Dynamic Simulation of the CH-47D Helicopter with Single and Multiple Slung Loads

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The long-term aim of this work is to define the operational limits of the Australian Army Chinook CH-47D when carrying mixed density slung loads. This paper presents the first phase in the program: the development of a simple helicopter slung-load model for simulation and analysis of the system dynamics.

General system equations of motion are obtained from the Newton-Euler equations in terms of generalised position and velocity coordinates. The coordinates are partitioned such that the motion due to cable stretching is separated from that due to rigid-body, coupled dynamics. In the formulation used, the constraint forces appear explicitly and an inelastic solution to the resultant generalised accelerations is determined by nulling the stretching coordinates to obtain a relation for the suspension forces.

The model is verified by imposing certain constraints in order to approximate a simple pendulum system and then comparing its behaviour against analytical results. A complete helicopter slung-load system, based on a CH-47B helicopter carrying a standard military container, is then examined in an investigation of the open-loop characteristics. In the investigation, several parameters such as the load-to-helicopter mass ratio are varied and the resulting system modes examined.

Nomenclature

A	square $6n \times 6n$ matrix defining the kinematic relation, $v = Au$
$A1$, L	column partitions of A for elastic and inelastic components of the suspension
$AI1^T$, Λ^T	corresponding row partitions of A^{-1}
D	block-diagonal matrix comprising the system's rigid-body masses and inertias
fg,fa,fc,f^*	vectors of the forces and moments on each body due to gravity, aerodynamics, suspension, and inertia reactions, respectively
$\mathcal{F}_a$	reference frame; $a = N$ for Newtonian space, $a = i$ for axes of body $\mathcal{B}i$ $(i = 1, 2, \ldots, n)$ or $a = cj$ for cable axes of cable $\mathcal{C}j$ $(j = 1, 2, \ldots, m)$
H	matrix which is a basis of the linear vector space containing fc
m	number of suspension cables
mi, Ji	mass and body-axes inertia matrices for body $\mathcal{B}i$
n, d, c	number of rigid bodies, degrees of freedom, and constraints in the inelastic system, respectively
q, u	generalised position and velocity coordinates for the unconstrained system
$q1$,λ	generalised position coordinates defining the inelastic and elastic components of the system motion
$u1$,$\dot{\lambda}$	generalised velocity coordinates defining the inelastic and elastic components of the system motion
r, v	vectors of inertial cg position and Euler angle attitudes, and the inertial cg velocities and angular velocities
s	vector of suspension force parameters
Wi_i	matrix transformation of angular velocities, ωi_i to $\dot{\alpha} i$, for body $\mathcal{B}i$
X	vector containing moments due to Coriolis effects on each body
δ	vector of control inputs for each body
$(\ )^T$	transpose operator
diag{ }	block-diagonal matrix comprised of listed elements aligned on main-diagonal
$(\ )_a$	physical vector given by its coordinates in the frame $\mathcal{F}_a$
$S(V_a)$	skew-symmetric matrix representing cross-product operation for vectors, V, referred to $\mathcal{F}_a$
$(\ )^*$	quantity associated with the cg of a rigid body in the system
∇z	gradient vector of partial derivatives with respect to z

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Introduction

THE operations of helicopters carrying externally slung loads has often been limited and, in some cases, seriously hindered by stability and control problems. Several incidences 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.

A program was consequently initiated within the Defence Science and Technology Organisation (DSTO) to use computer modelling and simulation to assist in defining the operational limits of the Australian Army Chinook CH-47D when carrying slung loads. The first phase in this program has entailed the development of a simple helicopter slung-load model for simulation and analysis in order to provide a better understanding of the system dynamics and various effects involved.

A selection of the results from this work is presented herein. In the second phase, a comprehensive slung-load model is to be developed for integration into a real-time helicopter simulation model. The simulation model will incorporate additional detail, such as the automatic flight control system, load aerodynamics, rotor wake effects, and sling elasticity. Furthermore, there is a requirement to model the dynamics of the helicopter with multiple slung loads of varying density and aerodynamic properties, which has not previously been investigated in this manner.

Background in Simulation

There has been a small but significant amount of work done in investigating the behaviour and control of helicopter slung-load systems. In the 1960's and early 1970's, most of this effort was concentrated in analytical studies, including various stabilisation system designs. Wind-tunnel and flight-test experiments were mainly limited to the establishment of operational limits based on gross aerodynamic instabilities. With the advancement of digital computing, however, came the ability to create more complex analytical models and perform dynamic simulations. This increase in the complexity of the system led to a requirement for better aerodynamic models – both helicopter and load – and the emphasis in experimental work shifted accordingly. These days, there is still some analytical work being done, particularly in the design of automatic control systems, but much of the research is now based on simulation.

