THE EVALUATION OF PROPELLER AERO-ACOUSTIC DESIGN METHODS BY MEANS OF SCALED-MODEL TESTING EMPLOYING PRESSURE TAPPED BLADES AND SPINNER

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Abstract

There is a projected demand from the market for propellers designed for increasingly high cruise speeds, typically ranging from Mach 0.6 to 0.75. Such propellers tend to have many wide chord blades, with some planform sweep, and operate at high lift coefficients and high helical Mach numbers. A need was identified for a new database of detailed aerodynamic and acoustic data applicable to such high speed blade designs in order to evaluate the new three-dimensional methods and further develop the traditional strip analysis methods for such applications. This paper describes the design, manufacture, and testing of a new pressure tapped model in an acoustically lined transonic wind tunnel. The unique database acquired comprises simultaneous measurements of running blade shapes, blade and spinner pressures, and the acoustic field, together with thrusts and torques. Methods evaluation work to date, also reported here, suggests that the Dowty Aerospace Propellers (DAP) three-dimensional Euler code, called JamProp, predicts pressures very well for cruise and climb conditions, and that the current strip analysis wake methods are valid for cruise design optimisations. Comparisons of noise predictions with the test data suggest that current methods are applicable to high speed cruise.

Nomenclature

P	Power (SHP)
C_L	Lift Coefficient
C_M	Pitching Moment Coefficient
D	Propeller Diameter (feet)
σ	Relative Density
dB	Decibels
M	Forward Mach Number
RPM	Revolutions per minute
r/R, Rc	Fractional Radius
Re	Reynolds Number
Cp	Pressure Coefficient
X/C	Fractional Chordwise Ordinate
HMn	Helical Mach Number
SPL	Sound Pressure Level
BPF	Blade Passing Frequency

Introduction

In the design process for aircraft propellers aerodynamic and acoustic prediction codes are used for the optimisation of blade and spinner geometries for maximum aerodynamic efficiency and minimum noise, and for providing aerodynamic loading information as an input to structural and control system design work.

Most methods currently in use for propeller blade aero-acoustics are based on strip analysis techniques, which involve the calculation of the aerodynamic angle of attack at each radius along a lifting line from a solution of the equations describing the distribution of circulation in the wake. This type of method has proved to be accurate for conventional propellers, and computationally inexpensive.

The aerodynamic design methods in use at Dowty Aerospace Propellers (DAP) are based upon the Lock-Goldstein solution for the ideal wake(1)(2), with significant modifications to represent finite aspect ratio, sweep, and propeller incidence effects. For more detailed, three-dimensional, analysis at the design stage an Euler code, called JamProp, is in regular use(3). This code, developed at the Aircraft Research Association (ARA) under contract to DAP, computes the steady flow about single and contra-rotating propeller configurations at zero incidence. DAP acoustic prediction methods take these aerodynamic solutions and solve the Ffowcs-Williams Hawkins analogy(4) in the time domain for loading and thickness noise components based on the methods of Succi(5) and Farassat(6). The quadrupole term is treated as a contribution to thickness noise by a consideration of the shock wave development on the blade aerofoils.

Current methods have been validated over the years by extensive full scale and model testing of mostly conventional propeller designs, making use of thrust, torque, blade pressures and wake flow data for aerodynamic code evaluations, and acoustic field data for noise code evaluations.

In contrast to conventional propellers, those designed for cruise speeds in excess of Mach 0.6 generally have high disc loadings which, coupled with the need to minimise tip helical Mach numbers, results in designs having typically a single row of 6 or more wide chord (low aspect ratio) blades embodying some planform sweep, operating at high lift coefficients at relatively high helical Mach numbers. Hence the greater three-dimensionality and loadings of such blades stretch the traditional methods towards the limits of their applicability, and may extend the newer methods beyond their current evaluation status.

In order to perform detailed evaluations of propeller aero-acoustic design and analysis codes it is necessary to have good quality experimental blade pressure and acoustic data, in conjunction with a knowledge of the running blade shapes. Much of the existing pressure data available in the open literature comes from large scale tests performed at NACA in the late 1940s(7). Although this data has proved useful, the blades used were not of modern design and strong viscous effects on the aerofoil sections used limit use of the data for evaluating methods. There is also a shortage of acoustic data in the open literature suitable for detailed methods evaluation, and none with simultaneous blade pressure measurements.

Hence the need was clear for a new database, applicable to modern high speed propellers, that would allow methods to be evaluated for axisymmetric conditions, from the prediction of running blade shapes, through aerodynamic behaviour to acoustic performance. Therefore DAP embarked upon a major project to gather extensive data, and to undertake methods evaluation across the flight regime from static, i.e. zero forward speed, forward and reverse thrust to Mach 0.75 cruise conditions. The necessary data would be obtained from a new pressure tapped wind tunnel model, to be tested in the acoustically lined ARA Transonic Wind Tunnel (TWT). It would employ pressure tapping technology largely developed jointly with Southampton University in the late 1980s.

Testing of this model was successfully completed in July 1993. The model consists of a single row of six blades mounted on a minimum interference spinner. The blade sections employed are representative of modern high speed designs, and two blade sets were tested, one set unswept, and the other having a moderately swept planform. The propeller test rig (known as the R4 rig), embodying a parallel nacelle, was sting mounted at zero incidence and yaw angle in the TWT working section which, with the acoustic liner installed, has a working section of 8ft by 7ft (2.44m by 2.13m). Drive power was provided by two 600 shp electric motors coupled together. To measure the steady blade shape changes under load a laser system was employed, courtesy of Rolls-Royce plc(8). Static tests were performed in the ARA Propeller Test House (PTH) commissioning facility.

This paper describes the design and testing of the model (referred to as the Pressure Tapped Propeller - PTP) and the subsequent methods evaluation work undertaken to date.

Pressure Tapped Propeller Design and Manufacture

The PTP tests were not aimed at performance verification of specific optimised propeller designs, but were designed to gather data intended for evaluating in-house methods across the speed range when applied to blades of various planforms. This lack of constraint enabled the blades to have a simple planform with relatively large chords towards the tip. A diameter of 3ft (0.914m) was chosen in order to provide a high disc loading with the available power, to make best use of the acoustic qualities of the tunnel, and to allow 28 pressure tappings to be incorporated at each of 9 radial stations from 35% to 95% radius. Six blades were chosen as being typical of modern propellers.

