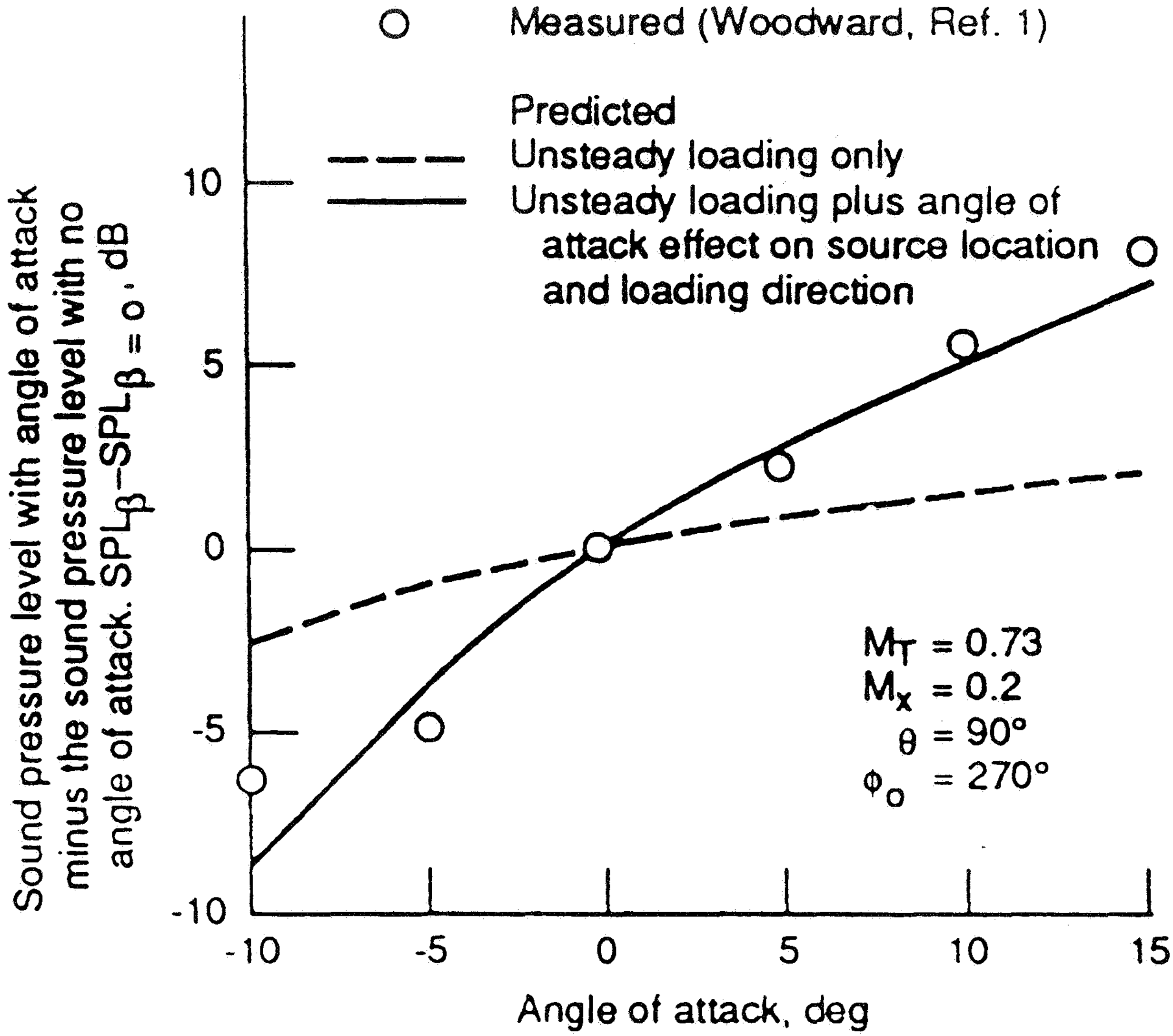

