1998

STRUCTURAL DYNAMIC RESPONSE OF THE RAH-66 COMANCHE HELICOPTER

E.R. Wood, Professor of Aeronautics & Astronautics
D.A. Danielson, Professor of Mathematics
J.H. Gordis, Associate Professor of Mechanical Engineering
Sponsor: Comanche Program Office and Naval Postgraduate School

OBJECTIVE: Professors Wood, Danielson, and Gordis continued their work in support of the ongoing development of the Army's RAH-66 Comanche helicopter. Tasks included static and dynamic analyses. A dynamic NASTRAN finite element model provided the basis for the analyses and is maintained at NPS to support the ongoing Comanche flight test development program. The objective of the analyses is the optimization of the airframe for dynamic response.

SUMMARY: Research for 1998 comprised two parts: For the first part, developmental flight testing of the Comanche helicopter had revealed high vibrations caused by buffeting of the aircraft empennage. From the flight test aircraft differential pressure transducer and accelerometer data, the spectral content of the response was determined. Then, using a NASTRAN model of the aircraft, the frequency response functions between selected points on the aircraft's tail and the flight test accelerometer locations were calculated. Finally, various assumptions as to the location and distribution of empennage air loads were made, and the magnitude of these airloads, and the relative importance of primary airframe modal responses to these airloads, were determined.

Efforts of the NPS Comanche team for the second half of 1998 were directed to a new area, that of designing the tailboom to withstand the high pressure blast emitted from a 23 mm HEI (High Explosive plus Incendiary) round. [See Ref. (1)] For the new work, special software, MSC/DYTRAN is required. DYTRAN is a three dimensional code that is well suited for analyzing short, transient dynamic events that involve large deformations, a high degree of nonlinearity, and interactions between fluids and structures. Typical applications include: (1) response of structures to explosive and blast loading; (2) high-velocity penetration; and (3) weapons design calculations that involve self-forging fragments.

DYTRAN makes Lagrangian and Eulerian solvers available to enable modeling of both structures and fluids. Meshes within each solver can be coupled together to analyze fluid-structures interactions. Solid, shell, beam, membrance, spring, and rigid elements are used within the Lagrangian solver to model the structure, and the three-dimensional Eulerian elements can then be used in addition to create Eulerian meshes.

DAMPER FREE ROTOR DESIGN METHODOLOGY BASED ON FULL ORDER MAPLE® GENERATED EQUATIONS OF MOTION AND SIMULINK NONLINEAR SIMULATION

E. Roberts Wood, Professor
Robert L. King, Lecturer
Department of aeronautics and Astronautics
Sponsor: Sikorsky Aircraft Corporation
(National Rotorcraft Technology Center/Rotorcraft Industry Technology Association)

OBJECTIVE: The objective of the present work is to explore the potential of eliminating the snubber damper on hingeless rotor designs and replacing it with a flexbeam that has been modified to possess nonlinear properties. This work is well suited to the new NPS rotor simulation analysis that can accurately model nonlinear mechanical properties so that these nonlinearities may be exploited to the helicopter's advantage. Tasks in this research included the formulation of a MAPLE® -based symbolic processing program that formulated nonlinear equations of motion given energy expressions for helicopter rotor model degrees of freedom. SIMULINK® based computer simulations were developed from the equations of motion derived by the symbolic processor. The resulting simulation is being used to analyze the effects of nonlinear material properties on aeromechanical rotor stability.

SUMMARY: This research presented results of a parametric study of damperless helicopter rotor blade lead/lag motion. Simulations of hub and blade lag motion were performed in the SIULINK® modeling environment using the symbolically derived equations of motion mentioned. Without including auxiliary lag dampers in the blade dynamics, this analysis incorporated nonlinear flexbeam stiffness properties to limit inplane motion of the blade. A parametric study was then performed simulating soft inplane rotors with lag natural frequencies from 0.3Ω to 0.7Ω and damping ratios for hub motion from <1% to 10%. For lead/lag motion, each blade in the study was modeled with a conventional linear restoring spring in parallel with a cubic restoring spring, found in the literature as a Duffing-type spring.

