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MATH MODELING AND COMPUTER MECHANIZATION
FOR REAL TIME SIMULATION OF ROTARY-WING
AIRCRAFT

Final Report

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1. Summary

The purpose of this grant has been the study of math modeling and computer mechanization for real-time simulation of rotary-wing aircraft. Such simulation is required for man-in-the-loop studies involving piloted rotary-wing aircraft. The problem is more difficult than real-time simulation of conventional aircraft because of the added complexity of comprehensive math models for rotary-wing aircraft and because of the higher frequency content in such models. One of the principal objectives of the grant was to study the current approaches in use by the helicopter manufacturers for computer simulation and, especially, real time simulation. The results of this study are presented in Section 2 of the report, which includes a summary of visits made to five U.S. helicopter companies. Section 3 of this report describes briefly the work accomplished in developing methods for error analysis in digital simulation of dynamic systems, such as rotary wing aircraft. Section 4 describes the new method for digital simulation of non-linearities with discontinuities, such as exist in typical flight control systems and rotor blade hinges. Finally, Section 5 summarizes the contractor's report which will be issued on rotor dynamics.

2. Visits to Helicopter Manufacturers

In order to review the math-modeling and computer techniques currently in use by industry for helicopter simulation, visits were made to five of the helicopter manufacturers. The results of these visits are summarized below:

2.1 Visit to Bell Helicopter Textron

On March 3-4, 1978, D. T. Greenwood, R. M. Howe and A. F. Messiter visited Bell Helicopter Textron in Ft Worth, Texas. Over the two day period meetings were held with a number of the Bell engineers, starting with an initial discussion with Dr. R. L. Bennett, who was one of the original architects of the BellC-81 general program for helicopter simulation. Bennett described the overall philosophy of modeling the helicopter equations of motion, pointing out that Bell helicopters use gimballed (teetoring) rotors in contrast to the articulated rotors generally used by other manufacturers. He showed some example computer printouts of steady-state rotor calculations from the C-81 program using a finite-element blade modeling approach for aerodynamic calculations. Typically Bell uses 20 segments per blade with 24 azimuthal positions per revolution (15 degree steps) in numerical integration of the blade equations of motion. The C-81 solutions are very much slower than real time, which is satisfactory for performance and load calculations.

Bennett pointed out that Link-Singer, in generating a model for real time helicopter simulation, used a slower-than-real-time blade-element mechanization to compute steady-state rotor forces as a function of advance

ratio, collective input, and inflow ratio. The results are then tabulated as three variable functions which are used with table lookup and linear interpolation in the real-time simulation. This is the so-called "rotor-map" approach.

Bennett pointed out the difficulty in accurately modeling the rotor inflow (induced velocity) effects, especially in transient low speed and hovering conditions and in ground effect. He felt that it would be ten more years before adequate models of these and other aerodynamic effects (e.g., unsteady aerodynamics) will permit good overall helicopter simulation. He noted that good correlation between flight-test and computer simulation lies in the eye of the beholder at the present time.

A meeting was then held with Frank Harris, Dave Komrek and Larry Dooley. Dooley noted that most of the handling-qualities simulation is done using the hybrid computer, but not in real time. The modeling is based on the C-81 approach, but there are real problems obtaining adequate data, e.g. fuselage forces at $\beta = 90^\circ$ (sideways flight). Interference effects, separation, etc., are real problems in modeling. Dooley stated that 90 percent of the flight-test problems can't be predicted by C-81 modeling.

Harris, who had recently left Boeing Vertol to join Bell as Chief of Aerodynamics, emphasized the importance of including unsteady aerodynamics effects in rotor modeling at high speed in order to obtain reasonable correlation with flight test. He felt that quasi-static torsional elasticity was more important than elastic bending in performance and handling simulation.

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Next Narendra Batra discussed the man-in-the-loop simulation and computer modeling approach for the XV-15 Tilt Rotor Aircraft. The rotors were simulated using a rotor disc model which was developed ahead of time with off-line integration along the blade and around the disc for the flight conditions of interest (see NASA CR 114614, April 1973). A 55 millisecond frame rate was used on the Sigma 8 and Sigma 9 mechanization at NASA Ames, and the simulation showed reasonable agreement with flight test. A similar rotor-disc modeling approach was used to simulate the Bell Model 214 helicopter and good correlation was obtained with wind tunnel and flight test. Batra feels that the rotor-disc model is in general satisfactory for handling research.