During model design a good deal of attention was paid to the manner in which the test data would be utilised for methods evaluation. The blades were designed using aerofoils from the ARA-D/A family, a development of the original ARA-D family for higher speed applications(1). The thickness:chord ratios, cambers and twists were chosen to provide a design that was representative of high speed applications, and two aerofoils that had previously been tested in the ARA 8inch x 18inch (0.20m x 0.46m) two-dimensional wind tunnel were incorporated at the 60% and 95% radius stations. Typical design cruise speeds for the blades would be approximately Mach 0.65 for unswept and Mach 0.7 for swept designs, at a disc loading of $50P/\sigma D^2$, and 650fps (200m/s) tip speed. It was also important that the designs should be able to highlight the more uncertain issues such as tip flows and sweep effects. For the latter, the geometry of the swept blades was kept similar to that of the unswept blades by utilising the same sections in a streamwise sense in order to isolate sweep effects, and they were pressure tapped at the same stations.

In order to allow useful comparisons of test data with aerodynamic predictions it is important that the test Reynolds numbers are sufficiently high to avoid gross separations, especially at the blade roots, and are as far as possible comparable to those used in the two-dimensional aerofoil tests upon which the strip analysis methods are based. PTP test Reynolds numbers at 70% radius lie in the range from 1 million at take-off conditions, to 1.7 million at cruise, compared to the aerofoil test range of 1.4 to 4 million.

Since strip analysis methods and the grids used with Euler codes cannot fully represent the details of root/spinner junctions, care was taken to minimise the blade/spinner clearance, consistent with allowing reverse thrust testing, and to ensure smooth blends in this area. Careful attention was paid to blade tip blend radii in order to avoid any spurious acoustic sources from unrepresentative tip vortex development.

The distribution of pressure tappings was chosen with reference to two-dimensional aerofoil test data and JamProp predictions, in order to ensure adequate pressure peak and shock wave identification and to minimise data gaps in the event of a tube becoming unserviceable. The same approach was applied to the spinner tappings along the profile and around the blade roots, with the added criterion of ensuring accurate integrated forces for thrust accounting. The spinner backplate and nacelle were also comprehensively pressure tapped.

The blades were made of carbon fibre with thin glass fibre skins, by the Resin Transfer Moulding process. Metal moulds were used, and the blades were hand finished to remove leading and trailing edge flash. Careful attention was paid to mould geometries and blade finishing in order to ensure a high degree of geometric accuracy and a good surface finish on the blades. The pressure tappings were made by drilling 0.016inch (0.4mm) holes into cupronickel tubes moulded into the blades beneath the glass skin. This tapping hole size was chosen by reference to the predicted boundary layer thicknesses, and by consideration of the scatter in the pressure readings that could arise from burrs around the holes.

The structural design of the blades was conducted by means of Finite Element analysis. The carbon layers were oriented in such a way as to minimise the running blade deformations under load according to the results of this analysis, so that the deformed aerofoils remained within the ARA-D/A family definitions. The actual test blade angle settings used took into account the predictions of running blade twist changes, in order to be more confident of obtaining the desired blade loadings. In order to furnish blade shape data that would allow a reasonable definition of the running blade geometries two radial stations were chosen for each blade set, on the basis of the Finite Element analysis, at which to perform the laser measurements.

Two blades in each set of six had integral strain gauges, bonded under the glass skin, in order to monitor bending and torsion behaviour during the tests without disturbing the aerodynamic properties of the blades.

The spinner profile was designed to simplify analysis of the blade root pressure data by minimising radial and axial velocity gradients, however its length and internal volume were dictated by the requirement to house two S48 Scanivalves on the axis of rotation. The 252 blade pressure tappings and 32 spinner tappings were connected to the Scanivalves by lengths of urethane and cupronickel tubing, the latter being fixed in permanent runs along the inside of the spinner and the outer surfaces of the Scanivalve housings. Careful attention was paid to the bracing of the urethane tubes against centrifugal forces, in order to prevent kinking.

The design of the hub system enabled two internal configurations to be used, either two Scanivalves for blade and spinner pressures, or one Scanivalve for extra spinner pressures plus a strain-gauged balance for thrust and torque measurement, see figure 1. The blades were clamped at fixed pitch by the two halves of the split hub. Blade angles were set using a Vernier protractor head mounted on a special tool designed to locate onto the front hub half. This gave setting accuracies of 0.1 degrees. In order to minimise blade angle setting time in the wind tunnel, a separate blade clamping device was incorporated into each blade port to counteract the tendency for blades adjacent to the one under adjustment to move. Special spinner tapping connectors were built into the hub system to allow automatic disconnection and reconnection of these tappings during spinner removal for blade angle setting operations.

All the hub components were machined from aluminium alloy, the spinner being machined from a casting.

Pressure Tapped Propeller Testing

Commissioning of the PTP model and rig systems, including the laser sytem, was undertaken in the Propeller Test House at ARA in April 1993, see figures 2 and 3, where static tests were also performed. The static test schedule was set up to explore the high thrust and stall behaviour of both sets of blades at constant predicted helical Mach numbers. Eight blade angles settings were used, including 2 specifically for reverse thrust. Smoke visualisation revealed some flow perturbations at the propeller disc plane originating from the test cell inlet. These were reduced by moving the rig back from the inlet.

Sublimation tests were performed in order to reveal the extent of laminar flow on the blade surfaces, with and without boundary layer transition trips. It was found that long stretches of laminar flow existed on the lower surfaces, but high leading edge suction peaks on the upper surfaces limited the extent of the laminar regions there, especially towards the blade tips. Throughout the range of blade angles wool tuft tests were performed, viewed under stroboscopic light, to look for flow separations on the blades. Little sign of separation was found at the blade roots, but a creeping flow separation was noted with increasing blade angle from the tips. These tests aided the interpretation of the pressure data.

No significant problems were encountered with the equipment, and pressure, thrust and torque, and blade shape data were obtained for power coefficients up to 25% greater than those experienced by current in-service propellers. At the highest loadings attempted stall flutter was encountered, close to where it was predicted.

Testing in the TWT followed in July, see figure 4. Mounted within the acoustic liner, in order to gather acoustic field data, was the Microphone Traverse Rig (MTR), which carried 4 microphones positioned at 125% and 163% radius. The MTR traversed axially 2ft (0.6m) forward and 2ft aft of the disc plane, recording data continuously. In addition two wall mounted in-flow microphones were used.

Prior to testing, tunnel calibrations were performed to account for all forms of blockage, and to check the choice of microphone angular locations. Testing proceeded in two phases. In the first pass through the test schedule measurements were made of blade and spinner pressures, the acoustic field, and blade tip deflections; and in the second pass, thrust and torque, further spinner pressures, and inboard blade deflections were measured.

