DYNAMIC SIMULATION OF THE CH-47D HELICOPTER AND EXTERNALLY SLUNG BOAT

R.A. Stuckey

Air Operations Division
Defence Science and Technology Organisation, Melbourne, Australia

A task involving the simulation of a helicopter slung-load system is described, including the software package developed at DSTO. The helicopter, a Boeing CH-47D, was modelled using the core functions from the RotorGen simulation model, supplied by the NASA Ames Research Center. The model for the load, a Rigid Inflatable Boat (RIB), was constructed from several generic aerodynamic and inertial models. A brief description of the coupled system is given, as well as details on the trim and simulation components of the software package. The package has been used in an exercise to reconstruct an incident that occurred during Australian Army flight trials when the RIB was slung, bow first, in a tandem-sling configuration beneath a CH-47D. The results of this reconstruction are outlined and some conclusions drawn.

Introduction

Initially, the primary goal of this work was to define the operational limits of the Australian Army Chinook CH-47D when carrying mixed density slung-loads. In the last year, however, the focus has shifted to the study of the dynamics of the CH-47D with aerodynamic loads, that is single slung loads with aerodynamic characteristics that typically have a low density and some sort of lifting behaviour. This paper presents the second phase in the program: the implementation of a full nonlinear flight dynamic model into the helicopter slung-load simulation, as well as load aerodynamics and sling elasticity. The first phase[1] comprised the development of a simple helicopter slung-load model for simulation and analysis of the system dynamics. One of the main driving forces behind the shift in focus was an incident[2] that occurred during Australian Army flight trials in late 1998, which involved a Rigid Inflatable Boat (RIB) coming into contact with the Chinook that

was carrying it. This was not the first incident of this type and several have been reported by the Australian Army alone, in which aerodynamic excitation or dynamic instability, resulting in uncontrollable oscillations, has forced premature release of the load. The end goal of this task is to build a capability that will provide some initial estimate of the dynamic behaviour and stability of any particular helicopter slung-load configuration prior to flight testing.

Helicopter Slung-load Simulation

The Helicopter Slung-load Simulation (HSLSIM) software was written in the Matlab[3] numerical computing environment and comprises the core helicopter-load model, trim and simulation routines, and a number of tools for graphical output and display. Figure 1 illustrates the layout of HSLSIM. Various components of the dynamic helicopter model RotorGen, as well as components of the trim and simulation routines, are outlined.
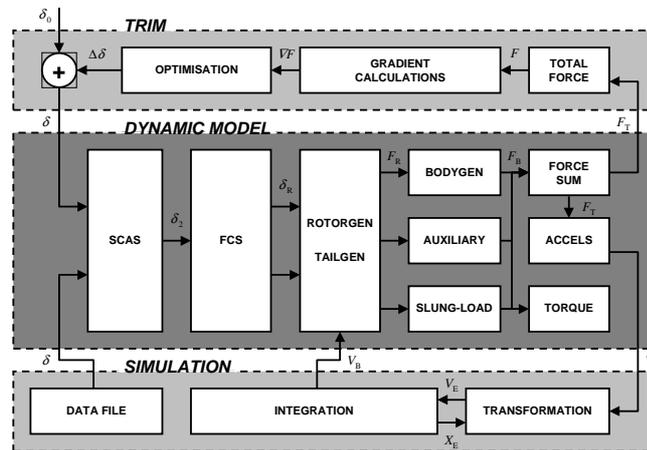
Fig. 1 HSLSIM Flow Diagram

RotorGen Helicopter Model

RotorGen was developed by Heffley[4] for the US Army Aeroflightdynamics Directorate under NASA contract to Hoh Aeronautics, Inc. It is described as a minimal-complexity generic rotorcraft model intended for manned simulation of large military helicopters and, in particular, the CH-47D Chinook tandem rotor helicopter.

The rotor inflow model is based on Glaurt's representation of thrust, with the orientation (incidence) of the tip path plane defined by a set of flapping equations. The body forces are based on a quadratic fluid-dynamics formulation, applicable to low-speed flight. RotorGen is a combination of two existing flight models: the Extended Stability Derivative (ESD) model developed for NASA, and the RotorGen thrust model developed for the US

Army. As such, the RotorGen model has a modular structure, which combines several features of the original ESD model. These include a primary Flight Control System (FCS), rotor and body forces, ground effects, simple slung load dynamics, and a Stability and Control Augmentation System (SCAS). An integration routine was also included in the software distribution, although this was not required.

The external load model provided with RotorGen comprised a simple single hook pendulum-type load with sling elasticity and a torsional restraint. However, this representation was insufficient for the analysis work set out by the current task, which included multiple loads and alternative sling configurations. The core helicopter dynamics and control model was therefore integrated into the slung load simulation package HSLSIM developed at DSTO.