In recognition of suspension-related problems encountered with the carriage of external cargo by helicopters, the US Army in 1970 initiated a program aimed at the establishment of design criteria for sling members and attachment points. This program, as well as many subsequent investigations, were undertaken by the Eustace Directorate, US Army Air Mobility Research and Development Laboratory (USAAMRDL). Part of the first phase in the contract, reported by Briczinski and Karas,[1] involved the computerised simulation of a helicopter and external load in real time with a pilot in the loop. Load aerodynamics were incorporated into the model, as well as rotor-downwash effects in hover.

Soon after this, in 1973, Liu[2] conducted an extensive study to select the best technical approaches for stabilising a wide spectrum of externally slung helicopter loads at forward speeds. The simulation model used extended that of Abzug[3] to include load aerodynamics. Several stabilisation systems were evaluated using a moving-base simulator and, of those, an electronic system providing rate and acceleration inputs to the helicopter stability augmentation system (SAS) was favoured.

Following the first program of work sponsored by the Eustace Directorate, a further study to define important flight control system design and handling qualities criteria for moving loads slung beneath tandem-rotor helicopters was conducted in 1974 by Kesler, *et al.*[4] It included theoretical analyses, acquisition, and evaluation of both wind-tunnel and flight-test data, analysis of various problems, and the actual flight simulation of a Boeing-Vertol Model 347 advanced tandem-rotor helicopter with an external load. Another program under the same sponsorship, investigated by Alansky, *et al*,[5] looked into the quantitative limitations of the CH-47 helicopter performing terrain flying with external loads. The simulation used in this investigation comprised a fully coupled total force and moment model and an alternative method of load position-control, named the Active Arm External Load Stabilisation System (AAELSS).

In 1979, a generalised real-time, piloted, visual simulation of a single-rotor helicopter, suspension system, and external load was developed by Shaughnessy, *et al*[6] and subsequently validated for the full flight envelope of a Sikorsky CH-54 Skycrane helicopter and cargo container. The mathematical model described used modified nonlinear classical rotor theory for both the main rotor and tail rotor, nonlinear fuselage aerodynamics, an elastic suspension system, nonlinear load aerodynamics, and a load-ground contact model.

Later, in 1980, Sampath[7] completed his dissertation on the dynamics of a tandem-rotor helicopter slung-load system, which involved modelling and simulation work as well as experimental wind-tunnel tasks. In his formulation, Lagrange's equations were used to write the equations of motion and were divided into two sets: one for the towing vehicle and the other for the slung load. The cables of the sling were modelled as massless linear springs with viscous damping and no aerodynamic properties. The aerodynamic models for the helicopter and load were both implemented using tabulated static data. In 1984, a full nonlinear simulation model of the CH-47B helicopter, developed by the Boeing Vertol Company, was adapted for use in the NASA Ames Research Center (ARC) simulation facility by Weber, *et al.*[8] The mathematical model developed was based on a total force approach in 6 rigid-body DOF along with the option for an externally suspended load in 3 DOF. The aerodynamic models were also quite comprehensive, including steady-state rotor flapping and load aerodynamic effects.

In 1986, Ronen, *et al*[9] developed a new model for a helicopter carrying a sling load on a single point suspension in order to improve on the existing dynamic models and investigate the open-loop characteristics of the system. For the first time, the model took into account the effects of rotor downwash on the load and the unsteady aerodynamics of bluff-body type loads. The nonlinear equations of motion were derived and then separated into two sets: the nonlinear trim equations and the linearised equations for small perturbation about the equilibrium state.

Some of the most recent work in the simulation of helicopter slung-load systems has been conducted by Cicolani and Kanning, *et al*[10,11] at the NASA Ames Research Center. In these reports, the general simulation equations were derived for the motion of slung-load systems consisting of several rigid bodies connected by straight-line cables or links, assumed to be either elastic or inelastic. A formulation for the general system was obtained from the Newton-Euler rigid-body equations with the introduction of generalised velocity coordinates. The same approach for simulating helicopter slung-load dynamics has been adopted in the current task. Following this paper, a DSTO Technical Report will present the implementation of the equations in more detail, including their extension to the case of multiple slung loads.

System Dynamics

System Description

Helicopter slung-load systems fall into a class of multibody systems consisting of two or more rigid bodies connected by massless 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. Several examples of the various configurations under consideration are illustrated in Figure 1. The model is comprised of n rigid bodies, with m straight-line links supporting a single force in the direction of the link. For cables, this is strictly a tensile force − cable collapse is not considered. If the links are modelled as inelastic, $c \leq m$ constraints are imposed on the motion of the bodies and the system has $d = 6n - c$ DOF. If the links are modelled as elastic, there are $6n$ DOF.

