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# JOINT ANGLO-AMERICAN EXPERIENCE OF THE ANALYSIS OF HELICOPTER ROTOR BLADE PRESSURE DISTRIBUTIONS

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## ABSTRACT

American and British interest in computer-assisted analysis of rotor blade pressure and stress measurements started in 1977 following flight tests with an AH-1G helicopter by the US Army and by NASA Langley, and with a Wessex helicopter at RAE Bedford, UK. Two suites of computer programs for analysing the data have evolved. The simpler system at RAE Bedford has been continuously adapted to suit different flight experiments, whereas the US Army developed a comprehensive system known as DATA-MAP. Two joint working sessions have been held so far, one at RAE Bedford and the other at ATL Fort Eustis during which comparisons of the measured and calculated rotor loads were made. In the event, the first session was mainly taken up with correcting program faults but specific topics were addressed at the second meeting where weaknesses in prediction methods were known to exist. The use of the data analysis systems in showing where, and possibly how theory can be improved is discussed.

## 1 INTRODUCTION

In 1976 collaborative research activity between NASA Langley, the US Army at Fort Eustis, and the Royal Aircraft Establishment, UK, led to an agreement to exchange data on helicopter rotor loads measured in flight. At that time extensive flight tests[1], during which rotor blade pressure distributions and strains were measured, had been completed by Bell for the US Army on an AH-1G helicopter, but these had not been processed and analysed in any detail. At NASA Langley a further series of flight tests[2], also on an AH-1G had provided pressure distribution data on experimental blades having an NLR 6223-62 blade section. At RAE Bedford the analysis of pressure distributions obtained from aerofoil tests of modified blades on a Wessex helicopter[3] was proceeding using a specially developed interactive graphics system to display these measurements. It was agreed that by arranging joint 'workshop sessions', the US data could be displayed using the RAE graphics system already in use, and consultative interpretations of the results of each of the flight experiments would be attempted.

In the first part of this paper, after a brief description of the flight experiments and data analysis techniques, an account of the workshop activities is given. Samples of the displays produced are used to show the quality of the results achieved during these first attempts to use a common graphics system, and to illustrate some of the difficulties which arise and how they are being overcome.

In the second part of the paper, a more detailed account is given of the latest results of further analysis which has become available in the US. It shows the full scope and value of flight measurements when applied to the validation of rotor performance prediction methods currently in use.

PART 1

## 2 FLIGHT EXPERIMENTS

### 2.1 Eustis/AH-1G

The US Army, under contract with Bell Helicopter Textron conducted an aerodynamic and structural loads survey of a helicopter during operational manoeuvres in order to describe in quantitative terms the aerodynamic operating environment of the rotor and the attendant dynamic responses of the vehicle. The blades were instrumented using the 'gloved blade' technique (Fig 1) to provide for instrumentation without affecting the blade's structural integrity while still maintaining a smooth profile. The glove thickness was uniformly 0.13 inch thick over the entire blade surface. Pressure distributions at five radial stations were measured using twenty-two absolute pressure sensors distributed around each chordline and sampled at a rate of approximately 128 times per rotor revolution.

### 2.2 Langley/AH-1G

These flight investigations, also with an AH-1G helicopter, have been conducted as part of a rotor aerofoil research programme. This programme is jointly sponsored by NASA and the Structures Laboratory - USARTL (AVRADCOM) at Langley. The objective of the total programme is to establish clear relationships between the rotor environment, with its unsteady three-dimensional flow and aerofoil design criteria derived from two-dimensional flow. The flight investigation provides the necessary data for correlation with both theoretical predictions and wind tunnel data. The aerofoils chosen for this study were designed primarily to have low drag on the advancing blade.

Three sets of blades were tested, each with a different blade section, and one blade from each set had a single chordwise pressure distribution measured with thirteen absolute pressure sensors along the chordline. These were sampled at a rate of approximately 180 samples per rotor revolution.

### 2.3 Royal Aircraft Establishment/Wessex

This experiment, on a Wessex helicopter, was designed to compare directly the performance of two different blade sections. Two opposite blades of the set of four were modified in the tip regions to produce instrumented test sections one having an NACA 0012 profile and the other an RAE 9615 profile. These blades were carefully balanced so that they could be flown together as a matched pair enabling a comparison of section performance in the same flight condition. Pressure distributions were measured using seventeen sensors around a single chordline on each of the two blades, with supporting sensors arrayed radially along the leading and trailing edge to give information on the three-dimensional features of the loading and to aid the interpretation of unsteady effects. The pressures were sampled 360 times per rotor revolution.

Summary of flight experiments

| Experiment | Aircraft | Blade sections | Radial location of chordlines | Number of sensors on chordline | Data rate samples/ rev |
|---|---|---|---|---|---|
| US Army/Bell (operational Loads Survey) | AH-1G | Standard AH-1G section + 0.13 inch glove | 40%<br>60%<br>75%<br>86.4%<br>95.5% | 14<br>20<br>24<br>28<br>24 | 128 |
| NASA/Langley (Army Structures Laboratory) | AH-1G | NLR6223-62 | 90% | 13 | 180 |
| Royal Aircraft Establishment (UK) | Westland Wessex | NACA 0012<br>RAE 9615 | 92% | 17 | 360 |

## 3 DATA ANALYSIS TECHNIQUE

### 3.1 Basic programs

The basis of the interactive graphics system is the set of programs developed by James at RAE for the analysis of the Wessex flight tests[4]. The programs perform curve fitting and integration routines with the seventeen pressure points around each chordline for each degree of rotation of the rotor. This enables force and moment coefficient plots to be displayed on a visual display unit, and for regions of interest, for instance where blade section limitations are apparent, to be located for the more detailed study of chordwise pressure distribution. This form of interactive analysis and display of selected data is considered to be essential for the efficient analysis of the very large number of pressure samples which must be recorded in the study of unsteady blade section performance on a rotor.

### 3.2 Changes to accommodate US data

Before flight data from the US tests could be displayed at RAE, modified versions of these programs had to be prepared to allow compatibility with computer hardware and to accommodate the different sensor layouts and sampling rates.

In preparation for the first joint experiment, James visited NASA Langley and ATL at Fort Eustis to clarify the details of these preparations. Initially, the programs written for the Xerox Sigma 8 at RAE Bedford were found to be incompatible with the IBM 360 used by ATL, in several major areas. New routines had to be written to replace the library routines used on the Sigma 8. Assembler coding was removed, and all Xerox dependent FORTRAN was replaced by

ANS-FORTRAN. Changes were made to allow for differences in the format of the AH-1G data, and in the event, the US teams successfully prepared sets of magnetic tapes in the agreed format in time for the first joint workshop at RAE Bedford.

## 4 THE FIRST JOINT WORKSHOP AT RAE BEDFORD

### 4.1 Scope of the analysis

In September 1977 a team including participants from Fort Eustis, NASA Langley and RAE worked together for two weeks at RAE Bedford, UK. One of the common aims of the flight test programmes is to study the limitations of the blade section performance on the rotor. With a view to completing detailed analyses in the future, it was decided that initially an attempt should be made to compare certain characteristic features of blade section performance limits, that is, retreating blade stall and advancing blade shock formation, as they occurred in each flight experiment. Also the effect of the wake geometry on blade-vortex interaction was of common interest, and for reference, low speed level flight conditions with no severe aerodynamic limits were included. These provided a useful comparison of the basic differences between two- and four-blade loading distributions at the same tip speed, thrust coefficient and advance ratio. Each contributor to the joint experiment prepared representative sets of data for comparison.

### 4.2 Tasks undertaken at the workshop

The first task was to process the tapes prepared by the teams from Langley and Fort Eustis to perform the curve fitting and integration. Inevitably there were many initial difficulties, mainly associated with the curve fitting routines, but recognising that these could be corrected in the long term, it was decided to display samples of all the data as an interim measure so that the collaborative exercise could proceed to interpret and compare the chosen samples.

### 4.3 Samples of results compared

Samples from each flight experiment have been selected to illustrate features of the flight cases studied and the quality of the plots obtained in this first attempt to use a common graphics system.

