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Flight Dynamics Analysis and Simulation of Heavy Lift Airships

Volume I: Executive Summary

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FOREWORD

This document is the first in a five volume report which describes a comprehensive digital computer simulation of the dynamics of heavy lift airships and generically similar vehicles.

The work was performed by Systems Technology, Inc., Hawthorne, California for the Aeronautical Systems Branch in the Helicopter and Powered Lift Division of the National Aeronautics and Space Administration, Ames Research Center, Moffett Field, California. The simulation development was carried on between September 1979 and January 1982 and is currently installed on the Ames Research Center CDC 7600 computer. The contract technical monitors for NASA were Dr. Mark Ardema, Mr. Alan Faye, and Mr. Peter Talbot. STI's Program Manager was Mr. Irving Ashkenas.

The authors wish to acknowledge the technical contributions of Mr. Robert Heffley, Mr. Thomas Myers, and Mr. Samuel Craig and the further contributions of Mr. Allyn Hall, Ms. Natalie Hokama and Ms. Leslie Hokama in simulation software development. Special thanks are due to Ms. Kay Wade, Ms. Linda Huffman, Mr. Charles Reaber, and STI's production department for the preparation of the five volumes of this report.

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INTRODUCTION

BACKGROUND AND OBJECTIVES

The heavy lift airship (HLA) is a vehicle (Fig. 1) in which the technologies of rotorcraft and lighter than air (LTA) are combined to provide a means of lifting, transporting, and placing extremely massive payloads — up to perhaps 100 tons. The lifting power of the buoyant gas offsets the weight of the structure and propulsion systems; the lifting power of the rotors supports the payload and provides vehicle control. The concept has received considerable attention in recent years with technology reviews and economic feasibility studies, Refs. 1-8.

The operation of these vehicles in their intended roles, and the associated engineering problems, have been studied to a much more limited extent, e.g., Refs. 9 and 10. Like the classic airships, the response to gusty environments is an important issue which has received limited analytical treatment (Refs. 11-13). Unlike its predecessors, the HLA will typically be used in missions requiring precise control through flight regimes encompassing large and rapid changes of speed, incidence, and load. There is a need, therefore, for an in-depth understanding of the flight mechanics, handling qualities and flight control requirements of the HLA.

The primary objective of the technical effort described in this report is the development of a generic, yet comprehensive mathematical model and computer simulation of the HLA flight dynamics over its entire flight envelope. Implicit in this simulation development are the data reviews and analyses which support the equations of motion and the calculation of forces and moments acting on the vehicle. The simulation, HYBRDS, is addressed to the broad requirement noted above and is intended for use as a synthesis and analysis tool for the evaluation of competing HLA design concepts.

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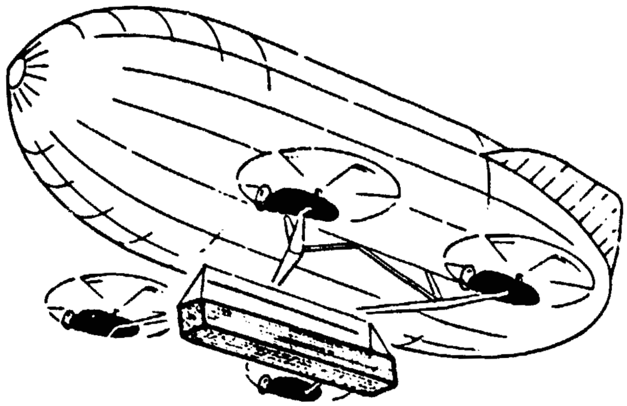

Figure 1. Typical Heavy Lift Airship With Slung Payload

SUMMARY SIMULATION DESCRIPTION

The HYBRDS (Hybrid Buoyant Rotorcraft Dynamic Simulation) is a set of computer programs that perform non-real-time, nonlinear simulations of the flight dynamics of HLA-like vehicles — hybrid multi-rotor aircraft. The three main programs available with HYBRDS are:

- HLASIM — models the powered vehicle in flight.
- HLAPAY — models the powered vehicle in flight carrying a slung payload.
- HLAMOR — models the unpowered vehicle moored to a rigid support at a single point.

Vehicle configurations that can be simulated include free balloons, classical airships, hybrid airships (HLAs), and non-buoyant multi-rotor helicopters. The modeling includes the so-called apparent mass effects of the buoyant hull, a number of interference effects arising out of the proximity of hull, rotors, tail surfaces, and ground plane, and quasi-static rotor coning and flapping. The formulation of the equations of motion allows calculation of loads between the main interfacing parts of the vehicle structure.

The basic configuration is the buoyant quad-rotor concept — four lift-propulsion units (LPUs) disposed about a central buoyant hull which has controllable tail surfaces. Each LPU has a lifting rotor and a thrusting rotor (propeller), both with collective controls; the rotor has lateral and longitudinal cyclic controls as well. Other configurations are achieved by selectively "turning off" various portions of the model by altering the input data.

The HYBRDS programs each perform three major functions:

1) Calculation of operating point or trim condition, e.g., for performance estimates.

2) Calculation of stability and response derivatives about selected operating points for use in linearized vehicle dynamic response models.

3) Forward integration in time of the vehicle state variables in response to control commands and aerodynamic disturbances, starting at selected trim conditions.

In addition to the independent state variables, the output data include a large number of dependent variables such as aerodynamic (and other) load contributions, rotor thrust levels, and control surface deflections.

The simulation was developed on a Cyber 176 using the interactive NOS operating system. It was written in ANSI FORTRAN IV and contains some 65,500 statements in 343 subroutines, most of which are shared among the three main programs. The simulation requires the IMSL library for numerical processing support. It is operational on CDC 7600 computer under the SCOPE 2.1 operating system at the Ames Research Center of the NASA. The source code is heavily commented to facilitate additions and modifications by the using organization to suit configuration-peculiar requirements.

DOCUMENTATION

The simulation program documentation is contained in the final report, "Flight Dynamics Analysis and Simulation of Heavy Lift

Airships." The report is in five volumes, of which this volume is the first. The volumes carry subtitles indicating the intended readership:

Volume I	Executive Summary
Volume II	Technical Manual
Volume III	User's Manual
Volume IV	User's Manual, Appendices
Volume V	Programmer's Manual

The following paragraphs briefly describe the contents of each.

This volume, the Executive Summary, provides an introduction to the remaining volumes. It contains a description of the simulation in sufficient detail to allow the reader to determine the potential applicability of HYBRDS to his own use. It describes key features of the technical development and outlines potential additions and modifications to the program foreseen at the time of writing.

The Technical Manual describes the mathematical models contained in the simulation in considerable detail with supporting evidence for the model forms chosen. It describes the trimming and linearization algorithms used in the simulation. Appendices to the manual outline the coefficient estimation procedure for the input data and provide example simulation results.

The User's Manual provides the basic information necessary to run the programs. This includes descriptions of the various data files necessary for the program, the various outputs from the program and the options available to the user when executing the program. Additional data file information is contained in the three appendices to the manual. These appendices list all input variables and their permissible values, an example listing of these variables, and all output variables available to the user.

