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Assessment of Aerodynamic Models in a Comprehensive Analysis for Rotorcraft

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SUMMARY

The history, status, and lessons of a comprehensive analysis for rotorcraft are reviewed. The development, features, and capabilities of the analysis are summarized, including the aerodynamic and dynamic models that were used. Examples of correlation of the computational results with experimental data are given, extensions of the analysis for research in several topics of helicopter technology are discussed, and the experiences of outside users are summarized. Finally, the required capabilities and approach for the next comprehensive analysis are described.

INTRODUCTION

In the design, testing, and evaluation of rotors and rotorcraft, it is necessary to predict and explain the rotor performance, loads, and noise; the helicopter vibration and gust response; the flight dynamics and handling qualities; and the system aeroelastic stability. This capability is required at several levels, including conceptual design; detailed design, development, and modification; and research. A comprehensive analysis makes it possible to perform these tasks with a consistent, balanced, yet high level of technology in a single code.

A comprehensive analysis for rotorcraft was published in 1980 (refs. 1-3). The origin, development, and structure of the analysis is described in references 4 and 5. This code has since found application both in government and in industry. The present paper will review the history, status, and lessons of this comprehensive analysis. The development, features, and capabilities of the code will be summarized. Examples of correlation of the computational results with experimental data will be given, extensions of the code for research in several topics of helicopter technology will be discussed, and the experiences of outside users will be summarized. Finally, the required capabilities and approach for the next comprehensive analysis will be described.

No attempt was made to invent a name for the code, beyond checking the initials of the title (ref. 1) for acceptability. It was not long before the code had acquired the name CAMRAD (for Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics), and that is how the code will be identified in this paper.

COMPREHENSIVE ANALYSES FOR HELICOPTERS

The work "comprehensive" takes on several meanings for helicopter analyses. It implies comprehensive technology: a code covering all disciplines, in a consistent and balanced fashion; dealing with the entire aircraft, with a concern for coupling of components and technology integration; incorporating a high technology level, and implementing recent advances.

It implies comprehensive modeling: the code must solve a wide range of problems in a single consistent analysis. The problems include performance and trim; blade motion and airloading; blade loads, control loads, vibration, and noise; aeroelastic stability; and handling qualities and response. The code must cover a wide range of configurations for both the rotor and the aircraft.

It implies comprehensive software: the flexibility to adapt or extend to new problems; and transportability for wide use throughout the government and in industry.

Helicopter problems are inherently complex and multidisciplinary, hence helicopter theory is ultimately driven toward a consideration of comprehensive modeling issues. What is desired in a comprehensive analysis is a practical tool, one that is reliable and accurate, efficient and economical; and good software, meaning good programming practice and documentation, for ease of test and maintenance. To obtain reliability and accuracy, it is necessary to devote resources to the checking, correcting, and proving of the codes, through extensive correlation and verification tasks. Efficiency and economy are also not automatically achieved, and require particular attention as the scope of an analysis expands. The software and documentation should not be assumed to be relatively unimportant because a code is intended for a single user. If the code is useful, it will grow in capability and acceptance, making the improvement of the programming and documentation even more difficult.

A comprehensive analysis involves a combination of elements from technology and disciplines, and a combination of components. Such a combination by itself goes beyond the state of the art, providing the opportunity to implement specialized developments for much wider practical use than in the original proof-of-method form. Moreover, the strong physical coupling of the modeled elements for a helicopter means that the solution capability is increased in a consistent combination of technology; in original developments, the combination is likely to be unbalanced.

EARLY CODES

The intent here is to describe a particular comprehensive analysis for rotorcraft, not to consider all such analyses. Providing a summary of other analyses is useful, however, as a further definition of what the subject is, and to describe the background against which CAMRAD was developed. A number of representative codes are identified in table 1.

Of the first generation codes, C81 is the classic example of a comprehensive analysis. The C81 code underwent at least six rounds of development, most sponsored by the U.S. Army. REXOR was developed for a four-bladed hingeless rotor. The code G400 was initially developed for bearingless rotor stability. In many cases, for the first generation codes "comprehensive" refers specifically to a wide range or high level of technology. A number of generic limitations are present in these first generation codes. These codes cannot treat all problems or all configurations. Sometimes there are major restrictions, such as incomplete trim, incomplete body or rotor motion, uniform inflow, or lack of eigenanalysis capability. These codes are 10 to 15 yr old (some have their roots in the early 1960s). Consequently much of presently available technology is often not well or uniformly utilized in the first generation analyses. Some are derivative analyses, developed from narrow origins; some have been continuously updated, but without good software control. The first generation codes were typically developed for narrow purposes, with limited time and resources. They were developed and verified only for particular helicopter types or particular technical problems, reflecting the specific interest of the originating organization. Consequently the codes frequently suffer from too little correlation and verification, too little reexamination of method and approach, and too narrow application. Certainly each code does not have all of these problems, and most remain quite useful. A consensus exists, however, that these limitations are no longer acceptable. Hence there have been several recent major code developments.

The recent codes (table 1) are characterized by an emphasis on the coupling of components. Often a substructure approach is used, and sometimes an automatic equation synthesis from a limited number of element types is used. The purpose of this emphasis is to obtain greater versatility than has been found in the first generation codes. The recent codes also show an increased concern about software, particularly the use of modular or structured software. Contemporary with the first generation comprehensive analyses there were also many special purpose codes, for individual subjects such as performance, flutter, and handling qualities. The use of special purpose codes is still apparent in recent developments.

The Second Generation Comprehensive Helicopter Analysis System (2GCHAS) is being developed by the U.S. Army and the helicopter industry. This analysis will emphasize the use of executive software for a flexible and unified structure, and the use of analysis options rather than a single technical basis (although the technical basis for the structural analysis will likely be finite element models).

BACKGROUND OF CAMRAD DEVELOPMENT

The development of CAMRAD had its origins in a number of theoretical investigations, including an empirical dynamic stall model (1968-1969; refs. 6 and 7);

vortex/blade interaction (1969-1970; refs. 8 and 9); nonuniform inflow (1968-1970; refs. 6 and 8); rotor/wing dynamic stability (1972-1975; refs. 10-12); and dynamic stability in free flight (1975-1976; refs. 13-15).

These aerodynamics investigations included the development of a rotor wake model, and the dynamic stall work (which required developing a method of solving for the periodic motion of a rotor blade). The stability investigations produced linearized equations of motion for the rotor. Impetus for the stability investigations was provided by the requirement to analyze tilting proprotor aircraft (refs. 10-14). As a consequence, early consideration was given to high inflow and large angles in the aerodynamics model; to large pitch and twist in the dynamics model; to rotor and body dynamics coupled through shaft motion and hub forces; and to a drive train model.

The development of CAMRAD (1978-1980; refs. 1-3) was built upon these earlier investigations. The rotor and airframe model that was derived for the stability analysis was used, but in the nonlinear form. A new wake analysis was developed, incorporating additional modeling capability. Solution techniques were developed for the trim, motion, wake, and inflow problems. The free-wake geometry model of Scully (ref. 16) was incorporated; this was the only part of the code adapted from an outside source. The new wake model was a major justification for the development of CAMRAD, a fact reflected in the initial applications of the code. In addition, it was desired to obtain a solid basis for further development of rotary wing technology (reflected in more recent applications).

DESCRIPTION OF CAMRAD MODELS AND CAPABILITIES

A summary of CAMRAD models and capabilities will be given. A full description of what is in the CAMRAD code is provided in references 1-3. A discussion of why the various modeling choices were made is given in references 4 and 5.

Computational Tasks

Figure 1 shows an outline of the tasks and problems of a comprehensive helicopter analysis. The structure at this level emphasizes solving the dynamic equations of motion. The first task is the trim analysis; other tasks start from the trim solution. The rotorcraft in trim is in a steady state, unaccelerated flight condition; hence the rotor and airframe motion are periodic. The inverse problem, determining the control required for a specified flight condition, is being solved. The solution involves calculating the periodic rotor motion and the steady trim variables. After the calculation has converged, the performance, loads, and noise may be calculated. In CAMRAD the blades of a rotor are assumed to be identical, with the same periodic motion. The assumption of periodicity (with a fundamental frequency equal to the rotor rotational speed) excludes a calculation of the vibratory dynamic and aerodynamic interaction between two rotors of unequal rotation rates, such as a main rotor and tail rotor; the static or mean interaction is always taken into account.

The flight dynamics analysis is based on a frequency separation of the motion of the rotor and body, allowing the use of a quasistatic rotor solution. Hence the rotor and airframe stability derivatives are calculated, using prescribed perturbations of the body motion and controls in the same analysis that is used for the trim solution (where the motion is truly steady state). Time-invariant linear differential equations for the aircraft rigid-body motions are constructed. The poles, zeros, and eigenvectors of these equations define the aircraft flying qualities.

The transient analysis involves an integration in time to obtain the general vehicle response. For CAMRAD, the only transients considered are those produced by rigid body dynamics, pilot inputs, and gusts, all of which are slow relative to the rotor rotational frequency. Hence a quasistatic rotor solution is sufficient, and again the rotor analysis is identical to that used for the trim solution. The rigid-body equations of motion are numerically integrated for prescribed control or gust inputs to calculate a nonequilibrium flightpath.

The flutter analysis involves the construction of a set of linear differential equations describing the motion of the rotor and the aircraft (all variables). The eigenvalues of these equations define the system stability. The equations may be time-invariant (for axial flow), or may have periodic coefficients (solved using Floquet theory). A constant coefficient approximation for the periodic coefficient equations, and various quasistatic reductions can be used (as implemented in CAMRAD, neither is applicable for a two-bladed rotor).

Trim Solution

The structure of the solution of the trim task in CAMRAD is outlined in figure 2. The periodic motion in a steady-state, unaccelerated flight condition is required. The final converged solution, not intermediate transients, is desired. Hence following a strictly physical approach in the solution is not necessary. For efficiency and improved convergence, computationally intensive calculations are moved outside inner loops (if weak coupling allows this approach), and the major iteration loops are split into several levels.

The control required to achieve a specified flight condition is to be calculated (the inverse problem). Hence algebraic equations (for free flight obtained from equilibrium of forces and moments on the helicopter, for a wind tunnel case obtained by setting the thrust, tip-path-plane tilt, etc., equal to target values) are solved for the trim variables (rotor or pilot controls, and aircraft Euler angles). Differential equations are solved for the periodic rotor motion and airframe vibration.