Since ground and air resonance are characterized by coupling of fuselage motion with led/lag motion of the rotor blades in their plane of rotation, the classic frequency shifts of a Duffing type blade constraint offer an intriguing option to conventional lead/lag dampers as a potential solution to the rotorcraft ground/air resonance problem.

With Duffing-type nonlinear stiffness employed in the flexbeam of the blades, stable lead/lag motion was successfully achieved in coupled rotor-fuselage simulations that are otherwise very unstable. Built-in-linear structural lag damping of 1% was assumed for the flexbeam in all cases.

Parametric studies were then conducted with the linear spring rate held constant but where the Duffing spring rate was gradually increased. Simulation time histories showed that the linear system, while initially unstable, became increasingly stable as the spring constant of the nonlinear Duffing spring was gradually increased. Additional analysis has been performed at rotor rotational frequencies above the center of instability.

RESEARCH IN DAMPER-FREE ROTOR DESIGN BASED ON MAPLE® GENERATED NONLINEAR SIMULATION

E. Roberts wood, Professor
Robert L. King, Lecturer
Department of Aeronautics and Astronautics
Sponsor: U.S. Army Research Office
Research Triangle Park, NC

OBJECTIVE: Recent work at NPS has resulted in a new and powerful tool for exploring ground and air resonance stability with the goal of eliminating lead/lag dampers on helicopters. The analysis take advantage of new advances in mathematical analysis such as Waterloo's Maple® for symbolic manipulation, Mathworks' Simulink® for control system simulation and the Moving Block Analysis or Hilbert Transform Method for accurate determination of damping values from simulation time histories. The resulting combined analysis tool is no longer hampered by the usual limitations that would restrict the method to small amplitudes and angles, linear springs, linear dampers and prescribed ordering schemes for variables. Instead, new features have been incorporated that for the first time use the full equations of motion to permit detailed studies of such topics as: (1) Nonlinear flexbeam constraint at blade root – stiffening approach versus stiffening approach; and (2) active feedback control – provided both by swashplate input HHC) and/or non-swashplate input (IBC).

SUMMARY: The approach is to apply nonlinear dynamics, control theory and enhanced computer graphics to provide a general rotor stability and analysis tool. Further research will enhance, simplify and verify the present code, then model the incorporation of material non-linearities at the blade root, exploring the effect on the stability solutions generated. The significance of this new research for the helicopter designer is that the allowance of non-linearities at the blade root may result in an acceptable bounded response in the parameter region where linear theory would predict instability. Evidence of the latter may be found in numerous aircraft lost in the documented cases of ground resonance. Modern soft-inplane rotors, such as that first introduced in the MBB BO-105, have the additional possibility of encountering this lead/lag instability in flight.

WEAPONS PERFORMANCE MODEL FOR RAH-66 *COMANCHE* HELICOPTER

E. Roberts Wood, Professor
Department of Aeronautics and Astronautics
Sponsor: U.S. Army Proving Ground
Yuma, AZ

OBJECTIVE: Using the NASTRAN structural dynamic model of the RAH-66 helicopter, determine biases between sensor LOS and weapon pointing to the target for specified conditions as a function of the flight envelope. Biases are to be applied as fire control corrections. Weapons of interest are 1.75-inch rockets and 20-mm nose mounted gun. Sensors include FCR, TV, and FLIR.

SUMMARY: This analysis is being conducted using the Boeing-Sikorsky finite element model of the Army's RAH-66 Comanche helicopter. The purpose of the work is to quantify errors in gun accuracy due to dynamic response of the airframe structure as it is subjected to gun firing recoil loads. In addition, related movement at the weapon sensor locations will be predicted to provide information on tracking and aiming errors. These results will ultimately be applied as corrections to the system's fire control computer.