The Programmer's Manual is intended for the maintenance programmer who will support the program. It contains explanations of the logic embodied in the various program modules, a dictionary of program variables, a subroutine listing, subroutine/common-block/cross-reference listing, and a calling/called subroutine cross-reference listing. The manual does not repeat data available in the User's Manual.

Wind tunnel tests of the quad-rotor design concept were originally planned to coincide with the time span of the simulation development. The purpose was to provide data currently lacking in the literature, particularly for hull-rotor interference effects. This effort was terminated before the wind tunnel model was built. The design considerations and model plans are contained in two technical memoranda, Refs. 14 and 15.

In addition, the formulation of the mathematical models, the software testing, and simulation exercise resulted in a number of papers, Refs. 16-19. The subject of most of these papers was a hypothetical four rotor, four thrusting propeller HLA configuration having a hull of low fineness ratio and small tail surface area. This particular configuration was defined early in the program to serve as a test case throughout simulation development.

SECTION 2

MATHEMATICAL MODEL DESCRIPTION

OVERVIEW

The heavy lift airship can be described as resembling a classic airship design where the propulsion scheme has been extended and elaborated. The several engines of the airship are replaced with considerably larger lift-propulsion units (LPUs) mounted on relatively long outrigger-like arms to provide clearance for the main rotor of each LPU. The LPUs also carry a propeller to provide propulsive force and/or additional control force, particularly when the main rotor is very lightly loaded. The payload, if any, is suspended below the HLA with a multicable sling system.

The most complex parts of the simulation are associated with the aerodynamic modeling of the vehicle. In calculating the aerodynamic loads acting on various parts of the vehicle structure, the emphasis is placed on determining the dominant effects using aerodynamic models based on uniformly valid first approximations. The details of the models are described fully in Volume II of this report; the intent here is to provide a broad catalog and explanation of the major features.

The simulation also includes models of the suspension cables, the landing gear, and the flight control system. In all cases these are quite simple in keeping with the overall philosophy of expressing the dominant properties of the generic HLA concept. The source code for the flight control system is confined to a few subroutines to make changing the system relatively easy; the flight control system is not "universal" because of the broad range of possible HLA control configurations.

MULTIBODY EQUATIONS OF MOTION

In the simulation equations of motion, the HLA is treated as an assembly of interconnected rigid bodies — the central hull and support structure assembly, and the several attached LPUs. The mathematical representation of similar structures has received considerable attention in recent years, particularly in connection with spacecraft dynamics, e.g., Refs. 20-22. The objective in most of these investigations is to arrive at a computationally economical set of equations for a specific configuration within a general class of related arrangements.

In the case of the heavy lift airship, the principal requirements are to provide for variability in the configuration and to give some measure of the loads between components. For these reasons each body is treated as a separate, albeit constrained, entity with its own axis system and equations of motion. There are additional constraint equations which express the relationships between the accelerations of pairs of bodies resulting from their interconnections.

To the user, this treatment of the rigid body modeling of the hull and attached LPUs is reflected in the input data requirements which call for the geometrical and inertial data of each body — the hull and each of the attached LPUs — rather than data for the structure as a whole. This facilitates changes in, for example, the location and orientation of the LPUs in predesign studies. One need n recompute the inertial properties for the structure as a whole. Th_s approach requires r defined net center of gravity for the entire HLA; the constraint forces and moments between the hull and each of the LPUs cause the structure to move as a rigid body.

When solved simultaneously in the program, the equations of motion and the equations of constraint yield solutions for the vehicle accelerations in the independent degrees of freedom as well as solutions for the forces and moments acting between pairs of bodies which provide the constraint. When the interfaces between the LPU and hull-plus-support (outrigger) structure are appropriately chosen, the result is a readout of these internal loads as well as motions of the vehicle.

AERODYNAMIC CALCULATIONS

The aerodynamic modeling of the HLA is similarly organized. Forces and moments are calculated for the hull (tail off), tail assembly, each

LPU, and the payload, if present. Figure 2 shows the computational flow for these calculations, the various steps of which are as follows:

1) The vehicle states are taken from the current time step; these include translational and rotary motions of each element, local airmass motions at each element (steady and turbulent wind inputs), and several control inputs.

2,3) These are resolved into relative air-to-element velocity components at each rotor and propeller hub, each LPU aerodynamic center, the hull center of volume, the tail reference center (the aerodynamic center of effective tail-plus-fuselage ensemble), and the slung payload, if present.

4) The relative velocities are adjusted by various factors or increments to account for interference due to:

   a) hull on rotors and propellers

   b) rotors and propellers on hull and tail

   c) rotors on propellers and LPU nacelles

   d) ground plane proximity to hull, tail, rotors and propellers

   Thus the net relative or apparent velocities are the vector sum:

   $$\underline{v}^{relative} = \underline{v}^{inertial} - \underline{v}^{interference} - \underline{v}^{local\ airmass}$$

5) The aerodynamic forces and moments are computed as functions of the relative velocity at each element. Interference effects that arise from changes in the nature of the local flow (e.g., rotor-induced turbulence in hull local flow) are accounted for in the equations of the respective element. Buoyant forces are computed at the hull center of volume from the normal atmospheric pressure gradient, and the horizontal pressure gradients arising from changing wind velocities or convergent wind fields.

6) Net hull forces at the center of volume (c.v.) are summed and transferred to the hull center of gravity (c.g.) along with the tail-on-hull forces. At this stage the major pitch and yaw stability effects of the hull and fin assembly are apparent.

7) The rotor and propeller forces and moments are transferred to the LPU c.g. for use in the multibody equations of motion.

8) The various loads and control deflections are inputs to other parts of the program.