The trim iteration is an outer loop (fig. 2(b)). In CAMRAD, the Newton-Raphson method (with a relation factor) is used to solve the algebraic equations. The periodic motion for fixed controls is calculated in an inner loop (fig. 2(b)). In

CAMRAD a harmonic analysis method is used that is equivalent to an integration in time with a filter over the last revolution that forces the solution to be periodic. The analysis advances the rotor around the azimuth, calculating the forcing function in the time-domain and then updating the harmonics of the motion at each time-step. The use of the frequency domain (a Fourier series representation) enforces periodicity, and allows the use of a large time-step since numerical stability is separated from the physical stability of the system (which often has low-damped or high-frequency modes). In CAMRAD, there are separate circulation and motion iterations (fig. 2(b)). In the circulation loop, the uniform or nonuniform induced velocity is calculated from the circulation or aerodynamic loading; the motion is calculated for fixed induced-velocity; the circulation is reevaluated; and the procedure is repeated until the circulation converges (a relaxation factor on the circulation is used to improve convergence). However, this circulation iteration is only asymptotically convergent at zero thrust. In the motion loop, there is an iteration between the calculation of the rotor motion and the airframe vibration, to avoid interharmonic coupling and to ensure proper filtering of harmonics of the hub forces.

The wake geometry and influence coefficient calculation are computationally expensive; they are, therefore, moved outside the trim iteration (fig. 2(a)). The influence coefficients relate the induced velocity to the rotor blade bound circulation. This approach is possible because of the weak coupling of the influence coefficient calculation and trim iteration, particularly when the rotor is trimmed to a specified thrust and tip-path-plane orientation. In CAMRAD there are three levels of analysis: uniform inflow, nonuniform inflow with prescribed wake geometry, and nonuniform inflow with free-wake geometry. Here "uniform inflow" refers to an empirical model based on momentum theory, and actually includes a linear variation of the inflow over the rotor disk. For accuracy, using the bound circulation distribution from the nonuniform inflow calculation in the free-wake geometry analysis is necessary. For efficiency, the nonuniform inflow calculation should originate from the trimmed uniform inflow solution. The wake influence coefficients and geometry (prescribed or free) depend on the rotor loading, so potentially an iteration between the influence coefficient calculation and trim solution is necessary (fig. 2(a)). In practice, if the rotor is trimmed to a specified thrust and tip-path-plane orientation at each level, the remaining influence of the loading changes on the wake geometry is small, and hence iteration is seldom necessary. It is most efficient to execute each of the three levels, once and only once, to obtain a nonuniform inflow, free-wake solution.

Configuration Model

CAMRAD analyzes a general two-rotor aircraft: the single main rotor and tandem helicopter configurations, the tilting proprotor aircraft configuration, and the case of a rotor in a wind tunnel. Articulated, hingeless, gimballed, and teetering rotors with an arbitrary number of blades can be analyzed.

Rotor Model

The rotor structural model is based on engineering beam theory for rotating wings with large pitch and twist. A single load path is assumed (multiple load path bearingless rotors can not be analyzed). The rotor blade is assumed to have a straight undeformed elastic axis, and specific root geometry possibilities. The blade motion considered includes inplane and out-of-plane bending, torsion, control system flexibility, flap/lag/gimbal/teeter hinges, and rotor rotational speed. The rotor shaft motion and hub forces are also considered.

The blade motion is described by rotating, free-vibration modes, equivalent to a Galerkin analysis. Nonlinear terms are retained in the equations of motion based on established knowledge of certain important nonlinear effects, and the requirement of consistency in the derivation. A vector formulation of the blade structural dynamics is used. The vector combination of inplane and out-of-plane moments and deflections eliminates the dependence on the coordinate system, with a simplification of the equations as a consequence.

The rotor aerodynamic model is based on lifting-line theory, using steady two-dimensional airfoil characteristics and a vortex wake. The model includes a correction for close blade-vortex passage loading using a linear lifting-surface theory solution; an empirical dynamic stall model; a yawed-flow correction; and unsteady aerodynamic forces from thin airfoil theory. The aerodynamic model is applicable to axial and nonaxial flight, with high inflow and large angles. The induced velocity is obtained from momentum theory or a vortex wake model. The momentum theory model includes a mean term and terms that vary linearly over the rotor disk (produced by forward flight or hub moments); rotor/rotor and rotor/airframe interference; and ground effect.

For the flutter analysis, multiblade coordinates and an inflow dynamics model to represent low-frequency unsteady aerodynamics of the rotor can be used. In the inflow dynamics model, the uniform and linear-induced velocity components are related, by first-order differential equations, to the net aerodynamic thrust and hub moments on the rotor.

The rotor model is characterized by a section analysis, which follows from the assumption of high-aspect ratio: engineering beam theory for the structural model and lifting-line theory for the aerodynamic model. The equations of motion are obtained from equilibrium of the inertial, aerodynamic, and elastic forces on the portion of blade outboard of a particular blade section. The interface between the aerodynamics and dynamics models is defined by the section aerodynamic forces and the section velocities.

Wake Model

The rotor wake model in CAMRAD is based on a vortex lattice (straight-line segments) approximation for the wake. A small viscous radius core is used for the tip vortices. A large core size is used for the inboard wake elements, not as a representation of a physical effect, but to produce an approximation for sheet elements. Sheet elements are available in CAMRAD for the inboard wake, but have not proved necessary in these applications so far. The wake influence coefficients are calculated for incompressible flow. Rotor/rotor interference can be calculated (but only the mean velocities at the hub for the single main rotor and tail rotor case). The mean interference velocities at the airframe can be calculated.

A model of the wake roll-up process is included. Eventually the tip vortex has the strength of the maximum bound circulation at the azimuth where the wake element was trailed. a number of parameters, prescribed not calculated, allow the tip vortex to have only a fraction of this maximum strength when it encounters the following blade, with the remainder of the vorticity still in the inboard wake. Often, however, insufficient information exists about the aerodynamics of a particular rotor to rationally use such a model. The radial location of the tip vortex at the generating blade is also prescribed in the model.

Close blade-vortex passage loading is calculated using a small viscous core radius for the vortex, and a lifting-surface theory correction for the induced loads. In addition, it is possible to increase the core radius after the first encounter with a blade, in order to model (not calculate) the phenomena limiting vortex-induced loads on a rotor blade. The core radius is a convenient parameter to use to limit the loads, but the physical nature of the phenomenon is still speculative. Suggested causes are local flow separation caused by the high vortex-induced radial pressure gradient; the bursting of the vortex core; and the interaction of the vortex with the trailed wake it induces behind the blade.

The wake geometry models in CAMRAD include simple undistorted models; hover prescribed wake models based on experimental measurements; and a calculated free wake. The free-wake analysis used (from ref. 16) calculates the distorted tip vortex geometry for a single rotor in forward flight. This free-wake analysis is very efficient, and has modeling features which are consistent with the CAMRAD wake model.

Aircraft Model

The aircraft model in CAMRAD allows for two rotors on a body having both rigid and elastic motion. A wind tunnel configuration (no rigid body motion) is also considered. The elastic airframe modes must be obtained from an outside analysis (such as NASTRAN). Simple quasistatic airframe aerodynamics are used. CAMRAD includes a drive train model, with the engine, governor, shaft flexibility, and rotor rotational speed degrees of freedom represented.

APPLICATIONS WITH LESSONS FOR FUTURE TECHNOLOGY DEVELOPMENT

In an analysis of hover loading and wake geometry (ref. 17), calculated blade-bound circulation was compared with measurements from a hovering model rotor with rectangular and ogee-tip planforms. Figure 3 is an example of the comparison (the measurements were obtained from ref. 18). Existing prescribed wake geometry models were used which, when compared with experiment, provided a good definition of the radial and vertical position of the tip vortex when it first encountered the following blade; this position has the major role in determining the radial distribution of the loading. Fine tuning of the far-wake vertical convection rate was needed to obtain a reasonable power calculation; further fine tuning of the parameters determining the position of the first blade/vortex interaction would improve the correlation also. It is the nature of such empirical models that they must be adjusted, within the scope of the original data, to give optimum results with a particular code. Another key factor for the ogee tip (fig. 3) was the radial location of the tip vortex at the generating blade; this was known from the experiment to be at 0.94R, and was set to that value in the analysis using the tip vortex roll-up model. The tip vortex roll-up was not calculated.

CAMRAD was used to solve the problem posed by Wheatley and later by Harris: the calculation of the influence of the distorted wake geometry on the lateral flapping at low advance ratio (ref. 19). Figure 4 shows the correlation obtained (the measurements were obtained from refs. 20 and 21). The primary factor determining the lateral flapping at low-advance ratio was the wake geometry. A secondary, but not minor, influence of the tip vortex core size was found when close vortex-blade passages were produced by using the distorted geometry. In the absence of calculations or even experimental data to guide the modeling of individual effects, a large vortex core radius represented the cumulative effect of all of the following: the amount of roll-up of the circulation into the tip vortex, the tip vortex strength, lifting-surface effects on the induced loading, possible vortex-induced stall or vortex bursting, and the actual viscous core size. Hence, much of the aerodynamics was being rather crudely modeled, rather than being calculated.

In a calculation of hingeless rotor ground-resonance stability in hover (ref. 22), unsteady aerodynamics was essential for the prediction of the body mode damping. Figure 5 is an example of the correlation (the experimental data were obtained from ref. 23). Although the inflow dynamics model is very useful, it involves significant approximations, representing a global, low-frequency relation between the rotor-induced velocity and loading. This investigation demonstrated an advantage of a comprehensive analysis: execution of a sophisticated code for a relatively simple problem involving a new combination of mathematical models was possible without developing a new analysis.

CAMRAD was used to calculate performance, blade loads, and aeroelastic stability for tilting proprotor aircraft (ref. 24), and to compare calculations with wind tunnel and flight test measurements for the XV-15 Tilt Rotor Research Aircraft. Regarding hover performance, it was concluded that even existing empirical wake geometry models are not entirely adequate for tilt rotors. Wing and airframe download is also extremely important to proprotor aircraft hover performance. The problem is more complex than the CAMRAD allowance for only the calculation of the download from the mean wake-induced velocity at a single point. Figure 6 shows typical results for the blade bending loads in helicopter-mode forward flight, which is calculated using static stall and uniform inflow models. The predicted loads tend to show a smaller increase than the measurements at high speeds do, presumably because of the limitations in the stall model. Current nonuniform inflow and dynamic stall models are all empirical to some extent. There is a requirement for development of these models specifically for the aerodynamic environment that characterizes tilting proprotors.

APPLICATIONS INVOLVING RESEARCH EXTENSIONS

CAMRAD has been modified to analyze a coaxial helicopter configuration. Like the tandem configuration, a coaxial helicopter has twin, contrarotating main rotors. Hence the only necessary modification, when compared to the tandem helicopter model, was the replacement of the matrix relating the pilot's controls to the rotor cyclic and collective pitch for the trim iteration. For the coaxial helicopter this matrix is similar to the single main rotor case, except that differential collective is used for yaw control. This analysis has been applied to the Advancing Blade Concept (ABC) in an evaluation of the performance of advanced rotorcraft configurations (ref. 25). CAMRAD provided the unique capability to analyze the ABC using nonuniform inflow. Additional modifications that would be desirable are a suitable wind tunnel trim option (trimming the forces and moments from both rotors); and an auxiliary propulsion representation (similar to the airframe aerodynamic forces, but involving different geometry and dependence on flight speed). Implementation of such modifications would be straightforward. Also desirable, and not so easy, is the capability to calculate the free-wake geometry for the two rotors together; this capability is also needed for the tandem helicopter configuration.