RESEARCH IN DAMPER-FREE ROTOR DESIGN BASED ON MAPLE® - GENERATED NONLINEAR SIMULATION

E. Roberts wood, Professor
Robert L. King, Lecturer
Department of Aeronautics and Astronautics
Sponsor: U.S. Army Research Office
Research Triangle Park, NC

OBJECTIVE: Recent work at NPS has resulted in a new and powerful tool for exploring ground and air resonance stability with the goal of eliminating lead/lag dampers on helicopters. The analysis takes advantage of new advances in mathematical analysis such as Waterloo's Maple® for symbolic manipulation, Mathworks' Simulink® for control system simulation and the Moving Block Analysis or Hilbert Transform Method for accurate determination of damping values from simulation time histories. The resulting combined analysis tool is no longer hampered by the usual limitations that would restrict the method to small amplitudes and angles, linear springs, linear dampers and prescribed ordering schemes for variables. Instead, new features have been incorporated that for the first time use the full equations of motion to permit detailed studies of such topics as: (1) Nonlinear flexbeam constraint at blade root – stiffening approach versus stiffening approach; and (2) active feedback control – provided both by swashplate input (HHC) and/or non-swashplate input (IBC).

SUMMARY: The approach is to apply nonlinear dynamics, control theory and enhanced computer graphics to provide a general rotor stability and analysis tool. Further research will enhance, simplify and verify the present code, then model the incorporation of material non-linearities at the blade root, exploring the effect on the stability solutions generated. The significance of this new research for the helicopter designer is that the allowance of non-linearities at the blade root may result in an acceptable bounded response in the parameter region where linear theory would predict instability. Evidence of the latter may be found in numerous aircraft lost in the documented cases of ground resonance. Modern soft-inplane rotors, such as that first introduced in the MBB BO-105, have the additional possibility of encountering this lead/lag instability in flight.

1997

STRUCTURAL DYNAMIC ANALYSIS OF THE RAH-66 "COMANCHE" HELICOPTER

E. Roberts wood, Professor
Donald A. Danielson, Professor
Joshua H. Gordis, Associate Professor
Sponsor: U.S. Army Aviation and Troop Command
Comanche Program Manager's Office

OBJECTIVE: Professor wood, Danielson and Gordis to continue their work in support of the ongoing development of the Army's RAH-66 *Comanche* helicopter. Tasks include vibration and structural dynamics analysis, and include correlation of calculated results with results of ground vibration tests. It is important that NPS maintain a "current" dynamic NASTRAN model of the *Comanche.* A current model permits NPS to respond quickly to requests from the Program Manager's Office to carry out parametric investigations of RAH-66 vibrations in cooperation with the Army and Sikorsky in which NPS results can be quickly compared to those of other principals and applied to the aircraft if desired.

SUMMARY: Described is a summary of engineering work conducted at the Naval Postgraduate School. In 1997 for the Comanche Program Manager's Office, in support of the Army-Boeing-Sikorsky RAH-66 Comanche helicopter program. The prototype helicopter is currently undergoing flight test envelop expansion at Sikorsky Aircraft's flight test facility at West Palm Beach, Florida.

The RAH-66 Comanche's stealth design requires the use of radar absorbing material (RAM) on the outer skin of the aircraft. The reduced stiffness properties of RAM produce insufficient tail torsional stiffness, necessitating the use of non-radar absorbing graphite on the outer skin of the prototype's tail section. An investigation was carried out to determine the structural design modifications required to increase the tailcone's stiffness to allow the use of RAM on the outer skin and still meet all structural requirements. The reference or baseline case is a finite element model that was constructed to represent the prototype aircraft. The goal is to identify stiffness-enhancing structural design changes, with minimum increase in weight, which allow the use of RAM while preserving the stiffness of the prototype aircraft.

Nine structural modifications to the tailcone were developed conceptually, then analyzed. NASTRAN analysis showed that the total effect of these modifications was to increase the torsional stiffness by 12 percent with respect to the baseline aircraft with graphite on the outer mold line. It is shown that the addition of radar absorbing material (RAM) to the outer skin of this modified model costs only a six percent reduction in torsional stiffness from baseline values as compared to a 24 percent reduction in tailcone stiffness for adding the same amount of RAM were these structural modifications not incorporated in the design. In other words, the design modifications developed in this work increased the torsional stiffness by 18 percent with respect to the baseline aircraft with Kevlar on the outer mold line (OML).