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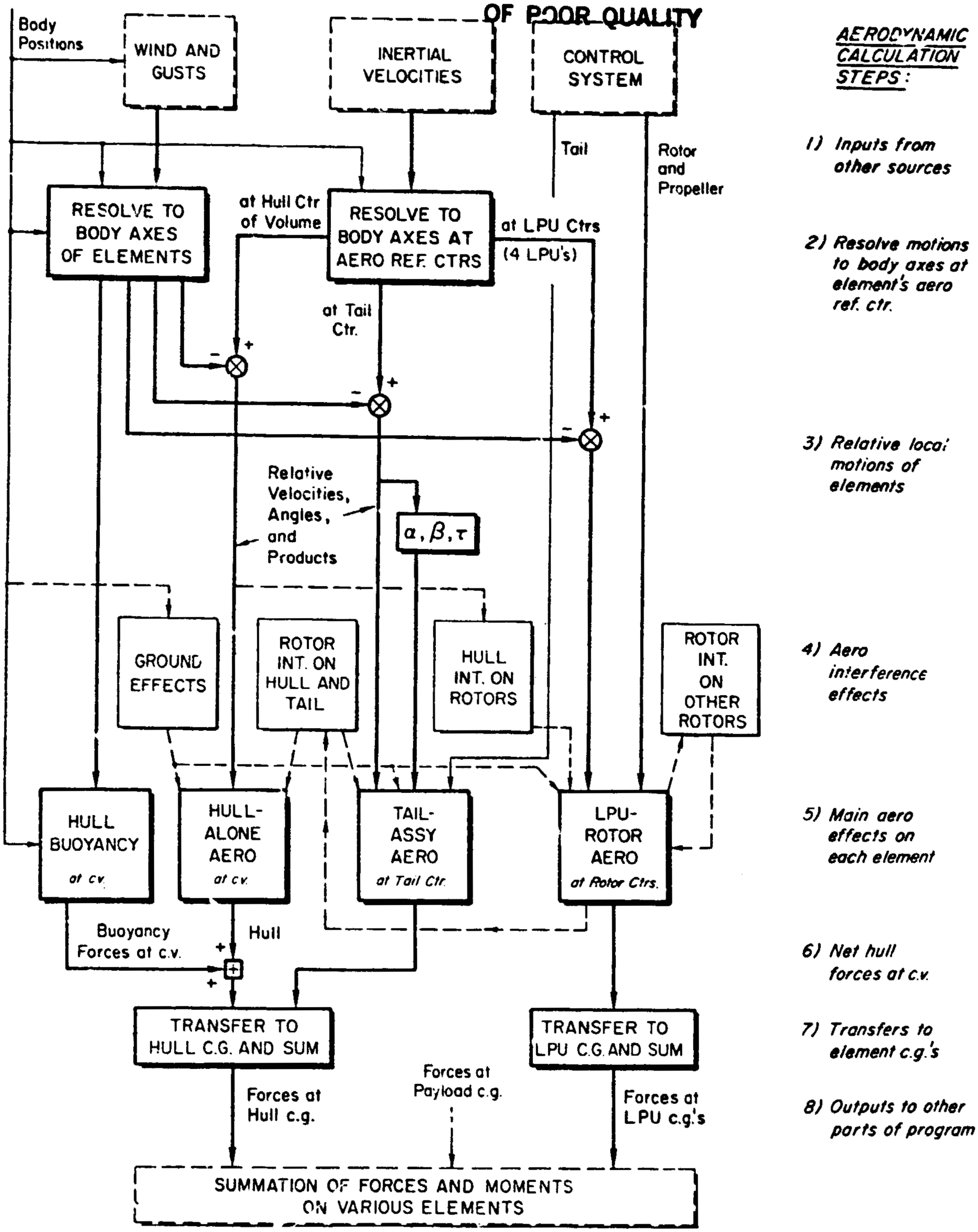

Figure 2. Computational Flow of Aerodynamic Subroutines

HULL AND TAIL AERODYNAMICS

Quasi-steady and unsteady aerodynamic loads are accounted for in the simulation for flight conditions encompassing large ranges in speed, incidence angle, and turbulence level. The modeling uses simple functional dependencies on body axis linear and angular velocities and accelerations relative to the airmass. The dependencies were selected to allow approximation of typical empirical data rather than being estimated from vehicle geometry. In the case of the tail surfaces, pre-stall, transition and post-stall flow regimes are included.

The quasi-steady aerodynamic models were validated against extensive wind tunnel data for certain of the classic airships, Refs. 23-27. Figure 3 shows an example of this comparison with data for the airship Akron for incidence angles out to twenty degrees. The closest match is for the drag data which is within 5 percent. Lift is matched within 10 percent for the hull-plus-tail configuration. The pitching moment data require adjustments (λ and η) to capture the low incidence instability and high incidence stability so typical of airships. Additional correlations with high incidence and oscillatory (damping) data indicate that the hull and tail aerodynamic forces are generally valid to within about 25 percent over the entire HLA operational envelope. Since nearly all of the aerodynamic problems requiring control are simulated in the model, further complexity was deemed unwarranted.

The unsteady aerodynamic forces are those arising out of vehicle acceleration with respect to the airmass and accelerated airflow due to gusts and turbulence. The effects modeled in the simulation are the classic accelerated motion forces (Refs. 28 and 29) which were supplied in the analysis of the classic airships (Refs. 30 and 31). Accelerated motion of the airmass also leads to horizontal buoyancy forces because of the pressure gradient associated with the acceleration. These, too, have been accounted for. However, the unsteady lift arising out of changes in circulation flow represents a considerably smaller contribution and has been neglected.

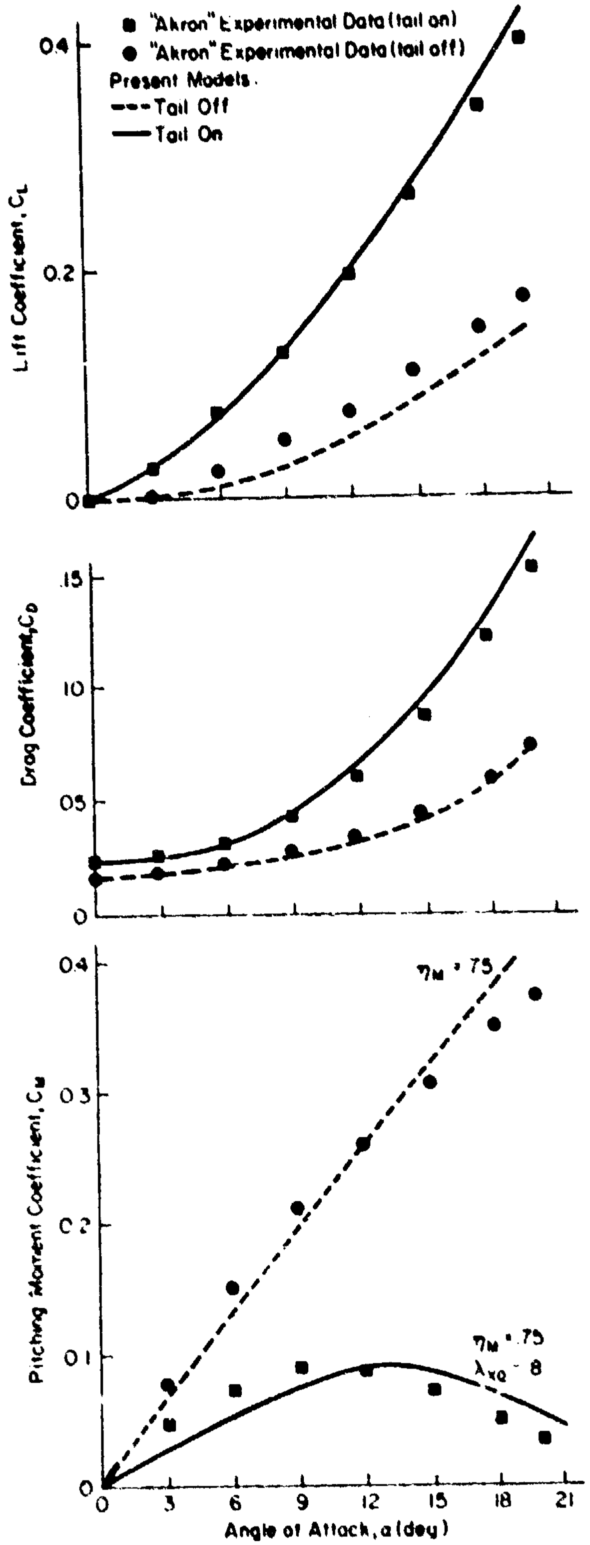

Figure 3. Simulation Quasi-Steady Aerodynamics Compared with "Akron" Wind Tunnel Data