In the model used, a number of simplifying assumptions were made. These included the exclusion of cable aerodynamics and rotor-downwash effects. Furthermore, load aerodynamics have been neglected for this initial stage of the work program. Despite these limitations, the system defined above has proven adequate for simulation studies[11] in which the low-frequency behaviour is of primary interest.

Generalised Equations of Motion

The simulation model used for this first stage of work was based on the helicopter slung-load system introduced by Cicolani, *et al*.[12] In this formulation, the general system equations of motion are obtained from the Newton-Euler equations in terms of generalised coordinates and velocities. Following the explicit constraint method, which utilises d'Alembert's principle, the system is partitioned into coordinates such that the motion due to cable stretching is separated from that due to rigid-body, coupled dynamics. As a consequence, the constraint forces appear explicitly and a solution to the resultant generalised accelerations is determined by assuming a simple spring model for the cable.

It is also possible to obtain a solution to the inelastic approximation by nulling the stretching coordinates to obtain an explicit relation for the suspension forces. The result is computationally more efficient than conventional procedures and is readily integrated with the

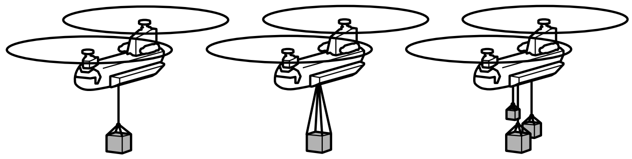


Fig. 1 Single Point Slung-Load Configurations

formulation for elastic suspension. Another benefit of the formulation is that it is easily applied to complex, multiple body systems, as in the current work. To date, all code development has been done in the MATLAB numerical computing environment, which provides a high-performance language, amenable to modelling and simulation type work.

Solution to Constrained System

The Newton-Euler equations of motion for a system of n rigid bodies can be expressed in 6 DOF as

$$\begin{aligned} mi\, g_N + FAi_N + FCi_N - mi\, \dot{V}i_N^* &= 0 \\ MAi_i + MCi_i - Ji\, \dot{\omega}i_i - S(\omega i_i)\, Ji\, \omega i_i &= 0 \end{aligned} \tag{1}$$

In this expression, the first set of equations represents the balance of translational forces, referred to inertial axes as indicated by the subscript N. The second set represents the sum of moments about each body's cg, referred to the corresponding axes as indicated by the subscript $i = 1, 2, \ldots n$. Both equations consist of several terms, including the forces and moments due to gravity, aerodynamics, and inertia. The first term, $mi\, g_N$, is the gravity force acting through each cg, FAi_N and MAi_i are the aerodynamic forces and moments, and FCi_N and MCi_i are the cable forces and moments, respectively. The terms, $mi\, \dot{V}i_N^*$ and $Ji\, \dot{\omega}i_i$ constitute the inertial reaction of each body and $S(\omega i_i)\, Ji\, \omega i_i$ is the moment induced by Coriolis' effect.

It is convenient to write these equations as a single expression in matrix form. This is achieved by defining the configuration position vector, r, which lists the rigid-body cg positions for each body and Euler angle rotations for each body. Similarly, the configuration velocity vector, v, lists the translational velocities and body-axis angular rates.

Using fg, fa, fc, and f^* for the combined force and moment vectors due to gravity, aerodynamics, cable suspension, and inertia reactions, the equations of motion can be written as

$$fg + fa + fc + f^* = 0 \tag{2}$$

where

$$f^* = -D\dot{v} - X \tag{3}$$

Here, D is a block-diagonal matrix comprising masses and inertias along the main diagonal, $\dot{v}$ is the configuration acceleration, and the vector X contains the Coriolis terms.

In order to derive a set of simulation equations for the system, a solution to the equations of motion described above must be found in terms of the configuration acceleration. For the helicopter slung-load system under consideration, it is useful to first formulate a set of generalised coordinates and velocities which describe the motion of the inelastic system and the effect of cable stretching as two distinct subsets. The cable-constraints on the helicopter slung-load system can be considered holomonic, that is, they are independent functions of position only. In addition, for the following system, the constraints are posed as time-invariant. The special cases of cable winching and attachment point movement are not considered.