The effect of elastic modes was discussed by Dr. Jing Yen, who described the DYN-5 program used to calculate rotor dynamic stability and loads. According to Yen the inertial coupling of the rotor to the pylon is important, as is the dynamic coupling between modes in general. Clearly such effects are not important in performance calculations. There seemed to be differences of opinion regarding their importance in aircraft handling characteristics.

Finally, a briefing on the Bell modeling approach in hybrid simulation was presented by Dick Dodds and Matt Landry, along with a tour of the hybrid facility. Landry described the three different modeling approaches used in hybrid simulation, as summarized in Figure 3.1. The "Hybrid C-81" uses a high-speed repetitive analog integration of blade forces from root to tip to

HYBRID GENERAL HELICOPTER SIMULATIONS

PROGRAM	MAIN ROTOR			TAIL ROTOR	FUSELAGE			TIME SCALE	% USED	
	NO. BLADES	MODES	APPROACH		RIGID BODY MODES	FLEX MODES	AERO-DYN.		ANA.	DIG.
HYBRID C-81	2 OR 4	FLAPPING CONING	PER BLADE CONTIN. BLADE (ANALOG)	POINT THRUST	ALL	PYLON PITCH & ROLL	ALL	1	95	80
GENERAL HELICOPTER	N	NONE	HIGH INFLOW POWER THEORY (DIGITAL)	SAME AS M/R	ALL	NONE	ALL	1	40	40
3/4 RADIUS ROTOR	2	INPLANE FLAPPING CONING RPM	3/4 RADIUS BLADE (ANALOG)	NONE	5(NO YAW)	PYLON PITCH ROLL VERT. FUSEL. SELECT-ABLE	SIM-PLI-FIED	10	80	40

Figure 2.1 Bell Textron Hybrid Programs

compute iteratively the overall blade forces and moments as needed to solve blade equations of motion. This appears to be similar to the approach utilized currently by Jack Hoffman at Paragon Pacific and used a number of years ago by Boeing Vertol. It is capable of helicopter simulation in real time and therefore can be used for man-in-the-loop simulation.

The Bell "General Helicopter" hybrid simulation uses a rotor disc modeling approach similar to the one described by Batra for the XV-15 and Model 214 Simulations. The analog computer is used to simulate the autopilot and controls, and to integrate body axis forces and moments into velocities, angular velocities, and attitude angles. It is also used as an interface to the operator and the instrumented mockup. The remainder of the simulation is digital. The "General Helicopter" hybrid simulation runs in real time and has been used principally for simulation of the engine, governor, fuel-control and drive system, although it can be used for man-in-the-loop studies as well as flight-control system integration studies.

The "3/4 Radius Rotor" hybrid program uses a simplified aeroelastic rotor with all aerodynamic and mass properties concentrated at the 3/4 radius point. Pylon and fuselage flexible modes are also included. The program runs at one-tenth real time and has been used to study clearance between the main rotor and tail boom during hard landings, flapping response during sloped landings, control phasing effects, and blade unbalance effects.

It should be noted that Bell arranged for the University of Michigan personnel (Greenwood, Howe, and Messiter) to have a demonstration ride in a Jet Ranger helicopter piloted by Bob Walker. Stability and control characteristics were demonstrated in hover and high-speed flight, and a several auto-rotation landings (more correctly, near landings) were also demonstrated.

To summarize, Bell Helicopter Textron relies heavily on the C-81 and the blade-element approach for calculation of helicopter performance, rotor-loads, etc, all done at considerably slower than real-time speeds. The hybrid computer, using either a rotor-disc model or iterative analog integration along rotor blades, is used for real time simulation. In general Bell feels that the rotor-disc approach, mechanized either with hybrid or all digital computation, is effective for man-in-the-loop simulation.

