Dynamic Simulation of a Helicopter Carrying a Slung Load[1]

Reddy, K. R., Truong, T. T., Stuckey, R. A. and Bourne, K. J.

Air Operations Division, Defence Science and Technology Organisation, Department of Defence, Australia
Email: rami.reddy@dsto.defence.gov.au

Keywords: Slung load simulations, parametric study, helicopters

EXTENDED ABSTRACT

The safety and operational flight envelope of helicopters carrying externally slung loads, as illustrated in Figure 1, in support of regular Army and Special Air Service (SAS) operations, is limited and sometimes seriously hindered by stability and control problems. Several incidences have been reported by the Australian Army in which possible aerodynamic excitation or dynamic instability of the slung load has resulted in a forced premature release.

Figure 1 Range of slung loads carried by Chinook Helicopter

Previously, there were no simulation tools that could be used successfully to predict the flight conditions under which a particular load becomes unstable. The safe operating envelope for loads is established through flight tests over a range of increasing airspeeds. This is a very costly exercise and is not without some risk. Consequently, the Defence Science and Technology Organisation (DSTO) is developing a comprehensive simulation program to assist in defining the operational limits of various Australian Army helicopters when carrying slung loads. A central part of the program has entailed the development of a comprehensive helicopter slung load model based on research from the National Aeronautics and Space Administration (NASA) Ames Research Center (Stuckey 1998, 2001). This is a highly complex dynamic system requiring detailed dynamic and aerodynamic representations of both the helicopter and the load. All code development has been done in the MATLAB numerical computing environment, which has the capability to utilise a number of high-order models previously developed in other languages.

Often aerodynamic and dynamic data for a particular load is not readily available. The operator is then compelled to develop appropriate data sets based on experience, and where applicable, the use of simple body shapes like flat plates, cones and cylinders. Knowledge of the effects of various slung load parameters on the stability of the load would be highly useful to operators. In this paper the effect of various parameters is studied, including dynamic and aerodynamic parameters of slung loads and the effects of pilot control input values, load mass variation, and load cg location on slung load stability. Finally, some concluding remarks are drawn and proposals for further research are made.

1. INTRODUCTION

Initially, the primary goal of this work was to define the operational limits of the Australian Army Chinook CH-47D when carrying multiple, mixed density slung-loads. However, the focus has since shifted to the study of the dynamics of the CH-47D with single, aerodynamically active, slung loads – that is, loads with aerodynamic characteristics that typically have a low mass density and some lifting behaviour. A variety of sling configurations are examined.

One of the main driving forces behind the shift in focus was an incident that occurred during Australian Army flight trials of a slung Rigid Inflatable Boat (RIB) in late 1998, which involved the RIB coming into contact with the Chinook that was carrying it. This was not the

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[1] *Proceedings of the International Congress on Modelling and Simulation, University of Canterbury, Christchurch, New Zealand, 10-13 December 2007*

first incident of this type and several have been reported by the Australian Army, in which aerodynamic excitation or dynamic instability, resulting in uncontrollable oscillations, has forced premature release of the load.

The overarching goal of this research is to build a capability that will provide an initial estimate of the dynamic behaviour and stability of any particular helicopter slung-load configuration prior to flight testing.

In this paper, Section 2 presents a broad overview of model development and its implementation in MATLAB.

Section 3 introduces RotorGen, a flight dynamic model used to represent the Chinook helicopter. Also discussed are methods used to estimate load aerodynamic characteristics.

In Section 4, numerical results show the effect of variation in (i) load aerodynamic properties, (ii) load cg and mass, (iii) helicopter speed, and (iv) pilot control inputs on maximum load deviation. The nature of the load oscillations underneath the helicopter is also presented.

In Section 5, some concluding remarks are drawn and proposals for further work are made.

2. MODEL DEVELOPMENT

Helicopter slung-load systems fall into a class of multi-body systems approximated by two or more rigid bodies connected by links. The links can be considered either elastic or inelastic, although the rigid-body assumption excludes any helicopter or load elastic modes. Typically, the system is characterised by the configuration geometry, mass, inertia, and aerodynamic behaviour of both helicopter and load, as well as the elastic properties of the links.

