FOREWORD

The Army's tactical and operational level doctrine, called AirLand Battle, places a heavy reliance on force flexibility and agility to fight the deep, close, and rear area battles. Vertical Takeoff and Landing (VTOL) aircraft systems, operating from unprepared surfaces, provide the Army the capability to execute AirLand Battle Doctrine on the modern battlefield. Rotary wing aircraft have evolved as the only viable VTOL concept for U.S. Army applications due to their (1) inherent low disk loading and downwash velocities which allow operation from unprepared surfaces, (2) excellent hovering performance and fuel efficiency, and (3) excellent low speed controllability. Figure 1 illustrates the efficiency of the rotor versus other VTOL concepts.

Like most VTOL aircraft, however, rotary wing aircraft are complex and require an interdisciplinary approach to understanding their unique characteristics and how to best exploit them. The interdisciplinary interaction that takes place in real time in a typical flight condition is illustrated in Figure 2. The technical disciplines involved are aerodynamics, aeroelasticity, structure and materials, and flight mechanics and controls. This complex interaction is found on any rotary wing aircraft wing aircraft whether it be a conventional helicopter, tilt rotor aircraft, or any unique hybrid configuration.
As illustrated in Figure 2, the interactions are a series of coupled feedback loops between one or more disciplines. For instance, loop 1 shows the feedback of the rotor wake into the aerodynamic theory. Loop 3 is an aeroelastic loop which illustrates the blade response to aerodynamic excitation. Table 1 is a summary of all the loops in Figure 2 and illustrates the necessary coupling between the principal and supporting disciplines in each loop.

**Table 1. Necessary Coupling for Rotorcraft Interdisciplinary Interaction**

<table>
<thead>
<tr>
<th>Discipline Area</th>
<th>Loops 1&amp;2</th>
<th>Loop 3</th>
<th>Loop 4</th>
<th>Loop 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerodynamics</td>
<td>P</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Aeroelasticity</td>
<td>S</td>
<td>P</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Structures &amp;</td>
<td>S</td>
<td>S</td>
<td>P</td>
<td>S</td>
</tr>
<tr>
<td>Materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flight Mechanics</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>P</td>
</tr>
<tr>
<td>&amp; Controls</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(P) - Principle Discipline  
(S) - Supporting Discipline
For different flight conditions and different types of calculations, certain loops take on increased importance. For instance, the interactional aerodynamics loop 2 is most important during low speed transition for flying qualities and high speed flight for fatigue loads. Obviously, to be able to accurately calculate vibrations throughout the entire flight envelope requires all the interaction in Figure 2. Programs such as the Army's Second Generation Comprehensive Helicopter Analysis Program (2GCHAS) are trying to take a systems approach to the Figure 2 interaction problem. Georgia Tech's Center of Excellence in Rotary Wing Aircraft Technology (CERWAT) has made great strides during its first five years in developing a center that can address the complex interaction loops of Figure 2 and is now in a unique position to make major contributions in the future. This position has been achieved by accumulating the necessary critical mass of rotary wing expertise, the required leadership and management philosophy, and by developing the necessary academic curriculum and facilities to support such an effort.

The principal CERWAT faculty and staff with their primary academic and research areas of concentration are provided in Table 2. The management and organizational structure for CERWAT is provided in Figure 3.

TABLE 2.

<table>
<thead>
<tr>
<th>Georgia Institute of Technology</th>
<th>CERWAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>FACULTY ACADEMIC &amp; RESEARCH</td>
<td>DISCIPLINE CONCENTRATIONS</td>
</tr>
<tr>
<td>Aerodynamics</td>
<td>Aerelasticity</td>
</tr>
<tr>
<td>Professor</td>
<td>R. B. Gray</td>
</tr>
<tr>
<td></td>
<td>J.C. Wu</td>
</tr>
<tr>
<td></td>
<td>H.M. McMahon</td>
</tr>
<tr>
<td>Assoc. Professor</td>
<td>D.P. Schrage</td>
</tr>
<tr>
<td>N.L. Sankar</td>
<td></td>
</tr>
<tr>
<td>Asst. Professor</td>
<td>N.M. Komerath</td>
</tr>
<tr>
<td>Research Engineer</td>
<td>W. Tang</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 3. CERWAT Organizational Chart within Georgia Institute of Technology, a Unit of the University System of Georgia

RECORD OF PAST ROTARY WING ACCOMPLISHMENTS

Georgia Tech's School of Aerospace Engineering has an outstanding reputation in furthering rotary wing aircraft technology which dates back to the School's inception in 1930 under one of the six Guggenheim Grants to establish U.S. schools of aeronautics. Montgomery Knight, the School's first director, made major contributions to the understanding of ground effect benefits for rotary wing aircraft. Basic courses in rotary wing theory have been taught continuously since the 1940's by such renowned individuals as Walter Castles and Robin Gray. This emphasis on rotary wing aircraft was strengthened in the 1960's and 1970's as the Army sent many military officers and civilian employees to Georgia Tech to take advantage of one of the nation's few rotary wing aircraft programs. Many of these individuals have gone on to become the rotary wing leaders in government and industry.

Since becoming a U.S. Army Center of Excellence in Rotary Wing Aircraft Technology (CERWAT) in 1982, as a result of the Vertical Lift Technology Review sponsored by the Assistant Secretary of the Army for Research, Development and Acquisition in 1980, Georgia Tech has established itself as the leading rotary wing university in the world. This claim can be substantiated in a number of ways: the faculty accumulated; the research conducted; the curriculum developed; the symposia held; the design awards won; and the graduates produced. The faculty accumulated, as listed in Table 2,
is unmatched in terms of rotary wing quality, quantity, and experience. It includes theoreticians, analysts, experimentalists, and leaders with U.S. Army and rotary wing operational experience. The breadth and depth of rotary wing research can best be appreciated by reviewing the publications listed in the Bibliography published later in this report. The Curriculum developed and expanded is provided in Table 4, and is the most comprehensive set of rotary wing courses ever assembled at one university.