2.2 Visit to Sikorsky Aircraft

On May 24, 1979, R. M. Howe and A. F. Messiter visited the Sikorsky Aircraft Division of United Technologies Corporation, Stratford, Connecticut. Discussions were held with Dean Cooper, head of handling qualities at Sikorsky, and Jim Howlett, who was responsible for the equations furnished by Sikorsky to NASA for the RSRA simulation. Sikorsky uses a common program called GENHEL for both real-time and non real-time helicopter simulation. The program uses a blade-element approach in the rotor math model and formed the basis for the RSRA equations. For non real-time computation the azimuthal steps in rotor angle are between 3 and 20 degrees. For real-time simulation the steps for integration are taken as large as 45 degrees.

Numerical instabilities which would result from taking such large steps with conventional integration algorithms are avoided by using a "tuned" integration scheme for solving the blade flapping and lagging equations. Over each integration interval the blade motion is assumed to be sinusoidal at the rotor frequency. The blade angle displacement and velocity at the $n + 1$ frame is then computed by sinusoidal extrapolation from the displacement and velocity at the nth frame, using the angular acceleration at the nth frame as computed from the blade equations of motion. The Sikorsky people agree that taking azimuthal steps up to 45 degrees can lead to substantial inaccuracies under certain flight conditions, but they feel that this disadvantage is outweighed by the advantage of a common modeling approach for both real and non-real time simulation. Because of their extensive experience with GENHEL they know where it gives less-accurate results for large azimuthal steps.

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Howlett pointed out that the important frequencies in dynamic simulation for load calculations tend to be considerably higher than the frequencies which are important in handling qualities and control-system design, but that these two frequency regimes are moving closer together in new helicopter designs. He feels that aeroelastic effects may in fact be important in handling simulation.

Additional discussions were held with Ray Thornberg, who is in charge of hybrid simulation at Sikorsky. He discussed correlation of simulator results with flight test and showed some typical comparison data. In general they obtain fairly good agreement in lateral dynamics, but have problems in obtaining good correlation in longitudinal-lateral coupling due to rotor effects. In comparisons between computed results and flight test they have obtained better results by using actual flight-test recordings of flight-control time histories as inputs to the simulation.

In summary, Sikorsky uses a single program, GENHEL, which employs a blade element rotor model for all helicopter simulation. Real-time computer operation is obtained simply by taking larger azimuthal steps.

2.3 Visit to Boeing Vertol

On May 24, 1978, D. T. Greenwood and R. M. Howe visited Boeing Vertol Helicopter in Philadelphia, where discussions were held with Bruce Blake and T. S. Garnett. Blake and Garnett summarized the various Vertol programs used for helicpter simulation. Vertol utilized hybrid simulation a number of years earlier, but gave it up because of setup and reliability problems. In real-time simulation for study of handling qualities they never consider frequencies above 1 per rev (15 to 25 radians per second). Vertol has a non real-time digital program, A9T, which is used for trim analysis and outputs stability derivatives. It employs a finite element rotor model with 10 radial and 18 azimuthal steps. A much more comprehensive dynamic program, B-29, includes flapping and lagging degrees of freedom for the rotors. It too is non real-time and much more expensive to run, so it is only used when deemed necessary, such as in accident investigations.

Another Vertol dynamic model uses linearized equations with stability derivatives determined from A9T. It uses 6 fuselage degrees of freedom and 6 quasi-normal coordinates for the rotors, and is quite fast running. It includes a reasonably good control system representation but very crude fuselage aerodynamics and is used only for hover in control systems and handling studies. It can also be used for ground resonance studies.

For real time man-in-the-loop simulation Vertol has used both the rotor map approach based on off-line pre-computation of rotor-map functions and the simple Wheatly-Bailey classical rotor model. They feel that the

latter works just as well for their typical real-time studies, which utilize a 30 to 50 millisecond integration frame time.

Because the Vertol helicopters utilize two tandem rotors, the rotor interference effects are very important, especially the effect of the front-rotor inflow on the rear rotor. Extensive powered wind-tunnel tests are utilized to obtain this data, which is used to modify the Wheatley-Bailey approach and is taken into account in the rotor-map mechanization. Also, Vertol uses dynamic models based on rotor-maps to compute trim conditions by implementing feedback gains analogous to a flight control system which cause the dynamic solution to converge to the steady-state trim solution. The vortex ring case (rotor descending in its own wake) presents both a simulation and flight problem.