In general terms, the system of interest consists of a single helicopter supporting one or more loads by means of some suspension. The model is comprised of n rigid bodies, with m straight-line links supporting a single force in the direction of the link. If the links are modelled as inelastic, $c \leq m$ constraints are imposed on the motion of the bodies and the system has $d = n*6 - c$ degrees-of-freedom (dof). If the links are modelled as elastic, there are $n*6$ dof.

A number of simplifying assumptions have been made in the model. These include the exclusion of cable mass, cable aerodynamics and rotor-downwash effects. Despite these limitations, the system has proven adequate for simulation studies in which the low-frequency behaviour is of primary interest and the helicopter is initially trimmed in forward flight.

The simulation model used is based on the helicopter slung-load system introduced by Cicolani, *et al* (1986). In this formulation, the general system equations of motion are obtained from the Newton-Euler equations in terms of generalised coordinates and velocities. Details of the model development can be found in references Stuckey (2001, 1998). Aside from the core helicopter model, all code development has been done in the MATLAB (1999) numerical computing environment.

The Helicopter Slung-Load Simulation program HSLSIM consists of several modules, written in the MATLAB language. These include the main script, an optimisation routine, a differential equation solution, an integration function, a flight-dynamic model, and various output and replay functions. There is also a graphical user interface for simplified control of the primary program functions. Alternatively, the simulation can be run through a main script, which generates the control inputs, configures the helicopter-load system properties (geometric and inertial), sets the initial system state, and then executes the trim and integration functions.

For successful simulation two components – the helicopter and slung load – need to be modelled in detail. The flight dynamic model, RotorGen, is used to model the helicopter aerodynamics, dynamics and control system. A range of methods are employed to estimate load aerodynamic properties. The following section presents a broad review of helicopter and load representations as used in the study.

3. HELICOPTER MODELS AND LOAD AERODYNAMICS

RotorGen was developed by Heffley (1997) 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, and a Stability and Control Augmentation System (SCAS). The core helicopter dynamics and control models were integrated into the slung load simulation package HSLSIM developed at DSTO. The inputs to RotorGen consist of the current flight state (orientation, rates, and altitude) and the control inputs. The outputs consist of the resultant forces and moments from both main rotors and the fuselage. In addition to interfacing and initialisation code, a set of trim routines was developed so that the simulation could be flown from an equilibrium state.

Often the loads requiring transportation tend to be bluff bodies operating in subsonic flows with high angle of flow incidence. Aerodynamic data for such bodies is often unavailable. In the accident investigation involving the RIB, several generic aerodynamic models were combined to represent the RIB. These included a Conex container and a cylinder with a rounded end.

The aerodynamic data for the container was taken from Ronen (1986) which was itself a compilation of several other aerodynamic models obtained from experiment. The aerodynamic behaviour of the cylinder was taken from Hoerner (1975) and ESDU (1980) 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˚. In situations where a model must be generated from composite shapes, clear understanding of the effect of various aerodynamic parameters on load oscillations is advantageous. In the following section results of such a study are presented.

4. NUMERICAL RESULTS AND DISCUSION

Preliminary results of research that is being conducted to evaluate the effect of load aerodynamics, dynamics, and pilot control inputs on slung load stability are presented here.

The baseline aerodynamic data chosen relates to a container with a weight of 4000 lbs and size 13 × 8 × 7 ft. To achieve a controlled initial load disturbance, a lateral manoeuvre was executed with a magnitude of 2.0 inches. For further details of the control input profiles, see Stuckey, 2001.

The airspeed was set at 100 kts and the altitude 200 ft. The load was suspended by cables that provided a 20 ft separation between helicopter cg and load cg. Each of the cable sling configurations are detailed in Figure 2.

Within figures 3 to 6 the origin indicates the initial steady trimmed load position prior to pilot lateral manoeuvre inputs. In these figures the movement of load cg, as well as the maximum load deviation values are measured with respect to the initial trim position.