CAMRAD has been used in the first fully consistent coupling of a finite-difference calculation for advancing-tip transonic loading with a solution for the rotor wake and blade motion (ref. 26). Finite difference (FD) calculations of transonic potential flows are so expensive that including the entire rotor flow field in the computation domain is impractivcal. Yet, without accounting for the influence of the rotor wake and blade motion, analyzing rotor in forward flight is not possible. A practical and consistent solution is obtained by limiting the FD computation domain to the vicinity of the rotor tip, and using CAMRAD to calculate the entire rotor flow field including wake and blade motion influence (fig. 7). The interface between CAMRAD and the FD solution is in terms of the blade angle of attack and section lift coefficient. Figure 8 shows typical results of the calculations. The shock position and strength are well predicted. The finite-difference code used was that of Caradonna and Chattot, which solves the three-dimensional, unsteady, transonic small disturbance potential equation. A fully converged solution was obtained after only two executions of the FD code; the results after the first execution were close. The computation time for CAMRAD is small when compared to that of the finite-difference code.

For an efficient solution, computationally intensive operations must be removed from inner loops in the comprehensive analysis; this approach will converge well if are shown in figures 10 and 11. A principal objective of this investigation was to obtain an efficient body model, hence a modified slender body theory was used. The body analysis produced essentially exact potential flow solutions for axisymmetric bodies at zero angle of attack, up to large thickness ratios. With an optimum update of the body-induced velocities, the computation time was only increased by 10-20% above that for the rotor alone. The coupling of CAMRAD with a panel method would use the same procedures, but would be much more expensive (even without updating the body-induced velocities so often). The free-wake geometry was not a significant factor, although nonuniform inflow was required since the problem concerned the detailed aerodynamic environment of the rotor. Hence body-induced changes to the wake geometry (which were not calculated) would not be significant either. The influence of the rotor on the body was not considered, so the body and rotor solutions were not fully coupled. Convergence of the coupled solution only involved updating the induced velocities as the rotor position (tip-path-plane tilt) relative to the body changed.

The modification to CAMRAD involved introducing the calculation of the body-induced velocities within the periodic motion and airloads solution (fig. 12). As implemented, the calculation of the body-induced velocities was performed for every control increment in the trim iteration. Performing the calculation only at the beginning of the trim iteration was not sufficient (but was close). A better procedure would be to perform the calculations only if the rotor position changes more than some specified amount during the trim iteration (fig. 12). For this investigation a single rotor in a wind tunnel was analyzed. Hence as implemented, the body-induced velocities were placed in the matrix that was normally used for the interference velocities from the other rotor; and considering body coordinates different from the wind tunnel axes was not necessary. Modifications to CAMRAD for the more general cases would be straightforward.

APPLICATIONS BY OTHER USERS

Other organizations will use a code such as CAMRAD if it offers them some unique capability; simply being good or even better does not outweigh the value of accumulated experience with their own codes. These organizations will use outside codes as a complement to, not as a replacement for, their internally developed capability. Users in the government are more likely than those in industry to find applications for outside codes, because they have less investment in analysis methods and are generally more interested in a wide range of configurations. The users in government are usually involved in research and evaluation tasks instead of support of aircraft development and production.

CAMRAD was used by NASA Langley Research Center to calculate hingeless rotor stability (ref. 31). Figure 13 shows the correlation obtained. The model was tested in the Transonic Dynamics Tunnel. The model rotor had flap and lag motion, and body pitch and roll motion. The analysis included these degrees of freedom and the dynamic inflow model. The correlation covered the influence of pitch-flap the code is operated in a manner such that the coupling is weak. In modifying CAMRAD to couple it with the FD code, an additional outer loop was introduced (fig. 9), iterating between the loads calculations by the two methods. Since the rotor is trimmed to a specified thrust and tip-path-plane orientation, recalculating the wake influence coefficients is not necessary; hence only in the first iteration is the computation time of CAMRAD large, and even that is small when compared to the time required by the FD code. The coupling of the two codes is in terms of the blade section angle of attack. When evaluating the angle of attack for the FD code, the near trailed and shed wake behind the rotor blade must not be counted twice. This wake is already included in the FD solution, so it must be excluded from the CAMRAD calculation of the angle of attack. The procedure in CAMRAD for calculating the influence coefficients, wake-induced velocity, and section angle of attack was used without modification to calculate the partial angle of attack for the FD code, except that the wake elements within the FD computation domain are excluded when calculating the influence coefficients. Returning wake elements from the other blades are included in the effective angle of attack, even if such elements are in the FD domain. Including such wake elements in the FD analysis is possible, and may prove necessary in order to achieve good accuracy with close blade-vortex encounters. The FD code calculated the pressure on the blade for the entire advancing side, using the partial angle of attack provided by CAMRAD. Simply setting the lift coefficient to the value from the FD code during the next execution of CAMRAD would not account for changes in the angle of attack as CAMRAD revises the blade motion and wake effects. Hence the difference between the lifting-line theory lift coefficients from the current and the previous executions of CAMRAD is added to the FD value. When this difference becomes zero, and the result of the CAMRAD solution is just the FD lift coefficient, the analysis has converged. The rotor trim iteration essentially constrains the mean and once-per-revolution aerodynamic loading, so the lift coefficients will not vary much in successive CAMRAD executions. Consequently the convergence of this method is rapid.

The required modifications to CAMRAD involved a new loop which was coupled with the finite-difference code (fig. 9), and a new routine to calculate the wake influence coefficients for the partial angle of attack. The latter was based on the existing influence coefficient routine, with extensive additions to check and modify the geometry of wake elements within, or intersecting, the boundary of the FD computation domain. As implemented, CAMRAD does not call the finite-difference code directly. The two codes were in fact on different computers, with communications handled by file transfer. Instead of calling the FD code, the partial angle of attack is written to a file; CAMRAD is exited; the FD code is executed, writing the lift coefficients to a file; CAMRAD is reentered, and the FD lift coefficients are read. The existing restart feature of CAMRAD was modified to handle the exit/reenter, with the addition of steps to save the FD influence coefficients and the old lift coefficients. Also, the test for convergence of the lift coefficients between CAMRAD and the FD code was not automated. CAMRAD has also been coupled with full-potential finite-difference calculations (refs. 27 and 28).

CAMRAD was used in an investigation of the influence of body-induced velocities on rotor performance and blade loads (refs. 29 and 30). Typical calculated results coupling, blade sweep, blade droop, and blade precone as a function of forward speed, rotor speed, and collective pitch.

For a hover test of a full-scale hingeless rotor, CAMRAD was used by NASA Ames Research Center to calculate the stability and performance (ref. 32). Figure 14 shows the lag mode stability (dynamic inflow was used for the top figure, whereas two bending and two torsion modes were used for the bottom figure--the solid lines represent the same model). For these calculations, the blade pitch and elastic torsion modes, and the dynamic inflow model were essential for accurate calculations. Although they were not a significant factor, the dynamics of the balance and the strut system supporting the test module were included. The influence of control system stiffness, number of bending and torsion modes, and dynamic inflow model on the calculations was examined. Figure 15 shows the hover performance. Nonuniform inflow with an existing prescribed wake geometry model was used to perform the calculations. To be able to achieve good correlation at thrust coefficient/solidity below approximately 0.06, the parameters in this empirical wake geometry were fine-tuned, reducing the vertical convection rate in the far wake by approximately 5-10%.

CAMRAD has been used by the U.S. Army in technical assessments of various rotor concepts (ref. 33). Figure 16 shows an example of calculated rotor performance; such results are used as a basis for the technology level incorporated in preliminary design studies. The code was also used to analyze other rotorcraft configurations, such as tilting proprotors and the ABC concept (ref. 25).

The Boeing Vertol Company has used CAMRAD to support the design and development of the V-22 tilting proprotor aircraft (ref. 34). Figure 17 shows the wing beam mode stability for a windmilling model rotor tested on a cantilever wing in the Langley Transonic Dynamics Tunnel. The rotor had an early V-22 gimballed hub design. Most applications of CAMRAD to tilt rotors have been for the gimballed rotor configuration of the XV-15 aircraft. The use of CAMRAD at Boeing Vertol has also shown the need for more flexibility to directly model newer hub configurtions.

DESIRED CAPABILITIES

The internal and external uses of CAMRAD had led to suggestions for revisions and extensions, in addition to the lessons from the applications cited above.

Many users need the capability to analyze bearingless rotors, but CAMRAD does not model multiple load paths at a blade root. CAMRAD can accept effective kinematic couplings to model such rotors, but that does not solve the problem of how to calculate the effective couplings. The capability to use in CAMRAD blade modes calculated for the bearingless hub would be a first step. The restriction of a straight undeformed elastic axis is often awkward, and the capability to treat a drooped tip is needed.

More robust procedures for the trim, circulation, and motion iterations are needed; these loops should converge more often in routine use. In CAMRAD the trim, circulation, and motion loops can all be viewed as the iterative solution of nonlinear algebraic equations; standard methods to improve the convergence of such problems exist. At least, the known actions users can take to improve convergence should be coded into CAMRAD for automatic execution.

Transportability of the code to virtual memory machines has been good. However, more detailed descriptions of typical cases and methods of use, reflecting experience since preparation of the original documentation, would be helpful. Outside users often prefer input and output format such that their own practices can be followed.

Many detailed extensions to the code have been identified that would produce significant increases in capability for particular users. However, such modifications are straightforward only after the user is familiar with the implementation of the code.

CONCLUDING REMARKS

The aerodynamics models in comprehensive helicopter analyses are characterized by a high degree of empiricism, which is required in order to cover all aspects of the problem. Continued development of advanced aerodynamics models is needed to progressively eliminate this empiricism.

New rotor or new helicopter configurations usually require new development of dynamics equations for comprehensive analyses. Historically, new configurations in the helicopter industry have been years, even decades, ahead of the analyses. A more flexible approach is needed, that separates the technical and mathematical modeling from the specification of the rotor or helicopter configuration.

There has been little systematic development of solution procedures for helicopter analyses. More robust methods are needed. Here also, a more flexible approach is needed, that separates the mathematical modeling of the aerodynamics and dynamics from the solution procedures, so each can be independently changed.

The above conclusions imply a different structure for the coding of the next comprehensive analysis. An obvious need exists for continued increase in the use of software tools and structured programming techniques; and for continued emphasis on transportability, ease of modification, good input and output formats, and complete documentation.

The opportunity exists for the improvement of CAMRAD through a series of enhancements; or for the development of a new code, utilizing a completely new approach.