In summary, Vertol favors the use of simple Wheatley-Bailey type rotor models for real-time man-in-the-loop studies, although they also use the rotor-map approach based on a blade-element quasi-static calculation.

2.4 Visit to Lockheed

On July 5, 1973, R. M. Howe visited Al Pothast at Lockheed Burbank, California, to discuss the Lockheed approach to helicopter simulation. Use of simulation for the Cheyanne program at Lockheed was for preflight design calculations, handling studies, etc. They were not concerned with post flight simulation for training. They considered using a blade-element approach to modeling, as well as the simple Wheatley-Bailey modeling approach. They found that the latter was inadequate for the Cheyanne. In 1971 they developed the REXOR program for the Army. This program was based on the blade-element approach and included unsteady aerodynamics, though Pothast stated that the unsteady aerodynamics were unimportant for handling qualities. They used 9 to 11 elements per blade in REXOR, with 6 to 12 degree azimuthal steps in the numerical integration. The program ran much slower than real time but was used as a basis for stability derivative calculations at any flight condition. In this way they could come up with a linearized model of the helicopter where the coefficients in the model are varied with changes in flight condition. This produced a satisfactory real-time dynamic model, but was obviously not a valid approach near the edges of the flight envelope where blade stall is occurring.

Pothast indicated that Lockheed has always had problems with a good representation of the rotor inflow. He indicated that some recent work sponsored by Robert Anderson at NSRDC (Naval Ship Research and Development Command) was very promising and was showing good agreement with 1/4 scale wind tunnel

tests. The current Lockheed concern was directed toward simulation methods for their X-wing aircraft, which has very stiff, servo-controlled blades which are more like propeller blades than conventional rotor blades. The X-wing aircraft also has controlled blowing along the rotor blades, and simulation of the dynamic lags associated with this is very important.

In summary, the Lockheed approach has been to use linearized models for real-time helicopter flight simulation which are based on pre-computation of stability derivatives from the REXOR blade element model at various flight conditions.

2.5 Visit to Hughes

On July 24, 1978, R. M. Howe visited Hughes Helicopters in Culver City for discussions with Robert Wood, Mike Harris, and Ray Pronty. Most of the Hughes engineers had previously worked at Lockheed so that much of the Lockheed philosophy prevailed. For real-time simulation and handling studies they use a rotor map approach, where steady-state rotor forces are precomputed as a function of collective pitch, advance ratio, and inflow ratio. The model allows variation in rotor speed and has been used successfully for autorotation studies, where computed results have shown fairly close agreement with flight test. Integration step size of 50 milliseconds is used for these simulations.

3. Dynamic Error Analysis of Digital Simulations

Math models of rotary-wing aircraft which include a direct representation of rotor dynamics will contain frequencies which equal or exceed the rotor frequency, which is typically 4 to 6 hertz. Digital computers used to mechanize such models will need to operate at integration frame rates which are many times the rotor frequency in order to achieve reasonable dynamic accuracy. The corresponding computational speed requirements often exceed the capabilities of existing digital computers, and therefore it becomes important to establish accurate lower limits on the required integration frame rates for prescribed dynamic accuracy.

The differential equations used in math modeling of rotary-wing aircraft are nonlinear, and there are no useful techniques for analyzing the effect of integration truncation errors in the numerical solution of such equations. Fortunately, the equations can usually be approximated by time-invariant linearized differential equations over limited regions of the state variables and/or over limited segments of time. Under these conditions the dynamic errors in digital solution of the equations can be obtained directly using the method of z-transforms. Furthermore, the analysis of an nth order system can be simplified by representing it as a collection of first and second order linear systems in parallel. These can be treated quite generally and the results extended to the overall nth order system by superposition.