RotorGen was written in Fortran and has been built on both Macintosh and VAX systems. Since HSLSIM was written in Matlab, several interface routines were needed to call the core model from within the simulation. The inputs to RotorGen consisted of the current flight state (orientation, rates, and altitude) and the control inputs. The outputs consisted of the resultant forces and moments from both main rotors and the fuselage. The model also required initialisation prior to integration, to set all of its internal variables, such as the rotor inflow velocity, to their nominal values and determine an initial operating state.

In addition to the interface and initialisation code, a set of trim routines had to be developed so that the simulation could be flown from an equilibrium state. The previous model, based on a linearised state-space representation[5] of a CH-47B, did not require such routines as the trim state was obtained from recorded data and specified *a-priori*.

RIB Aerodynamics

No aerodynamic data for the RIB was available, so in order to devise a suitable model, several generic aerodynamic models were combined. These included a conex container and a cylinder with a rounded end. The aerodynamic data for the container was taken from Ronen,[6] which was itself a compilation of several other aerodynamic models obtained from experiment. The aerodynamic behaviour of the cylinder was taken from Hoerner[7] and ESDU[8] in the form of analytical equations dependent on the free-stream Reynolds number and the angle of incidence.

Since the RIB was to be carried as an external load and would have the freedom to swing through large angles in flight, the model also needed to cover the entire angle-of-attack and sideslip range from $-180°$ to $180°$. The influence of the rotor downwash was also noted, although at his time it was not required to be implemented. Neither of the two models covered angles of incidence beyond $90°$ and so they were extrapolated using a simple symmetrical (mirror) transformation. More importantly, the cylindrical model did not include any aerodynamic moment data, only lift and drag force,

which meant that the moments could only be calculated from the container model data plus a normal-force contribution at the cg offset.

Figure 2 shows the lift and drag coefficients for both aerodynamic models mentioned above, as well as the resultant interpolated RIB model. The behaviour of the RIB was assumed to follow the cylinder for $0° < \alpha < 90°$, $-90° < \beta < 90°$, and the container for $-180° < \alpha < -90°$, $\beta = 180°$. In the intermediate regions, the model was approximated by a linear transition between the two bordering models. Furthermore, since the normal-force vector for the lateral model was orthogonal to the longitudinal one, a fraction of the same function could be used to represent the sideforce. However, the axial-force vector was in the same direction for both, and so an approximation to the overall drag was made by taking the maximum value.

a) Lift Coefficient **b)** Drag Coefficient
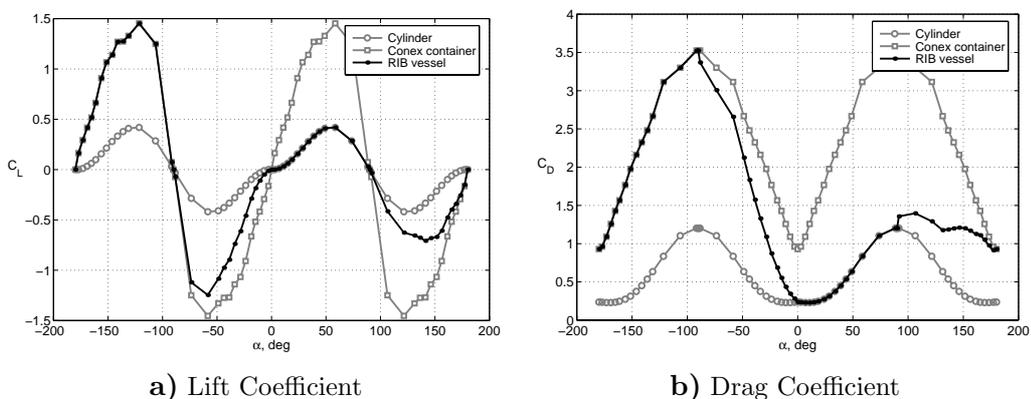
Fig. 2 Longitudinal Aerodynamic Coefficients for the RIB

System Trim

Once the core helicopter model had been integrated into the simulation system in Matlab, a trim routine was written to determine the steady state of the system under any given set of conditions. The Optimization Toolbox provided several functions suitable for use in the trim routine. That chosen was a nonlinear least-squares function, which is well suited to problems associated with the minimisation of several variables. Moreover, the function is based on a Levenberg-Marquardt algorithm, which has been shown to be more robust than the Gauss-Newton algorithm often used in these problems and more efficient than other unconstrained methods.

The optimisation problem can be divided into two cases, depending on whether or not the elasticity in the slings is assumed to be negligible. In the case of inelastic slings, the optimisation variables comprise the four helicopter control inputs (longitudinal cyclic and lateral cyclic, pedal, and collective), the attitude and bank angles, as well as several load-related angles particular to each sling configuration defining the load position and orientation. In the case of elastic slings, the optimisation variables comprise the helicopter control inputs and orientation as above, as well as the load position and orientation.

Simulation of the CH-47D and RIB

Following the flight trial incident, it was decided to attempt to simulate a reconstruction of the events. This was to be based solely on various reports given by the flight crew aboard at the time, since the trial was not recorded by video or any other means.