An important objective for the TWT tests was to gather enough data to reconstruct the aerofoil lift curve slopes for cruise and take-off/climb conditions at fixed helical Mach numbers, bracketing the 'design points' for each blade type, and enabling comparison between swept and unswept designs at fixed helical Mach numbers. Other objectives were to gather noise data for high loading and high thickness noise component conditions, as well as 'design' conditions, in order to evaluate predictions of these separately; to obtain aerodynamic twisting moment data for typical control system design conditions; and to explore the reverse thrust region.

Cruise conditions covered the Mach range from 0.6 to 0.75, and included 21 Mach number/RPM datapoints for the unswept blades and 20 for the swept blades. Take-off/climb conditions covered the speed range from Mach 0.125 to 0.25, with 15 datapoints for each blade set. For aircraft V_{dive} conditions 8 high speed, and 3 low speed (deep stall) datapoints were covered. Reverse thrust conditions were limited to 3 datapoints at Mach 0.11 due to tunnel calibration uncertainties. One blade angle was used per blade set per speed range.

The acoustic datapoints were a subset of the aerodynamic cases, at cruise speeds 13 Mach number/RPM noise polars were obtained for the unswept blades, and 8 for the swept. At take-off/climb speeds 6 were obtained for each.

A good range of operating conditions was therefore covered in the TWT, with lift coefficients being obtained from -0.4 to 1.8, at helical tip Mach numbers from 0.475 to 1.01, and disc loadings up to $140P/\sigma D^2$.

Test data was processed on-line in order to judge its quality and to make tactical changes within the test schedule. Pressure data was corrected for centrifugal effects and transducer temperature, and displayed for each aerofoil on colour screens, allowing comparative examinations from case to case. This allowed some initial methods evaluation to be performed during testing. Acoustic data was processed on-line by spectral analysis, and pressure time histories examined soon afterwards. In general, up to five propeller tones were detectable.

Methods Evaluation

Prior to commencing methods evaluations the quality of the test data was assessed by looking at repeatability, scatter, and the accuracy of the data processing. On-line assessments were made of the plausibility of the data, by looking at trends with RPM and forward speed, and by comparing with two-dimensional aerofoil test data and predictions where appropriate.

The repeatability of the pressure data within and between runs was found to be very good. Some differences occurred due to temperature changes within the pressure tubes, typically up to 0.04 in Cp, but these have little effect upon integrated lift. Generally, there was very little scatter in the data whilst on condition. For example, during microphone rig traverses, taking four minutes, pressures at a given tapping did not alter at all except where a tapping was situated under a shock wave. Despite careful attention to the support of the urethane tubing, at high tunnel temperature/rig RPM combinations kinking of some urethane tubes could not be completely eliminated. Therefore, some movement of pressures was apparent where a tube kinked, but this was confined to at most 5 out of 92 tubes. Some scatter was also evident during stalled flow conditions, especially at zero forward speed, which was to be expected. These factors combined with careful attention to data processing have established a high degree of confidence in the measured blade and spinner pressures.

Aerodynamic methods evaluation starts from a knowledge of the running blade shapes. Figure 5 shows a typical example of data from the laser blade shape measurement system. The lower surface of the blade is depicted by 800 coordinate measurements. The running geometry of the blades at each measurement station can be found from this data, for example figure 6 shows the measured twist trends at two Mach numbers for the unswept blade at the cruise blade angle. Some repeatability checks are included on the plot.

In order to give a flavour of the blade pressure data, four examples are given to compare with two-dimensional aerofoil flow behaviour. Figure 7 shows example pressure plots taken from the unswept blade static tests in the PTH, with two-dimensional test comparisons at similar lift coefficient and helical Mach number. Figure 8 presents similar data from Mach 0.6 tests in the TWT. It can be seen that the flow is quite two-dimensional inboard, but very three-dimensional near the tip.

Due to the greater three-dimensionality of the flow about high speed propeller designs the use of three-dimensional methods is becoming increasingly important, and so initial methods evaluation has concentrated on the JamProp code. The predictions that are shown were done 'blind', in that the standard DAP/ARA grid spacing and numerical control parameters were used throughout, this being a true test of predictive capability for a given geometry. These parameters were established during earlier methods evaluation work. Calculations have been performed for both blade sets, over a range of conditions, and compared with the PTP test data, see figures 9 to 12. Figures 9 and 10 show the pressure distributions at a Mach 0.65 condition on the unswept blade using the design and running geometries (including manufactured shape) respectively, for comparison. The points ringed indicate tubes where a leak was known to exist. Careful examination of the pressures shows that apart from small alterations to shock position and strength, the principal effect of running shape changes is to increase the lower surface leading edge suction peak. Figure 11 shows converged results for the unswept blades at a Mach 0.2 condition, generally a difficult condition for standard Euler methods with convergence being very slow. Figure 12 presents initial results for the swept blade set at a Mach 0.7 condition.

It can be seen from these examples that the JamProp code is predicting the surface pressures very well, faithfully picking up the three-dimensionality referred to above, with shock strength and position, and leading edge suction peaks well represented. The resulting radial loading distributions are in good agreement with experiment.

Despite its accuracy, a three-dimensional Euler code such as JamProp is not suitable for initial design optimisations due to its relatively higher computation costs. The bulk of initial design work still relies upon strip analysis methods, which need aerofoil lift and drag coefficient data.

Pressure drag cannot be calculated reliably from test pressures without densely packed pressure tappings around the leading edge. However, lift curves can be constructed by application of the wake methods within the strip analysis code. In this way the validity of the wake methods can be tested where the blade is known to behave two-dimensionally, for example figure 13 illustrates lift curve data at 60% radius for cruise conditions.

The test schedule was set up so that the top of the lift curve could be explored, where significant flow separation leading to stall occurs. This is of importance because three-dimensional effects imply that blade aerofoil stall differs significantly from two-dimensional aerofoil stall. Stall data is necessary not only for take-off performance estimation, but also for control system design where twisting moments are required for the weight-efficient sizing of counterweights and the hydraulic pitch change actuator. Figure 14 illustrates some data for 60% radius, showing pitching moments for 3 helical Mach numbers up to stall onset. Such lift and moment data, available for nine radial stations, is being used to further refine the strip analysis design methods.