These results were presented verbally to the Army and in detail in the thesis work carried out by MAJ Tobin and MAJ Shoop. A summary of the year's work is given in the referenced report by Profs. Wood, Danielson, and Gordis. NPS students participated actively in this program. U.S. Army CPT Pat Mason joined the Sikorsky Dynamics Group under Mr. Bob Blackwell for a 1997 summer internship in which he worked on Comanche vibrations. At the end of the summer, Sikorsky sent him to West Palm Beach to witness the Comanche flight test program and he even had the opportunity to fly as c-pilot in the S-76 helicopter that serves as the chase aircraft for the Comanche. MAJ Vince Tobin, who had interned at Sikorsky during the summer of 1996, completed his thesis on the Comanche and graduated in June with distinction. He was also the recipient of the Moffett Award for 1997 given annually by the Dept. of Aeronautics and Astronautics, as its highest award to the student judged most outstanding by the faculty. MAJ Brian Shoop extended the Work of MAJ Tobin to encompass the tailcone aft of the landing gear bay bulkhead. He completed his thesis and graduated in September. For his excellent work, MAJ Shoop was selected by the AA department to present his thesis to Rear Admiral Marsha Evans, Superintendent of the Naval Postgraduate School.

ADVANCED HELICOPTEPR TECHNOLOGY FOR SPECIAL OPERATIONS

E. Roberts Wood, Professor
Department of Aeronautics and Astronautics
Sponsor: Institute for Joint Warfare Analysis

OBJECTIVE: To provide proof-of-concept helicopter modifications for increase in agility and power available and decrease in vibration and noise for Special Operations rotorcraft using intermitten Higher Harmonic Control (HHC) and conduct a full-scale Higher Harmonic Flight test program.

SUMMARY: From 1976 through 1985, NASA and the Army sponsored extensive research in Higher Harmonic Control (HHC) for helicopters. The resulting OH-6A flight test program (1982-84) showed large payoffs in noise, performance and vibration (Ref. 1). For noise, it has been shown that HHC provides the capability to reduce and tailor the main rotor noise signature. For performance, it has been shown that HHC has the potential to provide a 10% improvement in hover, increasing up to a 20% improvement at 60 knots. For vibration, up to 90% reduction at n/rev can be realized throughout the aircraft. Since the 1985 time frame, there has not been any flight testing, but basic research into HHC has continued at leading aeronautical laboratories in both the US and Europe (NASA, US Army, DFLR, and ONERA).

This program makes the case that for military purposes; HHC flight-testing should be resumed again. The agency to conduct the flight test is SOCOM. Whereas the initial OH-6A program focused on vibrations the proposed future program will incorporate three HHC derivative systems in one aircraft. The three derivative system are: (1) Low noise-stealth; (2) Low vibrations; and (3) Performance. Since components of the prototype system still exist, costs can be kept low by selecting a helicopter that is an OH-6A derivative.

Technical leadership for the program is provided by the team that originally conducted the baseline OH-6A HHC flight test program. Dr. E.R. Wood, now at Naval Postgraduate School, but formerly of McDonnell-Douglas is Principal Investigator and is pursuing ACTD funding for the program through OSD. Dr. C.E. Hammond assists him. He is now at Lockheed-Martin, formerly at ft. Eustis, and previously served as Army Project Monitor on the OH-6A flight test program. Mr. Ron Rambin, formerly of McDonnell Douglas, is now President, Vista Controls. And Mr. Gene Munson, Flight Test Engineer with McDonnell Douglas (now Boeing) is still with the company that carried out the original flight test program. Prof. Wayne Hughes, Jr. (CAPT, USN, ret.) from the NPS Operations Research Department, fills an important roll in that he has a long association with SOCOM and also serves as a member of the Special Operations Curriculum Committee at NPS. LCDR ROB king, Military Instructor in the AA DEPT. and LT Mike Harman, former SH-60B pilot, now M.S. thesis student at NPS, support Dr. Wood in his efforts.

GROUND/AIR RESONANCE SIMULATION OF HELICOPTER ROTOR SYSTEMS BASED ON FULL NON-LINEAR EQUATIONS OF MOTION

E. Roberts Wood, Professor
LCDR Robert L. King, Lecturer
Department of aeronautics and Astronautics
Sponsor: Sikorsky Aircraft and National Rotorcraft Technology Center

OBJECTIVE: Professor and LCDR King continued the original thesis work of LT Christopher S. Robinson in the area of nonlinear helicopter rotor dynamics. As hingeless helicopter main rotors become more commonplace, a need has arisen for a rotor simulation tool that will accurately model nonlinear mechanical properties so that these nonlinearities may be exploited to the helicopter's advantage. Tasks in this research included the formulation of a MAPLE® based symbolic processing program that formulated nonlinear equations of motion given energy expressions for helicopter rotor model degrees of freedom. SIMULINK® based computer simulations were developed from the equations of motion derived by the symbolic process.