The unsteady aerodynamic forces can be a dominant contribution to the overall aerodynamic loads on the airship hull. Figure 4 shows an example simulation time history where the gust is applied only at the tail assembly. The HLA is not actively controlled. The comparison between the quasi-steady force contribution (Curve C2) and the total force (Curve C1) shows the dominance of the unsteady contribution (Curve C3). Note that the gust cannot include step discontinuities in velocity as this implies infinite acceleration.

LIFT-PROPULSION UNIT AERODYNAMICS

The individual lift-propulsion units may be likened to a helicopter where the tail rotor has been replaced by a thrusting propeller oriented in some arbitrary direction. The aerodynamic forces of importance are those originating in the main rotor and propeller and, to a much lesser extent, the LPU nacelle (helicopter fuselage). The control inputs are the rotor collective, lateral cyclic, longitudinal cyclic and rotational rate; and the propeller blade pitch (collective) and rotational rate.

The main rotor aerodynamics follow the modeling of Bram 11 in Ref. 32. Quasi-steady coning and flapping of the rotor blades is assumed with the flapping hinge located at the rotor hub. The inflow velocity is uniform across the rotor disk and is assumed quasi-steady. An iterative procedure is used to solve for the inflow velocity and thrust coefficient; torque and flapping coefficients follow directly.

An unusual added feature is the replacement of the Bramwell model by flat plate drag when the inflow approaches zero. This approximates the vortex ring state which is frequently encountered on an HLA, particularly when the vehicle is not carrying a payload. The modeling is not accurate in this region and the program flags this with a message telling the user when this flow condition occurs.

The propeller aerodynamics follow those of the rotor, deleting the cyclic controls. The nacelle is modeled as a bluff body having drag along each reference axis dependent upon the relative velocity along

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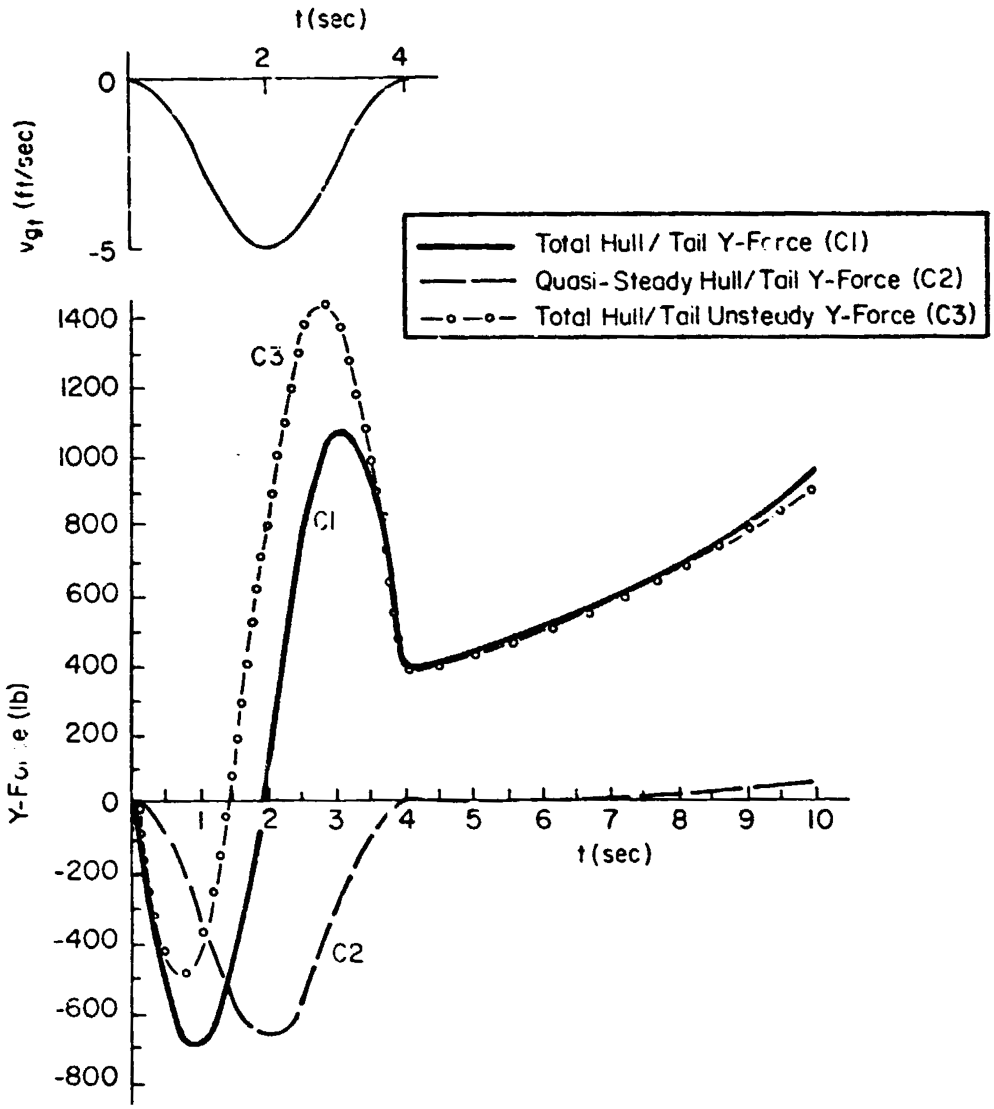

Figure 4. Time History of Aerodynamic Terms During a One-Minus-Cosine Sidewards Tail Gust

that axis. In all cases (rotor, propeller, nacelle), the forces calculated depend upon the local velocity relative to the airmass — at the rotor hub, propeller hub, and nacelle aerodynamic reference center.

PAYLOAD AERODYNAMICS

The payload aerodynamics are those of a rectangular container, neglecting unsteady (Strouhal) flow forces. The aerodynamics are somewhat more complex than those of the LPU fuselage in that moment terms dependent on linear and angular velocites are included.

INTERFERENCE EFFECTS

The proximity of the rotors and propellers to the hull the ground plane, and the tail surfaces leads to mutual interference effects of two kinds: those due to velocity changes and those due to the change in flow angularity. The former are modeled as velocity decrements; the latter by changes in certain of the aerodynamic coefficients. Since the modeling here as elsewhere concentrates on first-order effects, it was possible to avoid iterative calculations. The functional form of the models was formulated from the available literature on ground effects, e.g., Refs. 27 and 33, plus recent flow simulation work, Ref. 34, and ultimately by recourse to first principles (e.g., potential flow solutions, linear single dependency models, etc.).