In addition to the pressure measurements propeller thrust and torque were measured using the strain-gauged balance for all the take-off/climb and cruise conditions. This data enables comparisons to be made with thrust, power and efficiency predictions. The balance data was found to be very repeatable in the TWT, with some scatter in the PTH test data due to residual flow perturbations. So that blade performance can be isolated, a thrust accounting exercise is carried out to subtract spinner forces from the thrust data. Figure 15 illustrates the magnitude of the various terms, with backplate force being integrated from measured pressures, spinner form drag calculated from a validated JamProp prediction, and skin friction drag estimated using the measured pressures. Work is underway to make full use of all the above aerodynamic data.

Evaluation of acoustic prediction methods follows on from the evaluation of the aerodynamic methods. From the extensive acoustic data gathered, a few examples are given here. Figures 16 to 19 present noise polars taken at Mach 0.6 and Mach 0.25 for the unswept, and Mach 0.75 for the swept blade sets, representing climb and cruise conditions, and a high speed low loading case for the unswept blades representing a high thickness noise condition. In figures 16 and 17 the fourth tone has been removed for clarity, as it tended to be obscured by tunnel background noise for these cases, however it is shown in figures 18 and 19. Repeatability checks undertaken for a Mach 0.65 swept blade case indicated that the SPL could be relied upon to within 1dB at each tone for the 4 traversing rig microphones. Agreement between pairs of microphones at a given radius was also generally found to be within 1dB.

In the process of acoustic methods evaluation, comparisons can be made between prediction and test data for sound pressure levels, and their field shapes; pressure time histories; and phase data. Figures 20 and 21 illustrate comparisons of predictions of first tone phase, and sound pressure levels with test data for the unswept blades at Mach 0.65. This case was chosen for its relatively cleaner fourth tone signal. It can be seen that there is good agreement between prediction and test data, bearing in mind the measurement tolerances mentioned above.

These predictions used the measured thrust and torque loading per unit radius from the blade pressure data, and also used the measured chordwise loading distributions, and include an estimate of quadrupole noise. In this way in-house acoustic methods, based on the Succi and Farassat approaches, can be evaluated independently of the aerodynamic predictions, and techniques to predict quadrupole terms and sweep effects further developed.

Conclusions and Recommendations

The design, manufacture and testing of the pressure tapped propeller and the subsequent methods evaluation work described here represent a major project spanning three years. The acquisition of a database containing simultaneous measurements of blade shape, blade and spinner pressures and acoustic field data in an acoustically treated tunnel is believed to be unique.

A large quantity of good quality data has been obtained that has already made an impact upon in-house design methods. Notably, it has been shown that the JamProp code predicts the blade and spinner pressures of modern propeller designs well at cruise and climb conditions, making it a valuable tool for such design work. Future work on the JamProp code will concentrate on development of the viscous coupled version, which incorporates a stripwise boundary layer calculation, and improvements to grid details and low speed convergence capabilities.

The validity of a developed version of the strip analysis technique for design work has been shown. Future work in this area will concentrate on further improving the lift and drag predictions in the root and tip regions, and improving the representation of stall behaviour. The viscous coupled JamProp code, in conjunction with the measured blade thrust data, will prove useful for part of this work where it concerns attached flow conditions.

Inputting a propeller's known aerodynamic behaviour into acoustic predictions allows an independent evaluation of acoustic methods. Work continues in this area, and early indications are that, with the inclusion of the quadrupole terms, sound pressure levels can be predicted well for the first 4 tones at high speed cruise conditions. Future work will include improvements to quadrupole predictions, possibly using JamProp code solutions.

This test campaign has yielded an extensive database. Detailed evaluation of the various design methods for application to high speed designs will continue for some time.

Acknowledgements

The authors wish to thank the directors of Dowty Aerospace Propellers for giving permission to publish this paper, and to British Aerospace plc, Rolls-Royce plc, and ARA Ltd for their assistance with the PTP project.

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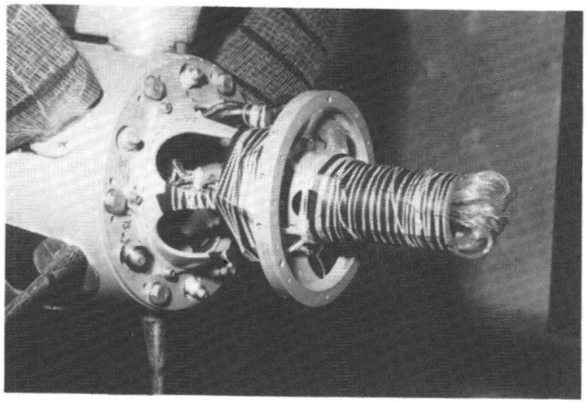

Figure 1
Pressure Tapped Propeller (PTP) Hub System.

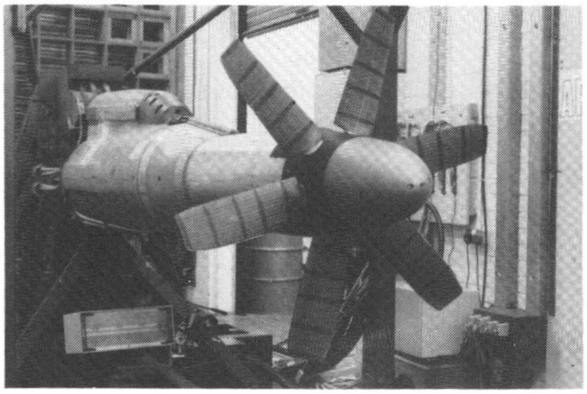

Figure 2
PTP with unswept blades in Propeller Test House (PTH).

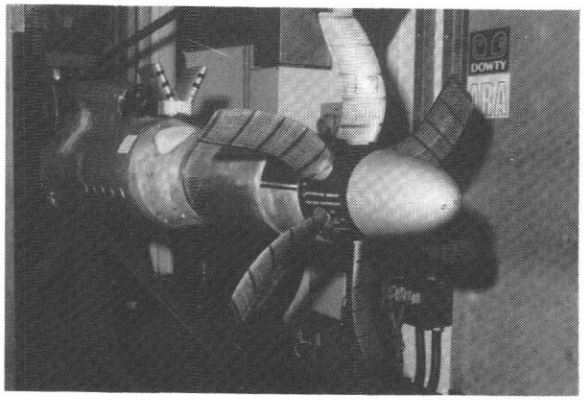

Figure 3
PTP with swept blades, in PTH.