TABLE 3.

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Existing</th>
<th>New</th>
<th>Updated</th>
<th>Professor</th>
</tr>
</thead>
<tbody>
<tr>
<td>4400</td>
<td>Introduction to Propeller and Rotor Theory</td>
<td>x</td>
<td></td>
<td></td>
<td>Gray</td>
</tr>
<tr>
<td>4600</td>
<td>Computational Aerodynamics</td>
<td></td>
<td></td>
<td></td>
<td>Sankar/Wu</td>
</tr>
<tr>
<td>6022</td>
<td>Advanced Compressible Flow III</td>
<td></td>
<td></td>
<td>Sankar</td>
<td></td>
</tr>
<tr>
<td>6400</td>
<td>Rotor Aerodynamics I</td>
<td>x</td>
<td></td>
<td></td>
<td>Gray</td>
</tr>
<tr>
<td>6401</td>
<td>Introduction to Helicopter Stability and Control II</td>
<td></td>
<td></td>
<td></td>
<td>Gray</td>
</tr>
<tr>
<td>6402</td>
<td>Aerodynamics of the Helicopter III</td>
<td>x</td>
<td></td>
<td></td>
<td>Gray</td>
</tr>
<tr>
<td>6802</td>
<td>Numerical Fluid Dynamics III</td>
<td></td>
<td></td>
<td></td>
<td>Wu</td>
</tr>
<tr>
<td>6810</td>
<td>Unsteady Aerodynamics</td>
<td>x</td>
<td></td>
<td></td>
<td>Wu</td>
</tr>
<tr>
<td>6030</td>
<td>Advanced Potential Flow I</td>
<td></td>
<td></td>
<td>Pierce</td>
<td></td>
</tr>
<tr>
<td>6031</td>
<td>Advanced Potential Flow II</td>
<td></td>
<td></td>
<td>Pierce</td>
<td></td>
</tr>
<tr>
<td>6200</td>
<td>Advanced Aeroelasticity I</td>
<td></td>
<td></td>
<td>Pierce</td>
<td></td>
</tr>
<tr>
<td>6201</td>
<td>Advanced Aeroelasticity II</td>
<td></td>
<td></td>
<td>Pierce</td>
<td></td>
</tr>
<tr>
<td>6202</td>
<td>Experimental Aeroelasticity</td>
<td></td>
<td></td>
<td>Pierce</td>
<td></td>
</tr>
<tr>
<td>8103</td>
<td>Rotorcraft Dynamics and Aeroelasticity I</td>
<td>x</td>
<td></td>
<td></td>
<td>Peters</td>
</tr>
<tr>
<td>8123</td>
<td>Rotorcraft Dynamics and Aeroelasticity II</td>
<td>x</td>
<td></td>
<td></td>
<td>Hodges</td>
</tr>
<tr>
<td>4115</td>
<td>Introduction to Fiber Reinforced Composites</td>
<td></td>
<td></td>
<td></td>
<td>Rehfield</td>
</tr>
<tr>
<td>4116</td>
<td>Manufacture of Composite Structures</td>
<td>x</td>
<td></td>
<td></td>
<td>Rehfield</td>
</tr>
<tr>
<td>6106</td>
<td>Finite Deformation of Aircraft Structures</td>
<td></td>
<td></td>
<td></td>
<td>Rehfield</td>
</tr>
<tr>
<td>6132</td>
<td>Vibration Measurement and Analysis</td>
<td></td>
<td></td>
<td></td>
<td>Craig</td>
</tr>
<tr>
<td>6133</td>
<td>System Identification</td>
<td></td>
<td></td>
<td></td>
<td>Hanagud</td>
</tr>
<tr>
<td>8104</td>
<td>Rotorcraft Design I</td>
<td>x</td>
<td></td>
<td></td>
<td>Schrage</td>
</tr>
<tr>
<td>8114</td>
<td>Rotorcraft Design II</td>
<td>x</td>
<td></td>
<td></td>
<td>Schrage</td>
</tr>
<tr>
<td>8113</td>
<td>Flight Mechanics and Controls</td>
<td>x</td>
<td></td>
<td></td>
<td>Calise</td>
</tr>
<tr>
<td>8133</td>
<td>Flight Dynamics and Controls</td>
<td>x</td>
<td></td>
<td></td>
<td>Calise</td>
</tr>
</tbody>
</table>
Since 1983, Georgia Tech has sponsored seven rotary wing related symposia as listed in Table 5.

<table>
<thead>
<tr>
<th>Georgia Institute of Technology</th>
<th>CERWAT</th>
<th>Conferences, Symposia and Short Courses</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPLICATION OF A SYSTEMS APPROACH TO ADVANCED ROTORCRAFT DESIGN AND TECHNOLOGY ASSESSMENT, Atlanta, GA, Sept. 11-13, 1985</td>
<td></td>
<td></td>
</tr>
<tr>
<td>US ARO/CERWAT CONFERENCE ON DYNAMICS AND AEROELASTIC STABILITY MODELING OF ROTOR SYSTEMS, Atlanta, GA, Dec. 4-5, 1985</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AMERICAN HELICOPTER SOCIETY NATIONAL ROTORCRAFT SPECIALIST'S MEETING ON CRASHWORTHY DESIGN OF ROTORCRAFT, Atlanta, GA, Apr. 7-9, 1986</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A SYSTEMS APPROACH TO ADVANCED ROTORCRAFT DESIGN AND TECHNOLOGY ASSESSMENT, Atlanta, GA, Jun. 23-27, 1986</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WORKSHOP ON APPLICATIONS OF THE DYNAMIC SYSTEMS COUPLER (DYSCO) MODELING PROGRAM, Atlanta, GA, Dec. 16-17, 1986</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROTORCRAFT ANALYSIS AND DESIGN, USA AVSCOM, St. Louis, MO, Mar. 23-27, 1987</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FOCUS ON COMPOSITE MATERIALS, Atlanta, GA, Jun. 9-12, 1987</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Georgia Tech's CERWAT student design teams have won seven of the nine awards given for the AHS/Boeing Vertol Student Design Competitions. Georgia Tech's students have won more Vertical Flight Foundation (VFF) fellowships over the last five years than any other university. Graduated CERWAT fellows are making major contributions in the rotorcraft industry and government laboratories.