The system can be partitioned according to the $6n$ generalised position coordinates as

$$q = \begin{bmatrix} q1 \\ \lambda \end{bmatrix} \tag{4}$$

where $q1$ is the list of d position coordinates for a system with inelastic suspension and λ are the c coordinates which describe the variation in cable length due to stretching. The configuration velocity can be expressed as a linear function of the generalised velocity coordinates, that is,

$$v = Au \tag{5}$$

where

$$u = \begin{bmatrix} u1 \\ \dot{\lambda} \end{bmatrix} \text{ and } A = \begin{bmatrix} A1 \\ L \end{bmatrix} \tag{6}$$

Differentiating equation (5) and substituting $\dot{v}$ into equation (3) yields

$$f^* = -D\dot{A}u - DA\dot{u} - X \tag{7}$$

Now, replacing f^* in equation (2), a simplified version of the equations of motion can be written as

$$fo + fc - DA\dot{u} = 0 \tag{8}$$

where the vector fo, the sum of all external forces and inertial coupling terms, is given by

$$fo = fg + fa - D\dot{A}u - X \tag{9}$$

Since the system has been specified in terms of its generalised coordinates, A is a square $6n \times 6n$ nonsingular matrix and a solution for the generalised acceleration coordinates exists. From equation (8),

$$\dot{u} = A^{-1}D^{-1}[fo + fc] \tag{10}$$

It should be noted here that the inverse matrix A^{-1} simply represents the relation $u(v)$, which can be derived analytically from the kinematics, just as the matrix A represents $v(u)$. In partitioned form, the acceleration equation may be written as

$$\begin{bmatrix} \dot{u}1 \\ \ddot{\lambda} \end{bmatrix} = \begin{bmatrix} AI1^T \\ \Lambda^T \end{bmatrix} D^{-1}[fo + fc] \tag{11}$$

where $AI1^T$ and Λ^T are the $6n - c$ and c rows of A^{-1} which define the inelastic and elastic acceleration components, $\dot{u}1$ and $\ddot{\lambda}$, respectively.

The last step required in determining a solution for the generalised accelerations is to calculate the constraint force, fc. For a system with c constraints, the constraint force can be expressed as

$$fc = Hs \tag{12}$$

where the columns of the matrix H are configuration vectors and $\text{rank}\{H\} = c$. The elements of the vector s are arbitrary scalars. The exact form of this equation and its solution depend on whether the cables are considered elastic or not.

For a general elastic system, the suspension forces can be given as the sum of forces and moments applied at each attachment point by the suspension cables. The tension in each cable can be represented by a simple spring model.

For an inelastic system, it can be shown that the columns of H and Λ both form bases of the same linear vector space and therefore Λ can be used to define the constraint force, that is,

$$fc = \Lambda s \tag{13}$$

where the vector s will have units of force if the coordinates λ are lengths. To find a solution for the inelastic system, the constraint acceleration, $\ddot{\lambda}$, is set to zero. Substituting into the elastic component of equation (11) gives

$$0 = \Lambda^T D^{-1}[fo + \Lambda s] \tag{14}$$

the solution to which is

$$s = -[\Lambda^T D^{-1}\Lambda]^{-1}\Lambda^T D^{-1} fo \tag{15}$$

Hence, the constraint forces can be calculated and the generalised accelerations solved using equation (10).

Simulation of System Dynamics

Prior to executing the simulation, several components must be customised to the helicopter slung-load configuration of interest.

The first step in setting up the simulation equations involves determining the constraints of the inelastic system and then defining the generalised velocity coordinates ($u1$, $\dot{\lambda}$). Using these coordinates in kinematic relations for the system, it is then possible to obtain expressions for the system matrices, A, A^{-1}, and $\dot{A}$. The selection of appropriate coordinates is case specific; however, it is possible to choose them so that they consist largely of natural vectors. In most applications, including that discussed in this paper, u is comprised of the cg velocity of a reference body (typically the helicopter), the cable velocities, and the angular velocities of all bodies including both helicopter and loads.

Next, an appropriate representation for the suspension cables must be chosen. For inelastic cables, fc is calculated from any basis of the constraint force space, Λ, and the corresponding constraint force parameters, s, as in equation (13).