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TABLE 1.- REPRESENTATIVE COMPREHENSIVE HELICOPTER ANALYSES

FIRST GENERATION (ROOTS IN EARLY 1960's)	
HANDLING QUALITIES ORIGINS	
C81	BELL (LATE 1960's)
REXOR	LOCKHEED (ABOUT 1971)
LOADS AND STABILITY ORIGINS	
C60	BOEING (ABOUT 1965)
NORMAL MODES	SIKORSKY (1968)
G400	UTRC (1975)
AERODYNAMICS ORIGINS	
PIZIALI AND DUWALDT	CAL (1962-1966)
MILLER AND SCULLY	MIT (1962-1964, 1975)
LANDGREBE	UTRC (1969-1972)
RECENT (OFTEN SPURRED BY 2GCHAS)	
RDYNE	SIKORSKY
CRAVA	SIKORSKY
COPTER	BELL
DYSCO	KAMAN
CAMRAD	NASA Ames
SECOND GENERATION	
2GCHAS	U S. ARMY

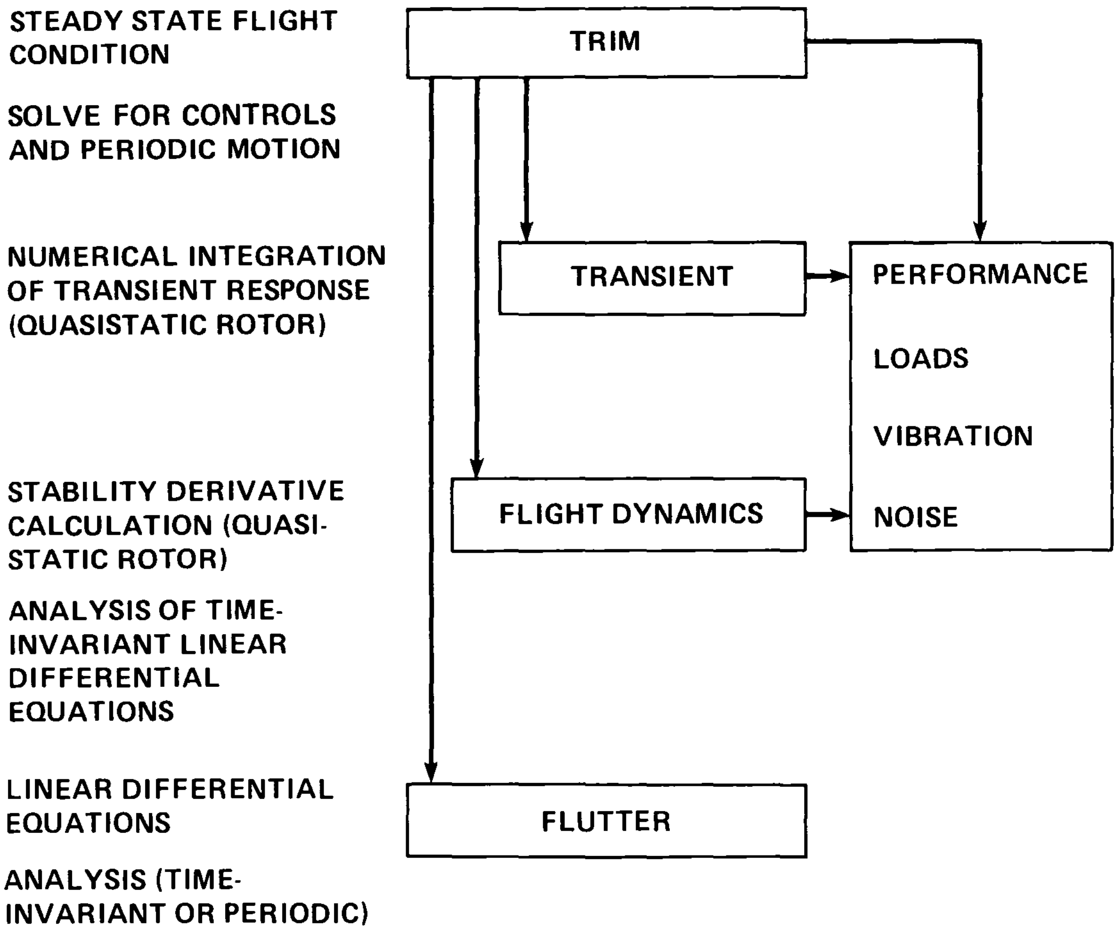
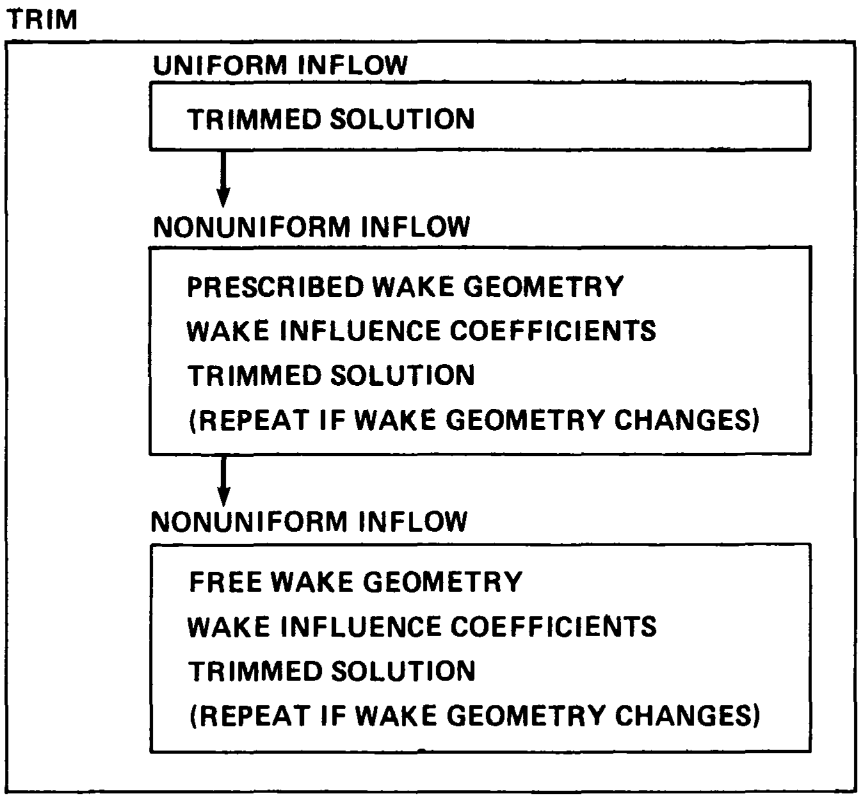


Figure 1.- CAMRAD tasks and solutions.



(a) Inflow analysis levels.

Figure 2.- Solution of trim task in CAMRAD.

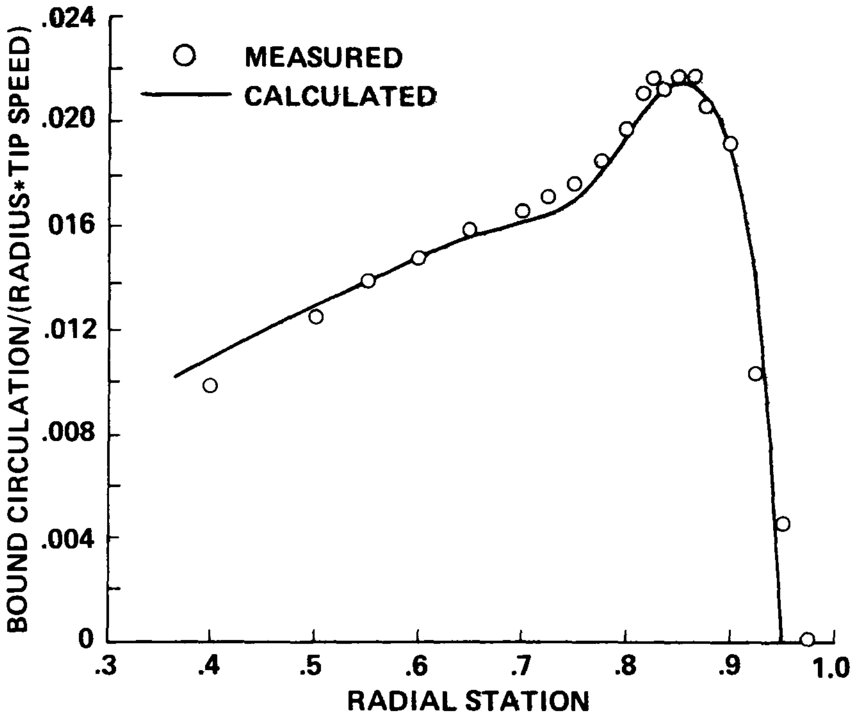
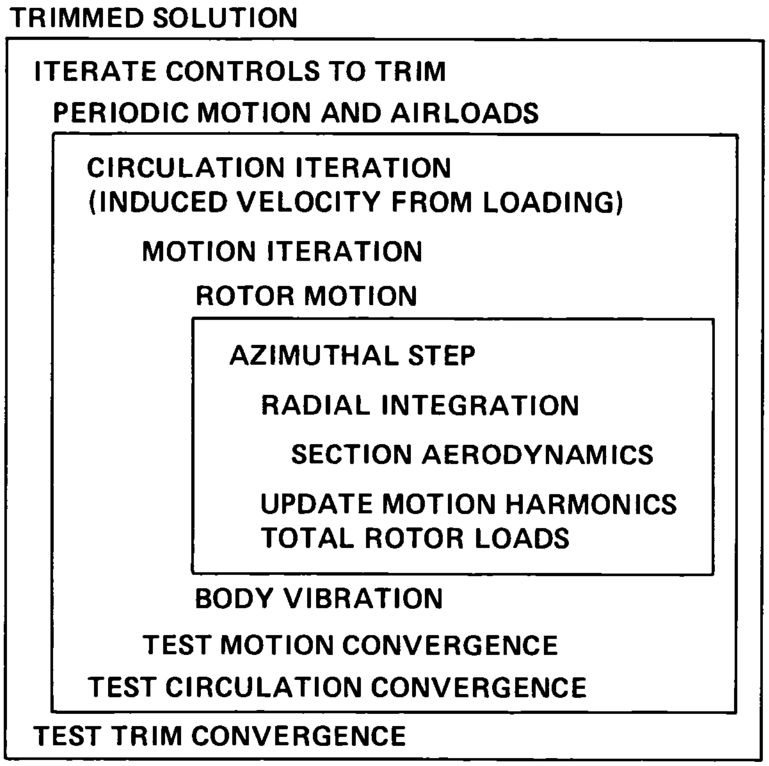
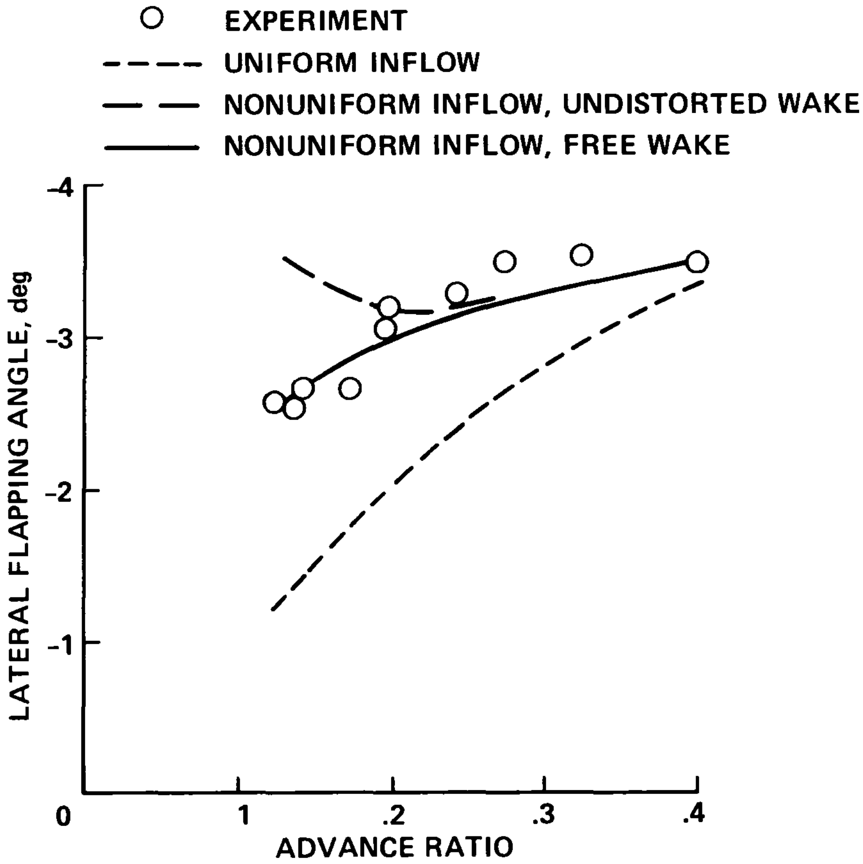