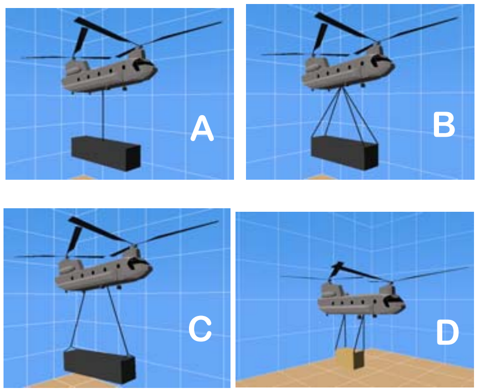

Figure 2 Rigging configuration; A single point, B multiple point, C bifilar and D tandem

Figure 3 shows the effect of load drag coefficient (CD) variation on load oscillations. All sling configurations yielded similar trends between reduced CD values (i.e. CD/2, CD/10, CD/100), and the base value, although the track shape is unique to each configuration. It was seen that as CD was decreased, the load deviation increased. Conversely, as CD was increased, the load deviation decreased. All three configurations showed similar maximum load deviation trends. The maximum load deviation values were consistent at low CD values, with relatively small decreases up until CD/2. The decrease after this is significant.

Figure 4 shows the effect of load lift coefficient (CL) variation on slung load oscillations. For all configurations, results that lay between CLx2 and CL/100 indicated that a reduction in CL corresponded to an increase in load deviation. However the results for CLx10 differed notably. For each sling configuration, the trend shown by the tracks for CLx10 are dissimilar from the characteristic traces, that is, the load displacement path shown most frequently. The responses for the single and multiple configurations at CLx10 followed the general trend, but the bifilar configuration showed a significantly large load deviation. The maximum load deviation trends for the single and bifilar sling configurations are quite similar, whereas the response for the multiple sling configuration is quite different. For the single and bifilar configurations, the load deviation decreased with an increase in CL. For the multiple sling configuration, the maximum load deviation increased slightly to peak at the base line CL value before decreasing.

The results for variation in CL were not expected. It was anticipated that increasing CL values would decrease stability, as the threshold for “lifting” behaviour was decreased; however this was not the case. The most probable reason for the trends displayed was that as the system was trimmed for forward flight, the orientation of the load was nose-down. Simulation replays indicate it is likely that there was insufficient airflow underneath the box to excite the increased CL.

Figure 5 shows the effect of load pitching moment variation (CM) on slung load oscillations. For both the single and multiple sling configurations, all results showed the same trend; that for a decrease in CM, overall the load deviation also decreased. The bifilar configuration exhibited only a slight increase in load deviation for an increase in CM values. It is interesting to note that the bifilar sling configuration responses of CM/100 to CMx2 show extremely similar oscillatory characteristics and magnitude.

Figure 6 shows the effect of load side force coefficient (CS) variation on slung load oscillations. The results from the bifilar sling configuration indicated a decrease in CS increased load deviation, whereas the single configuration yielded opposite trends. The tracks for the multiple sling configuration are a little more difficult to generalise. The overall trend for CS/100 to CSx10 indicated a similar overall response to the bifilar case; however the result for CSx100 reverses the trend that an increase in CS decreases the load deviation. The evidence of an apparent ‘local minima’ is much more difficult to reason without taking into account the simulation replays. Conversely, the bifilar configuration showed an increase in load deviation for an increase in CM values. The maximum load deviation trend for each sling configuration is quite unique.

One general trend noted for both CL and CD result sets was that the reduction in coefficient magnitude tended to increase the overall load deviation. The main explanation for this behaviour is that when the coefficient was decreased, so too was the aerodynamic damping in that axis, and the load movement is more strongly influenced by the other aerodynamic parameters. It can almost be likened to removing a restraint from the system. In contrast, increasing an individual coefficient amplified the load movement most influenced by that coefficient.

This behaviour was also exhibited by variation in CM; however the trends apply in reverse. By extrapolation of the previously mentioned theory, this infers that as a single coefficient, CM has a destabilising effect on the load. When it is dominant, the load deviation increases, however when it is reduced overall deviation decreases.

Considering this, the results for CS are quite interesting, as each configuration displays a unique trend as the magnitude of CS is varied. It is most likely that as CS represents the effect of the side-force, the system resistance to the yaw tendency of the load is under scrutiny. As such, the maximum load deviation values generated after the variation in CS were more heavily influenced by the sling configuration than the other aerodynamic coefficients.

Careful observation of results presented in Figures 3 to 6 show that there are flight conditions where the slung load behaviour is quite different to the general trend. At this stage it is not clear whether this is due to the aerodynamic approximations made in formulating the load model or if it is in fact a true representation of the physical world. This will be further investigated as part of future work.