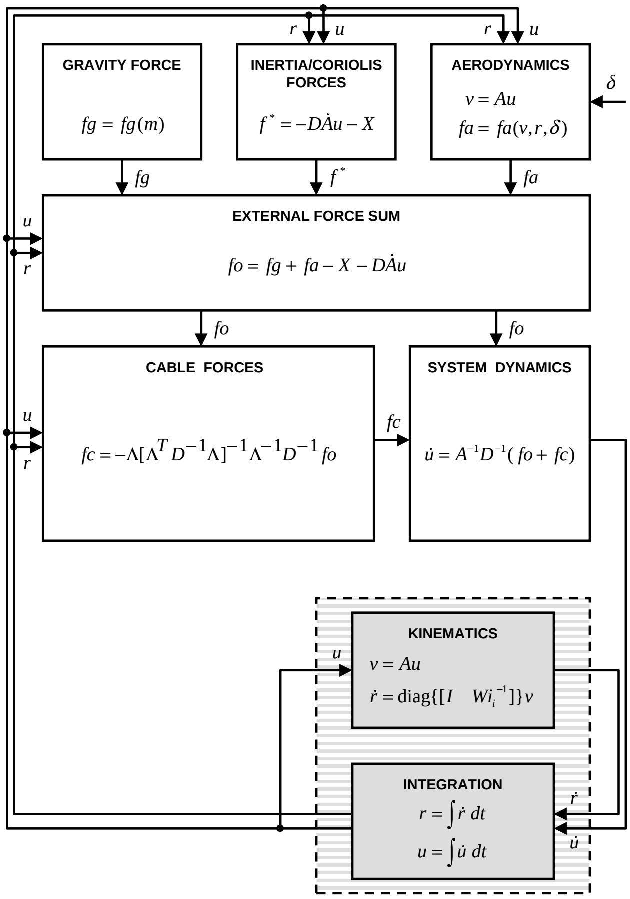


Fig. 2 Simulation Flow Diagram

For the last step, the aerodynamic and inertial properties of the both helicopter and loads need to be implemented in the model. For most rigid bodies, the aerodynamic forces and moments are a function of the configuration velocities and displacements, v and r, and the control inputs, δ. Typically, the helicopter aerodynamic model neglects position- and acceleration-dependant effects, such as interbody/ground interference and unsteady aerodynamics. However, these are often secondary in nature and the resulting model is adequate for simulation under most conditions. Aerodynamic models for loads, which are generally unsteady and of much higher order, are less well understood or replicated.

Once the system has been configured, the dynamic simulation can proceed. First, the initial state, (u, r), and the trim state, (u_0, r_0), must be set. Then the integration loop is started and the following steps are executed in sequence, according to the flow-diagram of Figure 2:

1. Determine the aerodynamic force, fa, inertia and Coriolis forces, f^*, and gravity force, fg, all in inertial axes. Assuming the aerodynamic model is written in body axes, an angular transformation will be required for fa. The configuration velocity, v, can be calculated from the generalised velocity, u, using the kinematic matrix, A.

2. Sum the external forces, fa, f^*, and fg to yield the configuration force, fo.

3. Using the configuration force along with matrices derived from the current state, (u, r), and the configuration geometry, solve the cable force, fc, for either elastic or inelastic suspension models.

4. Compute the generalised accelerations, $\dot{u}$, from the inverse kinematic matrix, A^{-1}, and the inverse mass matrix, D^{-1}.

5. Compute the velocity, $\dot{r}$, from the configuration velocity and inverse transformation matrix, W^{-1}.

6. Apply an integration step to predict the new state, (u, r), and repeat the sequence.

At this early stage, all code development has been done in the MATLAB[13] numerical computing environment, which provides a high-performance language amenable to modelling- and simulation-type work. It is important to stress that this *pilot* simulation was not intended to run in real-time, but rather produce the appropriate output for subsequent replay and analysis. At a later stage, the code will be ported to a platform-specific compiled language suitable for piloted, real-time simulation.

The Helicopter Slung-Load Simulation program, HSLSIM, consists of several modules. These including the main script, integration function, differential equation solution, aerodynamic model, and various output and replay functions. The simulation is run through the 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 integration function. The integration function, ODE45, is problem independent and based on an algorithm which combines 4th and 5th order Runge-Kutta formulas for ordinary differential equations. It requires a function tailored to the problem at hand, which provides a point solution to the differential equation. For the helicopter slung-load simulation, this function represents the core of the code and implements much of the above flow diagram. The aerodynamic models for both helicopter and loads are called from within this function. They can be as simple or as complex as desired, but must output total force and moment variables. Hence, if small-perturbation aerodynamic models are to be used, they must be augmented with the corresponding trim forces and moments. The cable elastic model can also be implemented as a separate function, although this was not done, since the spring-damper model is fairly standard and easily included in the solution function. Following summation of the external forces and solution of the internal (cable) forces, the solution function computes the generalised accelerations and velocities, $(\dot{u}, \dot{r})$, at the current state. This point solution is passed to the integration function and the simulation loop continues.

It is also possible to calculate a linear model by numerical approximation of the Jacobians $\nabla_u \dot{u}$ and $\nabla_\delta \dot{u}$ from the nonlinear system.

This model will have the form

$$\dot{u} = [\nabla_u \dot{u}]u + [\nabla_\delta \dot{u}]\delta \tag{16}$$

and can be used for an alternative linear simulation about the trim state. Another use is in various linear system analyses, such as the determination of the natural modes, as will be discussed in the following section.