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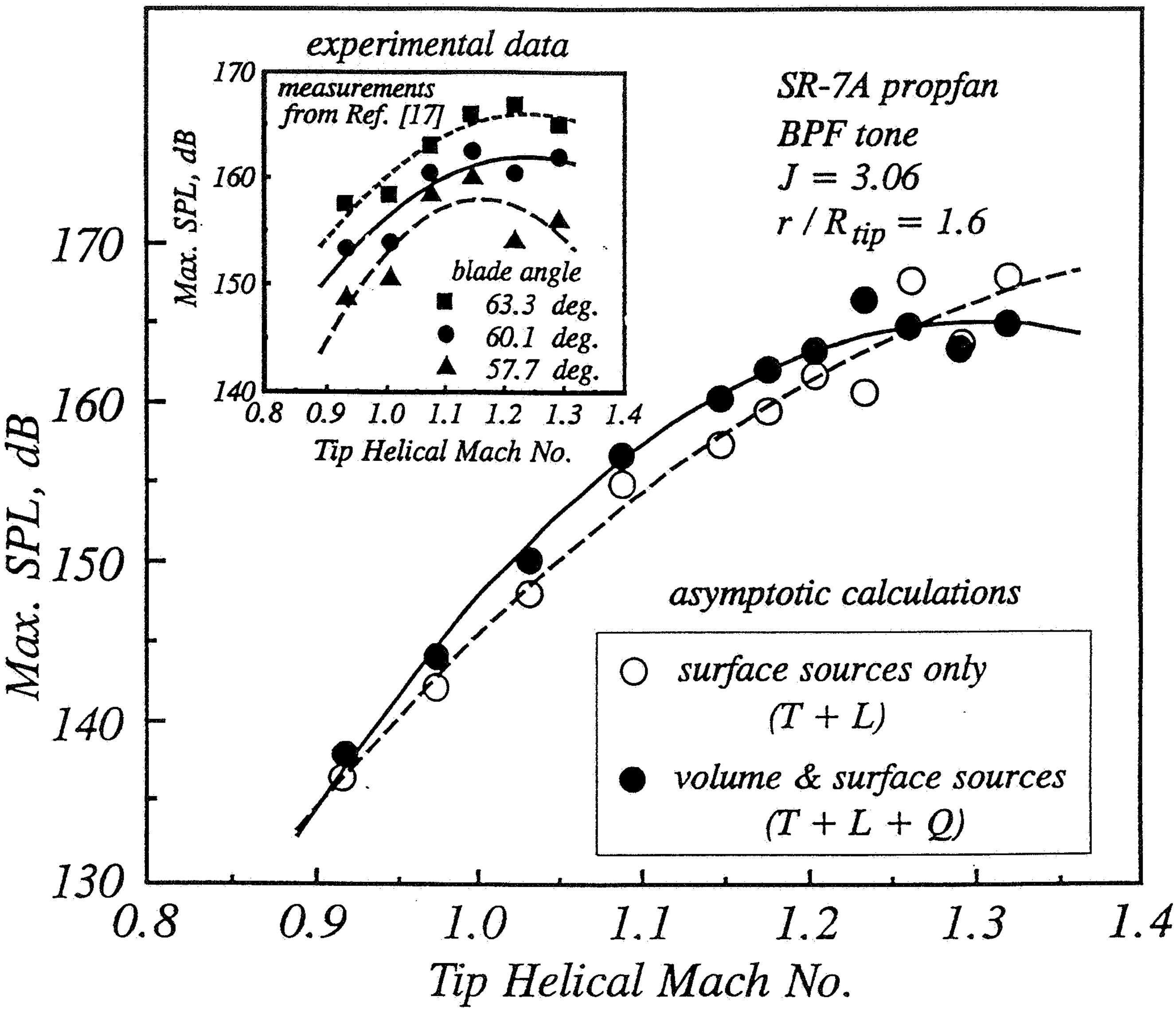