From the RAE (Wessex) tests, sample chordwise pressure distributions are given in Fig 2. The accuracy of the curve fitting routines is well illustrated by this example. In Fig 3, the force and moment coefficient time histories, and the individual upper surface pressure time histories show a considerable extent of blade stall on the retreating blade for this flight condition. The rate of propagation of the stall in a radial direction along the blade and the spread of separation across the blade chord are features which are being analysed. Also included in this analysis, by comparison with related flight conditions, are the contributions which the blade torsional response and local wake interactions make to the characteristics of this stall cycle.

The data from the US Army AH-1G reference flight conditions flown well within the aerofoil limitations, correlated well with the NASA Langley AH-1G calibration cases chosen to match them, giving confidence in the validity of the measurements obtained in these quite independent flight experiments. From the Army data, the two upper surface pressure plots in Fig 4 reveal several features of the blade pressure distribution of interest. In the upper plot, the strength location and duration of the shock on the advancing blade is evident from the 'troughs' in the pressure time histories and the beginning of a slight stall is revealed by the fluctuations of the leading edge sensors in the fourth quadrant of the rotor disc. The high incidences causing stall near the blade tip in this azimuth region are attributable to local blade-vortex interaction. In the lower plot of Fig 4 the rapid changes in loading associated with more numerous wake interactions at a lower advance ratio are clearly reflected in the shape of the pressure time histories, especially near the leading edge of the blade. A vortex intersection is also visible on the retreating blade. Note also that the presence of a shock is revealed by the 'trough' on the advancing blade in one of the traces even at this low speed, due to the relatively high tip speed of the two-bladed rotor. This type of plot is of value in checking the accuracy of the geometry of the wake models used in rotor performance predictions.

Although not included here, the NASA Langley tests with the NLR6223-62 aerofoil showed many interesting features, including negative lift in the second quadrant and large negative pitching moments in the same region. However from these measurements, some preliminary comparisons with theoretical calculations of the section pressure distributions were attempted as shown in Fig 5. These calculations used the NYU transonic aerofoil analysis program[5]. The program allows for an attached turbulent boundary layer in steady two-dimensional flow, and the comparisons in these examples suggest good agreement considering the limitations of the methods.

### 4.4 Assessment of First Workshop

The team successfully displayed the (hitherto unseen) results of the US flight experiments on the RAE computer at Bedford. Once the problems of adapting the graphics program to the format of the new input data had been overcome, the difficulties which arose in the course of the collaboration were mainly associated with the curve fitting routines used in the automatic calculation of the blade forces and moments. The problem was to find simple curve fitting methods which would produce consistently reliable force and moment integrals for the full range of incidences and Mach numbers encountered, especially for the data sets which had a limited number of chordwise pressure points. Further discussion of this problem is included in section 6.2.

By working together in this way, a reasoned assessment of the validity of the US flight data displays was possible, referring to corresponding Wessex flight cases previously analysed in detail. Applying the criteria defined by the known behaviour of the blade pressure distributions near the trailing edge and close to the front stagnation point, early faults due to incorrect reference static pressures and stagnation point locations were largely eliminated, although these factors continue to pose some difficulties in the analysis of flight measurements having a limited number of pressure points around the chordline.

At the conclusion of this workshop the participants agreed to continue the exchange of flight data on the specific analysis topics of interest to each, and an abbreviated format for the flight data was agreed so that relatively large amounts of data could be conveyed concisely on magnetic tape.

## 5 DEVELOPMENT OF DATA-MAP

After this first workshop, the team from the Applied Technology Laboratory (ATL), US Army Research and Technology Laboratories at Fort Eustis, proceeded with the development of the graphics system, primarily for the analysis of the data from the Operational Loads Survey, but with the intention of it being general enough for the display of both measured and analytic data. The basis of this development was a computer program initially developed to recover the raw data, but this program had proved to be inconvenient, and time consuming to apply, discouraging potential users.

Bell Helicopter Textron was selected to develop this software[6]. The attractive proven features of the RAE interactive graphics used for the analysis of the Wessex data were incorporated, and considerably extended, the resulting computer software system being called DATA-MAP (Data from Aeromechanics' Test and Analytics - Management and Analysis Package).

Briefly this package offers the user the convenience of fully interactive graphics to display the pressure measurements in absolute values or coefficient form against time, chord or radius, to derive forces and moments, and to optimise scaling as the analysis proceeds. Many other features such as harmonic analysis, averaging and filtering are also included. Examples of the type of plots available are shown in Fig 6 where the distribution of normal force coefficient over the disc is displayed as a polar contour plot and also as a surface plot. The next figure (Fig 7) shows a series of plots of the upper surface pressures for a range of flight speeds. A feature which is very clear on these plots is the development of the supercritical region on the advancing blade as speed is increased.

## 6 THE SECOND JOINT WORKSHOP

The development of the DATA-MAP system at ATL and continuing analysis of the Wessex measurements together with work on improved rotor performance prediction methods at RAE led to the convening of a second 'Rotor Loads Data Workshop', this time at ATL, Fort Eustis in March 1980. The two week workshop was again a joint effort of specialists from the US Army, NASA Ames and the Royal Aircraft Establishment, UK.

The objectives at this session were to explore the capabilities of the DATA-MAP system in the analysis of RAE and US Army flight data, to jointly interpret the results displayed, and to provide analytic predictions for the test cases to serve as a guide in data interpretation. The planning for this workshop during 1979 included the exchange of flight data on tapes of the agreed common format. The major features investigated were advancing blade compressibility phenomena, blade vortex effects and retreating blade stall.

Despite the last minute computing difficulties which inevitably accompany plans such as this, the team succeeded in displaying a considerable amount of the selected data using the DATA-MAP facilities.

### 6.1 Vortex interaction on the two-bladed rotor

This part of the work was mainly based on the Army AH-1G measurements because pressures were measured at five radial positions, and the vortex interactions were stronger, if less numerous than for the four-bladed rotor of the Wessex. The azimuth location of these interactions, after correction of an initial azimuth error, was found to agree closely with the positions calculated from an undistorted cycloidal model of the wake geometry.

An interesting example arises at a flight speed of 60 knots, where in this particular case a pronounced blade slap noise was observed with a highly loaded two-bladed rotor[5]. Fig 8 illustrates well the capability of the DATA-MAP system to collate a set of pressures from different chordlines along the blade to produce a 'contour' plot. The plot shown is of pressure coefficient contours derived from measurements at 10% chord on each of the five chordlines. It gives a guide to the overall blade incidence distributions associated with the close proximity of the wake. The corresponding plot of the absolute pressures (Fig 9) gives a better indication of the abruptness of the loading changes which occur simultaneously along a considerable extent of the blade radius, giving rise to the characteristic noise signature.

## 6.2 Comparison of measured and predicted blade loads

An example of the initial attempts to compare the measured $C_N$ values from the Army AH-1G flight tests with RAE, and with US/C81 calculations is shown in Fig 10.

In these comparisons, the C81 calculations included the blade dynamic response, but the downwash description was unable to represent the perturbations due to close wake interaction. On the other hand Young's prediction included a vortex ring representation of the wake, but only allowed for rigid blade motion in the simplified version adapted to the two-bladed rotor configuration. Both methods included a representation of unsteady aerofoil effects, and predictions were run with and without this feature to assess its value.

By a similar process, the extent of the agreement between the calculated and measured pitching moments was assessed. For this quantity the agreement was less satisfactory than for the normal force coefficients, especially in regions of the rotor disc where strong shocks were present on the blade, and also in blade stall regions. Closer investigation of the measured values revealed discrepancies between the DATA-MAP computed integrals and those derived using the RAE curve fitting routines.

The RAE routines plot $C_p\sqrt{x/c}$ against $\sqrt{x/c}$ as shown in Fig 2 to give a smoother plot which can be more easily fitted by a continuous curve through the measured points. However, inspection of individual pressure distributions revealed that errors were included in the integrals derived in this way in cases where conditions outside the normal aerofoil limits were met.

These investigations highlight the requirement to develop automatic curve fitting routines which can accurately reflect characteristic features of the highly irregular pressure distributions associated with supercritical and unsteady separated flows, given the relatively small number of pressure sensors which it is feasible to fit around a blade chord in a flight experiment.

## 7 CONCLUSIONS FOR PART 1

These workshops have proved to be a fruitful and informative exchange between US and UK helicopter research teams. The development of the DATA-MAP graphics has been assisted by the incorporation of techniques used by RAE, whilst some of the US flight data has been included in the continuing analysis of rotor blade phenomena at RAE.