Analysis of Model Behaviour

The open-loop behaviour of the simulation model developed was analysed at two levels of complexity. First, the system was approximated by an equivalent pendulum model in order to investigate the dynamics of the load itself. Second, a fully coupled helicopter slung-load model was constructed to assess the general behaviour and effect of various parameters on the system dynamics.

The simulation was verified for both models using the system given by Ronen[9] for a 35000 lb CH-53D helicopter with a single slung load. The aerodynamic stability derivatives used were obtained from Heffley, *et al*[14], with several small modifications made as reported by Ronen. Since the aim of this analysis was simply to determine the modes of oscillation for the helicopter slung-load system, the Automatic Flight Control System (AFCS) was not implemented.

The slung load chosen was a standard military container, known as a MILVAN, which is a common helicopter cargo used in many commercial and military operations. The dimensions of a MILVAN container are 20×20×8 ft and the mass typically varies from 4000 lb (empty) to 20000 lb (full).

Simple Pendulum-type System

The first phase of the analysis involved an investigation into the dynamics of simple pendulum-type systems. For this purpose, the full helicopter slung-load simulation model developed was constrained so as to approximate a two-body pendulum system. Furthermore, the aerodynamic effects of both helicopter and load were excluded from the model.

In order to verify the simulation developed, a number of accuracy checks were made within the code itself, such as the requirement $\ddot{\lambda} = 0$ for inelastic suspension. Comparisons were also made against those previously reported in a numerical example given by Ronen.[9] In addition, analytical results were calculated for the modes of similar pendulum systems.

In this example, the load-to-helicopter mass ratio, η, was set to 0.05. The sling configuration used consisted of a single pendant suspension and bridle, similar to the first system of Figure 1. The total length between the helicopter attachment point and the load cg was 25 ft and the bridle-to-sling length ratio was 0.4.

For the system examined, there are two modes in both longitudinal and lateral axes. Essentially, the low frequency mode is associated with the pendulous motion of the load along the total sling length. The higher frequency mode is associated with the coupled pitching (or rolling) motion of the load and bridle and the pendant suspension. Values for the natural frequencies obtained from the analytical formulation and the simulation programs are listed in Table 1. The analytical results were obtained from the characteristic equation for a simple two-body pendulum system. Natural frequencies generated by the simulation code HSLSIM are shown for two conditions. One was constrained so as to approximate the pendulum system used in the analytical derivation, which for the longitudinal case included constraints in translation along both y and z axes and constraint in rotation about the y axis. The other model was free to move in all axes, providing a closer approximation to the real system. The frequencies obtained in the analysis by Ronen, using the simulation code EOMPROG, are also shown.

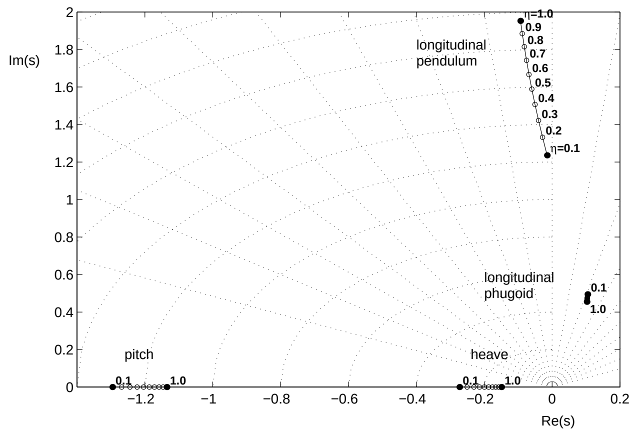
Table 1 Longitudinal Pendulum Natural Frequencies for the CH-53D and MILVAN System in Hover

Technique	Frequencies (rad/s)	
	1st Mode	2nd Mode
Analytical	1.12	3.86
HSLSIM (*Constrained*)	1.12	3.86
HSLSIM (*Free*)	1.15	3.86
EOMPROG[9] (*Free*)	1.14	3.84

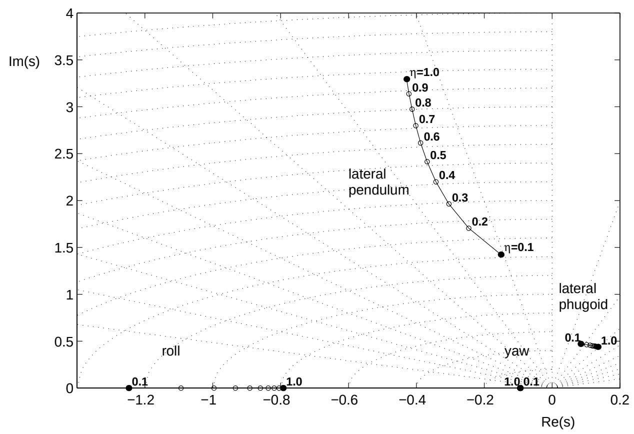
Table 2 Lateral Pendulum Natural Frequencies for the CH-53D and MILVAN System in Hover