SUMMARY: This research has reported on a new method for formulating the full non-linear equations of motion for ground/air resonance stability analysis of helicopter rotor systems. A full set of non-linear equations was developed by Lagrangian approach using the well-known MAPLE® symbolic processing software for expanding the equations. The symbolic software was further utilized to automatically convert the equations of motion into C, Fortran or MATLAB® source code formatted specifically for numerical integration. The compiled C or Fortran code was then access and numerically integrated by the dynamic control simulation software, SIMULINK®. SIMULINK® then applied a Runga-Kutta integration scheme to generate time history plots of blade and fuselage motion. The method was used to explore the effects of damping non-linearities, structural non-linearities, active control, individual blade control (IBC), and damper failure on air/ground resonance. Damping levels were determined from the time history plots by a MATLAB® program, which used the Moving Block Technique for determining critical damping levels from the coupled rotor-fuselage response.

For validation, the analysis was compared with Coleman's classic theory and was also applied to representative cases that included: (1) The classic instability on isotropic supports; (2) The case of one blade damper inoperative; and (3) The case of one blade damaged by a ballistic strike.

1996

STRUCTURAL DYNAMIC ANALYSIS OF THE RAH-66 "COMANCHE" HELICOPTER

E. Roberts Wood, Professor
Department of Aeronautics and Astronautics
Sponsor: U.S. Army Aviation and Troop Command
Commanche Program Manager's Office

OBJECTIVE: Professors Wood, Danielson and Gordis will continue their work in support of the ongoing development of the Army's RAH-66 *Comanche* helicopter. Tasks include vibration and structural dynamics analysis, and include correlation of calculated results with results of ground vibration tests. It is important that NPS maintain a "current" dynamic NASTRAN model of the *Comanche*. A current model permits NPS to respond quickly to requests from the Program Manager's Office to carry out parametric investigations of RAH=66 vibrations in cooperation with the Army and Sikorsky in which NPS results can be quickly compared to those of other principals and applied to the aircraft if desired.

SUMMARY: During the current year we were provided with Sikorsky's *correlated* NASTRAN mode. "Correlated" refers to the fact that changes were made in both the stiffness and mass distribution of the initial or uncorrelated model to bring it into agreement with the actual vibration test measured data During the past year this model was implemented at NPS. Modes shapes and frequencies were obtained up to 50 Hz. Forced response runs of the model were made under representative rotor loads at both 1/rev. and 5/rev. rotor excitation. Plots of the response of the structure were obtained for significant eigenvalue cases and all forced response cases. These results were presented to the Army as part of the NPS presentation given to the St. Louis Chapter.

NPS students also participated in the program. LT Bill Beaver jointed the Silorsky Dynamics Group under Bob Blakwell for a 1996 summer internship in which he worked on Comanche vibrations. LT John Harris conducted suspended vibration test of the OH-6A for his MSAE thesis. Vibration results agreed favorably with MDHC measured values. LT Mike Pampalon implemented a dynamic NASTRAN model of the OH-6A helicopter for his MSME thesis. His calculated frequency results agreed favorably with those obtained by McDonnell Douglas.

A MULTIDISCIPLINARY ASSESSMENT OF THE CHANGING ROLE OF ROTORCRAFT IN JOINT WARFARE

E. Roberts Wood, Professor
Department of Aeronautics and Astronautics
Sponsor: Institute of Joint Warfare Analysis
Naval Postgraduate School

OBJECTIVE: Rotorcaft play a key role in the joint warfare arena with their unique capabilities which include ASW, reconnaissance, Special Operations, and anti-tank warfare. This is a program directed at coordinating the activities of the NPS Vertical Flight Technology Center with the Institute of Joint Warfare Analysis. Under this activity a school-wide interdisciplinary program is developed in which Special Operations rotorcraft technology needs are identified, the needs are broken out and then allocated to relevant NPS activities for implementation.