AERODYNAMIC DISTURBANCES

The aerodynamic environment is made up of three separate components:

1) Discrete, one-minus-cosine gust inputs acting on isolated vehicle elements (e.g., tail only as in Fig. 4). These can be applied at several points at arbitrary time intervals to represent gust "waves." They translate and rotate with the vehicle and are intended for test purposes only.

2) Steady wind which is constant with respect to the non-rotating inertial reference frame. The wind contributes to the unsteady aerodynamic forces acting on the hull and tail when the vehicle is rotating with respect to inertial space.

3) Spatially distributed random turbulence which is approximated by a four (or five when payload is present) point source model.

The aerodynamic force calculations require local relative velocities at widely separated points on the vehicle. These locations are far enough apart that extrapolation of point gust values and gradients from a single point gives inaccurate results (Ref. 35). The degree of gust component correlation between any pair of locations drops off as the space between them increases, so that at 100 ft apart — a dimension typical of the distance between rotors in a quad-rotor HLA — the correlation nearly vanishes.

In the simulation, the hull is treated as a spatial averager of gusts that originate at four points around a meridional plane. They are selected by the user to be close to the rotors, the tail surfaces, and the reference length of the hull. Appropriately weighted averages of these four sources are taken as the gust component "seen" by the LPUs, by the hull, and by the tail assembly. This same model also provides gradients along and across the hull which gives rise to rotary gust and airmass acceleration terms.

The model requires that a set of twelve inertial velocity component time histories be computed ahead of time, three mutually perpendicular components at each of the four source points. For computational convenience, the input points translate but do not rotate with the vehicle. This allows use of actual gust records, or artificially generated time histories containing both correlated and uncorrelated components. The user might want correlated components to represent local airflow in close proximity to irregular terrain (e.g., a ridge, near a large hangar, etc.).

The payload, if present, requires an additional six components, three translational and three rotational terms, the latter being required because of the single-point nature of the payload gust modeling.

PAYLOAD SLING DYNAMICS

In the HLAPAY simulation the payload is suspended below the hull on as many as four suspension cables, each modeled as a spring-damper system. The geometry is arbitrary within constraints imposed by the trimming routines. Generally this means that sling geometries that do not restrain payload angular motion are not allowed and must be approximated by geometries that do provide these restraints, see Volume III.

This modeling approach was chosen over an alternate rigid link constraint modeling for reasons of simplicity. The rigid link approach requires a rework of the multibody equations of motion and constraint equations. The constraint equations change for each variation in sling topology, e.g., two versus four cables, bifilar versus paired inverted vee, etc., The flexible link approach adopted requires only a single computer code configuration to represent arbitrary geometries involving up to four cables.

LANDING GEAR DYNAMICS

Each of the as many as four landing gears is modeled as a vertically oriented spring-damper combination with two gradients. A Coulomb friction model is used for the forces acting at the ground contact patch. The stronger of the two gradients accounts for structural deflection when the weaker spring has bottomed out.

MOORING SYSTEM

In the HLAMOR simulation, a single mooring attach point is modeled as an additional constraint on the hull motion; the set of constraint equations is augmented. The HLA is modeled with zero rotor and propeller speeds; the aerodynamics are replaced by simpler models of the at-rest forces acting on the rotor and propeller.

FLIGHT CONTROL SYSTEM

The flight control system operates the rotor, propeller, and tail surface deflection controls through the software equivalent of a mixer box. The exact nature of the mixing is alterable by the user by making changes within the source code of a single subroutine.

The mixing "organizes" the many individual vehicle controls into six approximately orthogonal linked controls, one for each of the six degrees of vehicle motion freedom. Thus changes in the vehicle control configuration being analyzed by the user require changes in simulation code.

The mixing is effective not only for operation of the flight control system but also for establishing vehicle trim conditions. The trim routine operates through this mixing as does the determination of the linked control response derivatives.

The flight control laws themselves are of the classic proportional, integral, derivative (PID) type where the integrator output defines the trim deflection of the linked control point. Figure 5 illustrates the operation of this system in regulating against discrete downward gust at the tail. The sensed quantities include angular rates, body attitudes, accelerations and speeds (either inertial or airmass referenced). The system includes limits on the integrator output, on the linked control deflection, and on each of the individual control points of the vehicle. Thus the simulation is capable of investigating situations where limited control power is a factor.

The system accommodates user command inputs at several points. The individual control surfaces and the linked control points can have finite-duration pulses applied for test purposes. The flight control loops themselves can be commanded by user-specified time sequences of commands for execution of maneuvers, for example.

The system design is not intended to be universal; quite the contrary. The generic nature of the HLA configuration and the range of missions for which it is designed both imply control objectives that vary over a broad range. As presently defined, the system is oriented toward the hover condition with user-specified limits, gains, and sensor selection (from a limited set); the software mixer box is intended for four rotor, four propeller configurations. Source code changes in a