Two measures of dynamic error which result from a specific integration algorithm and frame time are considered, (1) the error in characteristic root, and (2) the error in sinusoidal transfer function. These error measures can

be used either to determine the maximum allowable integration frame time for a required dynamic accuracy, or to determine the dynamic accuracy for a given frame time. Results have been obtained for a number of popular integration algorithms for real-time flight simulation, including Euler, second and fourth order Runge Kutta, and second, third, and fourth order Adams Bashforth. Asymptotic formulas for characteristic root and transfer function errors have been obtained as well as graphical plots of root errors versus frame time. These results allow straightforward determination of optimal integration algorithms and frame times for given performance criteria. The results are given in a paper presented at the 1979 Joint Automatic Control Conference. The specific reference is given in the List of References at the end of this report. Although there have been previous publications on dynamic error analysis in digital simulation based on the same z-transform techniques, it is believed that the results reported here are more comprehensive and generally useful.

4. Nonlinearities with Discontinuities

One of the sizeable sources of error in real-time digital simulation results from nonlinearities with discontinuities in slope or displacement. Simple limiting functions, on-off control, Coulomb (dry) function, controller dead-zone, etc, all occur in flight control systems and are also involved in the simulation of rotor-blade hinge dynamics and blade airfoil stall characteristics. When a fixed numerical integration step size is used, an almost certain requirement in real-time digital simulation, the discontinuities occur at times which are completely assynchronous with respect to the fixed integration time intervals. In the conventional mechanization the nonlinear function is simply evaluated at the integration frame time without any consideration of when the discontinuity occurred. This causes substantially increased dynamic errors.

Under the grant a technique has been developed which predicts to second-order accuracy the effect which a discontinuous nonlinearity will have on a state variable. The method is described in detail in a paper presented at the 1978 Summer Computer Simulation Conference (see the List of References at the end of this report). Simply stated, the method computes by extrapolation the time at which a function discontinuity will be crossed. This in turn is used to compute the average value of the function over the next integration interval, which then is multiplied by the interval itself to compute the change in state variable.

Simple analytic formulas which can easily be mechanized have been developed for both unit step and unit ramp functions. By superposition the

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formulas can then be used to represent any nonlinear function with discontinuities in displacement and slope. Computer simulation of second-order dynamic systems with effort-limited linear control, coulomb friction, and bang-bang (relay) control have been run using second and third order Adams-Bashforth and second and fourth order Runge-Kutta integration algorithms. The new method shows dramatic accuracy improvement compared with the standard function evaluation method. Furthermore, in every case the new method exhibits errors which vary with interval size raised to one higher power than the standard method. For a given dynamic error the new technique will allow a considerably increased numerical integration step size, which in turn will decrease real-time computer speed requirements.

5. Helicopter Rotor Dynamics

The equations of motion for rigid rotor blades with flapping and lagging degrees of freedom were developed in NASA CR-2877 by R. M. Howe and L. E. Fogarty of the University of Michigan as part of the predecessor grant. To generalize the rotor math model to include elastic degrees of freedom D. T. Greenwood, as part of this grant, has developed a more comprehensive set of equations which are described in a NASA contractor's report currently in final typing. In this report the differential equations of motion of the rotor are developed with particular emphasis on the methods used in obtaining the equations. These methods are general enough to allow rather obvious extensions of the theory to rotor representations which have additional degrees of freedom and which may not be explicitly considered in the report.

The overall approach involves the use of generalized coordinates and Lagrange's equations of motion. For the most part, these generalized coordinates are associated with deflection forms which are considered to be arbitrary. In other words, either assumed modes or calculated vibrational mode shapes may be used with this method. Particular attention is given to the influence of centrifugal force effects upon the flapping motion and also on the torsional motion through the "tennis racquet" effect. Coriolis acceleration effects upon the rotor shaft moments are given careful consideration.

Greenwood's equations have subsequently been applied to a Bell teetor-type rotor with two bending and two torsional elastic modes in addition to a rigid teetor mode.

REFERENCE

The following publications report directly on research accomplished under this grant.

1. Howe, R. M., "A New Method of Handling Discontinuous Nonlinear Functions in Digital Simulation of Dynamic Systems," Proc. 1978 Summer Computer Simulation Conference, San Diego, California, July 1978, pp 72-79.

2. Howe, R. M., "Special Considerations in Digital Simulation of Control Systems, Including Nonlinearities," Proceedings 1979 Joint Automatic Control Conference, Denver, Colorado, June 17-21, 1979, pp 330-335.

3. Greenwood, D. T., "Helicopter Rotor Dynamics" NASA CR to be released.