Technique	Frequencies (rad/s)	
	1st Mode	2nd Mode
Analytical	1.15	7.17
HSLSIM (*Constrained*)	1.16	7.17
HSLSIM (*Free*)	1.25	7.18
EOMPROG[9] (*Free*)	1.24	7.14

Agreement between the analytical results and the constrained model is very good. However, there are some small discrepancies between these results and those obtained for the unconstrained models. This can be explained by an additional coupling effect in the unconstrained models, as the sling force at the attachment point produces a moment about the helicopter cg. The effect is more prominent in the lateral case, since the helicopter moment of inertia is much lower in that axis. Differences between the unconstrained models generated in HSLSIM and EOMPROG are understandable, as they were generated by two different approaches. The simulation code HSLSIM incorporates a full nonlinear representation of the helicopter slung-load system, which was linearised numerically about the trim state to obtain a Jacobian matrix for model analysis. Using this approach would therefore incur errors in the numerical approximation. EOMPROG, on the other hand, is based on an explicitly linear small-perturbation formulation and consequently errors would arise from such simplification as the small angle assumptions and the exclusion of higher order terms.



a) Longitudinal Eigenvalues



b) Lateral Eigenvalues

Fig. 3 Variation of CH-47B + Load System Eigenvalues with Load-to-Helicopter Mass Ratio

Helicopter Slung-Load System

In this phase, the complete helicopter slung-load system, based on a Chinook CH-47B carrying a standard military container, was examined in an investigation of the open-loop characteristics. The models used were obtained through numerical linearisation of the full nonlinear system, as previously explained. Neither the load aerodynamics, nor the effect of rotor downwash on the dynamics of the load were taken into account. Several parameters such as the load-to-helicopter mass ratio, suspension configuration, and number of loads were varied and the resulting system modes examined. Only the first set of results has been included here. The complete set will be detailed in a forthcoming DSTO report.

A multiple-cable configuration similar to the second system of Figure 1 was used in this analysis. Eigenvalues for the decoupled longitudinal and lateral models at 0.1 KTAS were calculated for a range of values in the load-to-helicopter mass ratio (0.1 to 1.0) and are presented in Figure 3.

The longitudinal motion consists of essentially four modes: pitch subsidence, heave, load pendulum, and phugoid. The pitch subsidence and heave are pure-damping modes, whereas the phugoid and load pendulum modes also have oscillatory components. The damping of these former two modes can be seen to reduce with an increase in the mass ratio. The load pendulum mode, which describes the motion of the load with respect to the helicopter, changes quite considerably with the mass ratio. For low ratios (small load mass), this mode behaves much like a simple pendulum independent of the helicopter motion, with corresponding frequency. As the mass ratio is increased, the inertia of the load becomes more significant and the frequency increases similar to an equivalent double-pendulum system. The unstable phugoid mode is characteristic of most aircraft and, for helicopters, describes a long-period 'swinging' motion in which the forward velocity and attitude oscillate 180° out of phase. There is little change in this mode, save a slight decrease in frequency with an increase in the mass ratio.

The decoupled lateral motion also consists of four modes: roll subsidence, yaw subsidence, pendulum, and phugoid. In this case, the roll and yaw subsidence modes are pure damping. The lateral phugoid and pendulum modes are similar to their longitudinal counterparts and have oscillatory components. The damping of the roll mode reduces significantly with an increase in the mass ratio. The pendulum mode also becomes slightly more stable and increases in frequency, much like the longitudinal pendulum mode. However, the frequency is generally much higher, because of the difference in the moments of inertia about x and y axes. Perhaps the most important feature of this behaviour is the variation in the phugoid mode. Unlike the longitudinal case, the phugoid mode becomes much more unstable with an increase in the mass ratio. This mode will have the greatest effect on the system dynamics and thus helicopters carrying heavy loads will generally require a greater degree of lateral control.

Further to the modal analysis, a number of simulations were run in order to demonstrate the typical behaviour of the helicopter slung-load system. One such simulation is illustrated in Figures 4 and 5 for a multiple-load configuration with individual attachment points and single cable slings.