Currently available graphics techniques have been explored, and some of the limitations exposed, especially those concerned with the integration of measured pressure distributions. The relative merits of simple straight line joining of measured points, and more complicated methods involving the construction of continuous curves through transformed plots of the pressure distributions have been compared. The findings indicate that further improvements are still required to give sufficiently accurate force and moment values. This can perhaps best be achieved by constructing curve fitting routines for the automatic analysis which comply with the known pertinent features of pressure distributions derived from supporting wind tunnel and theoretical studies.

Having developed the methods of data exchange, processing and display here described, the opportunity to compare prediction methods with selected flight cases will be taken during a forthcoming workshop planned for Autumn this year.

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## 8. US ARMY SUMMARY OF JOINT ACTIVITIES

The TTCP Helicopter Aerodynamics and Dynamics Action Group (HAG4) was established in 1977 to promote the exchange of American and British data on rotor loads measurement and processing methods. A joint US/UK working session was conducted at RAE Bedford in 1977 in which the participants established the feasibility of exchanging data, conducting joint work sessions, and extending the applicability of the British interactive graphics system to other data bases. The success of this collaborative effort indicated directions for continued co-operation in the areas of rotor loads data analysis and interpretation.

The Technical Panel, HTP-6, Helicopter Aerodynamics, Dynamics and Man/Machine Integration, was formed in 1980, combining activities formerly addressed by HAG-4 and HTP-4, Helicopter Operations. A second Joint Working Session was conducted at the Applied Technology Laboratory (ATL) USAAVRADCOM, Fort Eustis, Virginia in March 1980, under the auspices of TTCP HTP-6. The interpretation of data from the US Army AH-1G Operational loads Survey and the RAE Wessex was aided with analytical predictions of rotor loads providing a necessary link in interpreting the measured airfoil pressure distributions and to evaluate the ability of the chosen methods to predict local loading features. Particular emphasis was placed in the areas of advancing blade compressibility and blade vortex interactions. Selected results are presented in Section 11.

## 9. ARMY OPERATIONAL LOADS SURVEY (OLS)

The US Army, under contract with Bell Helicopter Textron (BHT), conducted a flight test using an Army AH-1G helicopter to obtain experimental data from which insight of rotor aerodynamic environments and structural dynamics of helicopters might be gained. A comprehensive data base was acquired of rotor aerodynamic forces, aeroelastic loads, blade motions, acoustics and the attendant responses of the control system and airframe that result from flying operational maneuvers.

The test helicopter and instrumented rotor are shown in figure 1. Continuous and simultaneous data were recorded from 387 transducers for 244 different flight conditions. For a complete description of the instrumentation on the rotor and vehicle, see Reference 1. Only that instrumentation relevant to the HTP-6 flight loads analysis exercise will be described here.

Both main rotor blades were instrumented utilizing the 'gloved blade' approach to provide for instrumentation without affecting the blade's structural integrity and still maintain a smooth surface and accurate airfoil contour. All rotating transducers and associated wiring were embedded within the glove contour. The glove thickness was .130 inches (.33 cm). The trailing edge was extended 1.5 inches (3.81 cm), terminating in a thickness of .10 inch (.254 cm). The following table gives a comparison of the production AH-1G blade and the gloved instrumented blade.

| | Production AH-1G Blade | Gloved Instrumented Blade |
|---|---|---|
| Chord, in. (CM) | 27 (68.58) | 28.63 (72.72) |
| Trailing edge extension, in. (CM) | - | 1.50 (3.81) |
| Thickness, in. (CM) | 2.52 (6.4) | 2.78 (7.06) |
| Thickness Ratio, % | 9.33 | 9.71 |
| Leading edge ratio, % | 1.229 | 1.596 |

One blade contained 110 absolute pressure transducers located along chord lines on the upper and lower aerofoil surfaces at 40, 60, 75, 86 and 95 percent radial stations. The other main rotor blade had hot wire sensors located at the same five radial stations from which stagnation point location was derived. A rotating electronics/multiplex package (R-MUX) was mounted on top of the main rotor yoke which filtered and regulated critical excitation voltages, conditioned signals and multiplexed the measurements to reduce slip ring requirements.

The FM multiplex signals, consisting of 16 data channels each, were recorded on the multiplex flight recorder, one multiplex signal per tape track. Digital data tapes were produced by processing the analogue tape prime data records into a digital formal. Over 72,000 separate functions of time were digitized and recorded on 175 magnetic tapes. A computer program was developed to retrieve the raw data; however, it was inconvenient, time consumming and discouraged potential users. It was difficult to manage such a large data base without the proper software tools. ATL developed the functional descriptions for such a software system to utilize the OLS data base and yet be general enough to use with other data sets, both analytical and test. This software system was developed under contract with BHT Scientific and Technical Computing and is described in Section 10.2.

10. Computer Software Programs - A short description of the various US Army computer software tools utilized in the joint work sessions is given here.

## 10.1 Rotorcraft Flight Simulation Program, C-81

The Rotorcraft Flight Simulation Computer Program C-81 is a multidisciplinary mathematical model that may be used to simulate a wide variety of helicopter or V/STOL aircraft configurations using a digital computer. Aircraft performance, stability and control, and maneuver characteristics, as well as rotor blade loads, may be estimated using this model. The fuselage, two rotors, each with a modal pylon, aeroelstic blades, and a nacelle; a wing; four stabilizing surfaces, none of which must be purely vertical or horizontal; four external stores or aerodynamic brakes; a nonlinear, coupled control system including a collective bobweight, stability and control augmentation system, and maneuver autopilot simulator; two jets; and a weapon with recoil, are treated as separate aircraft components, allowing detailed representation of the aircraft for design or detailed analysis applications. Six rigid-body fuselage degrees of freedom and up to six rotor blade elastic degrees of freedom for each of two rotors are accounted for.

For a complete overview of C-81 capabilities and discussions of the background and development of the principle mathematical models in the program refer to reference 7.

## 10.2 DATAMAP

DATAMAP (Data from Aeromechanics' Test and Analytics Management and Analysis Package) is a computer software system that provides direct access to large time history data bases, performs analyses and derivations, and provides the user with various options for output displays; inactively or through batch processing.

DATAMAP consists of two major programs, the File Creation Program and the Processing Program, as well as several utility programs. Only the Processing Program will be described here in any detail; for a complete description of DATAMAP see references 6 and 8. The basic execution sequence is illustrated in figure 11. The File Creation Program reads data from some storage medium (digital tape or disc), selectively transfers data to a direct access disc called the Master File and creates a directory of the data thus stored. The Master File is then the data input source for the Processing Program. The

Processing Program retrieves data from the Master File, accepts user commands interactively or in batch mode, processes the data, and outputs data in graphic or printed formats. The Processing Program provides the user with various analyses that may be performed on the basic data contained on the Master File, and in addition, certain parameters may be derived from the basic or processed data. The computational capabilities available to the user in the Processing Program are detailed in figure 12. These analyses and derivations can be performed in multiple dimensions (e.g., time, chord, and radius). Sequences of analyses and/or derivations can be performed on a set of data in any appropriate combination.

DATAMAP has been installed and is operational on various computers including IBM 360 Model 65, IBM 4341, and VAX 11/780. It is a data analysis and management system that has been shown to be versatile and user oriented. It provides an engineering user, not necessarily computer oriented, a powerful tool to interactively analyze and interpret a vast amount of data which may otherwise be unmanagable.

11. Joint Work Session Results. Selected results from the Second Joint Work Session are presented and discussed in this section, illustrating some of the analysis and plotting features of DATAMAP and the RPP suite of programs including comparisons with the various analytical results.

## 11.1 Comparisons of Predicted Aerodynamic Loading With Measurements

A very versatile characteristic of DATAMAP is its ability to access various data sets during the same interactive session or batch run, providing the means of direct comparison and correlation between data from the different sets. Analytical results from helicopter simulations can therefore be directly correlated with actual flight test data to evaluate the accuracy and limitations of the analytical simulations. The results presented in this section were generated in this manner. The data sets represent parameters derived from the OLS measurements, and analytically predicted parameters using the Rotorcraft Flight Simulation Program C-81, and Young's Analysis. Emphasis is placed on the differences and similarities of the results presented here without discussion of the details of the two analyses. A comparison of the Normal Force Coefficient, CN, derived from measured blade pressures and analytically predicted by C-81 and Young's Analysis is shown in figure 13. The flight test data represents an AH-1G forward level flight case for which the advance ratio is 0.31.