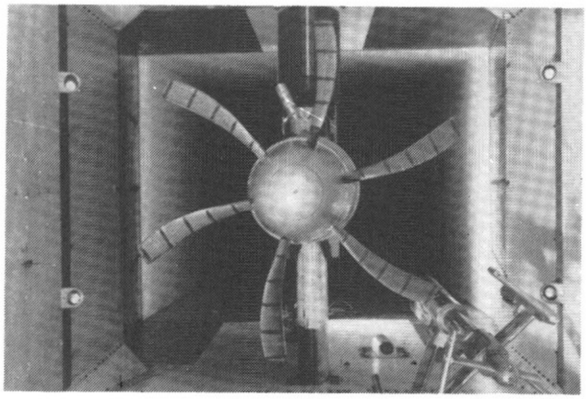

Figure 4
PTP with swept blades installed in the ARA Transonic Wind Tunnel (TWT).

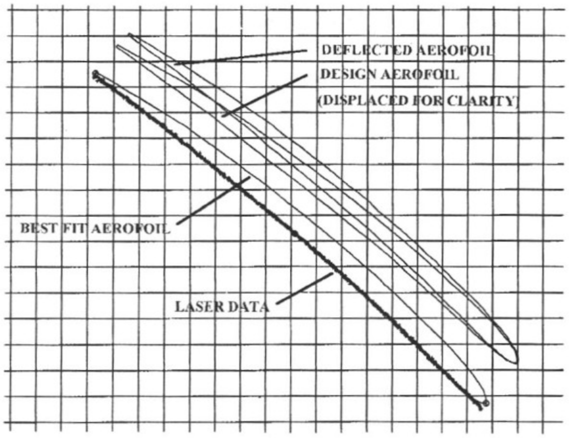

Figure 5
Example of blade measurement data from laser system.

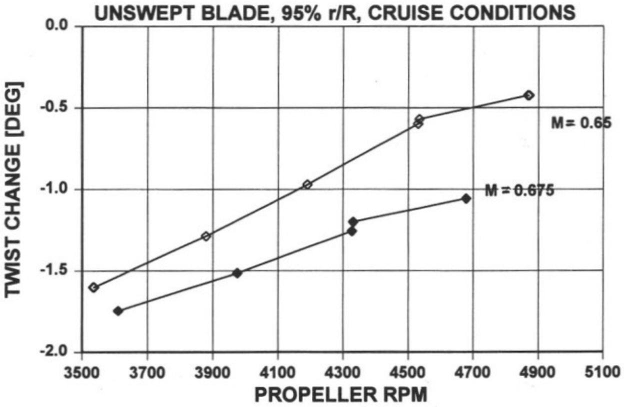

Figure 6
Measured blade twist changes at 95% radius, unswept blades, cruise conditions.

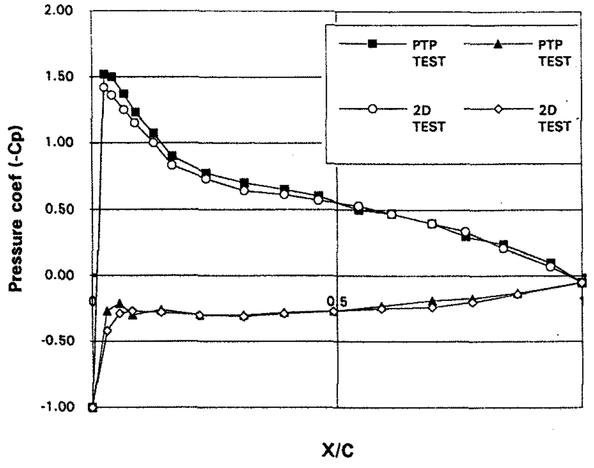

Figure 7a
PTP Pressures at 60% radius, measured in
Propeller Test House

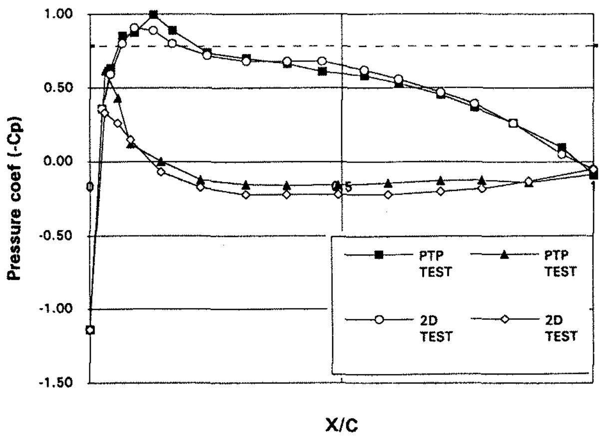

Figure 8a
PTP Pressures at 60% radius, measured in
Transonic Wind Tunnel, at Mach 0.6

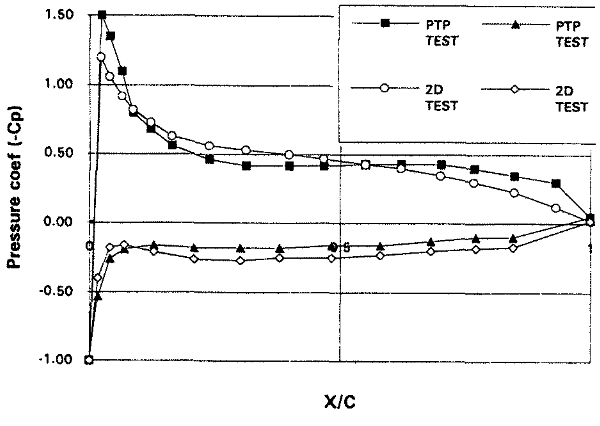

Figure 7b
PTP Pressures at 95% radius, measured in
Propeller Test House

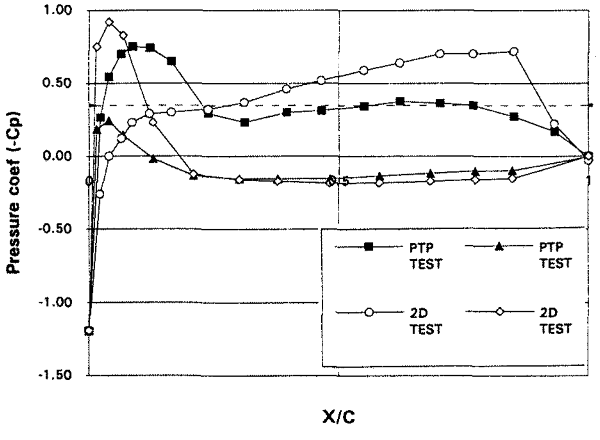

Figure 8b
PTP Pressures at 95% radius, measured in
Transonic Wind Tunnel, at Mach 0.6