Figure 7 shows the effect of variation in load mass, cg, and pilot control input on maximum load deviation for a tandem rigging configuration. For the mass variation study, the cg is at the centre of the load and the pilot control input magnitude (PCIM) is fixed at 2 inches for all simulations. The results show that an increase in forward speed increases the maximum load deviation and the lighter the load the greater the deviation. For the cg variation study load mass is set to 4000 lbs and PCIM is set to 2 inches. Results indicate that the load is more stable as the cg moves forward. For the PCIM variation study load mass is 4,000 lbs, cg is at the centre of the load and the PCIM varies between 0.5, 1 and 2 inches. As expected the higher the pilot control input magnitude, the greater the load disturbance, and hence the greater the maximum load deviation.

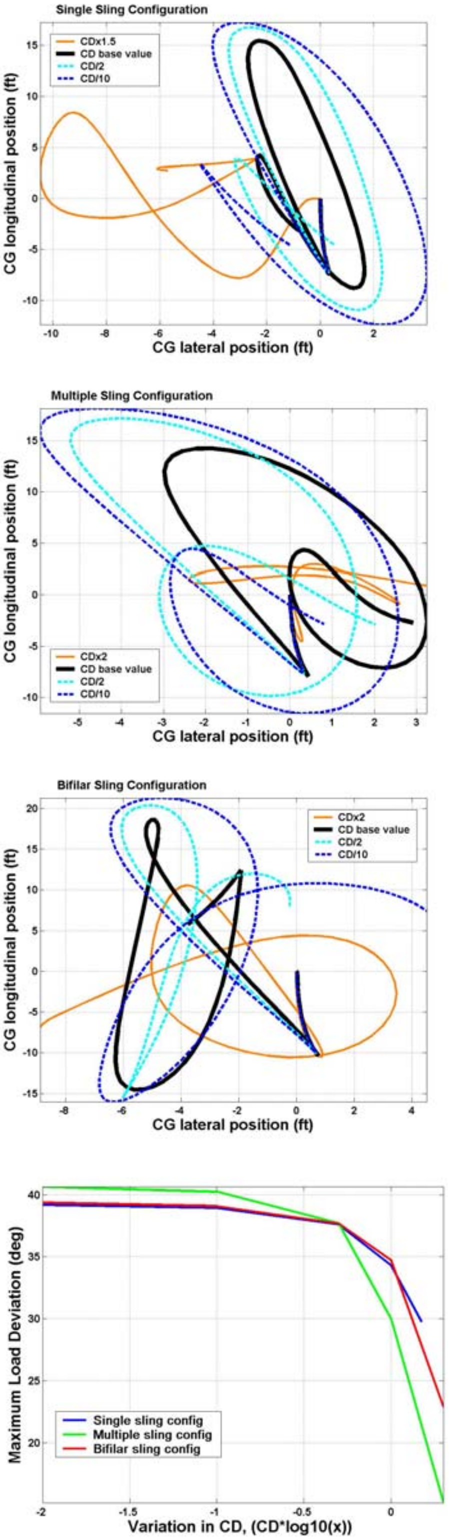

Figure 3 Plan view of load oscillation, and maximum load deviation for variation in load drag coefficient (CD)