The CN is derived from measured data by nondimensionalizing the integral of the pressure force perpendicular to the blade chord reference line. All of the C-81 predictions incorporate unsteady aerodynamics and nonuniform inflow unless otherwise specified. Excellent agreement is generally shown between the predicted and derived CN's; however, some discrepancies are exhibited. Young's Analysis under predicted the maximum CN on the retreating blade particularily inboard, which may reflect the difficulty in predicting unsteady aerodynamic characteristics. For the outboard case, r/R = .955, both analytical models predict negative CN on the advancing blade, which is not indicated from the measured data.

The importance of the inclusion of unsteady aerodynamics is illustrated in figure 14. The CN is shown for the 40-percent radial station which is within the reverse flow region on the retreating blade. CN derived from flight measurements and two C-81 predictions are shown, one with the BUNS unsteady aerodynamic option invoked, and the other without unsteady aerodynamics representation. Both simulations show good correlation for the advancing blade; however, for the retreating blade, the steady aerodynamic simulation is clearly inadequate.

The comparisons of quarter chord Pitching Moment Coefficient, CM, for the same flight condition, in figure 15 do not exhibit the same degree of correlation.

The worst case is at the most inboard radial station, r/R = .40. Both analytical models predict negative Pitching Moment Coefficients for the retreating blade; however, the CM derived from the measured data reaches a large positive value of 1.2 on the retreating blade. An examination of the measured chordwise pressure distribution reveals that the blade experiences trailing edge flow separation on the retreating side. These trailing edge pressure readings cause the resulting integrated pressures times the moment arm to be very large and positive for this region. The analytical models fail to reproduce this effect. The failure to model this phenomenon is emphasized in the case of the pitching moment since it is amplified by multiplying the pressures by the distance to the quarter chord, which has the effect of making the CM very sensitive to contributions near the trailing edge, which raises questions relative to the accuracy of blade pitching moment parameters derived from test data. Normally, in a test program, the number of pressure taps are fewer near the trailing edge than at the more critical leading edge; furthermore, the contributions of the pressure differences at the trailing edge, i.e., at X/C = 1.0, are based on extrapolated data, since the most aft chordwise station is X/C = .97, with the assumption that the Kutta condition is satisfied. Therefore, if this extrapolation is incorrect, the resulting contribution to CM would be in error. Other general areas in which error may be introduced in deriving parameters from any measured data are in the methods used for curve fitting a discrete number of test point and integrating techniques.

Comparisons of the pitching moments for r/R = .75, and r/R = .864 show good agreement on the advancing blade but not for the retreating blade, while the advancing blade comparison is not good for the outboard case at r/R = .955.

11.2 Blade Vortex Interaction. Blade tip vortices influence blade loading distributions by intersecting or coming within close proximity with the blades. Therefore, wake modelling is important when predicting rotor loads, locations of impulsive loads for structural dynamic responses and origin of rotor noise generated by vortex interactions. Tip vortex interaction, experienced during flight, can be evaluated by examining the measured leading edge pressure patterns. The leading edge pressure measurements exhibit abrupt changes in pressure resulting in characteristic patterns associated with the velocity distributions of the vortex itself. A typical plot of the variations of leading edge absolute pressure is given in figure 16, from which vortex locations can be determined. The strongest interaction is that from the vortex incountered from the preceding blade. Other less severe vortex interactions are evident, and their origin can be identified with the aid of cycloid plots for the particular advance ratio. Figure 17 shows a comparison of the locus of intersection locations as predicted by simple cycloid theory and determined from measurements for a level flight case with advance ratio equal to 0.146. Figure 18 illustrates results in polar form, comparing Young's Analysis, cycloid blade tip path of preceding blade, and locations of vortex interactions derived from measurements. The solid line traversing from approximately 80 degrees azimuth to 280 degrees azimuth is the locus of intersections of the preceding blade shed tip vortex, as predicted by simple cycloid representation. Note that this line follows the pattern of very closely spaced contour lines (indicating steep gradients) of Normal Force Coefficients predicted by Young's Analysis, as one would expect for intersections or close encounters of a blade with a vortex. Young's Analysis uses the vortex ring wake model which displaces the vortex ring according to cycloid equations. The circled data points on the figure represent the locations of vortex interactions as indicated from the OLS flight measurements.

## 12. CONCLUDING REMARKS

This paper has discussed current Anglo-American cooprative efforts of analyzing and interpreting large quantities of various data bases with the aid of interactive computer systems. The ability to derive, analyze and display various data sets quickly in a workshop environment has been demonstrated to be a versatile and powerful engineering tool which has lead to a considerable advance in the understanding of rotor aerodynamics. The capacity to easily correlate the various data bases (test and analytics) provides a link in interpreting the measured test data and to evaluate the ability of the analytics to predict various characteristics. Future cooperative efforts are being planned toward improvements in data analysis and interpretation techniques and to emphasize areas in which analytical predictions can be improved.

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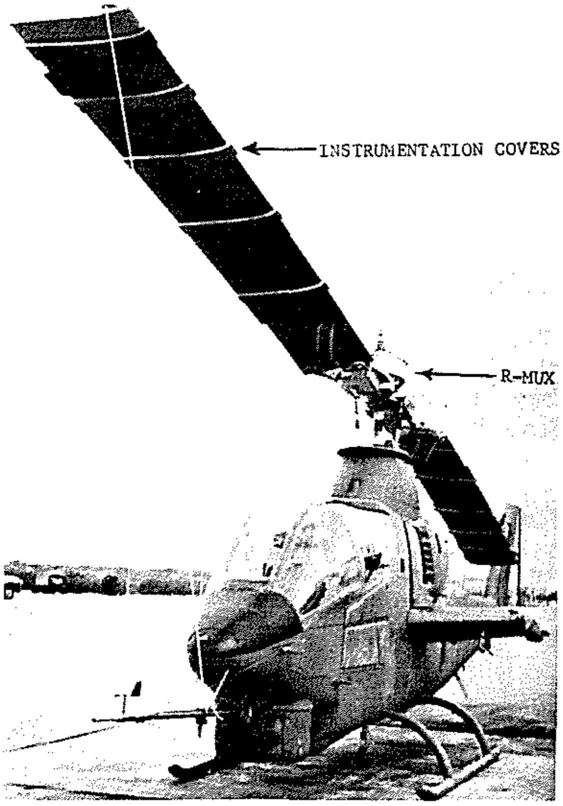