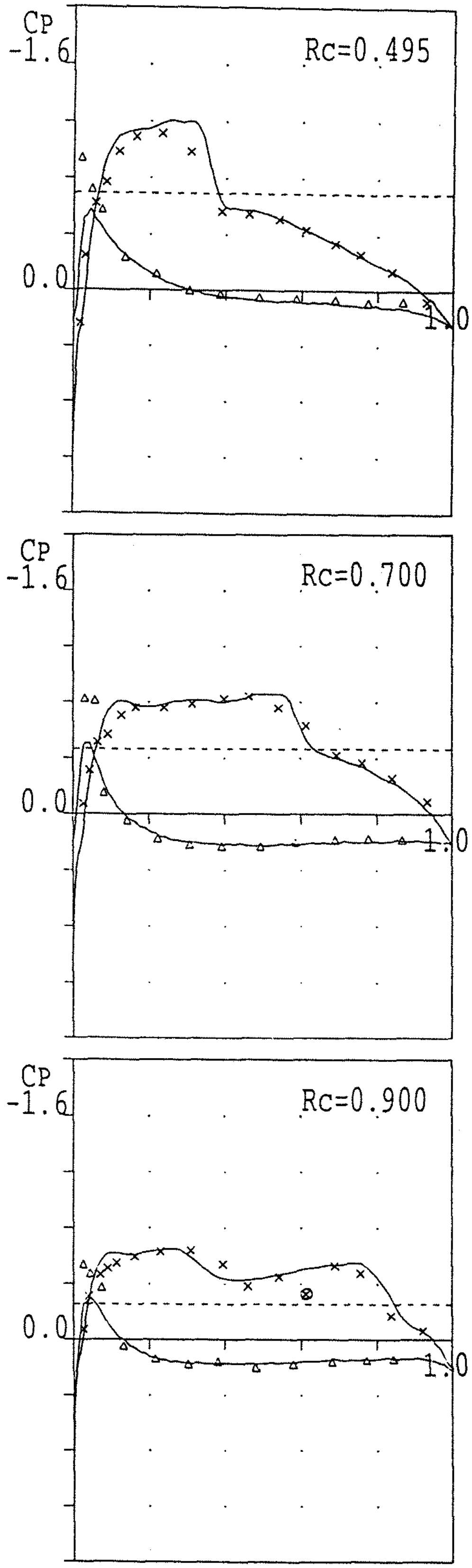

FIG 9 UNSWEPT BLADE, JAMPROP
DESIGN GEOMETRY
M = 0.645, RPM = 4532

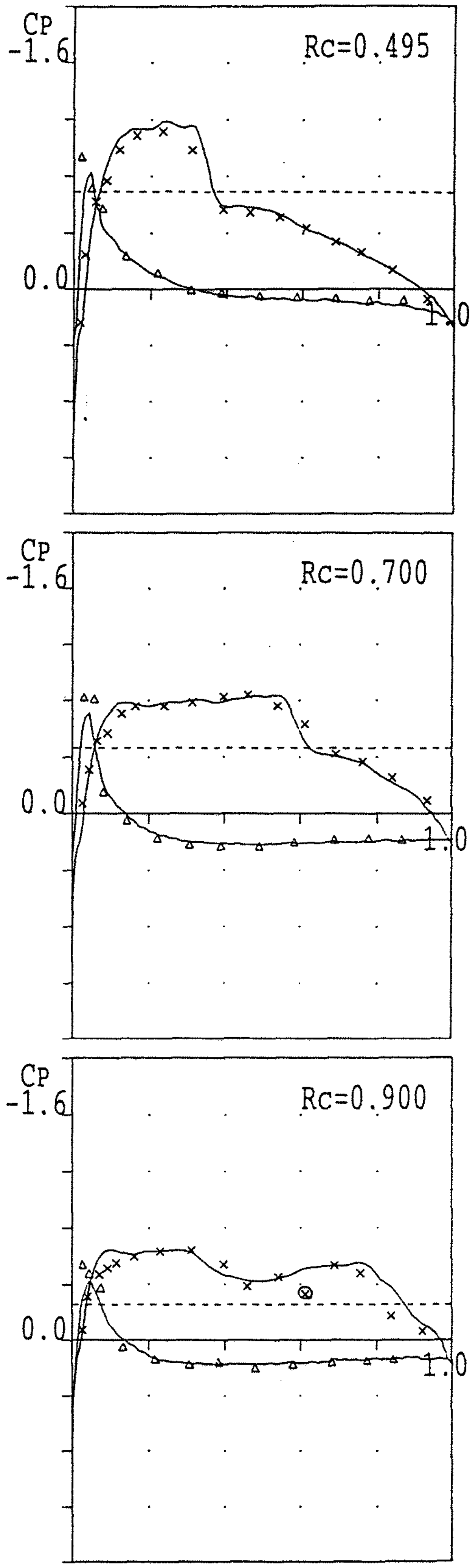

FIG 10 UNSWEPT BLADE, JAMPROP
RUNNING GEOMETRY
M = 0.645, RPM = 4532

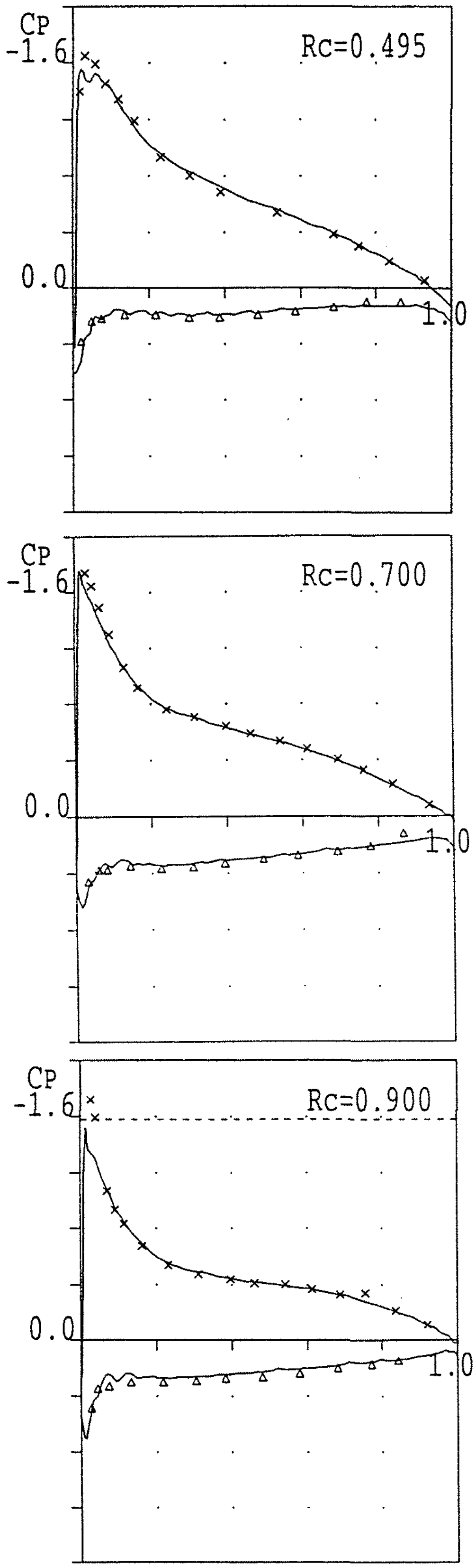

FIG 11 UNSWEPT BLADE, JAMPROP
RUNNING GEOMETRY
M = 0.2, RPM = 4143

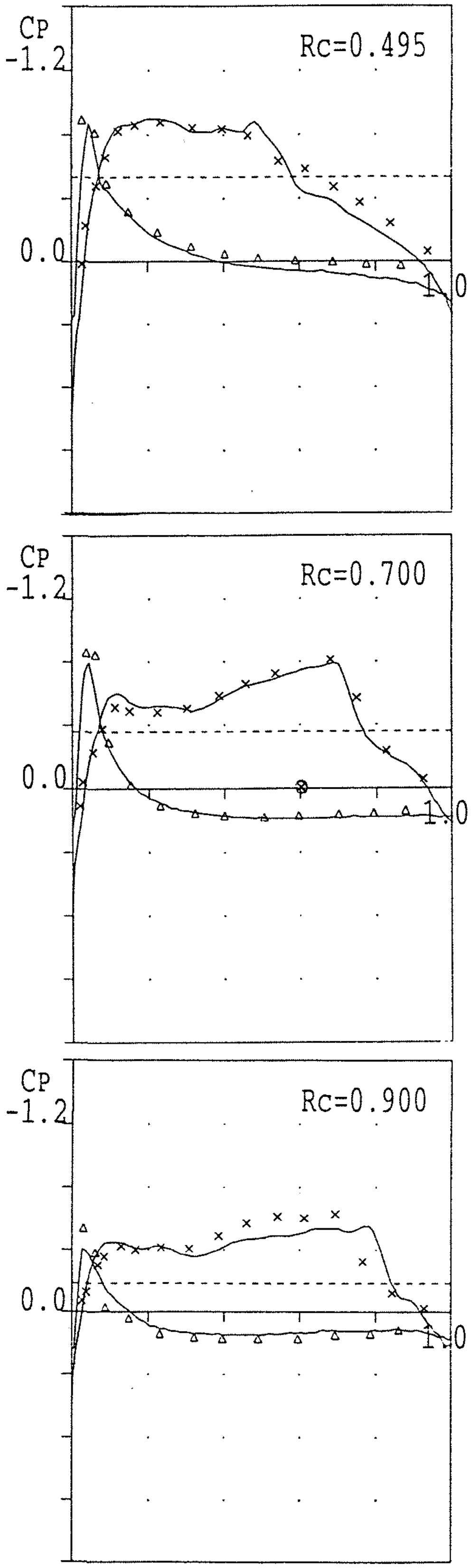

FIG 12 SWEPT BLADE, JAMPROP
RUNNING GEOMETRY
M = 0.7, RPM = 4444