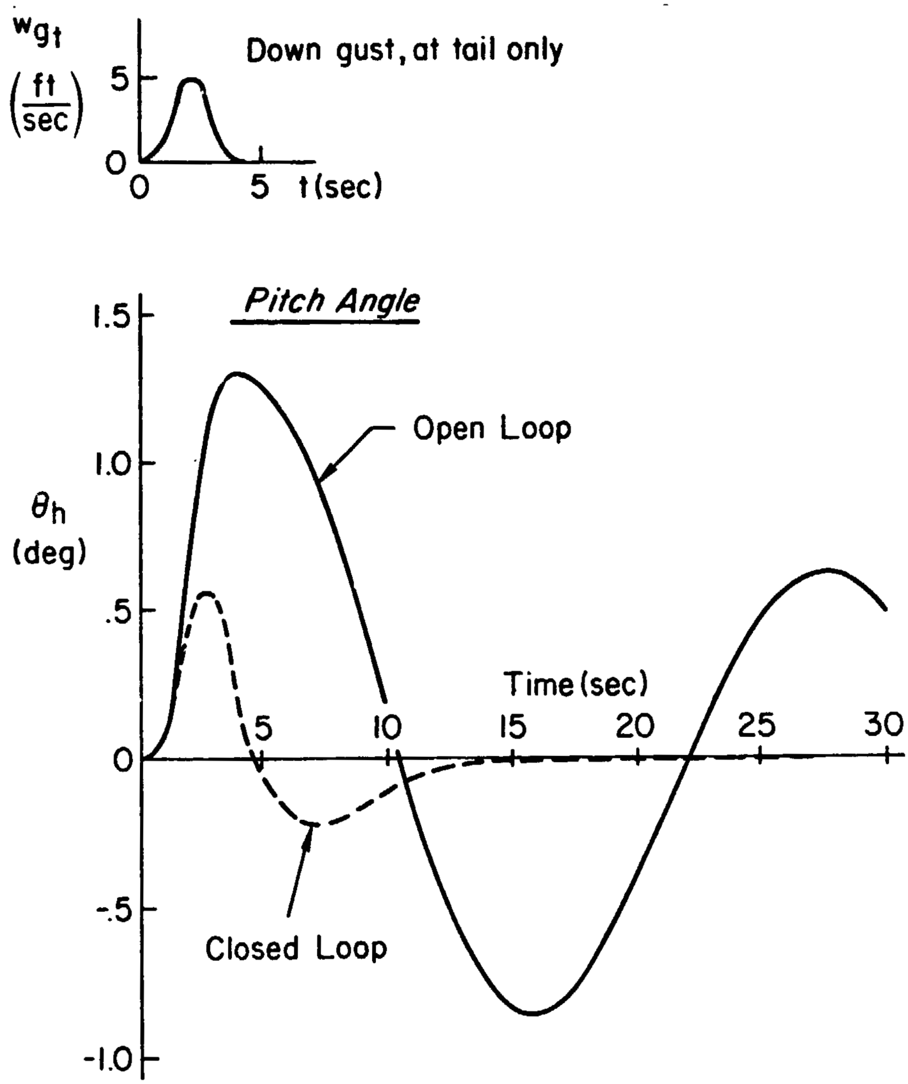

Figure 5. Comparison of Open- and Closed-Loop Responses to Tail Down Gust

SECTION 3

SOFTWARE DESCRIPTION

SOURCE CODE DEVELOPMENT

The source code was developed in a top-down fashion wherein the data structure, input/output characteristics, basic program algorithm, etc., were defined early to establish a framework for the development that followed. The major modules, each consisting of an interrelated set of subroutines, were developed in sequence, then incorporated and tested with the main program(s).

The individual modules were developed by a four-step sequence of model definition, code development, software test, and comment preparation. Model definition required establishing the pertinent equations and data requirements. This was often a lengthy process involving careful consideration of the relative merits of competing models. Sometimes, e.g., hull/tail aerodynamics and hull/rotor interference effects, it required extensive literature review and analysis to establish the form of the model and the relevant data structures and interfaces with the remainder of the program.

Reducing the model to FORTRAN source code was straightforward, but the testing that followed often was not. "Stiff" equations, e.g., landing gear spring-dampers, resulted in the expected problems with trimming the vehicle and integrating the states forward in time unless the parameters were chosen with discretion. During and following the testing of the individual modules the code was heavily commented by the engineer and programmer involved. These comments complement the program documentation given in these volumes.

The development of HLASIM followed the above procedure, the first major module being the multibody equations of motion. This was followed by the trimming module and the LPU aerodynamics. The modules for the hull and tail aerodynamics, the stability and response derivative determination, the flight control system, and the test gust inputs followed in that order.

Adding the slung payload began with an entire separate program in which the dynamics of the slung payload were modeled in isolation — payload equations of motion, aerodynamic and cable forces, and trimming routines. Following verification, it was "merged" with the HLASIM program to create HLAPAY. This involved revisions to the trim, stability and response derivative and integration routines. Interference effects and movable tail surfaces were then added to both programs.

HLAMOR was developed by assembling pieces of HLASIM, adding the mooring point constraint, and zero speed rotor and propeller aerodynamics to the system. Again the trim and stability and response derivative routines were specialized for this simulation program.

HYBRDS development was completed by recasting HLASIM and HLAPAY into an overlay structure and adding two small post-processor routines. HLAMOR is small enough to fit on the CDC 7600 without overlays. The programs were installed and checked out on the host computer by comparing test runs with previously computed check cases.

MAIN PROGRAM ALGORITHM

Each of the three programs has the same basic execution algorithm:

- Read vehicle data and initialize
- Read trim specifications
- Calculate trim state and print
- Calculate derivatives and print (if requested)
- Read time history specifications and initialize
- Integrate forward one time step
- Print output at print interval
- Stop

The program first reads in the geometric, inertial and aerodynamic data describing the HLA configuration and initializes the various data arrays. Following this, additional data specifying the trim condition, which includes atmospheric parameters, is read in and a trim state is computed. The printout that follows includes trim routine performance measures to inform the user of any difficulties encountered in trimming, e.g., limiting of the control surfaces. The program now loops back to calculate another trim condition.

Figure 6 shows an example of a trim state sequence, in this case illustrating lateral cyclic deflection requirements as [illegible]unction of crosswind velocity for an HLA with and without slung pa[illegible] At each trim condition, if the user has so requested, the program calculates the stability and response derivative matrices associated with the trim condition and prints them out before looping back to calculate another trim state. For each set of derivatives, the program also calculates the eigenvalues and eigenvectors of the system. Figure 7 shows an example of how certain of the eigenvalues vary with flight condition in a typical HLA.

The structure of the program to this point supports analyses of vehicle performance (Fig. 6) and flight dynamics (Fig. 7). The trim specifications can cover the intended operating envelope of the HLA; the results can point out potential performance or control authority problems. The linearized dynamics support studies of flying qualities and control system synthesis. Following calculation of the last trim or derivative array, the program stops unless the user has requested a simulation run.

If a time history has been requested, the program reads in the specifications that include the flight control system parameters, the commands, and the gust disturbances. The run begins at the last trim condition calculated. The program integrates the state vector rate of change forward one time step, writes all program output (approximately 1000 variables in the largest program, HLAPAY) to a plot file, then loops back to calculate another time step. This process continues until the print interval is encountered at which point user-selected