Fig 1 Army AH–1G with instrumented rotor

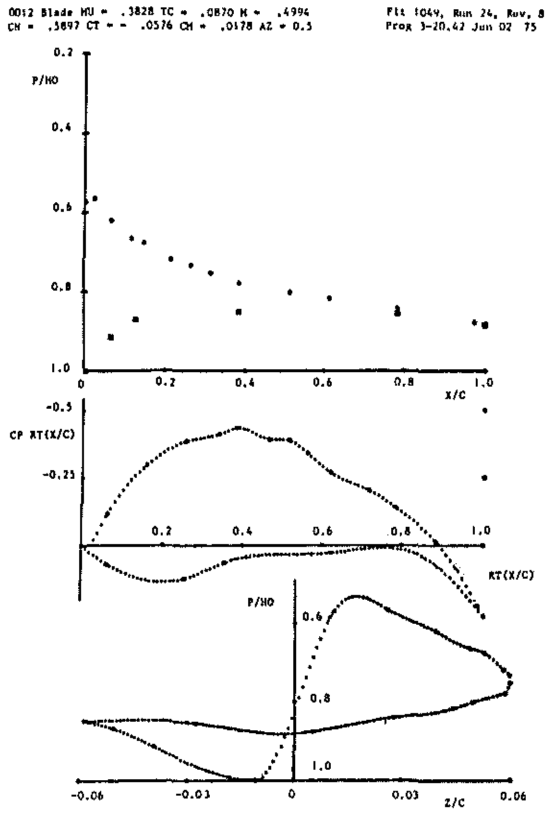

Fig 2 Chordwise pressure distributions – RAE/Wessex

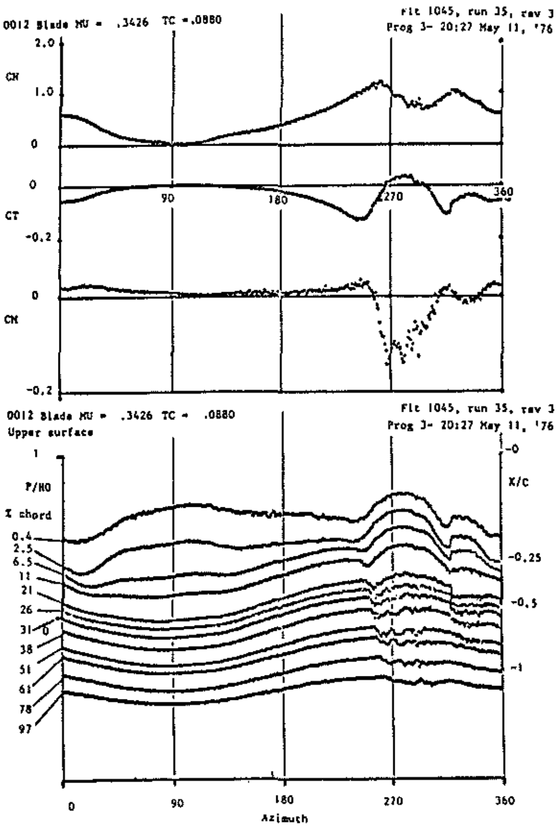

Fig 3 Force coefficients and upper surface pressure plots – RAE/Wessex

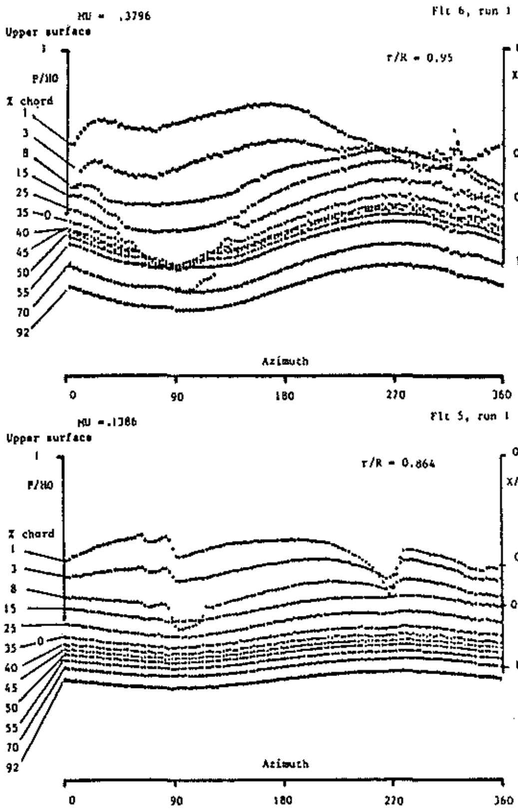

Fig 4 Upper surface pressure plots – Eustis/AH–1G

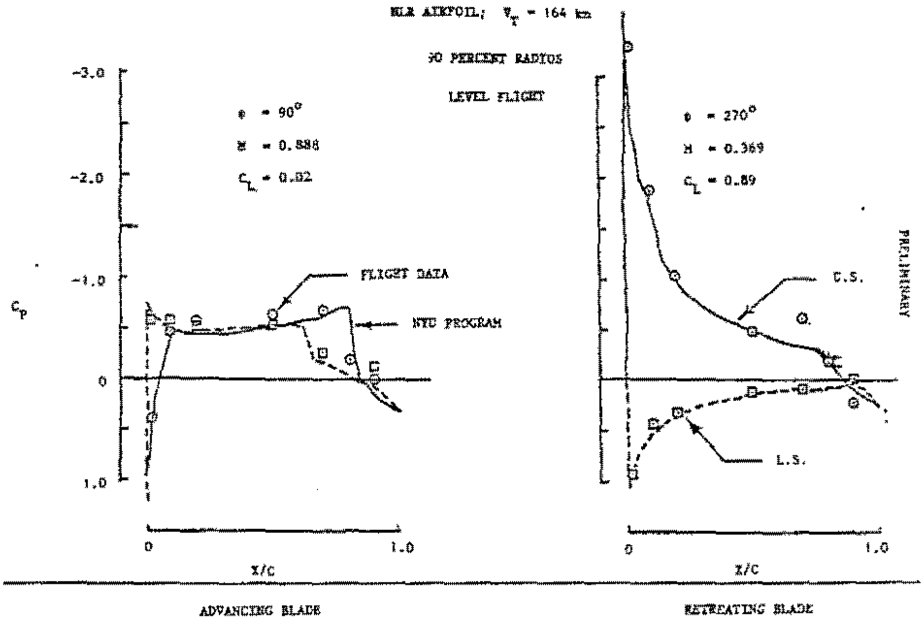


Fig 5 Measured and calculated chordwise pressure distributions – Langley/AH–1G

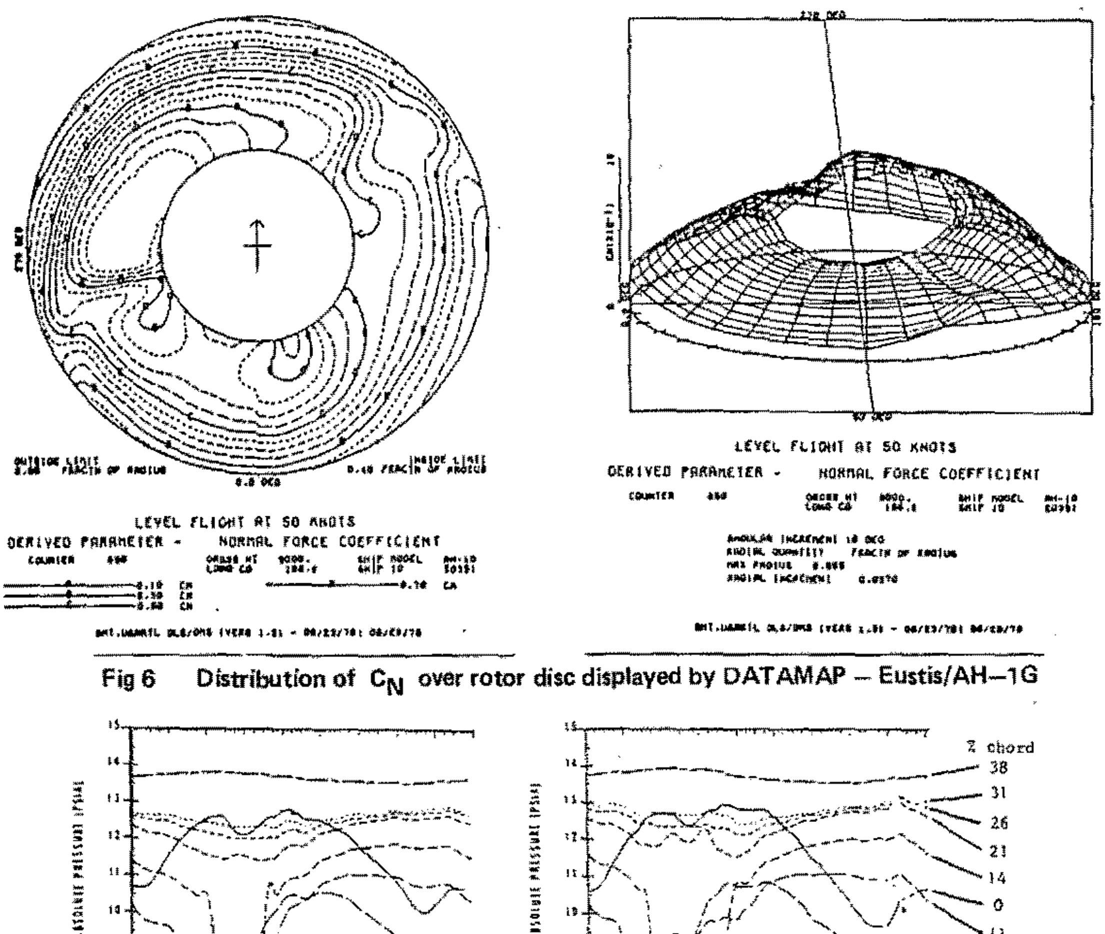


Fig 6 Distribution of $C_N$ over rotor disc displayed by DATAMAP – Eustis/AH–1G

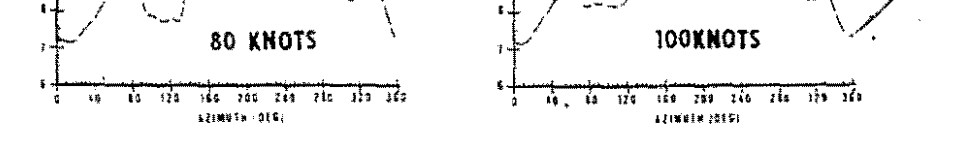


Fig 7 Upper surface pressures measured at 95% radius in accelerating flight – Eustis/AH–1G