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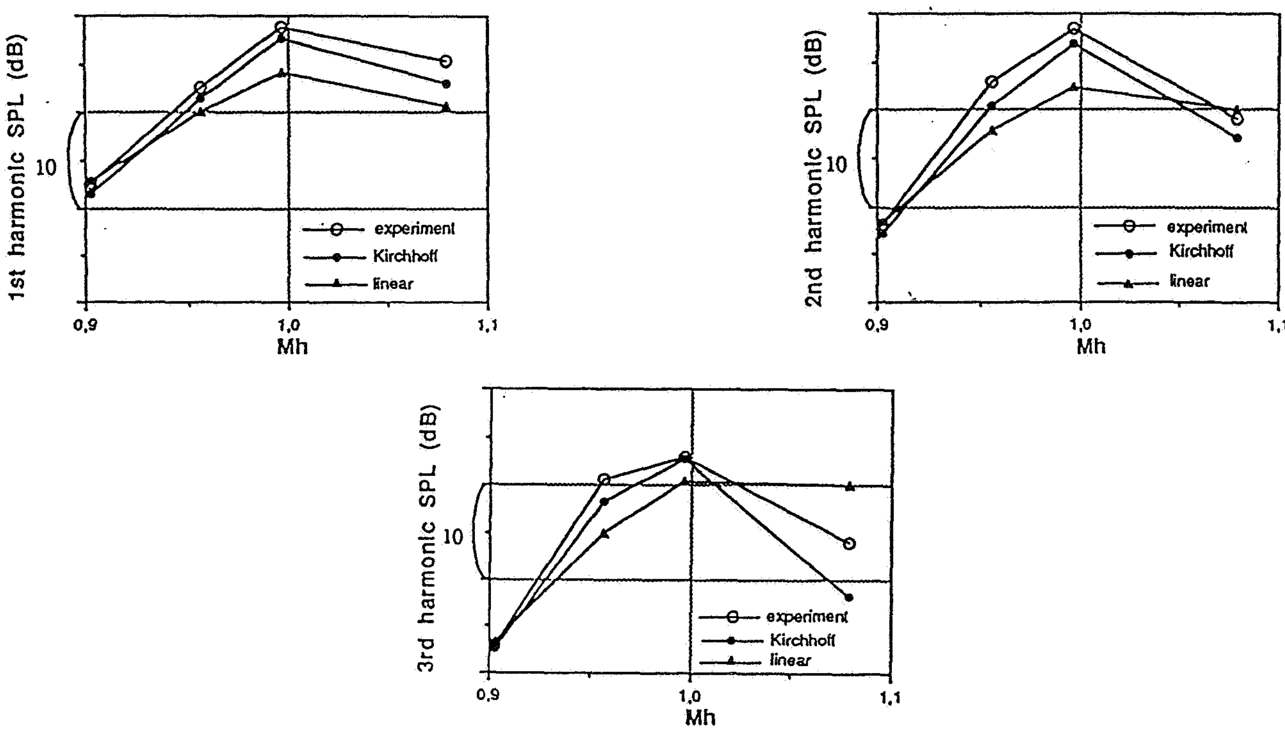