SUMMARY: A number of technical problem areas were identified that related to use of helicopters in Special Operations. Some solutions were developed as well. Amont those participating were Mr. Rhett Flater, Executive Director of the American Helicopter Society, U.S. Army Capt. Neil Thurgood, a helicopter pilot assigned to the 160^{th} Special Operations Regiment, Prof. Wayne Hughes of NPS, Prof. Joshua Gordis of NPS, and Prof. Don Danielson of NPS.

Central to rotary wing special operations is stealth. As a result helicopters fly at night, under the most adverse weather conditions, and take advantage of all possible means to avoid detection. Flight is generally carried out in nap-of-the-earth conditions, including flight up canyons and in relatively densely wooded areas. Tools of the trade include FLIR, Night Vision Goggles, and more recently aircraft-installed PNVS. The NOTAR® ani-torque system developed by McDonnell Douglas reduces the tail rotor noise signature of the helicopter and is much better suited to flight through wooded. Areas. For these and other reasons, it has been seen wide use on the smaller Special Operations helicopters.

HIGHER HARMONIC CONTROL RESEARCH
FOR IMPROVED ROTOR PERFORMANCE

E. Roberts wood, Professor
Department of Aeronautics and Astronautics
Sponsor: SatCon Technology Corporation
McDonnell Douglas Helicopter Systems

OBJECTIVE: The objective of this research is to provide technical support to SatCon Technology Corporation and McDonnell Douglas Helicopter Systems in support of the SBIR contract with NAWC, Patuxent River, MD. The SBIR contract calls for whirl tests of an OH-6A rotor system and application of Higher Harmonic Control to the rotor. Objective of the tests is to explore the effect of HHC on rotor power required.

SUMMARY: This program was delayed more than a year due to contracting problems between McDonnell Douglas Helicopter Systems and SatCon Technology Corp. The SBDI contract it between SatCon and NAWC. McDonnell Douglas is under subcontract to satCon. The major part of the work is the responsibility of MDHS. SBDIR regulations require that the prime contractor (in this case, SatCon) must perform more than 50% of the work. Delay in the program has been due to SatCon and MDHS restructuring the program so that SatCon meets the 50% or greater requirement that must be met by the prime.

Work is just now getting underway. NAWC is represented by Mr. Dean Carico of the Rotary Wing Directorate at Patuxent River MD. Mr. Gene Munson is the key person at McDonnell Douglas and Prof. Bob Wood is the point-of-contact at the Naval Postgraduate School.

The test program to be carried out is as follows. Hub and blades for the OH-6A rotor system will be provided by NPS. These will be installed on the main rotor whirl tower at McDonnell Douglas's helicopter facility in Mesa, AZ. The rotor system will initially be tested in the hover mode with the main rotor operating at 480 rpm, which is 100% N_R for the OH-6A. The rotor will be operated through a range of collective pitch settings covering the thrust range from 1500 lbs. To 2700 lbs. (Normal gross weight for the OH-6A is 2500 lbs.). Key measurements that will be taken are main rotor torque, main rotor rpm, and main rotor collective pitch setting.

For each data point, the rotor system will be operated in two modes: (1) For Mode 1, HHC will be disengaged; (2) For Mode 2, HHC will be on. With "HHC On" the test operator will have a choice of possible as many as three combinations of collective and cyclic pitch at which to test. The total amplitude of HHC applied will be limited to less than 1^o.

1995

SH-60B HELICOPTER NON-LINEAR SIMULATION IN *FLIGHTLAB*

E.R. Wood, Professor
Department of Aeronautics and Astronautics
Sponsor: Rotary Wing Directorate, Naval Air Warfare Center, Patuxent River, MD

OBJECTIVE/SUMMARY: The objective of this research is to develop a non-linear model of the Navy's SH-60B helicopter in *Flightlab.* A full dynamic model of the helicopter will be provided which will include its control system, coupled dynamics of flexible rotor blades, landing gear dynamics, and the helicopter's basic flight characteristics (stability derivatives, etc.). The end objective of this effort will be to provide a *Flightlab* model of the SH-60B for implementation by NAWC flight test engineers for better planning of flight tests prior to performance of the actual flight test card. Project is continuing.