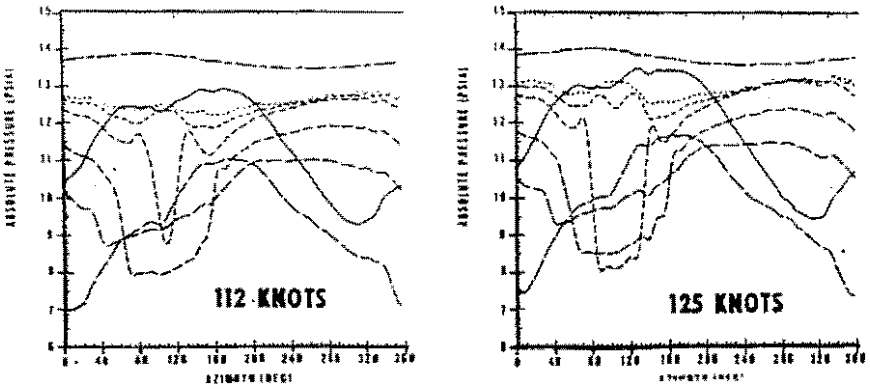


Fig 7 Upper surface pressures measured at 95% radius in accelerating flight – Eustis/AH–1G

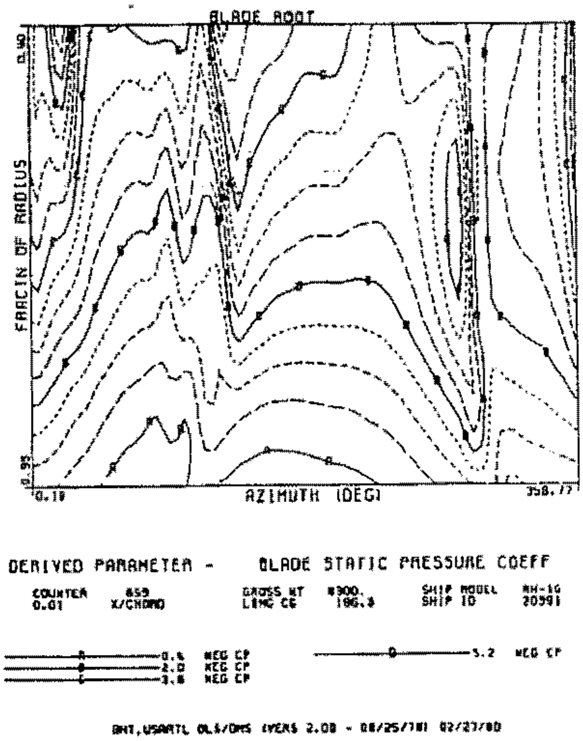


Fig 8 Contour plot derived by DATAMAP from pressure coefficients measured at 10% chord – Eustis/AH–1G

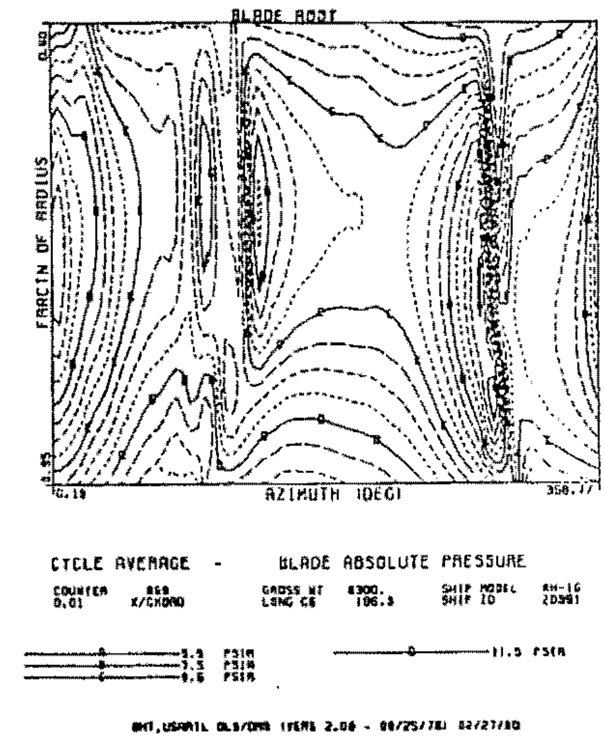


Fig 9 Contour plot derived by DATAMAP from absolute pressures measured at 10% chord – Eustis/AH–1G

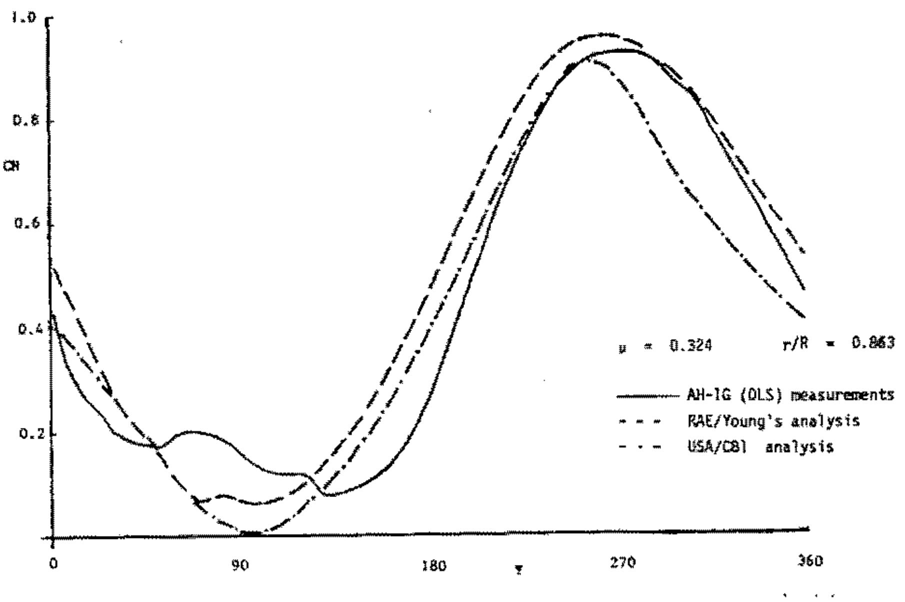


Fig 10 Eustis/AH–1G measurements of $C_N$ compared with RAE/Young's and US/C81 calculations