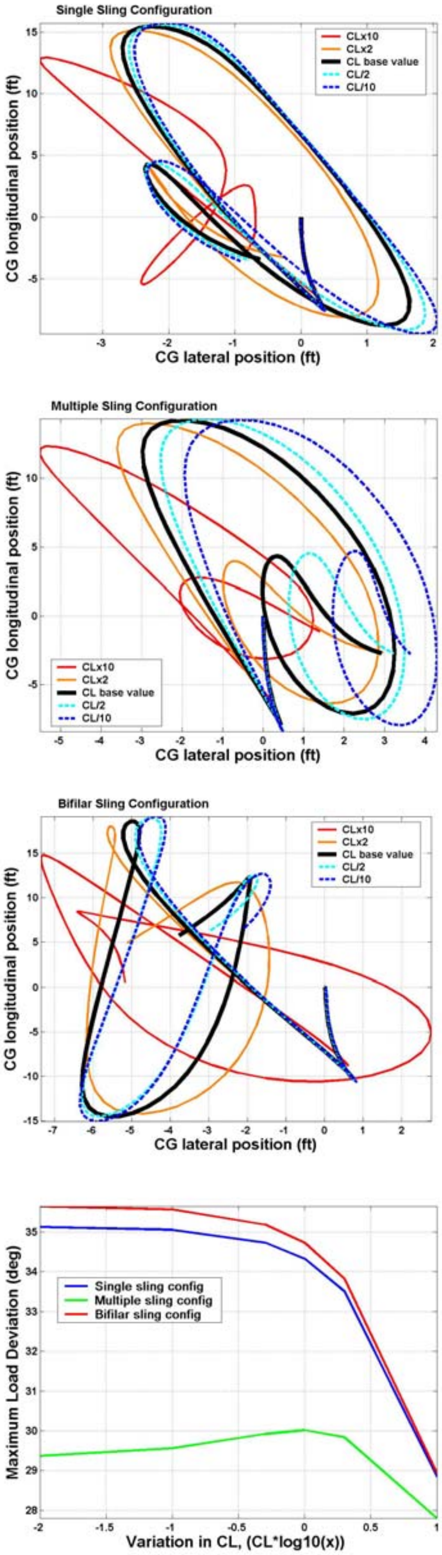

Figure 4 Plan view of load oscillation, and maximum load deviation for variation in load lift coefficient (CL)

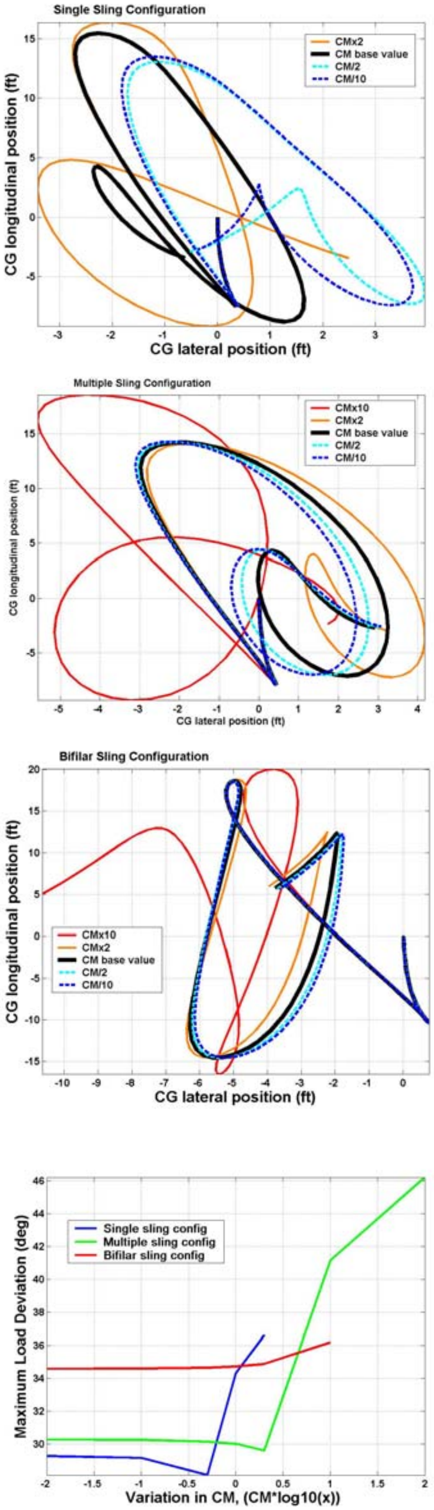

Figure 5 Plan view of load oscillation, and maximum load deviation for variation in load pitching moment coefficient (CM)