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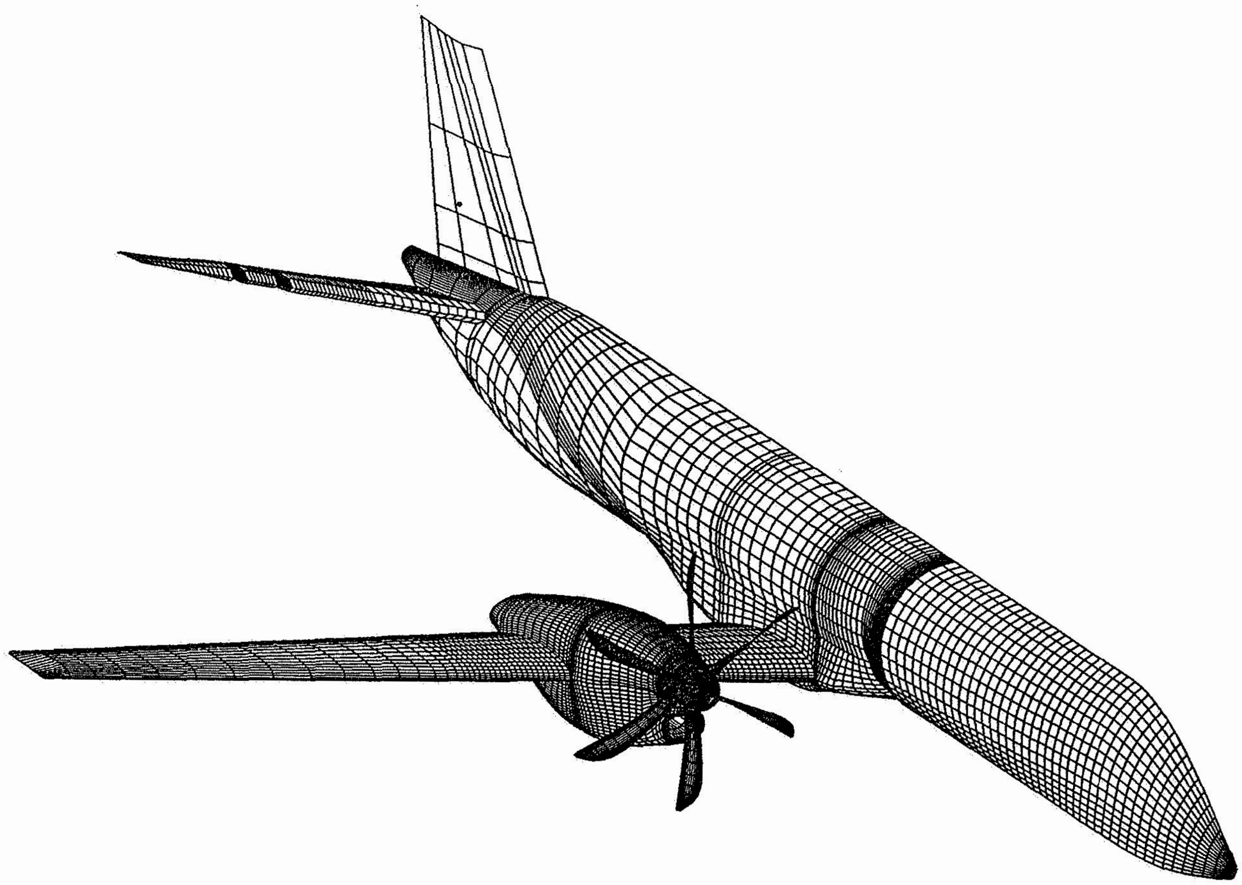

Figure 6.2- Propeller/Airplane Computational Grid for Noise Predictions Using a Computational Acoustics Method (Ref. 6.9)

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13. ABSTRACT *(Maximum 200 words)*

This report summarizes a review of the literature regarding propeller noise prediction methods. The review is divided into six sections: (1) early methods, (2) more recent methods based on earlier theory, (3) more recent methods based on the Acoustic Analogy, (4) more recent methods based on Computational Acoustics, (5) empirical methods, and (6) broadband methods. The report concludes that there are a large number of noise prediction procedures available which vary markedly in complexity. Deficiencies in accuracy of methods in many cases may be related, not to the methods themselves, but the accuracy and detail of the aerodynamic inputs used to calculate noise. The steps recommended in the report to provide accurate and easy to use prediction methods are:(1) identify reliable test data , (2) define and conduct test programs to fill gaps in the existing data base, (3) identify the most promising prediction methods, (4) evaluate promising prediction methods relative to the data base, (5) identify and correct the weaknesses in the prediction methods, including lack of user friendliness, and include features now available only in research codes, (6) confirm the accuracy of improved prediction methods relative to the data base, and (7) make the methods widely available and provide training in their use.

14. SUBJECT TERMS
Propeller, Propfan, High Speed Turboprop, Propeller Noise, Propfan Noise, Propeller Acoustics, Propeller Noise Prediction, Propeller Tone Noise, Propeller Broadband Noise, Empirical Methods, Prediction Methods

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