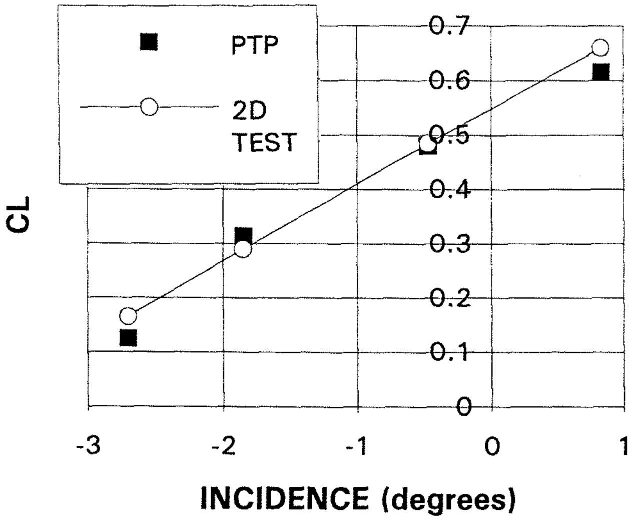

Figure 13
Lift curve data at fixed helical Mach number, for 60% radius, unswept blades, at cruise conditons.

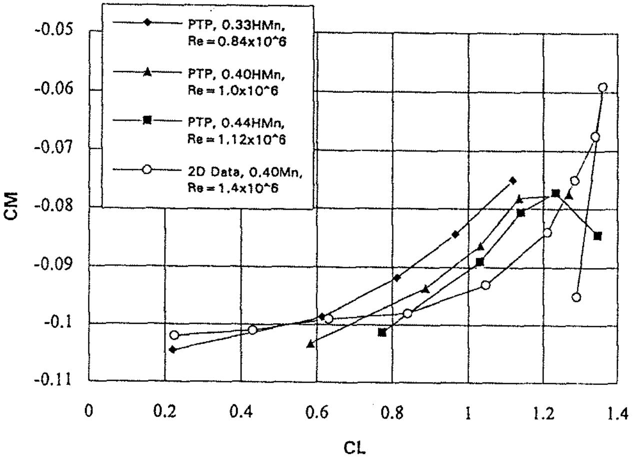

Figure 14
Piching moment data at take-off/climb conditions. 60% radius, unswept blades.

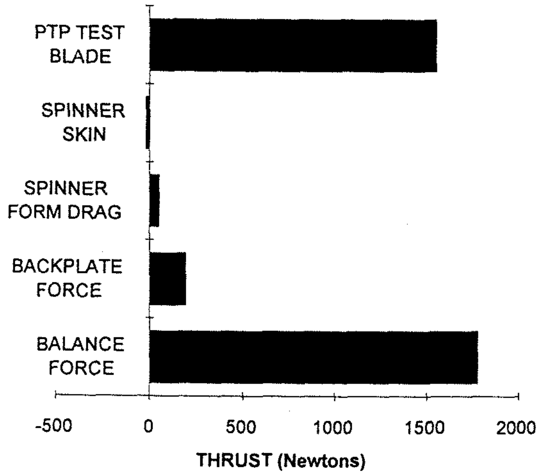

Figure 15
Example of thrust accounting for measured performance. Unswept blades, at Mach 0.65.