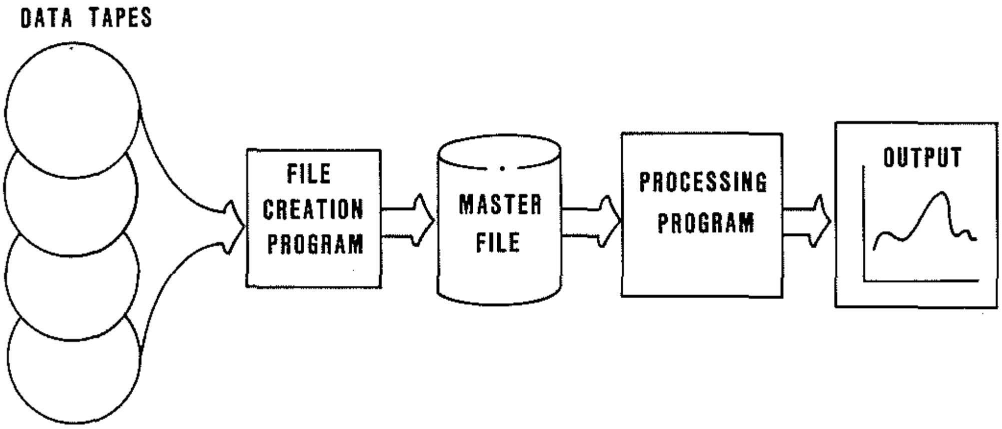


Fig 11 Typical DATA-MAP execution sequence

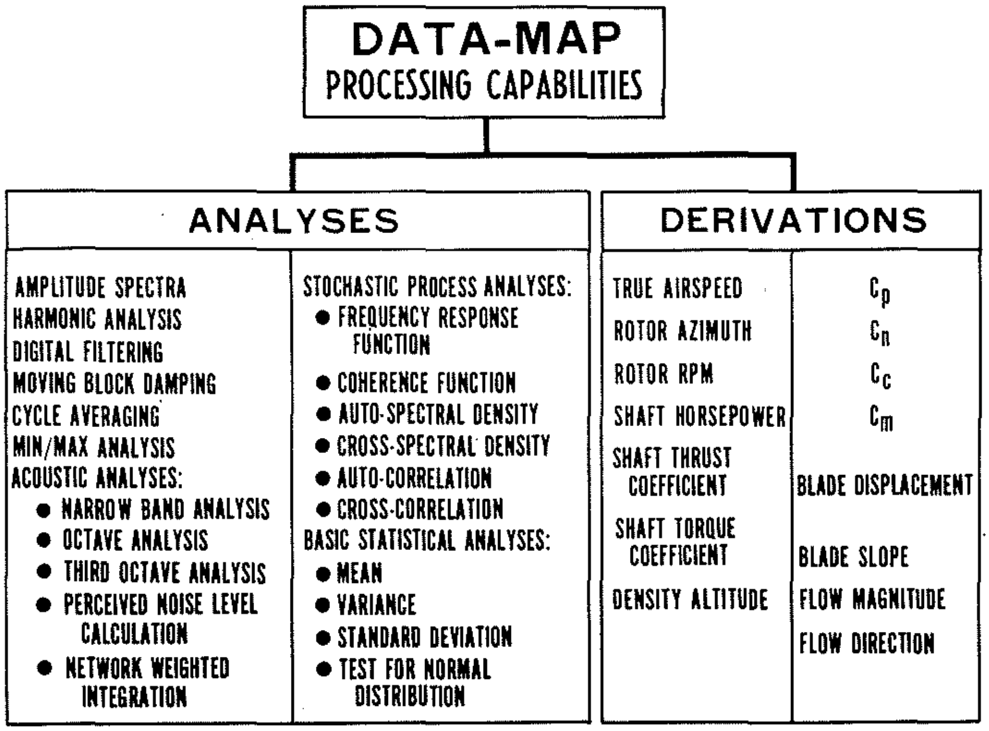


Fig 12 DATA-MAP processing capabilities

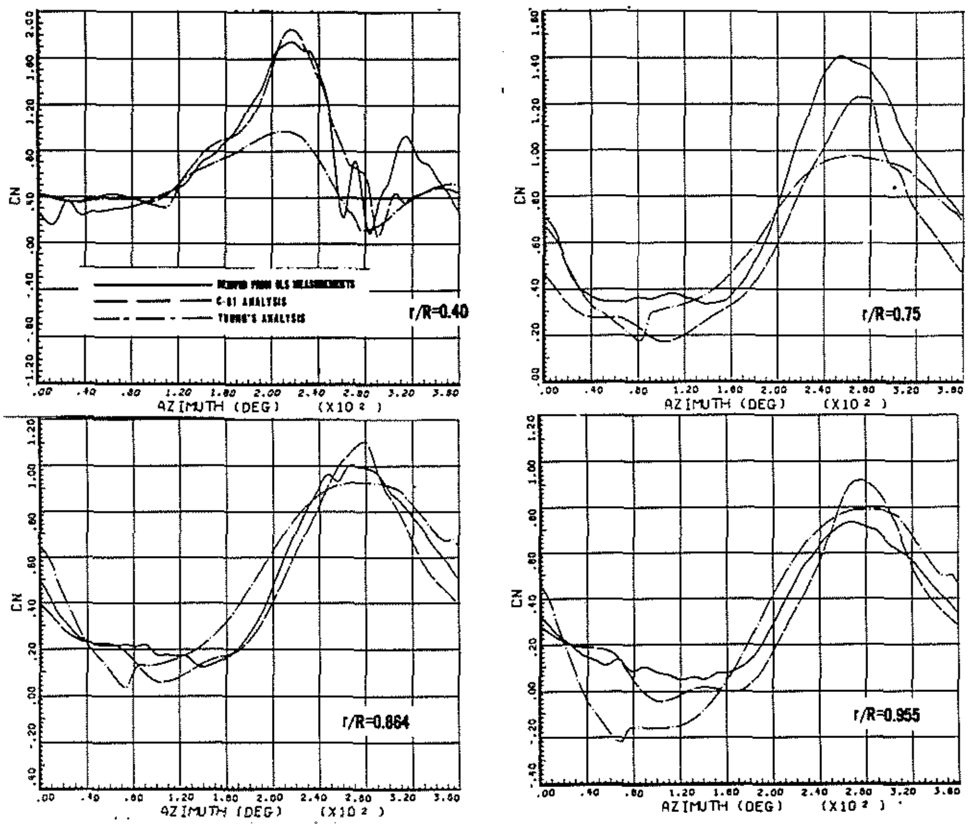


**Fig 13** Normal force coefficient distributions for various radial stations on the AH1G rotor at 0.31 advance ratio

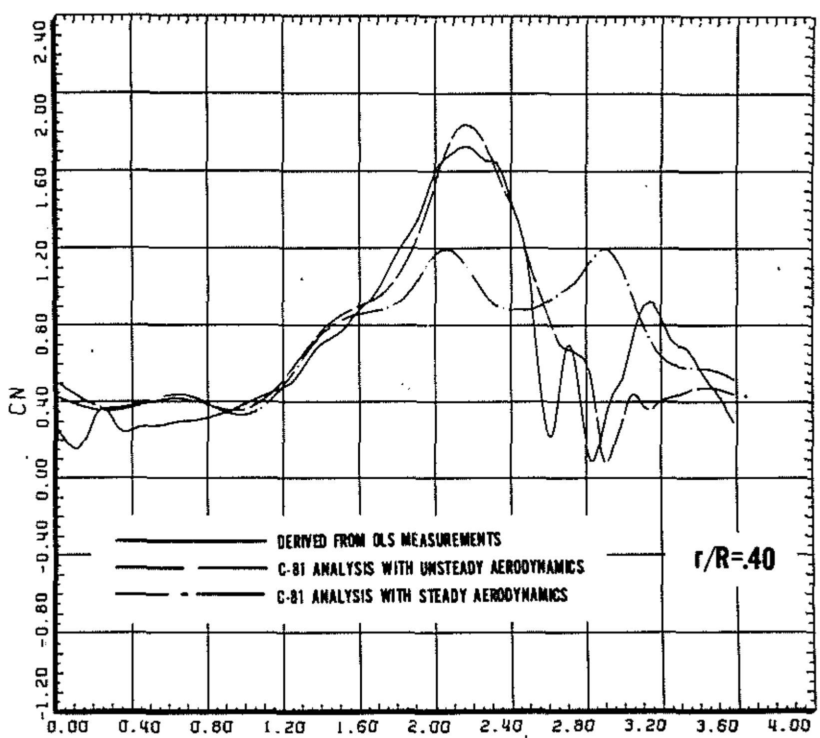


**Fig 14** Normal force coefficient distribution comparing the effects of predicted unsteady aerodynamic representation at 0.31 advance ratio