This final report for the first five years of the CERWAT program provides a summary of the results of this Army Research Office sponsored research.
TABLE OF CONTENTS

1. Foreword ........................................................................................................................................ 1
2. Table of Contents ........................................................................................................................... 7
3. List of Appendices, Illustrations and Tables .................................................................................. 8
4. Research Tasks
   A. Aerodynamics Tasks
      Task 1. Experimental Studies for Tip Vortex Core Modeling....................................................... 9
      Task 2. Modification of Blade Tip Loading to Improve Hovering Figure of Merit ..................... 10
      Task 4. Studies of Unsteady Rotor Aerodynamics .................................................................... 13
      Task 5. Studies of the Airframe Flowfield in Forward Flight ....................................................... 16
   B. Structures Tasks
      Task 1. Structural Dynamic System Identification .......................................................................... 18
      Task 2. Crashworthy Characteristics of Composite Rotorcraft Structures ................................. 19
   C. Aeroelasticity Tasks
      Task 1. Helicopter Vibration Suppression Techniques ................................................................. 22
      Task 2. Rotorcraft Aeroelastic Active Control Investigations .................................................... 24

5. Bibliography .................................................................................................................................... 26
6. Appendices ...................................................................................................................................... 42
LIST OF
APPENDICES, ILLUSTRATIONS,
AND TABLES

Appendices:

A. Participating Scientific Personnel..............................................42
B. Degrees Awarded........................................................................44
C. Distinguished Fellowship Program..............................................46

Illustrations:

Figure 1. Hover Efficiency of VTOL Aircraft................................. 1
Figure 2. Rotorcraft Interdisciplinary Interaction............................ 2
Figure 3. CERWAT Organizational Chart within Georgia Institute of Technology, a Unit of the University System of Georgia..................................................3

Tables:

Table 1. Necessary Coupling for Rotorcraft Interdisciplinary Interaction............................................................2
Table 2. Georgia Institute of Technology CERWAT Faculty Academic and Research Discipline Concentrations......................................................3
Table 3. Georgia Tech Rotorcraft Academic Program Growth 1982 - 1987..............................................................................5
Table 4. Georgia Institute of Technology CERWAT Conferences, Symposia and Short Courses.................................................................6
RESEARCH TASKS

A. Aerodynamics Tasks:

Task 1. Experimental Studies for Tip Vortex Core Modeling

Investigators: R. B. Gray and N. M. Komerauth

Problem Studied:

The objectives of this task were to develop a capability for measuring the flow field near the tip and in the wake of a hovering helicopter model rotor using a laser velocimeter and to use the data to guide the development of a tip vortex core model for use in free wake analyses for blade loading predictions.

Summary of Results:

A two-component laser doppler velocimeter system was purchased and installed, and was used to generate an extensive and detailed database on the flow field of a single-bladed rotor in hover. Seeding and data acquisition and processing techniques were developed to enable these measurements, and the use of this instrument became routine in this facility.

The inflow and near wake regions of the rotor were documented in detail, and the data have since been used to validate two codes at Georgia Tech, as well as one at McDonnell-Douglas. Two AIAA Conference papers and one Journal of Aircraft publication resulted from these measurements.

The technique of laser sheet flow visualization was adopted and developed at this facility to enable qualitative observation and quantitative documentation of the dynamics of the tip vortex system. For the first time, this technique was applied to uniformly seeded flow fields, where the vortex core cross-sections became visible due to their lack of light-scattering seed particles. Up to three turns of the vortex could be photographed. Quantitative measures were obtained of the core size and unsteadiness of the vortex as a function of age. The work done on this task has since resulted in major advances in other tasks, notably task 5, and also served to guide precise LDV measurement of the vortex core. This work was initially performed as an undergraduate Special Problem, which was presented as a Student Paper at the AIAA Regional Student Conference.

To make velocity measurements in the core of the tip vortex, it was found to be essential to use seed particles which were small enough to stay and follow the flow in the highly accelerated inner core. Suitable particles were found (incense smoke), but they could not be observed in back-scatter by the LDV. This problem was solved by developing, for the first time, a remote-aligned off-axis scatter receiving system. This system enabled detailed
measurement of the velocity profiles inside the core of the tip vortex. For the first time, the component of velocity along the axis of these rotary-wing tip vortices was measured as well. Complex secondary structures were found inside the core, showing that the roll-up process of the vortex sheet into the tip vortex must be included in constructing vortex core models. This work resulted in a Ph.D. Thesis, an AIAA Conference paper, and a Journal of Aircraft publication. The data base awaits development of prediction techniques capable of modeling this flow field.

The problem of particle lag in vortex flows, and the attendant difficulties in making accurate LDV measurements, led to work on modeling and correcting for particle lag. To date, a numerical procedure has been developed for correcting measurements made in accelerating flow around a three-dimensional source. This work is being extended to vortices in uniform flows. At the same time, work has also been performed on a method to simultaneously measure velocity and particle size in such facilities. These efforts have resulted, to date, in one undergraduate Special Problem and three MS Special Problems.

Efforts to validate Navier-Stokes computations of the blade tip flow field using the data acquired in this task have resulted in two Conference papers.

List of Publications and Technical Reports:
See Bibliography

Participating Scientific Personnel:
See Appendix 1

Task 2. Modification of Blade Tip Loading to Improve Hovering Figure of Merit

Investigators: R. B. Gray and T. Thompson

Problem Studied:

Measured pressure distributions on the tip of a hovering model rotor blade show a low pressure region which is associated with the roll-up and rearward sweep of the tip vortex over the trailing 50% for the blade upper surface. This low pressure region near the trailing edge contributes significantly to the section pressure drag and hence to the rotor power required. The objective of this task is to explore the possibilities of improving performance by modifying the tip pressure distribution.