In these plots, u and w are the velocities in x and z directions of the body axes, respectively, q is the pitch rate, θ is the pitch angle, and θ_c is the cable angle displaced from the vertical position. The cable tension force, nondimensionalised by the load weight, is denoted by fc. For this simulation, the helicopter and slung loads were given an initial forward velocity of 80 ft/s and the loads were displaced from their static equilibrium positions by arbitrary amounts. The controls were held fixed throughout the 10 second manoeuvre. Both primary and secondary pendulum modes can be identified in the response of each load, most notably in the cable angle displacement. In general, the system behaved as expected, with the momentum of each load – functions of θ_c – feeding into the longitudinal acceleration of the helicopter, and vice versa. It is also worth noting that the peaks in the cable tensions correspond to the extrema of the pitch rates and have a maximum value of up to 1.2 times their static load.

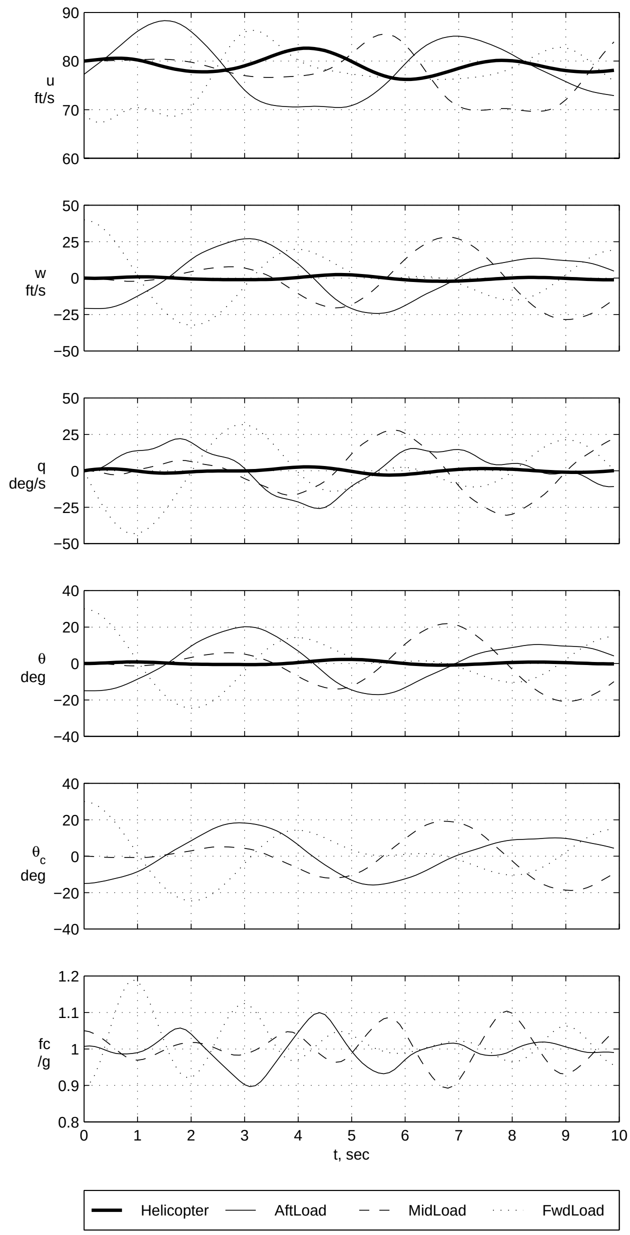


Fig. 4 CH-47B Time-History Reponse

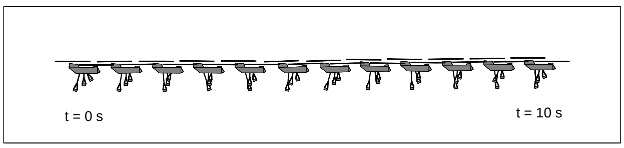


Fig. 5 CH-47B Response Simulation

Concluding Remarks

A simulation model was produced using the equations of motion for general slung-load systems developed by Cicolani, *et al.*[12] The formulation used is based on the Newton-Euler equations written in terms of generalised coordinates and can be readily adapted to systems with either elastic or inelastic suspension. All code development, including the simulation routine, linear analysis, and graphical replay tools, has been done in MATLAB. Further to the model described, the simulation has also been extended to incorporate multiple-load systems.

Following validation of the code against both analytical solutions and previously pubilshed results, using a simple pendulum-type system, the open-loop characteristics of a full helicopter slung-load system was examined. The results presented include modal analysis of a single-load system and simulation of a multiple-load system. It was found that the frequency of the longitudinal and lateral pendulum modes generally increases with the load-to-helicopter mass ratio. More importantly, the lateral phugoid becomes significantly more unstable as the mass ratio is increased. For the simulation demonstrated, the dominant natural frequencies were identified.

This paper presents only a broad overview of the generalised equations and some selected results from the system analysis. The full details of the simulation model and various analyses will be published in a forthcoming DSTO report.

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