PREDICTING VIBRATION CHARACTERISTICS OF RAH-66 *COMANCHE* HELICOPTER BY APPLICATION OF DYNAMIC NASTRAN FINITE ELEMENT MODELLING

E.R. Wood, D.A. Danielson, J.H. Gordis
Sponsor: U.S. Army Aviation and Troop Command, St. Louis, MO

OBJECTIVE: The objective of this project is to provide vibration support to the Army's RAH-66 Boeing-Sikorsky flight program in which the primary tool for vibration diagnosis and analysis is a dynamic finite element model of the aircraft of about 60,000 degrees of freedom.

SUMMARY: This program is being accomplished as a joint effort of the Vertical Flight Technology Center. Other faculty participating are Professors Don Danielson of the Mathematics Department and Joshua Gordis of the Mechanical Engineering Department. Boeing and Sikorsky are steamed as Contractors for the Army's RAH-66 *Comanche* program. Currently three finite element models are being maintained for the *Comanche*. One is at the Sikorsky facility in Trumbull, CT, another is at Hq. U.S. Army ATCOM in St. Louis, MO, and a third model is at NPS in Monterey. It is the intent of the Army PMO in St. Louis that these models duplicate as much as possible the true vibrational characteristics of the actual aircraft. In order to accomplish that it is mandatory that the models be extremely detailed. The present RAH-66 finite element model at NPS has more than 60,000 degrees of freedom. The models are to be used to explore solutions to vibrations problems should any occur as the *Comanche* successively expands its flight test envelope in current ongoing tests at Sikorsky's flight test facility. First flight of the *Comanche* was on4 January 1996. Project is continuing.

ROTOR RECOVERY SYSTEM FOR SPACPE PAYLOAD RETRIEVAL

E.R. Wood, Professor
Department of Aeronautics and Astronautics
Sponsor: Naval Research Laboratory, Washington, D.C.

OBJECTIVE/SUMMARY: The objective of this research is to provide technical support to NRL in a feasability program to design, fabricate, develop, and flight test a prototype rotor recovery system for retrieval of space payloads. NPS support will include: dynamic analysis; aerodynamic analysis; stability and control analysis; and simulation modeling of the system; plus serving as consultants. In May NRL terminated total project due to lack of funds.

HIGHER HARMONIC CONTROL RESEARCH FOR IMPROVE ROTOR PERFORMANCE

E.R. Wood, Professor
Sponsor: SatCon Technology corp., Cambridge, MA and McDonnell Douglas Helicopter Systems, Mesa, AZ

OBJECTIVE: The objective of this research is to provide technical support to SatCon Technology Corporation, including the loan of an OH-6A rotor system for conduct of their SBIR contract with NAWC to explore the effects of HHC on helicopter rotor performance.

SUMMARY: This project which has undergone over a year's delay is just now getting underway. This is an SBIR contract between SatCon Technology and NAWC Rotary Wing Directorate at Patuxent River. Primary reason for delay has been due to difficulties in diving work between SatCona nd McDonnell Douglas to assure that 51% of work is done by SatCon, which is required by law. Tasks include whirl tests (at McDonnell Douglas) of a fully instrumented OH-6A rotor system equipped with higher harmonic control and support analysis using *Flightlab.* Initial plans were to conduct the whirl tests at the U.S. Naval Academy whirl tower in Annapolis, Md. The OH-6A rotor system is to be provided by NPS from one of the two aircraft recently given us by the Army. The goal of the research is to investigate the effect of HHC on helicopter rotor performance.

1992

AUTONOMOUS LANDING AND TAKEOFF SYSTEMS (ALTOS)

E.R. Wood, Professor
Department of Aeronautics and Astronautics
Sponsor: UAV Joint Project Office
Naval Air Systems Command
Funding: (same as above)

OBJECTIVE: The objective of this project was to evaluate five candidate technologies for an Autonomous Landing and Takeoff System (ALTOS) to guide Unmanned Aerial vehicles (UAV's) being launched from U.S. Navy surface combatants. The evaluation was divided into four tasks which were: (1) define selection criteria; (2) identify candidate technologies; (3) evaluate the candidate technologies; and (4) recommend technologies to be investigated further.