Summary of Results:

This task was completed and a final report was written in 1986 (Ref. 2.1.3).


Problem Studied:

The objective of this research task is to develop a procedure to accurately predict the flow field and hence the airloads in the vicinity of the tip of a rotor blade. This requires an accurate modeling of the tip vortex formation and roll up processes, and capture of the strength and location of embedded shock waves.

Summary of Results:

Two approaches were developed for study of this problem. First, a panel code capable of handling isolated rotor blades in hover or in forward flight was developed by O. Kwon, a graduate student. This code uses panels of constant source and doublet strengths to account for the thickness and lift effects respectively. The shed vortices from the tip were modeled using a prescribed wake model developed by Gray for hover applications. In forward flight applications, a free wake model developed by Scully was used. The vortex geometry in the vicinity of the blade tip was parametrically modified to determine the effects of the various tip vortex parameters on the predicted surface pressure distribution.

A version of this solver has been coupled to a curved beam nonlinear structural model developed by Hodges, and may be used to evaluate the static stability characteristics of modern rotor blades of arbitrary planform. As part of his Ph.D. thesis, O. Kwon is working on extending the above analysis to predict dynamic instability of rotor blades.

A hybrid time marching scheme for solving three-dimensional compressible Navier-Stokes equations developed under Aerodynamics Task 4 was adapted in the present work to study three-dimensional, unsteady, compressible flow past rotor blades. The resulting computer code is capable of handling rotor blades of arbitrary planform and can predict the flow around the entire rotor disk, including massively separated flows that may occur over the retreating side. If viscous effects are not important, this solver may be used as an Euler code to reduce the computer time.
In a cooperative effort with the scientists at the U.S. Army Research Laboratory, this solver was coupled with the free wake model embedded in the CAMRAD code, and was evaluated through the following benchmark calculations, performed in the Euler mode:

a) NACA 0012 rotor of rectangular planform, tip Mach number 0.7, advance ratio 0.3, zero degree collective pitch.

b) NACA 0012 rotor of rectangular planform, tip Mach Number 0.8, advance ratio 0.2, zero degree collective pitch.

c) A 1/7th scale model of the Cobra OLS rotor, tip Mach number 0.663, advance ratio 0.28. In this case, the collective pitch was iteratively adjusted using a procedure originally developed by Tung and Caradonna\(^1\) to match the computed thrust coefficient with the experiment.

d) A three-bladed rotor tested in France.

In all the cases studied, very reasonable agreement with experiments was obtained.\(^2\)

As part of his Ph.D. thesis work, B. E. Wake repeated calculations a) and b) mentioned above using the Navier-Stokes version of the code, and demonstrated that the viscous effects weaken the shock, and tend to place it forward of the Euler results. Viscous flow calculations were also carried out for a NACA 0012 rotor of rectangular planform in hover.\(^3\)

A version of this solver capable of handling 3-D blade vortex interaction was developed and correlated with experiments.\(^2\)

Detailed comparisons of the velocity field predicted by the 3-D Navier-Stokes solver for a model rotor blade in hover, tested under Aerodynamics Task 1, demonstrate that this solver provides a good quantitative modeling of the velocity field around the rotor blade. The velocity vector plots around the tip of the rotor blade which show the formation of the tip vortex are in good agreement with experiments.\(^4\)

In a joint study between Bell Helicopter Textron, Cray Research and the present researchers, this 3-D Navier-Stokes code is being used to evaluate the massively separated flow over a rotor blade in a high-G maneuver.\(^5\)

**Technology Transfer:**

Latest versions of this computer code have been made available to United Technologies Research Center (A. Egolf, B.E. Wake), McDonnell-Douglas Helicopter Co. (A. Hassan), Bell Helicopter Textron (J. Narramore), and the U.S. Army Aeroflightdynamics Directorate (C. Tung).

Lockheed Georgia Co. has obtained a version of this solver, and has adapted it for fixed wing aeroelastic applications.
Under the support of the NASA Lewis Research Center, a version of the 3-D Navier-Stokes solver capable of analyzing fixed wing performance under leading edge icing is being developed.

References:


List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1

Task 4. Studies of Unsteady Rotor Aerodynamics

Investigators: J.C. Wu, L.N. Sankar, M. Patterson

Problem Studied:

The primary objective of this work was to develop efficient computational tools for the prediction of the aerodynamic characteristics of airfoil. These tools should be capable of generating the static load characteristics of advanced airfoil configurations (Lift vs. Angle of Attack, Drag Polar, Drag vs. Mach Number), and should be capable of predicting the dynamic stall characteristics of airfoils. A second objective of this research effort was the development of efficient solution algorithms for the prediction of 3-D unsteady viscous flow over rotor blades.
Summary of Results:

Two computer codes were developed as part of this work. The first computer code solves the incompressible viscous flow over airfoils of arbitrary shape using an efficient zonal procedure. The flow field over the airfoil undergoing dynamic stall is usually attached over the lower surface, and separated over the upper surface. The zonal procedure solves the unsteady boundary layer equations written in the vorticity-stream function form over the lower surface. Only in the massively separated region over the upper surface is computation performed using the full Navier-Stokes equations, written in the vorticity-stream function form. The attached and separated flow regions are coupled to each other through the Poisson's equation for the stream function, and was solved in this work using an integral representation.

Efficient solution procedures were developed for the computation of the stream function at every time step as a function of the vorticity field. Procedures were also developed for the computation of new vorticity generated at the solid surface at every time step. As a result, an extremely efficient computer code has resulted which can predict the static load characteristics of any airfoil for the entire range of interest (from 0 degree angle of attack to post-stall angles of attack) within 10 minutes of CRAY XMP computer time. The same solver can be used to compute dynamic stall hysteresis loops for a given airfoil within one minute of CRAY XMP time per flight condition.