Figure 3.- Radial distribution of bound circulation for ogee tip blade in hover (teetering rotor with two blades, thrust coefficient/solidity = 0.103, radius = 1.045 m, tip speed = 77 m/sec).



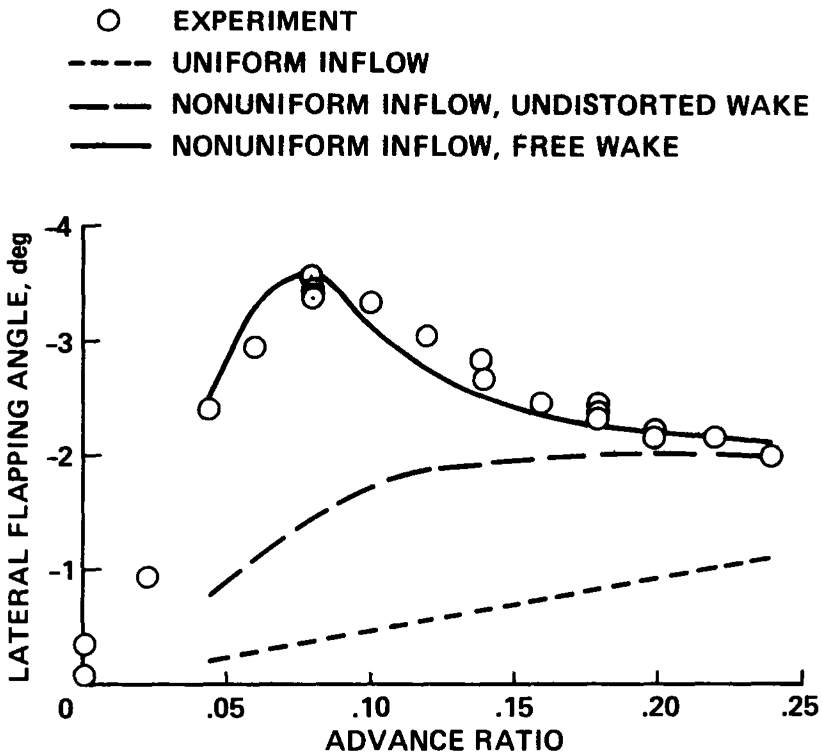
(b) Trim, circulation, and motion iterations.

Figure 2.- Concluded.



(a) Autogiro rotor (four blades, thrust coefficient/solidity = 0.064, radius = 6.86 m, tip speed = 102 m/sec).

Figure 4.- Rotor lateral flapping angle, positive for tilt toward retreating side, as a function of advance ratio.



(b) Model rotor (four blades, thrust coefficient/solidity = 0.08, radius = 0.832 m, tip speed = 137 m/sec).

Figure 4.- Concluded.

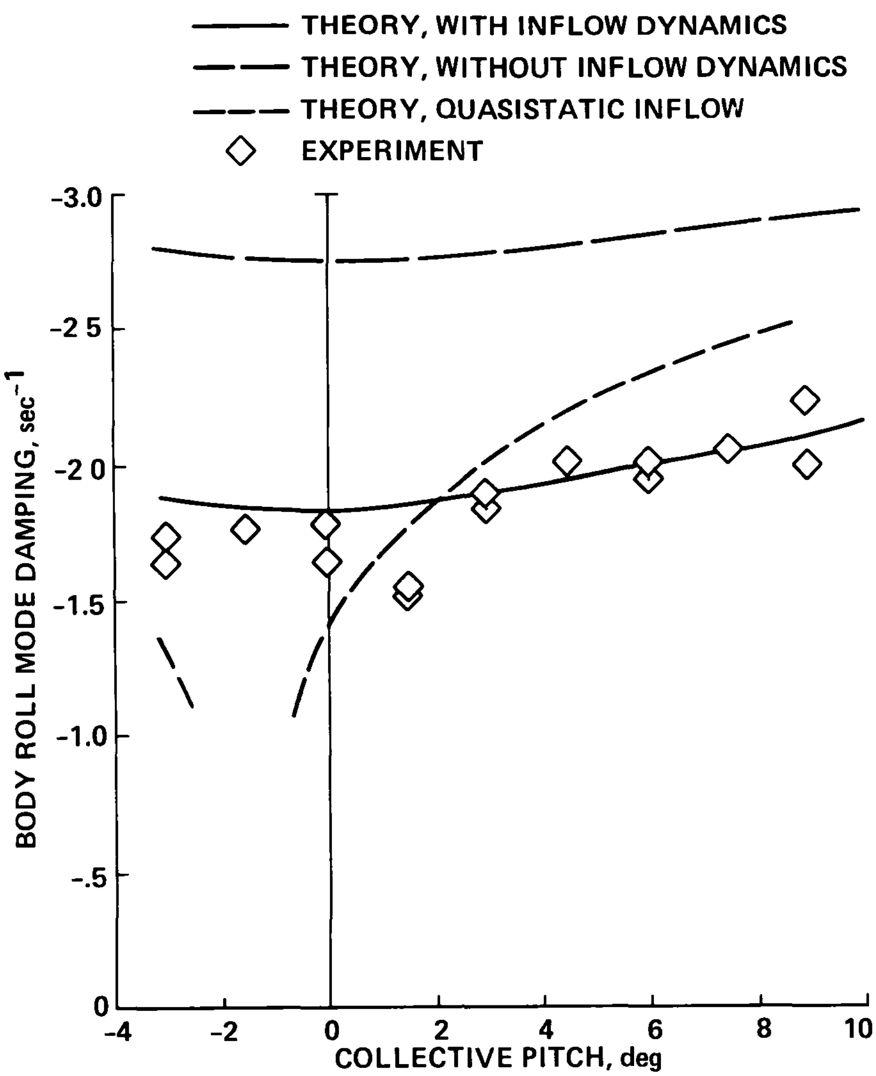


Figure 5.- Body roll mode damping in hover as a function of collective pitch (hingeless rotor with three blades on body gimbal with pitch and roll motion, rotor radius = 0.811 m, tip speed = 55 m/sec).

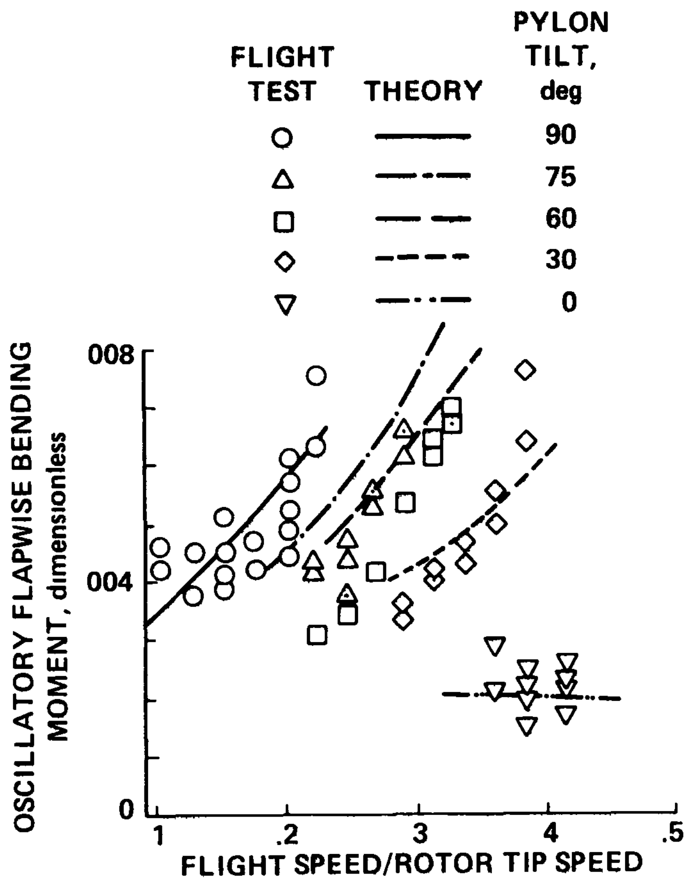


Figure 6.- Oscillatory flapwise bending moment on a tilting proprotor at 35% radial station, as a function of speed and pylon tilt angle (gimballed rotor with three blades, gross weight = 5900 kg, rotor radius = 3.81 m, tip speed = 221 m/sec).