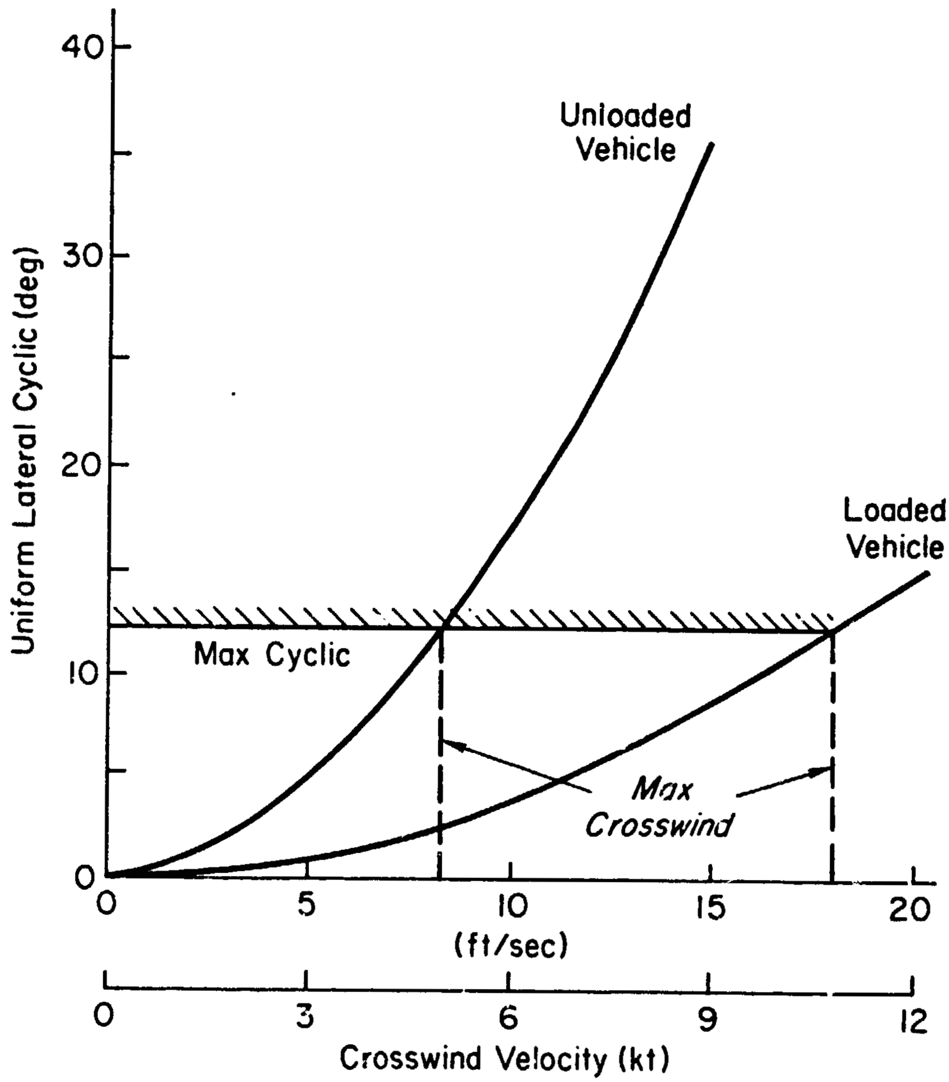

Figure 6. Trimming for Hover in a Steady Crosswind

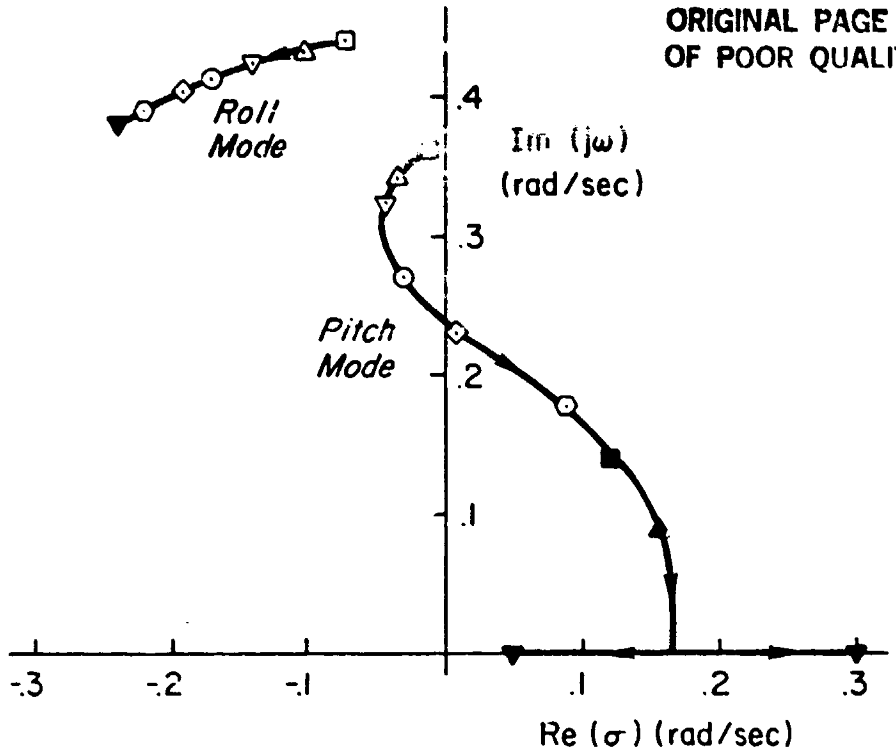

Figure 7. Motion of HLA Complex Roots with Airspeed

output variables are printed out. The program then enters the integration loops once again. The sequence ultimately stops when the maximum simulation time specified by the user is encountered.

TRIM ALGORITHMS

The trim algorithm determines the elements of a control vector that set pertinent elements of the state vector rate of change to zero. It is based on a generalized secant method described in Ref. 36. To accommodate wide variations in the HLA mathematical model, it starts with an estimate of the needed control vector which is necessarily quite crude.

Each of the three programs has a different implementation. In HLASIM, the control vector corresponds to the six linked controls of the vehicle. In HLAPAY, the payload is first trimmed in isolation, the control vector being the three angular components and three linear components of payload position. This results in fixed cable forces on the hull, which are then trimmed with the same six linked controls as before. In HLAMOR, the control vector consists of the three angular components of hull position.

The trim condition printout is preceded by measures of the trim algorithm's performance. These data are intended to provide clues to the user in the event that the trimmer has difficulty in establishing the trim condition.

STABILITY AND RESPONSE DERIVATIVE ALGORITHM

The derivatives are determined by forward and backward differences in the state vector rate of change and in a selected set of dependent variables, e.g., the constraint forces between the LPUs and the hull. The printout of these arrays is followed by an identification of those array elements where the forward and backward differences are marked. This is intended to flag instances of pronounced nonlinearity around the operating point. An IMSL routine is used to calculate the eigenvalues and eigenvectors.

INTEGRATION ALGORITHM

The integration routine, DVERK, used in the program is based on the Runge-Kutta-Verner method. It is an IMSL routine documented in Ref. 37. This routine varies the size of the time step within user-specified limits to satisfy its error criterion. Operation of the routine therefore requires interpolation between successive data points defining the time history of the commands and disturbances. Even though these may be random disturbances, they must be predetermined from the standpoint of the integration routine. Gust inputs and control sequences are required to be data strings established prior to the beginning of a run, i.e., "prerecorded" data.

POST-PROCESSOR ROUTINES

Two post-processors are included in HYBRDS. One formats data for plotting by utility routines on the Ames 7600 machine. The other modifies the gust input response derivative matrix so that the effective input points are the four or five gust sources rather than six points on the hull-LPU assembly and a seventh on the payload.

INPUT

The input file structure is such that a common set of files accommodates all three programs within HYBRDS. Which of the three programs is run is specified in an operating system procedure file. Instructions for the programs are contained within a file named INPUT. This file specifies the number of trim conditions to be calculated, whether or not a time history is to be calculated, and the system of units — English or metric.

The vehicle data are contained in GMDTA (geometry and inertial data), ARODTA (aerodynamics of hull-LPU assembly), IFCDTA (interference effects data), and PLMDTA (control surface limits and rotor/propeller speeds). The trim states are calculated using the specifications contained in TRMDTA. This file also flags whether or not derivatives are to be calculated for the individual states.