First, a reconstruction was made by specifying the position and orientation of the helicopter-load model at key points during the manoeuvre and then interpolating between those points. For this, there were no kinematics involved and no cable stretching. The intermediate points were obtained by fitting a cubic spline through the key points at set intervals and, although not dynamically correct, this first reconstruction gave a rough picture of what may have occurred.

Second, a simulation was performed using the HSLSIM-RotorGen model with pre-specified control inputs. The helicopter slung-load configuration was initially trimmed with a forward airspeed of 200 ft/s and sideslip-angle of $5°$ (nose port). During the flight trial, this was done to simulate the aircraft state with the AFCS switched off. In this state, the RIB was stable and had a yaw offset to starboard of approximately $4°$ (sideslip-angle of $1°$). The pilot then proceeded to yaw the helicopter to starboard to test the stability of the load with a negative sideslip-angle. This was implemented in the simulation by applying a yaw-control doublet while utilising simple rate feedback for the other controls in order to maintain a steady attitude and bank angle for the helicopter. As reported in the flight trial, the RIB then swung around rapidly to starboard, pitching up as it continued to yaw. The simulation was halted at the point of contact between the RIB and the helicopter fuselage. The response time, as suggested by the simulation, took approximately 6 seconds. Figure 3(a) shows the response of the CH-47D and RIB to the yaw control inputs, shown in Figure 3(c). The vertical lines through the plot of the yaw-control indicates the time at which each of the frames above were taken. Also shown in Figure 3(b) is the response of a different configuration, with the RIB slung stern first, to the same inputs. For comparison, the load in this case did not diverge rapidly in yaw, but instead settled back to an equilibrium position under the helicopter.

It should be noted as this point that the initial state and the control inputs created for the simulation were purely approximations based on those reports given by the flight crew at the time. They do not represent the true values, and hence, the simulation can only provide a 'best guess' of the event that transpired.

Concluding Remarks

In summary, the software package HSLSIM coupled with the RotorGen CH-47D helicopter model and a basic aerodynamic model of a Rigid Inflatable Boat has been used to reconstruct an incident that occurred during flight trials. The software developed at DSTO comprises a trim and sim-

a) Bow forward configuration

b) Bow aft configuration
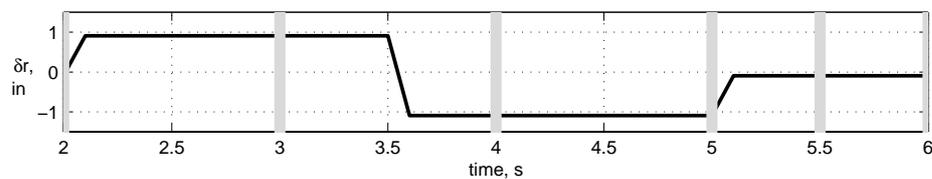
c) Yaw-control input

Fig. 3 CH47D-RIB Response Simulation

ulation routine, as well as various graphical tools for output and replay of the simulation. The response of the load displayed by the simulation was consistent with reports on the incident given by flight crew.

References

[1]Stuckey, R., "Dynamic Simulation of the CH-47D Helicopter with Single and Multiple Loads," *Second Australian-Pacific Vertiflite Conference on Helicopter Technology*, Australian Defence Force Academy & American Helicopter Society, Jul. 1998.

[2]Scarr, D., "AMTDU Malfunction Invesigation: Inflight Contact between Rigid Inflatable Boat AM233 and CH-47D A15-104 at Townsville on 10 Dec 98," AMTDU Report 31/111/231/Air Pt 1, Air Movements and Training Development Unit, Australian Army, Feb. 1999.

[3]The MathWorks, Inc., *MATLAB, The Language of Technical Computing: Using Matlab Version 5*, The Mathworks, Natick, MA, 1999.

[4]Heffley, R., "ROTORGEN Minimal-Complexity Simulator Math Model with Application to Cargo Helicopters," Contractor Report NASA-CR-196705, Hoh Aeronautics, Inc., Lomita, CA., Mar. 1997.

[5]Weber, J., Liu, T., and Chung, W., "A Mathematical Simulation Model of the CH-47B Helicopter, Volumes 1 & 2," Technical Memorandum NASA-TM-84351-VOL-1/2, NASA Ames Research Center, Aug. 1984.

[6]Ronen, T., *Dynamics of a Helicopter with a Sling Load*, Ph.D. thesis, Stanford Univ., CA., 1986.

[7]Hoerner, S. and Borst, H., *Fluid-Dynamic Lift*, Hoerner Fluid Dynamics, Midland Park, NJ, 1975.

[8]ESDU, *Item No.80025: Mean Forces, Pressures and Flow Field Velocities for Circular Cylindrical Structures: Single Cylinder with Two-Dimensional Flow*, Engineering Sciences Data Unit, London, UK, 1980.