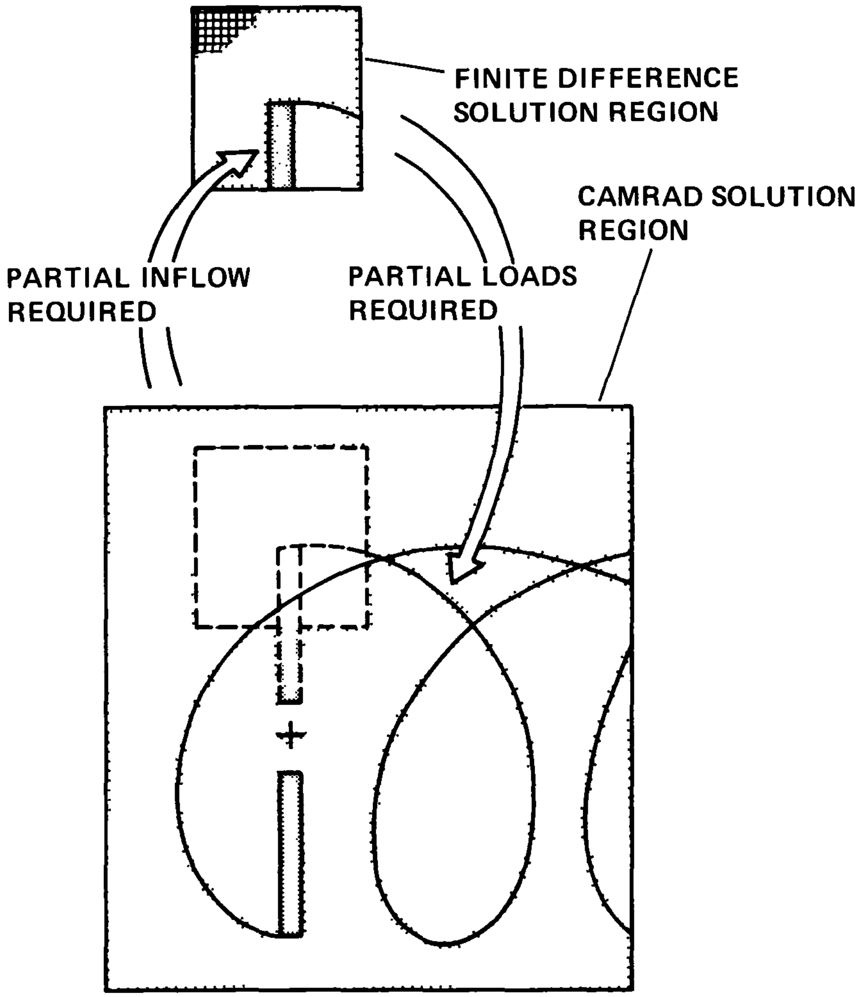


Figure 7.- Matching CAMRAD with a finite difference solution for transonic tip aerodynamics.

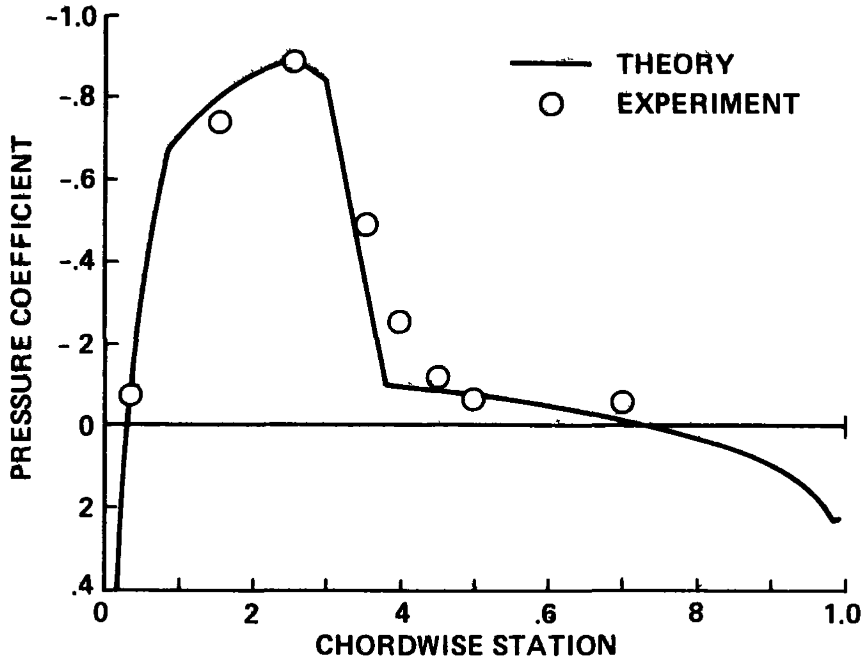
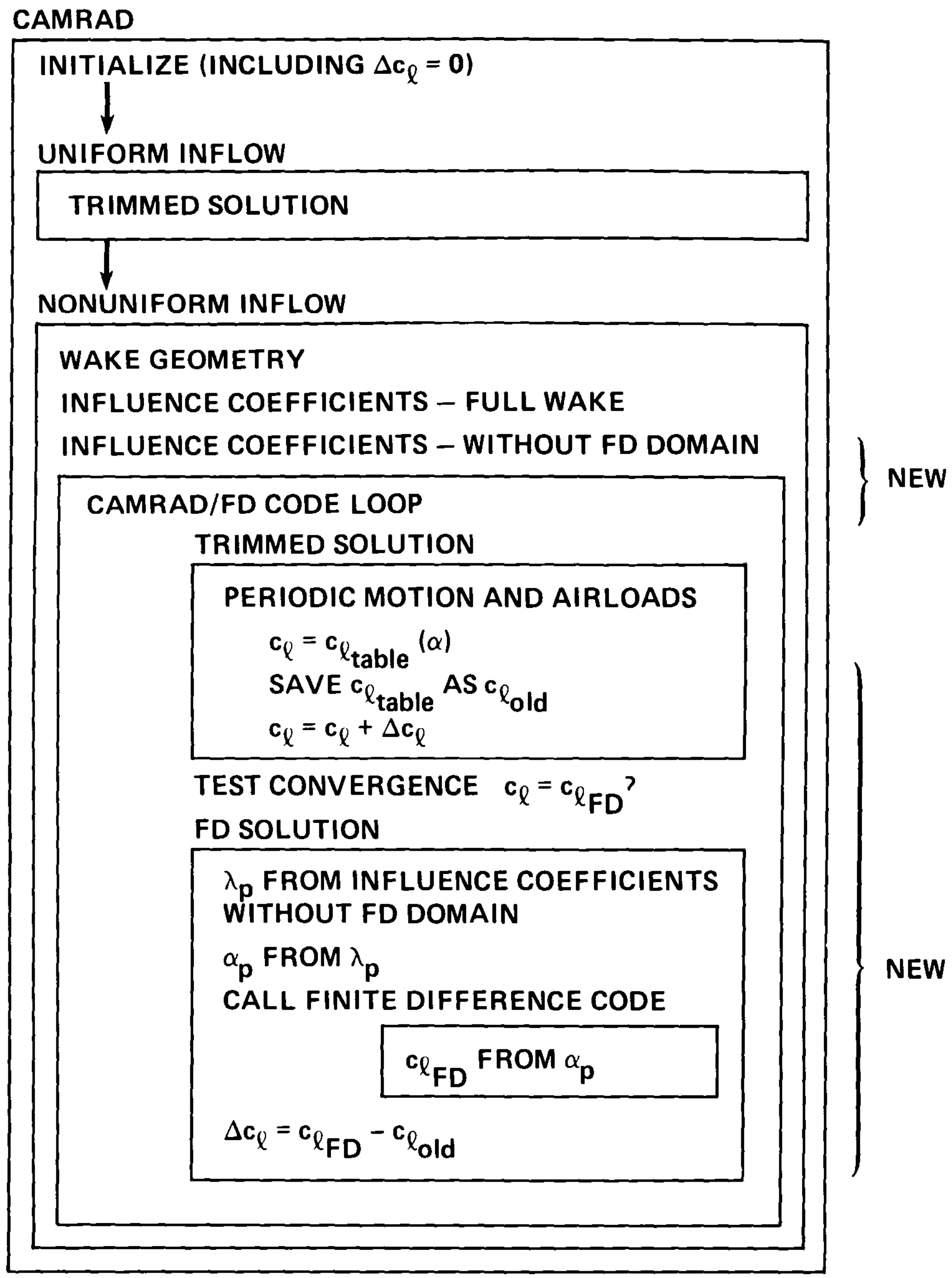


Figure 8.- Upper surface pressure on rotor blade at 95% radial station and 90° azimuth (teetering rotor with two blades, thrust coefficient/solidity = 0.077, radius = 0.958 m, tip speed = 227 m/sec, advance ratio = 0.298, tip Mach number = 0.663).



λ_p AND α_p ARE PARTIAL INFLOW AND ANGLE-OF-ATTACK, WITHOUT FINITE DIFFERENCE DOMAIN

$c_{\ell_{FD}}$ CALCULATED ON ADVANCING SIDE ONLY, $\Delta c_\ell = 0$ ON RETREATING SIDE

$$c_\ell(\alpha) = c_{\ell_{FD}}(\alpha_{old}) + c_{\ell_{table}}(\alpha) - c_{\ell_{table}}(\alpha_{old}) = c_{\ell_{table}}(\alpha) + \Delta c_\ell$$

Figure 9.- Coupling of CAMRAD with a finite difference code.

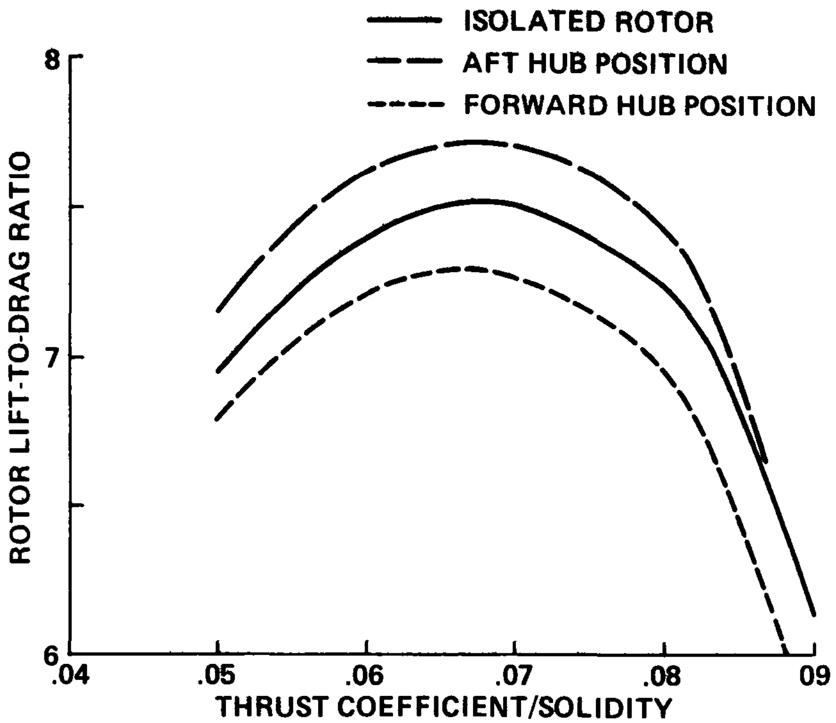


Figure 10.- Calculated influence of axisymmetric body on rotor forward flight performance (teetering rotor with two blades, advance ratio = 0.3, tip Mach number = 0.6, tip-path-plane angle of attack = 0; body with NACA 0031 thickness distribution, angle of attack = 0; body length = 1.02 rotor radius, rotor/body vertical separation = 7% body length, rotor hub 47.1% and 19.9% body length behind nose).