Time histories are calculated per the flight control system and command specifications in HISDTA, and the gust input strings for the four gust sources contained in four files, RG1-RG4. The printout variables are specified by code numbers contained in OUTLST.

The foregoing is applicable to running the HLASIM program. To run HLAPAY, additional files are needed. PAYDTA contains the payload geometric, inertial, and suspension cable data. RG5 and RG6 contain the payload translational and rotational gust components and PYOUTL identifies the additional, payload-peculiar variables desired in the output listing. To run HLAMOR, the data file MORDTA is needed, which contains the mooring trim specifications and initial offsets from the trim condition which are used to excite the mooring dynamics.

OUTPUT

If the user has so requested (in INPUT), all of the output variables are written to binary format file, PLOT, after each trim calculation and each integration time step.

The printed output starts with a run description — the comments the user has inserted in INPUT. Following this is a labeled listing of all the input variables (except the gust input strings) if the user has so requested.

Next are the results of the trim calculations -- the variables specified in OUTLST and PYOUTL for each trim condition, together with certain additional variables pertinent to trim -- the occurrence of limiting, the existence of the vortex ring state on one or more propellers or rotors, etc.

Following each trim state (when so requested) is a listing of the stability and response derivative arrays.

When a time history has been requested, additional listings of variables follow, one for each print interval beginning with the initial trim condition at t = 0. The variables are the same as those printed out for the various trim conditions called for. This continues until the specified simulation time occurs.

SECTION 4

DEVELOPMENT POTENTIAL

OVERVIEW

The HYBRDS programs were written with future expansion possibilities in mind, depending upon the nature of the application. The majority of the extensions or elaborations are quite straightforward, meaning that the subroutines involved and the interfaces with the remaining program are few in number. This section briefly describes the nature of the changes required for the elaborations envisioned at the time of writing.

FORCE AND MOMENT CHANGES

The equations for the forces and moments acting on the hull assembly and the payload can be altered or elaborated relatively easily when there are no changes in the independent state variables which are integrated forward in time. The guideline here is to consider the operation of the trimming routines. If the forces and moments are quite sensitive to changes in the state variables, the trim routine can run into trouble, e.g., with the landing gear in HLAMOR and with the payload suspension cables in HLAPAY.

Multipoint Mooring

The present simulation assumes an ideal translational constraint at a single point and can trim the vehicle with one or more landing gears touching the ground. Additional restraining cables, modeled as spring-damper combinations, can be added relatively easily if one is careful to consider how the trim routine will operate.

Payload Ground Contact

When ground contact forces are added to the payload it will become possible to simulate the changing flight conditions associated with load pickup and placement. The pickup case is more complicated as it requires the trimming sequence to be altered. The payload attitude must be trimmed on the ground with ground contact forces providing the controls for the trim routine's operation.

ADDITIONAL STATE VARIABLES

The simulation already has provision for additional state variables in a number of areas. Taking advantage of these provisions is straightforward to the extent that the trimming function is left unchanged.

Flight Control System

The present flight control system has six state variables requiring integration which are associated with the integral equalization (and control surface autotrim) of the system. Additional states involving filtering, i.e., sensor filters, actuation lag filters, etc., can be added -- spare elements are available in the vector of state variable rate of change for the HLASIM and HLAPAY programs. Changes in the loop structure apart from adding additional states are also possible.

Propulsion System

The dynamics of a governor-controlled turbine-powered propulsion system can be added easily if the mathematical model trim operating point is completely specified by the input data. Consider a three-state propulsion system model for each LPU where rotor speed, primary turbine speed, and fuel flow are the three states. If simple enough, the rotor speed implies the trim values of the remaining variables without the iterative operation of a trimmer being required. The propulsion system dynamics can be thought of as additional flight control loops where the trim control deflections, rotor speeds, are specified at the outset.

LPU Orientation Relative to the Hull

In the early stages of the HYBRDS development, one of the mathematical model features was controllable LPU angles, as in, for example, the XV-15 Tilt Rotor Aircraft. The structure of the multibody equations of motion is such that three gimbal angle accelerations are potential control variables at each LPU attach point. In fact, the angular accelerations and velocities are still integrated in the program. A program statement sets the velocity integrand to zero each time step to avoid drift in the gimbal angles.

If the mathematical model for LPU gimbal angle control is such that gimbal angle acceleration (rather than torque) is the controlled variable, modest changes to the program will restore these degrees of freedom. A further requirement is that the gimbal acceleration and velocity both be zero and the gimbal angle be specified at trim to avoid elaborating the trim routine operation. Such a modeling is quite adequate for irreversible controls such as screw jacks. The program will integrate the accelerations and velocities and compute the constraining torque as a dependent variable.

Trim Control with Ballonets

The HLA hull and tail assembly is currently modeled as having constant inertial properties, the latter including the so-called apparent mass terms which arise in the nonsteady and acceleration-dependent terms in the aerodynamic forces. However, airship-peculiar properties associated with the expansion, contraction, and distribution of buoyant gas within the envelope are not present.

Adding these effects requires that the mass matrix be inverted each time step. Currently, this is done once as a part of the input data processing. In addition, center-of-gravity offset and center-of-buoyancy offset (from the nominal in each case) terms need to be added to the equations of motion. Finally, the trim routine logic requires modification of ballonet air distribution as well as rotor thrust — both used for control of pitching moment by the flight control system.

PRE- AND POST-PROCESSING

HYBRDS has two post-processors, one for formatting plotting files and the other for computing additional gust response derivative matrices. There are no pre-processor routines. Clearly anything in the extensive input data set is a potential candidate for pre-processing; and there are obvious possibilities for post-processing. An example of each is cited below.

Gust Inputs

The simulation accepts the equivalent of prerecorded data for the disturbance inputs. That the data be prerecorded is a requirement of the error-correcting integration routine which alters step size as required to satisfy its error criterion. There are several sets of these data corresponding to the four (or five in HLAPAY) gust "sources" of the model. The nature of the data (amplitude, random versus deterministic characteristics, correlation among the sources, etc.) is user specified. Given the appropriate models of these disturbances, one could create a pre-processing routine to generate the required data files based on user-specified parameters.

Load Distribution

The simulation generates as a part of its output the internal forces and moments acting at a number of points in the structure as well as a number of external force summations. Internal forces include:

- LPU attach point constraint forces and moments
- Payload suspension cable tensions
- Landing gear compressive loads
- Mooring attach point loads
- Rotor and propeller forces and torques

External force summations include the forces and moments acting at the several areodynamic centers in the system — the tail, the hull center of volume, the payload and LPU reference centers.

The simulation does not perform a piecewise integration of the forces acting along the length of the hull. However, within the accuracy of the assumptions making up the aerodynamic force model, one can "work backwards" to infer such data from the one thousand or so data elements available at each time step. From these data, hull bending moment and related loads can be inferred. This is a candidate for a post-processing routine.

One could, of course, add this processing to the simulation itself. With additional changes, this would allow computation of transfer functions relating, e.g., bending loads, to control inputs and disturbances for linear systems analyses.

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