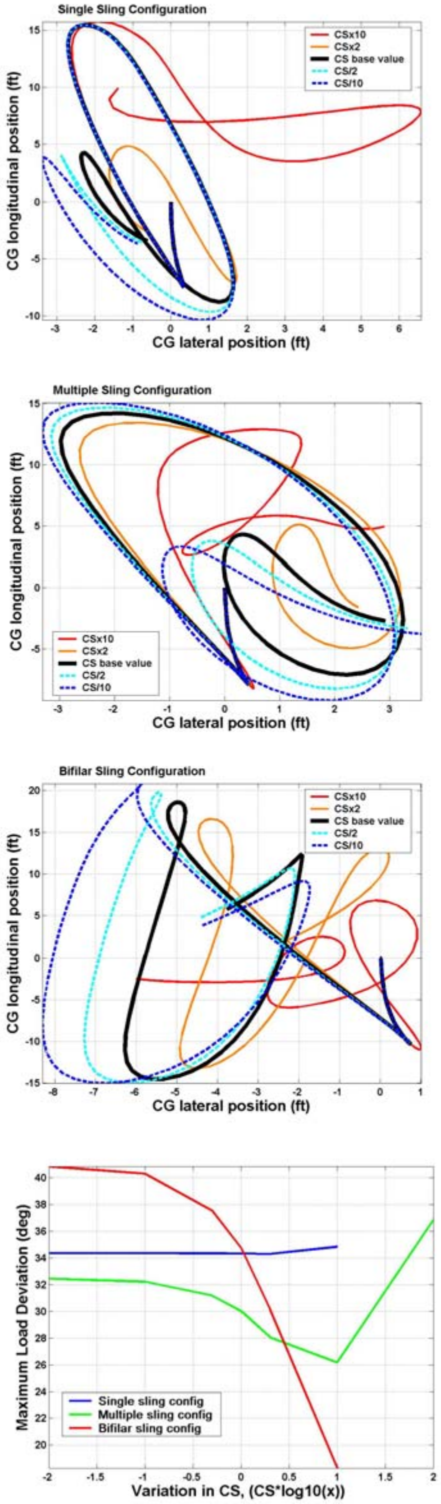

Figure 6 Plan view of load oscillation, and maximum load deviation for variation in load side force coefficient (CS)

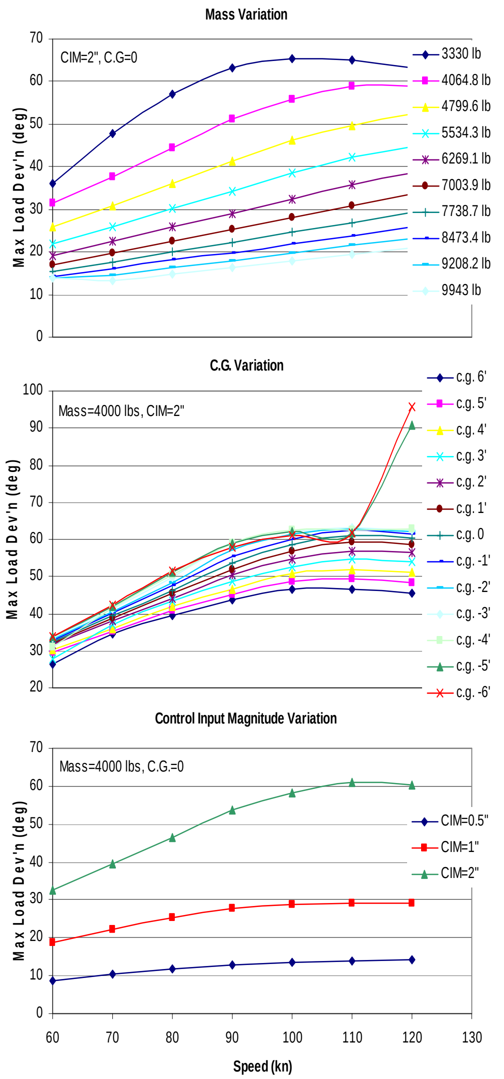

Figure 7 Effect of variation in load mass, cg location and pilot control input on maximum load deviation

5. CONCLUDING REMARKS

A simulation model recently developed using the equations of motion for general slung load systems has been used to examine the effect of various parameters. This has included investigation into the dynamic and aerodynamic parameters of slung loads, and the effects of load mass variation, cg location and pilot control input magnitude on slung load stability.

The preliminary results of the research presented in this paper cover the nature of load oscillations and maximum load deviations. It is hoped these results will aid operators in the identification of load parameters most critical to load stability.

From the test scenarios detailed, the following conclusions can be drawn:

- Increasing CD and CL decreases maximum load deviation
- Increasing CM increases load deviation
- The lighter the load the greater the maximum load deviation
- Increasing forward speed increases maximum load deviation
- The load experiences increased stability for cg positions forward of the center-point
- The larger the pilot control input magnitude, the larger the maximum load deviation

This research is expected to continue and simulation results that do not follow the general trends will be more closely examined.

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