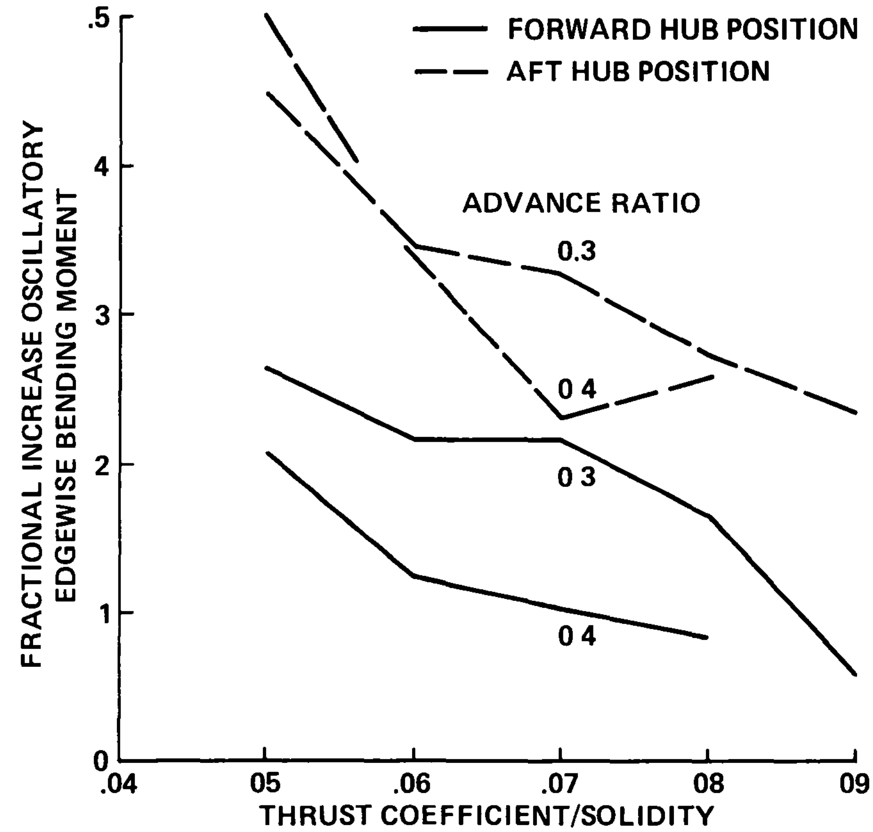


Figure 11.- Calculated increase in rotor blade oscillatory edgewise bending moments at 50% radial station due to an axisymmetric body, as a fraction of the loads without the body (articulated rotor with four blades, tip Mach number = 0.7, tip-path-plane angle of attack = -4°; body with NACA 0031 thickness distribution, angle of attack = 0; body length = 0.94 rotor radius, rotor/body vertical separation = 8.5% body length, rotor hub 50% and 20.6% body length behind nose).

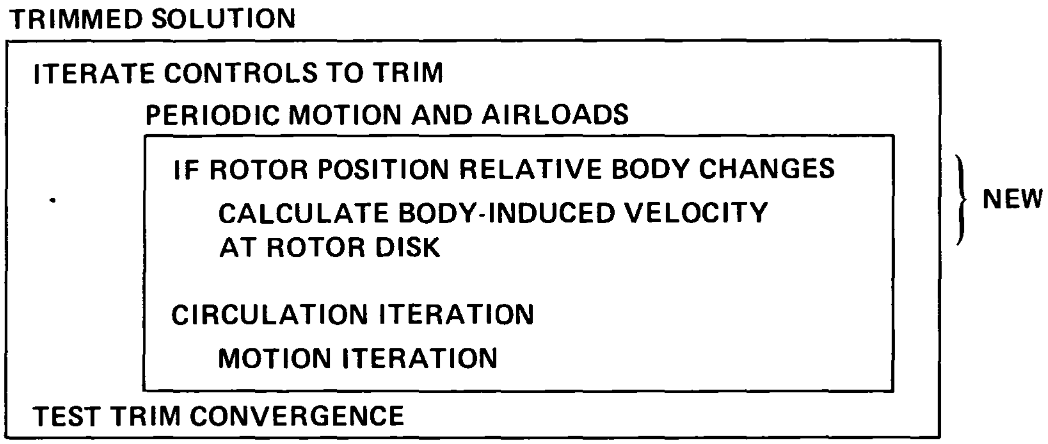


Figure 12.- Coupling of CAMRAD with body-induced velocity calculation.

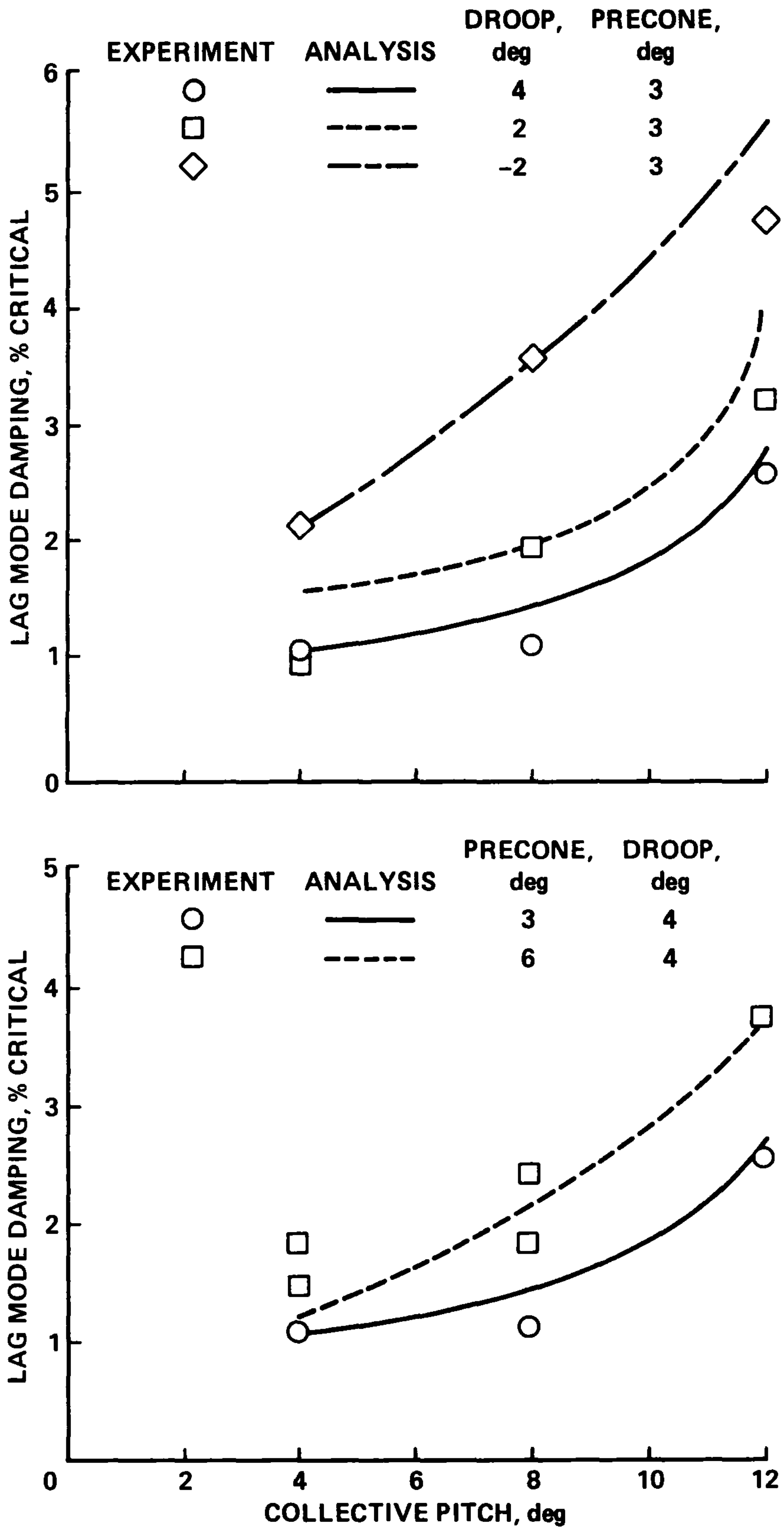


Figure 13.- Blade regressing lag mode damping ratio as a function of collective pitch at advance ratio = 0.3 (hingeless rotor with four blades on a support with pitch and roll motion, rotor pitch/flap coupling = 42.5°, radius = 1.38 m, tip speed = 89 m/sec, in Freon-12).