SUMMARY: The project was carried out by a team comprised of students from the Naval Postgraduate School (as part of course requirements for AE 4306) and a subcontractor, Orion Aviation, Inc. of Palos Verdes, California. Also in order to carry out Task 3 above, the students made use out a flight simulation computer program, FLIGHTLAB II, which was rented from Advanced Rotorcraft Technology, Inc. of Mountain View, California.

For the first task, defining the selection criteria, a total of nineteen different criteria were identified, defined and assigned weighting factors. Representative criteria included **Acquisition Range, Air Vehicle Compatibility, Wave-Off Capability, Ground Station/Ship Compatibility, Guidance Accuracy, Landing Accuracy, and Maintainability, Probability of Intercept, etc.** These selection criteria were also reviewed by the students as part of task three. Their assessments are documented in Appendix D of part three of the project report.

The second task required the students to identify candidate technologies. The technologies identified were millimeter wave radar, micro wave radar, laser, acoustic, and global positioning system (GPS). Each technology was briefly described along with a recommended math model and performance parameters.

For the third task, evaluating the candidate technologies, several of the selection criteria required the use of a mathematical model to simulate and analyze the inflight performance. For this, the students used a simulation program called **FLIGHTLAB II.** Millimeter wave radar and GPS technologies were modeled. The micro wave and laser technologies were not modeled because their physical performance parameters are similar to millimeter wave radar. The acoustic technology was not modeled because the performance parameters were defined as a function of range which **FLIGHTLAB** is unable to simulate.

RESEARCH IN HELICOPTER HIGHER HARMONIC CONTROL

E.R. Wood, Professor
Department of Aeronautics and Astronautics
Sponsor: Research Administration Office
Funding: Naval Postgraduate School

OBJECTIVE: Higher Harmonic Control (HHC) is an active control system concept for helicopters that promises a major breakthrough in such important areas as helicopter vibrations, performance, and acoustics. In addition, under this heading has been included other research related to improving helicopter vibrations, performance, and acoustics at NPS such as: (1) NOTAR research; (2) scale model helicopter flight research; and (3) flight simulation modeling of helicopters.

SUMMARY: A major goal of HHC research being conducted at NPS is to explain on a theoretical basis the open-loop test results obtained from the NASA/Army/Hughes HHC flight test program conducted in the period 1982-85. This research is made possible in part by McDonnell Douglas Helicopter Company, who has made available for analysis the extensive flight test data taken during the earlier research program.

The data is used as follows. The vibration task requires reduction and analysis of the closed and open-loop data obtained from flight testing the HHC-equipped OH-6A helicopter in Yuma, Arizona. The performance task requires correlating performance flight test data against a theoretical model based upon Garrick's unsteady aerodynamic theory. In addition, it is planned to conduct supporting flight tests using a radio-controlled helicopter model that is being modified for HHC. Modifications are being made to a newly acquired helicopter which has a rotor diameter of 11 feet, a gross weight of 180 lbs, and a 60-lb. Payload.

For research on NOTAR a 1/4 scale tailboom which incorporates Coanda circulation control has been designed by the students and is currently being fabricated. The 1/4 scale tailboom is suitable for flight testing on the remotely piloted helicopter. It has also been designed to be compatible with the NASA-Langley 1/4 scale V/STOL wind tunnel.

Studies continue to be conducted on exploring and developing better methods for conducting scaled rotorcraft flight test research. Areas being investigated include remotely-piloted model and fullscale helicopters. The Robinson R-22 is currently under serious study for fullscale testing. Also under consideration for full scale testing is the whirl tower at Annapolis and the QH-50 coaxial remotely controlled helicopter at China Lake.

In the area of flight simulation modeling, two MS students are currently extending NPS's capability using FLIGHTLAB. The FLIGHTLAB simulation computer program can be used for real-time flight simulation studies of rotorcraft. A pilot work station can be coupled to the simulator so that the mathematical model can literally be flown in the computer. FLIGHTLAB is presently being used to model both UAV's and full scale helicopters.