The second computer code developed solves the 2-D compressible Navier-Stokes equations in a strong conservation form using an alternating direction implicit (ADI) time-marching scheme. This solver may be used when compressibility effects are important. The governing equations are solved in a coordinate system that is free to rotate with the airfoil. The airfoil may also undergo sinusoidal flapping and/or lungeing motion. This solver requires about 40 minutes of computer time on a CRAY XMP to generate the static stall characteristics, and about 2 hours of CRAY XMP time to generate a dynamic stall loop.

Both the flow solvers have been validated by correlating the computed results with the experimental data obtained by Carr, McAlister, and McCroskey. Excellent agreement with experiment has been obtained. The code validation studies have been documented in open literature (see Bibliography).

Special versions of the incompressible and compressible Navier-Stokes solvers were developed which may be used to study the 2-D Blade-Vortex-Interaction (BVI) problem. These solvers can handle weak interactions as well as strong interactions where the vortex collides with the airfoil and causes large disturbances within the boundary layer.

A version of the incompressible Navier-Stokes solver that can handle circulation control applications was also developed. Because conventional circulation control techniques that rely on the tangential blowing of air jets over the airfoil upper surface are well understood, effort was focused on the use of solid surface motion to postpone or avoid stall. In this approach, a portion of the airfoil surface is free to move in the direction of the flow, say
through the use of a rotating cylinder positioned at the nose of the airfoil. These studies indicate that very small surface velocities are often adequate to postpone stall or completely avoid stall on the retreading side of the rotor disk.

Some work was also done towards development of efficient algorithms for calculation of 3-D unsteady viscous flow. Pilot versions of 3-D incompressible flow solvers that use pressure-velocity formulation, and velocity-vorticity formulation were developed. A hybrid (explicit-implicit) time marching scheme for the 3-D compressible Navier-Stokes equations, as well as 3-D grid generation schemes that can handle rotor blade geometries of arbitrary planform were developed as part of this research task. The 3-D compressible flow solver was made available to Aerodynamics Task 3 to tip vortex studies.

**Technology Transfer:**

The computer codes developed as a part of this task have been distributed to U.S. helicopter companies, government laboratories, and universities. The following agencies have received and routinely use the computer codes:

- a. NASA - Ames Research Center (Larry Carr and Prof. Bodapadi: Dynamic Stall Studies)
- b. NASA - Lewis Research Center (K.R.V. Kaza, Reddy and Dennis Huff: Propfan Studies, Stall Flutter, Airfoil Icing, k-ε turbulence models)
- d. McDonnell-Douglas Helicopter Company (A. Hassan: Dynamic Stall Studies)
- e. Bell Helicopter Textron (Steve Fodelsky: Dynamic Stall Studies, Flapping and Lunger Motion Applications)
- f. Duke University (E. Dowell: Transonic Flutter Applications)

During the period 1985-1987, small research grants from the McDonnell-Douglas Helicopter Company and NASA Lewis Research Center also resulted as a result of the progress made in the present research task, and led to modifications to the computer codes for specialized applications.

**List of Publications and Technical Reports:**

See Bibliography

**Participating Scientific Personnel:**

See Appendix 1
Task 5. Studies of Rotor-Airframe Aerodynamic Interactions

Investigators: H.M. McMahon and N.M. Komerath

Problem Studied:

This task aimed to develop a physical understanding of aerodynamic interaction phenomena between the rotor and airframe of rotorcraft. The database developed was to be used in validating and developing prediction methods for rotor-airframe interactions.

Summary of Results:

An integrated experimental/numerical approach has been used. To keep the problem tractable, the simplest generic rotor/airframe configurations have been employed, but a variety of techniques have been used to enable clear definition of the flowfield and its effects.

The Low-Speed Wind Tunnel at Georgia Tech was modified into a Forward Flight Facility with a powered rotor installation and a modern control room and digital data acquisition system. Software for pressure surveys, probe traverses, LDV data acquisition, time-series analysis, rotor dynamic balancing, and high-speed time history acquisition have been developed and used.

A detailed data base has been accumulated on mean and time-resolved surface pressure distributions on the airframe surface for a range of variation of advance ratio, and vertical and horizontal rotor-airframe separation, with two different rotors. The data have been published as a Data Report, which has been transmitted both in document and electronic forms to industry, university, and NASA researchers at their request. Two Conference papers and an AIAA Journal publication (under review) have resulted from this effort.

The mean and time-resolved velocity field near the airframe and the rotor, and airframe effects on the rotor flow field, have been documented in an extensive and unique set of measurements made using the laser velocimeter. Besides demonstrating routine LDV operations in this wind tunnel, these tests have provided precise quantitative information on the complex velocity field, including vortex interaction effects on the rotor and airframe, secondary vortex generation at the rotor disc edges, the effects of the rotor hub, and the inflow to the rotor disc. These have been published in two Conference papers, and one Journal of Aircraft paper (under review).

Major strides have been taken in applying laser sheet flow visualization to the rotor-airframe flow field. The trajectories and dynamics of the vortex system of the rotor have been documented in detail. Secondary vortex generation phenomena and vortex interactions with the airframe have been captured. Distortions to the trajectories caused by the airframe have been measured. One Conference paper and two Journal of Aircraft publications (one accepted, the other under review) have resulted from this effort.
Vortex-surface interactions have been closely studied by the synchronized application of pressure sensing, LDV measurements, and flow visualization. The results have been documented in a publication submitted for peer review.

Existing prediction codes including the Freeman-Hess code and the VSROTOR code were examined against the experimental data. It was found that the inclusion of a time-resolved rotor wake was essential to useful prediction, and hence work on a new code was started. Modified forms of Scully's Free Wake code and the AMI VSAERO body panel code have been linked. Success has been achieved in predicting mean pressure distributions over the airframe surface, and progress has been made towards a full prediction of the periodic pressure and velocity variations.