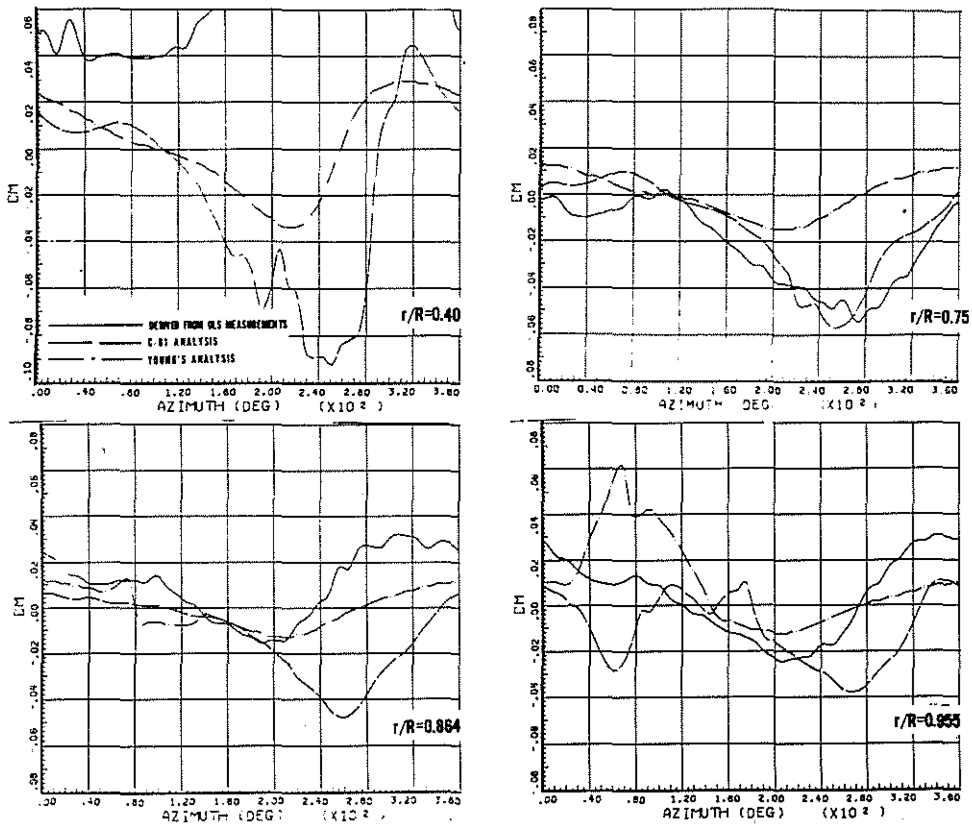


**Fig 15** Quarter chord pitching moment coefficient distributions for various radial stations on the AH1G rotor at 0.31 advance ratio

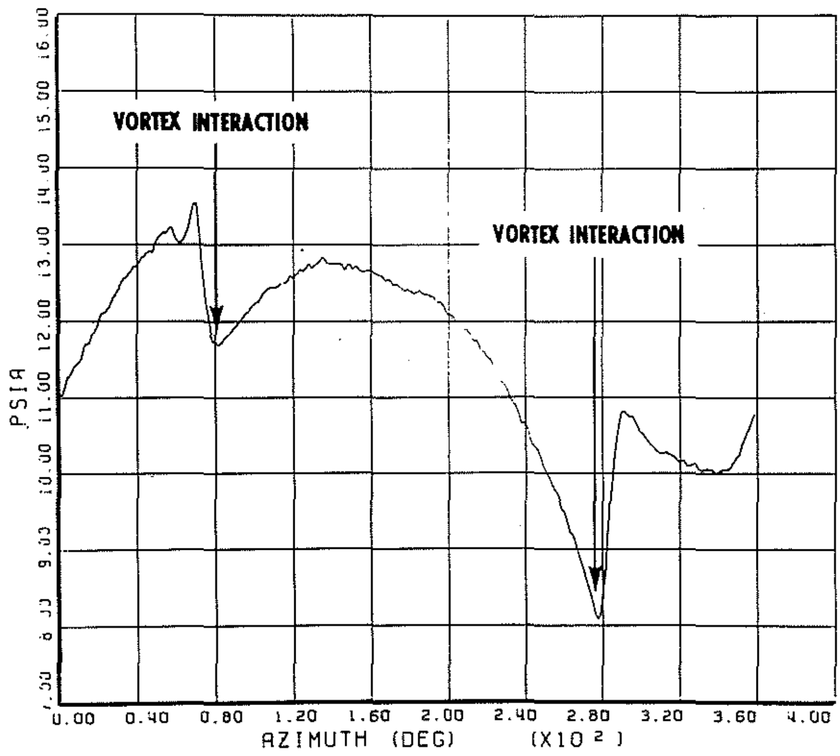


**Fig 16** Blade leading edge absolute pressure distribution indication vortex interaction locations

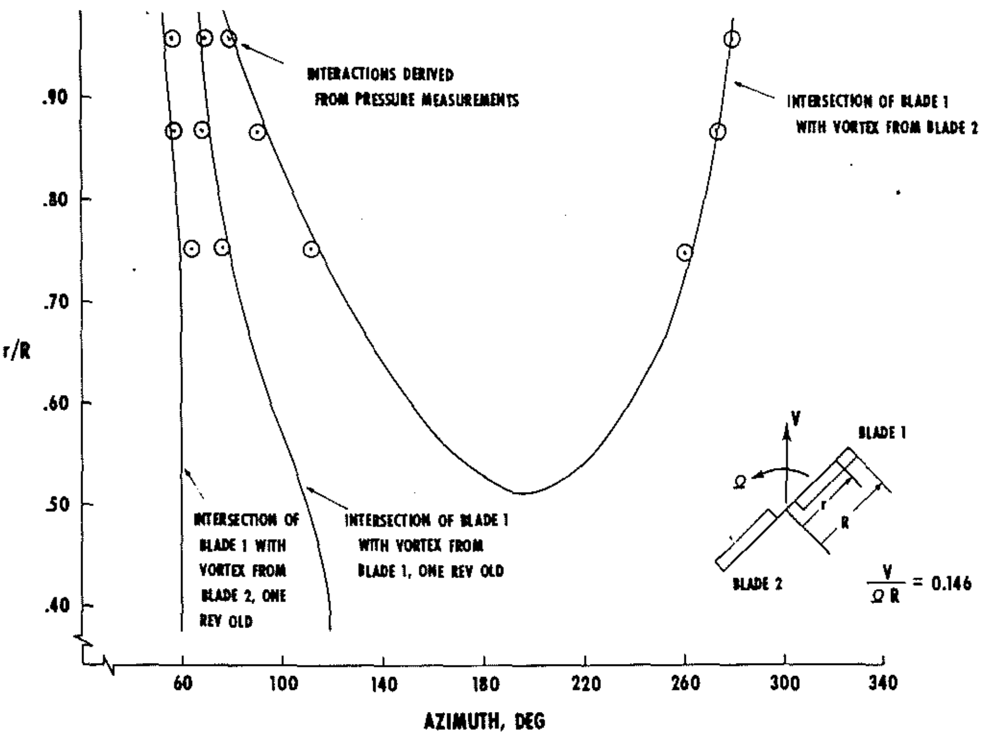


Fig 17 Comparison of vortex interactions derived from cycloid equations and measured data

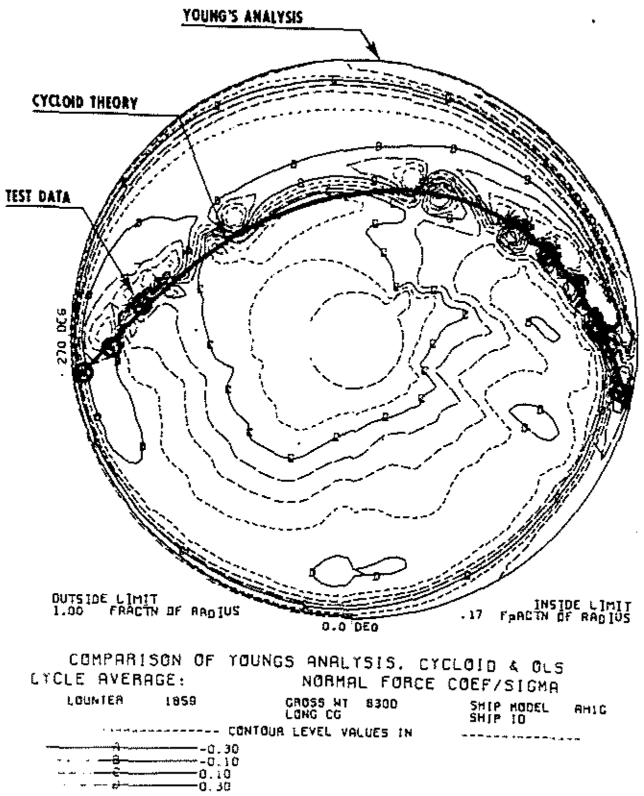


Fig 18 Comparison of Young's analysis, cycloid path and interactions derived from test data for the AH1G at 0.31 advance ratio