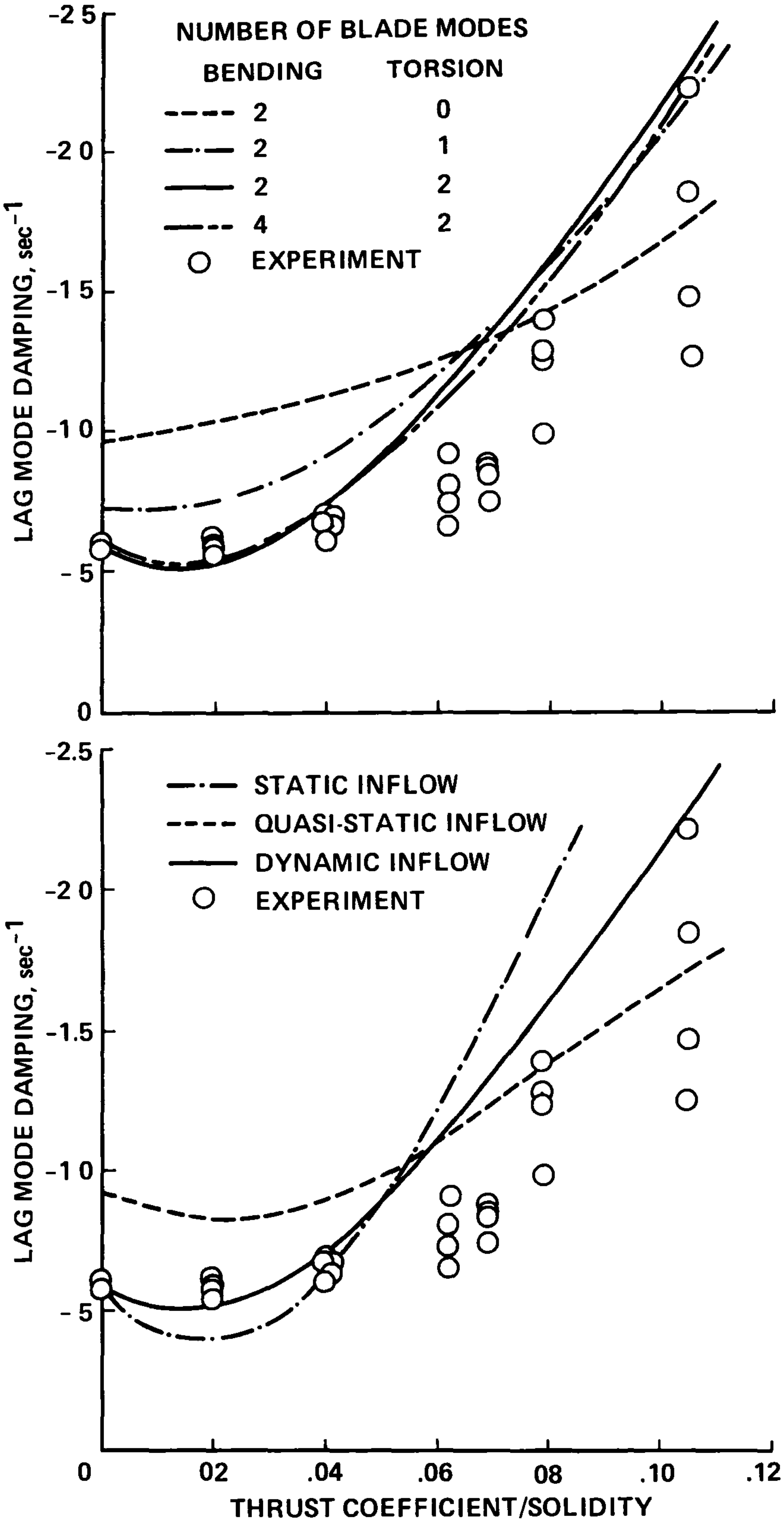


Figure 14.- Rotor blade regressing lag mode damping in hover as a function of thrust (hingeless rotor with four blades, radius = 4.91 m, tip speed = 218 m/sec).

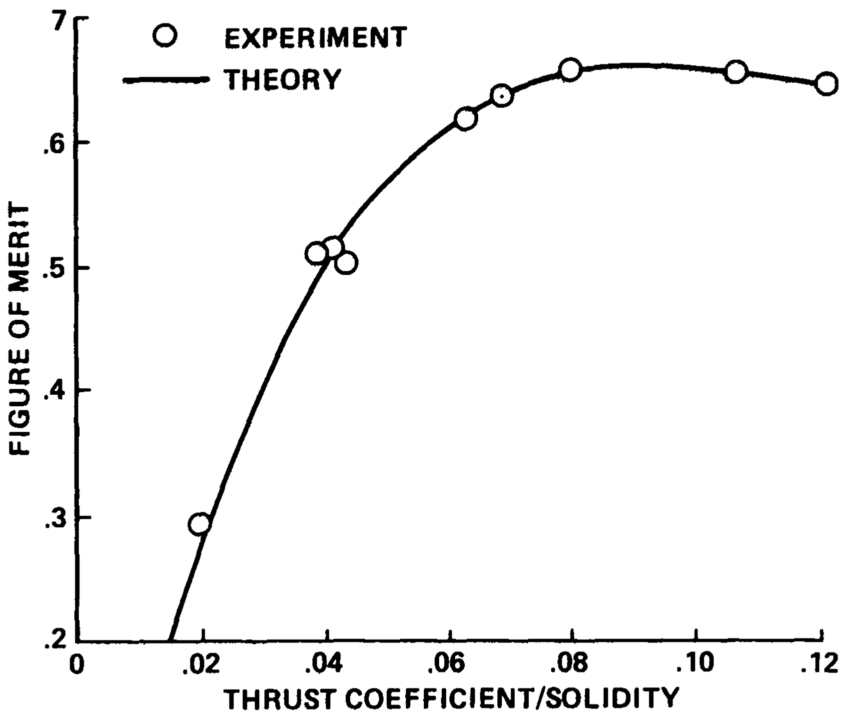


Figure 15.- Rotor hover performance as a function of thrust (hingeless rotor with four blades, radius = 4.91 m, tip speed = 218 m/sec).

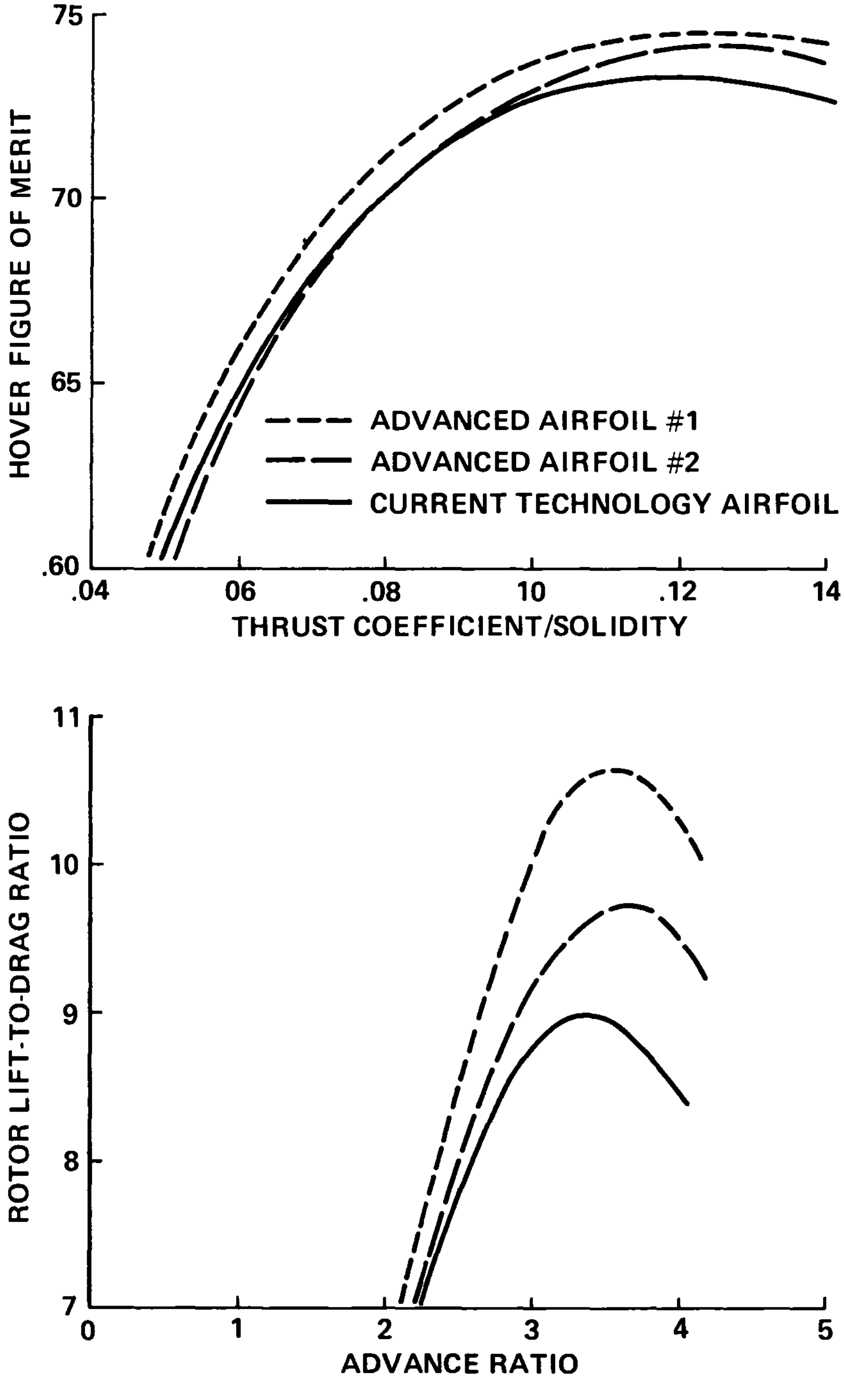


Figure 16.- Calculated effect of advanced airfoils on rotor hover and forward flight performance (articulated rotor with four blades, tip Mach number = 0.6, forward flight thrust coefficient/solidity = 0.07).

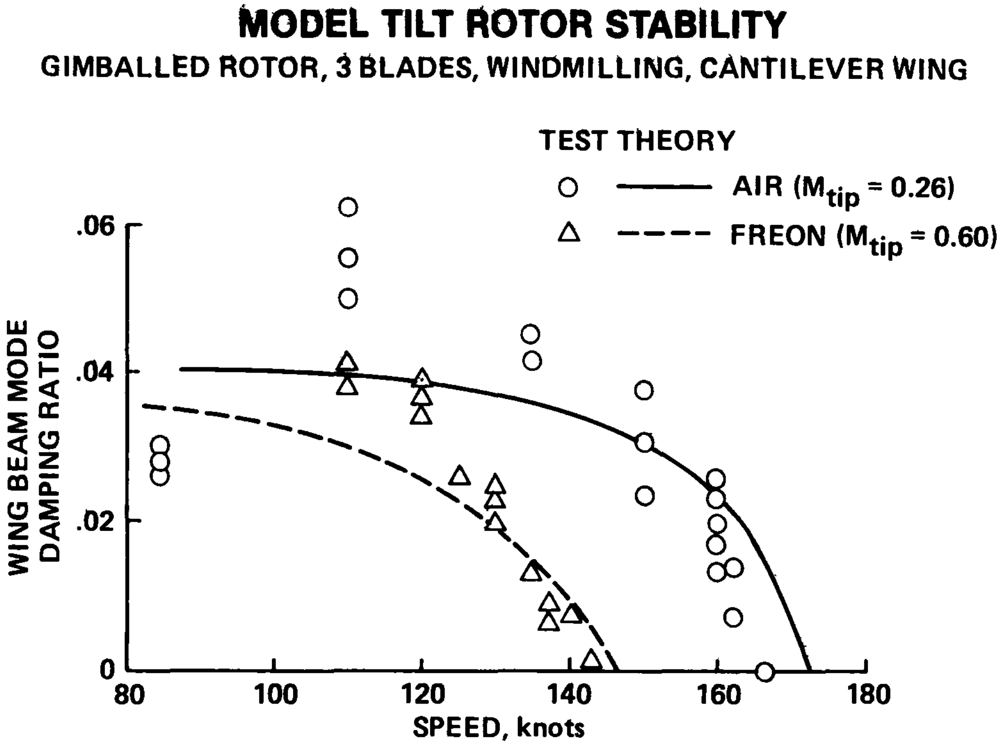


Figure 17.- Tilting proprotor wing beam mode damping ratio as a function of tunnel speed (windmilling, gimballed rotor with three blades on cantilever wing, radius = 1.16 m, tip speed = 90 m/sec).

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16. Abstract

The history, status, and lessons of a comprehensive analysis for rotorcraft are reviewed. The development, features, and capabilities of the analysis are summarized, including the aerodynamic and dynamic models that were used. Examples of correlation of the computational results with experimental data are given, extensions of the analysis for research in several topics of helicopter technology are discussed, and the experiences of outside users are summarized. Finally, the required capabilities and approach for the next comprehensive analysis are described.

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