The experiments have produced a set of test cases where interaction effects between the rotor and airframe are very significant and measurable. However, the multi-faceted measurements have shown that most of the interaction effects are consistent with simple potential-flow models, and that the dominant features of the flow field are accessible to prediction by relatively simple techniques. More complex effects such as massive flow separation around the airframe and rotor aeroelastic phenomena are subjects for future test cases.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1
B. Structures Tasks

Task 1. Structural Dynamic System Identification

Investigators: S.V. Hanagud, J.I. Craig, M. Meyappa, S. Sarkar, Y. Yillicki

Problem Studied:

The objective of this task is to develop techniques to effectively identify structural dynamic models that realistically and accurately describe physical structural systems. The research has concentrated on both measurement and analysis methods and has considered the effects of simple nonlinearities, nonproportional damping and large concentrated masses. The most recent work has been directed at the problem of rotor blade system identification with particular interest in the damping characteristics and the uniqueness of the identification. The current work is concerned primarily with fundamental techniques for identification of distributed parameter models that uniquely describe physical systems.

Summary of Results:

Structural dynamic models have been developed including damping by using identification techniques and experimental results. Techniques have also been developed for the identification of structural dynamic models with nonproportional damping from experimental measurements. Aeromechanical equations in a concise form have been developed by using Kane's and Gibb's method. These will be used in programs like the Army's 2GCHAS. Multiple scale identification procedures have been developed to formulate nonlinear systems.

Artificial Intelligence based techniques of model identification were developed by using A* search and object oriented programming techniques. Another accomplishment was the use of scale models in structural dynamic testing as well as development of methods of using identification and elastic fuselage models in vibration control. Methods of vibration control were developed by using lightweight sensors and actuators mounted on the structure (piezoceramic sensor and actuators) with possible application to Individual Blade Control (IBC).

Other results of this research include the prediction of random-like responses (in blades and fuselage) which are in reality not random vibration, but a new concept known as chaotic vibration in deterministic systems. Also developed were computer-aided engineering methods for structural dynamics systems.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1
Task 2. Crashworthy Characteristics of Composite Rotorcraft Structures

Investigators: S.V. Hanagud, J.I. Craig, R. Chander, P. Sriram, C.C. Won, and W. Zhou

Problem Studied:

The objective of this task was to conduct basic research to develop improved techniques and procedures for designing crashworthy composite structures for rotorcraft. This includes the development of analysis methods, testing techniques, and crashworthy design optimization under constraints of weight, cost, and performance.

Summary of Results:

Portable noncontact measurement techniques were developed for use in the laboratory and in field crash tests. Analysis, design and testing was conducted for curved web structures for energy absorption in crashworthy designs. A computerized Crash Energy Absorption Laboratory test facility was developed.

Also developed in this research were methods of optimization of structures. Static and dynamic test correlation of energy absorbing structures was performed. Accurate analytical models for the analysis of crash impact on energy absorbing and airframe structures were developed. Additionally, analysis was performed on flight data recorders for obtaining crash and crash test information.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1

Investigator: L.W. Rehfield

Problem Studied:

This task is concerned with crippling and postcrippling behavior of thin walled graphite/epoxy composite airframe members in axial compression. The main objectives are to 1) generate an experimental database on the crippling and postcrippling behavior, 2) develop simple analytical methods to predict these behaviors, and 3) provide better insight into the failure processes for this type of structure.

A second thrust concerns the structural modeling and analysis of composite rotor blades. The objective is to create an analysis methodology suitable for design which predicts response reliably and contains the capability of representing general composite construction. The opportunities presented by elastic tailoring utilizing the orientation effects that can be created with composite materials can be exploited easily with this analysis methodology.

Summary of Results:

Research findings pertaining to the concept of postbuckled structure is reported in publications listed in the bibliography. Emphasis has been given to analysis and correlation with previous experiments. A crippling law for no-edge-free composite plate elements has been created with a completely theoretical basis. The experimental data agree fairly well with the theory. It is based upon a maximum strain failure criterion.

A simplified analysis of composite plate elements has been created and is currently being evaluated for one-edge-free configurations. A new variational formulation has been created to characterize the situation being modeled. Simple, approximate solutions are currently being sought based upon the variational principle developed.

A very simple crippling law for one-edge-free elements has been established based upon a maximum strain failure criterion. It is presently being evaluated.

Rotor blade modeling results have been reported in the publications listed in the bibliography. In the course of this work, close working relationships were maintained with M.W. Nixon, R. Lake, G.L. Farley, and W. Mantay of the AVSCOM Aerostructures Directorate. Also, persons in the Aeroflightdynamics Directorate have been briefed on a regular basis.

The development of a theory valid for large deflections and moderate rotations has been completed. The single cell theory has also been improved. The improvements relate to twisting kinematics. These results are also reported in the publications in the bibliography.
A study has been completed which thoroughly develops the basis for extension-twist coupling in blades, the primary form of coupling useful for tilt rotor applications. Among the more important findings is the discovery that a single coupling parameter controls the structural design. General behavioral laws in terms of this parameter have been established.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1
C. Aeroelasticity Tasks

Task 1. Helicopter Vibration Suppression Techniques


Problem Studied:

The overall purpose of this program is to develop and validate comprehensive vibratory analyses for the evaluation of vibration suppression techniques. The load analyses are to be applicable to nonuniform multibladed systems with various hub constraints. Special emphasis is to be placed on blade structural dynamics and unsteady blade aerodynamics.

To facilitate validation of the analyses, an aeroelastic rotor test chamber (AeroTech) has been developed. The primary purpose of AeroTech is to experimentally simulate and record various aeroelastic phenomena associated with contemporary helicopter systems. The information compiled with this facility will form a valuable data base with which to correlate the predictions obtained from newly developed analytical techniques.

This facility has a computer-based acquisition system which can simultaneously receive, condition, record and analyze up to forty-eight channels of response parameters. The on-line analysis of these data can be preprogrammed in FORTRAN-77 or can be processed by a time-series analyzer. The facility also has a three-channel hydraulic excitation system which permits on-line computer control of a swashplate mechanism for the dynamic excitation and control of the model rotor in blade pitch. Both static and dynamic calibrations of this actuator system have been installed in the computer, which has been programmed for stability and harmonic response testing.