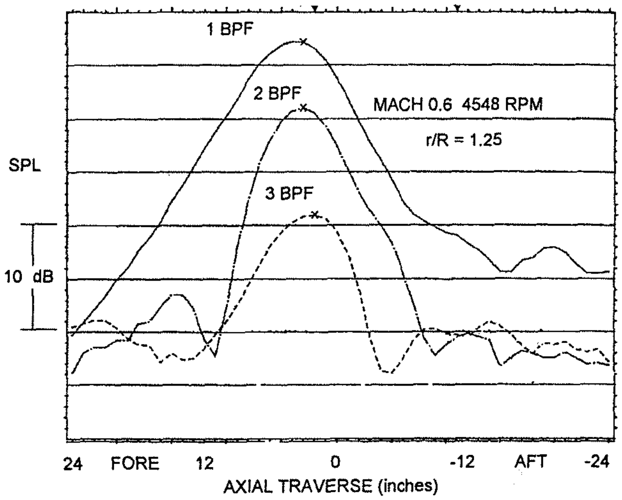

Figure 16
Noise polar for unswept blades, Mach 0.6.

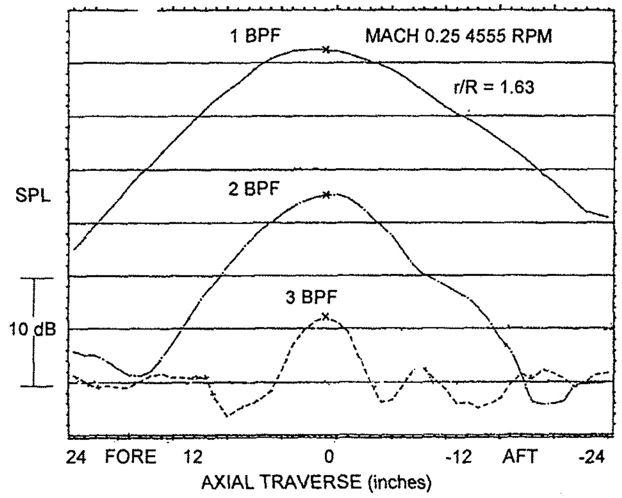

Figure 17
Noise polar for unswept blades, Mach 0.25.

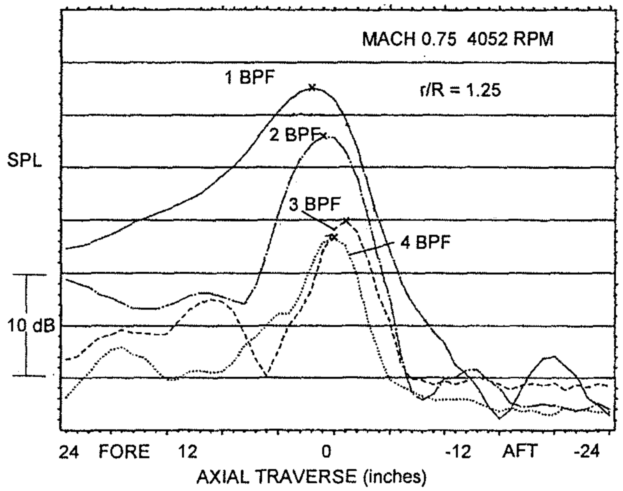

Figure 18
Noise polar for swept blades, Mach 0.75.

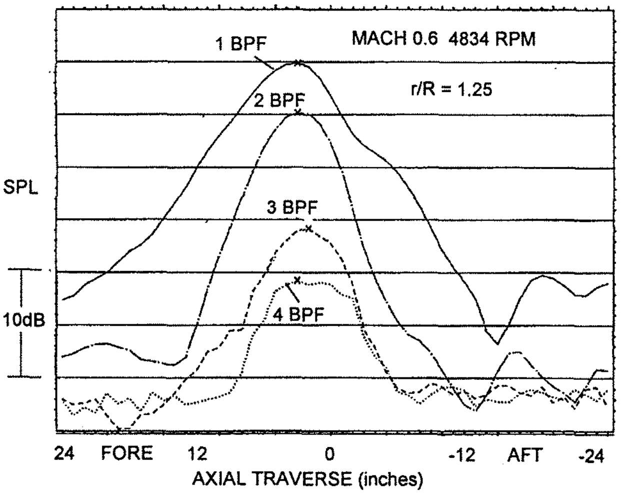

Figure 19
Noise polar for a low loading, high thickness noise case. Unswept blades, Mach 0.6.

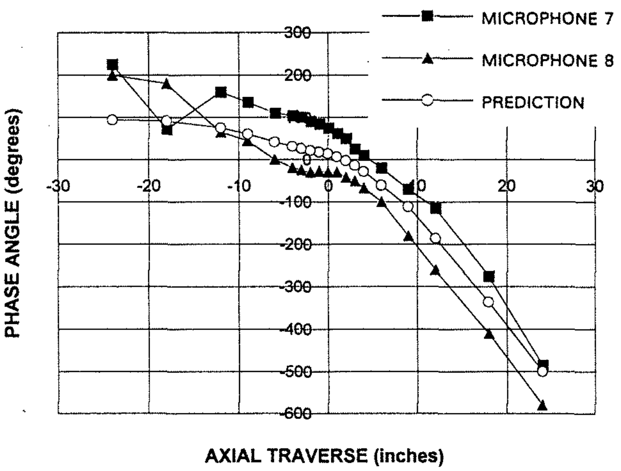

Figure 20
Comparison between measured and predicted first tone phase angle. Unswept blades, Mach 0.65.

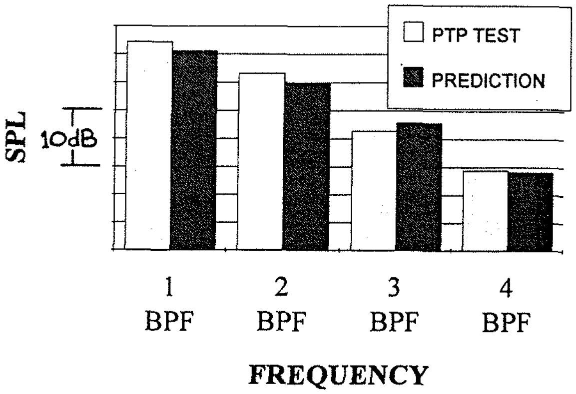

Figure 21
Comparison between measured and predicted noise. Unswept blades, Mach 0.65.