Summary of Results:

Two comprehensive methods of analysis have been developed for the determination of elastic rotor blade response in forward flight. Both of these analyses are sufficiently general to handle nonuniform blades with various parametric offsets. Results obtained from these methods have been correlated with each other and published data from other analytical studies.

The first method of analysis is based on a new formulation of the blade equations for flap-lag-torsion deformations. A unique aspect of this formulation is in the treatment of the pitch control inputs. A transformation for the collective and cyclic control is performed prior to the transformation from undeformed to deformed coordinates. The spatial solution is obtained by a Galerkin technique with nonrotating modes, while the time dependency is computed by numerical integration.
The second method is an extension of the well-known structural dynamic development of Hodges and Dowell to include time-dependent pitch control inputs. This flap-lag-torsion representation has been programmed for solution using a harmonic balance technique by combining the previously used Galerkin approach with integer harmonic components for the generalized coordinates. This method provides two outstanding benefits. First, it is computationally very efficient; and secondly, it is ideally suited for the incorporation of unsteady aerodynamic formulations which are based on simple harmonic motion.

Dynamic testing has been performed on the ACR (Aeroelastically Conformable Rotor) model. This system is an articulated nine-foot diameter four-bladed rotor on loan from NASA Langley. Four types of response tests were conducted with this model. The first was a series of steady pitch control runs at various speeds and combinations of collective, longitudinal and lateral pitch settings. Secondly, a series of runs were made with a four-per-rev collective pitch about various mean collective settings and speeds. The third type of testing examined the transient behavior of the rotor system as the four-per-rev collective excitation was abruptly removed again at various mean settings and speeds. The fourth and final type of testing consisted of imposing various rapid ramp changes to the collective pitch at different speeds.

The HARP (Hughes Advanced Rotor Program) model was obtained on loan from McDonnell Douglas Helicopter Company (MDHC). This model is a bearingless eight-feet diameter four bladed rotor. Mechanical adapters have been designed and constructed so that the model can be tested in AeroTech. These tests were scheduled to begin earlier this year, but the model had to be returned to MDHC. The instrumentation on the blades is being replaced in preparation for a Whirl Test at the Ames facility and subsequent wind tunnel tests at the DNW facility in the Netherlands. It is anticipated that the model will be returned to AeroTech for additional dynamic testing during 1988. Plans are being made to include CERWAT personnel in the NASA/Army/MDHC test program and to make available much of the data obtained in these tests.

Technology Transfer:

Testing in the AeroTech facility has involved rotor systems from NASA Langley and MDHC. There is an on-going dialogue with these agencies and as further testing is accomplished, there will be a sharing of data between Georgia Tech and them.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1
Problem Studied:

The objective of this task, which began during CERWAT's fifth year, was to study, evaluate and compare various controller configurations that have been shown either theoretically or experimentally to have the potential for providing favorable aeroelastic response and to improve unsteady aerodynamics representation with dynamics inflow. The research consisted of both an analysis and an experimental program.

Summary of Results:

The analysis program consisted of modelling various higher harmonic control (HHC) controller configurations and including them in a Dynamic Systems Coupler (DYSCO) program to investigate rotorcraft aeroelastic response. For the first time, an analytical free-flight simulation of HHC was reported utilizing and comparing five different HHC controllers. These five different controllers were incorporated into a dynamic response simulation of the OH-6A helicopter using the DYSCO flexible modeling system. The results were reported in K.P. Nygren's doctoral dissertation (Ref. 4.1.4), as well as his AHS Southeast Region Lichten Award-winning paper. These five HHC controllers were also applied to a DYSCO aeroelastic representation of the CERWAT AeroTech facility with Aeroelastic Conformable Rotor (ACR) blades and similar results were achieved.

Significant progress was also made in developing the dynamic inflow theory for use in aeroelastic response investigations. A strong correlation between dynamic-inflow theory and the lift-deficiency function of Loewy was found, which will allow simulation of an n-bladed rotor with dynamic-inflow by allowing n-pressure spikes to rotate around an actuator disk. These results have been reported in Reference 4.2.13.

On December 9-10, 1986, a DYSCO Workshop was sponsored by CERWAT and was held at Georgia Tech. Representatives from several AVSCOM laboratories, as well as the USAF Flight Dynamics Laboratory and Kaman Aerospace Corporation were in attendance. Presentations were made illustrating how the various controllers were incorporated into DYSCO. In addition, a discussion on dynamic-inflow and an approach on how it could be included in DYSCO was presented.

During the six-month extension to the fifth-year effort, the various controllers developed in the frequency domain for the fixed system HHC applications were extended to the time domain for Individual Blade Control (IBC) applications. The time-domain regulator used a frequency-shaped cost functional to minimize narrow band vibration levels. The dynamic model parameters are being identified with a least-squares/fourier series method with full state feedback. Plans are to extend the method to output feedback which will allow more practical application. The result of extending the
various controllers to both the frequency and time domains will allow investigation of active control for a variety of aeroelastic response phenomena during follow-on efforts. The approach and results to date were reported in the Reference 4.1.14 paper and presentation and the Reference 4.2.15 presentation.

Also, during the six-month extension, we continued application of dynamic inflow. As a spin-off of this work, we received a grant from NASA Ames Research Center to develop an unsteady aerodynamic theory (based on dynamic inflow) for aeroelastic analysis. Under CERWAT, on the other hand, we continued quasi-steady application studies. These included application to measured static inflow of a rotor in forward flight as well as comparisons with Fridovitch's original collective-step response studies. Our results were as good as the free-wake results of Quackenbush. Lastly, we were able to show how dynamic inflow could be applied in a finite-element setting; and we began work on comparing dynamic-inflow results with those of a panel code also developed at Georgia Tech.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1
BIBLIOGRAPHY

1. **CERWAT PUBLICATIONS**

1.1 Notes of Short Course on Application of a *Systems Approach to Advanced Rotorcraft Design and Technology Assessment*, Atlanta, GA, September 1985


1.4 Notes of Short Course on *A Systems Approach to Advanced Rotorcraft Design and Technology Assessment*, Atlanta, GA, June 1986


1.6 Notes of Short Course on *Rotorcraft Analysis and Design* to USA AVSCOM, St. Louis, MO, March 1987.


2. **AERODYNAMICS**

2.1 **Peer Reviewed Publications:**


2.1 Peer Reviewed Publications (continued):


2.1 **Peer Reviewed Publications (continued):**

2.1.18 Thompson, T.L., Komerath, N.M., and Gray, R.B. "Visualization and Measurement of the Tip Vortex Core of a Rotor Blade in Hover". Accepted by the *Journal of Aircraft*.

2.2 **Meeting Publications:**


2.2.6 Wu, J.C., "Computational and Theoretical Studies of Unsteady Viscous Aerodynamics," Low Reynolds Number Aerodynamics Conference, Notre Dame University, South Bend, IN, June 1985.


2.2 Meeting Publications (continued):


2.2 Meeting Publications (continued):


2.3 Contract Reports:

2.3 **Contract Reports (Continued):**


### 2.4 Student Special Problems:

2.4.1 Kemnitz, J.L. "Correcting LDV Data for Particle Inertia". M.S. Special Problem Report, Georgia Institute of Technology, School of Aerospace Engineering, August 1986.

2.4.2 Sullivan, A. "Application of Backsolving Technique to Correct LDV Data". M.S. Special Problem Report, Georgia Institute of Technology, School of Aerospace Engineering, August 1987.

2.4.3 Leland, B. "Determination of Rotor Tip Vortex Trajectories Using Synchronized Laser Screen Visualization". Special Problem Report, Georgia Institute of Technology, School of Aerospace Engineering, March 1986.

### 3. **Structures and Materials:**

3.1 **Peer Reviewed Publications:**


3.1 Peer Reviewed Publications (continued):


3.2 Meeting Publications:


3.2 Meeting Publications (continued):


33
3.2 Meeting Publications (continued):


3.2.32 Craig, N., Hanagud, S., Zhon, W and Suram, P., "Correlation of Experimental Static and Dynamic Response of Simple Structural Components.


3.2 Meeting Publications (continued):


4. AEROELASTICITY AND DYNAMICS

4.1 Peer Reviewed Publications:


4.1 Peer Reviewed Publications (continued):


4.2 Meeting Publications:


4.2 Meeting Publications (continued):


5. FLIGHT MECHANICS AND CONTROL

5.1 Peer Reviewed Publications:

5.2 Meeting Publications (continued):


6. DESIGN:

6.1 Peer Reviewed Publications:


6.2 Meeting Publications:


7. OTHER ROTORCRAFT RELATED

7.1 Meeting Publications:

7.1.1 Gray, R. B., "Graduate Rotorcraft Programs at Georgia Tech," ASEE Annual Conference, Salt Lake City, UT, June 1984.


40
7.1 Meeting Publications (continued):


APPENDIX A

Scientific Personnel Supported by this Project

Co-Principal Investigators:

  R. B. Gray
  D. P. Schrage

Faculty:

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  N. Komerath
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- S.G. Liou
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M.S.
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Contributors not supported by project funds:

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Research Engineer:
- V.R.P. Jonnalagadda

M.S. Students:
- W.P. Crisler
- O. Schreiber
# APPENDIX B

## DEGREES AWARDED

<table>
<thead>
<tr>
<th>NAME</th>
<th>DEGREE - DATE</th>
<th>LAST KNOWN AFFILIATION</th>
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<tr>
<td>V.R. Anand</td>
<td>PhD - Dec 1982</td>
<td>Georgia Tech</td>
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<tr>
<td>Jerry W. Anders</td>
<td>MS - Jun 1987</td>
<td>Lockheed-Georgia</td>
</tr>
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<td>A.R. Attilgan</td>
<td>MS - Jun 1987</td>
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<td>Gilbert E. Boen</td>
<td>MS - Mar 1985</td>
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<td>A.G. Brand</td>
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<td>T. Boyd</td>
<td>MS - Sep 1983</td>
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<td>C. Boyette</td>
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<td>C. Brevoort</td>
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<td>MAJ M. Clifford</td>
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<td>W.P. Crisler</td>
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One of the most significant accomplishments of CERWAT during its first five years has been the quality and quantity of U.S. citizens that have entered the rotary wing field. The magnet that has attracted them to rotary wing has been the Distinguished Fellowship Program. The CERWAT fellows, which numbered a total of sixteen for the first five years, came from a variety of sources. Many were the top graduates in our undergraduate program who took Robin Gray's "Introduction to Propellor and Rotor Theory" their senior year and then entered the CERWAT program. Some came from other outstanding engineering universities, especially once the CERWAT reputation was established. Still others came from the rotorcraft industry which has provided a natural means for interaction. All of the students awarded fellowships have been outstanding with greater than 3.5 out of 4.0 GPA's. All had expressed an intent of obtaining a Ph.D. degree. Some were not awarded fellowships their first year and had to demonstrate their abilities and rotary wing interest. Our goal has been to have one CERWAT fellow per research task with additional graduate research assistants (GRA's) as required. We plan to follow the same successful procedure during the next five year program. We have an outstanding group of graduate students entering next fall, many applying based upon CERWAT's reputation. A summary of the procedure follows:

1. Principle Investigators nominate candidates for CERWAT Fellowships to the Technical Director. Minimum criteria are:
   a. Minimum GPA of 3.5 out of 4.0 for undergraduate work. Exceptions can be made for candidates with extensive rotary wing experience and outstanding recommendations from their former employers,
   b. Candidate must express an intent to continue pursuit of a Ph.D. degree;

2. A CERWAT Review Board consisting of the Technical Director, Administrative and Finance Director, and one principle investigator from each discipline (Table 2) reviews the candidates' applications and selects the CERWAT Fellows; and

3. CERWAT Fellows' progress is checked each year by the Technical Director using the School of Aerospace Engineering's standard graduate student evaluation form which is submitted each quarter.