Helicopter Slung Load Simulations Using Heli-Dyn+

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This paper demonstrates a fast and convenient way to model the dynamics of a helicopter with a slung load. A new software tool called Heli-Dyn+ is used to generate high fidelity helicopter math models. One of the benefits of Heli-Dyn+ is that helicopter math models can be exported as dynamic libraries into different software environments. In this paper we develop a generic 3-DOF slung load dynamic model in MATLAB/Simulink. Then the slung load model is integrated with a nonlinear 6-DOF helicopter model exported from Heli-Dyn+. Simulation results showing longitudinal and lateral responses of the combined model are presented for various flight scenarios.

I. Introduction

Applications of helicopters carrying external suspended loads are of significant interest in the aerospace research community for the last 40 years. Especially, most research has been concentrated on the mathematical modeling and stability analysis of such systems. In previous works, mathematical modeling and the stability of single-slung loads as well as multiple loads are studied considering rigid and elastic wires, including single and multiple connection points (Refs.1,2,4,6). Generally, such systems are known to have inherent stability problems, according to this some of previous works focused on (Refs.3,5) the design of stability augmentation systems for slung load conditions. Various flight tests and wind tunnel experiments are performed as well in the past, to predict the aerodynamic characteristics of suspended slung loads (Refs.7,8,9).

Modeling the interaction between a slung load and a helicopter is usually a challenging modeling and simulation problem. The combination of right methods and software, however, would ease the job and allow fast modeling and high fidelity simulations. Helicopter itself, without any suspended load, is already known to be a difficult modeling problem. Since fidelity is already a question for helicopter models, helicopter-slung load interaction becomes even difficult to predict. Therefore, using high fidelity helicopter models might be an appropriate option to increase the correctness of helicopter-slung load interactions. Especially, for the simulation environments where the rotorcraft is interacted with various external dynamics (such as a suspended slung load), high fidelity helicopter models which can be integrated with ease to any external dynamics, becomes an essential need.

In this paper, we use an in-house build modeling and simulation tool called, Heli-Dyn+. The modeling activity is fast as the software uses geometric, inertial and minimal aerodynamic data to model the helicopter. Yet, high fidelity component model libraries allow for a 6-DOF nonlinear helicopter simulation. Next the model can be trimmed and exported into MATLAB/Simulink (Ref.10). A slung load model developed in MATLAB/Simulink is then integrated to the simulation. As the modeling is fast and simple, variations in the helicopter model or the slung load characteristics can be reflected to the simulation rather quick.

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II. Helicopter Model

The helicopter model is developed using the Heli-Dyn+ software (Ref.14). Heli-Dyn+ is a new software tool developed by Aerotim LLC. to build helicopter models, trim, linearize, perform simulations and export models to be used in third party applications. A screenshot of Heli-Dyn+ is presented in Figure 1. Heli-Dyn+ uses component built-up to generate a nonlinear 6-DOF simulation model. Model libraries are used for each helicopter component, such as the main rotor, tail rotor, fuselage, landing gear, etc (Figure 2). Each component library requires geometric, inertial and aerodynamic parameters. For example, in order to model the main rotor, parameters like radius, chord, hub position, blade twist, blade profile etc. are needed. Once the parameters are established, the user can analyze the helicopter model by trimming, linearizing or evaluating performance characteristics of the helicopter (Figure 2). The software is developed such that simulations can be run within the software, however a model export function allows the model to be integrated into a C++ or MATLAB/Simulink software environments via a dynamic link library (.dll) and configuration file (Figure 3). A common use is to export a helicopter model and integrate it with a controller algorithm developed in MATLAB/Simulink. Moreover, the model can than be integrated with a real-time simulation environment like Flightgear (Refs.14,15).

Export function of Heli-Dyn+ allows the user to export not the helicopter only but the components as well. Main rotor, tail rotor and such components can be exported independently into MATLAB/Simulink and C++ environments. In Figure 3, the components which can be exported through the graphical user interface is presented.

Heli-Dyn+ allows the exported model to interact with external components through its force and moment input scheme. In this paper the slung load model is integrated with the exported model in MATLAB/Simulink. The slung load dynamics receive the state information from the helicopter model and combine it with its own. The generated forces and moments due to the slung load dynamics are then fed back to the helicopter model through the external force moment scheme of the helicopter model.

![Heli-Dyn+ Graphical User Interface](image.png)

Generated helicopter models can be trimmed at various flight conditions using the trim function of Heli-Dyn+. As well as trimming, linearization of the helicopter model can be performed using the linearization button (Figure 2). In that way, the famous linear matrices are made available to the user. Therefore, the stability of the generated models can be analyzed and controller designs become available. We developed controller algorithms using the linear matrices obtained from Heli-Dyn+. In all the simulations, performed in that paper, those controllers are used.
A helicopter model similar to the UH-1H utility helicopter is modeled in Heli-Dyn+ and exported to the Simulink environment. The main rotor is modeled using Peters-He Finite State Dynamic Wake model with second order flapping dynamics, whereas tail rotor is modeled using Blade Element Momentum Theory. Flat plate drag areas are used to model the fuselage and first order aerodynamic models are used for the aerodynamic surfaces.

Figure 2. Model Input Tabs Of Heli-Dyn+

Figure 3. DLL Export Function Of Heli-Dyn+
III. 3-DOF Slung Load Model

The slung load dynamics is developed in Matlab/Simulink and is later integrated with the helicopter model. Slung load is treated as a pendulum and equations of motion of a 3-DOF pendulum is presented in this section. In Refs. 1, 2, 6, 11, 12 and 13 similar models are given.

Slung Load Kinematics

A depiction of the slung load with the helicopter is given in Fig. 4. Here, the slung load is assumed to be at a constant distance from the confluence point. In other words the distance of B with respect to point C is fixed. The following kinematic relations can be written for the position and the velocity vectors of the slung load.

\[ r_b = T_{ib} r_c + r_{cb} \]  

Here, \( r_b \) is the position vector of the slung load with respect to the inertial frame shown in Figure 4. Note that, in these derivations Earth is assumed to be flat and non-rotating. \( T_{ib} \) is the transformation matrix from the inertial to the slung load body frame. The velocity (\( V_b \)) and acceleration (\( a_b \)) vectors of the slung load can be found by differentiation:

\[ V_b = T_{ib} V_c + \omega_b \times r_{cb} \]

\[ a_b = T_{ib} V_c + \Omega_b r_{cb} + \dot{\Omega}_{cb} \]

In eqns. 2 and 3, \( \omega_b \) is the angular velocity vector of the slung load and all components are given as components of the slung load body frame, \( \omega_b = [\omega_b(1) \ \omega_b(2) \ \omega_b(3)] \). \( T_{ib} \), \( \Omega_b \) and \( R_{cb} \) which are the skew symmetric forms of \( \omega_b \) and \( r_{cb} \) are defined below.

\[ T_{ib} = \begin{bmatrix} \cos \theta_b \cos \psi_b & \cos \theta_b \sin \psi_b & -\sin \theta_b \\ \sin \phi_b \sin \theta_b \cos \psi_b - \cos \phi_b \sin \psi_b & \sin \phi_b \sin \theta_b \sin \psi_b + \cos \phi_b \cos \psi_b & \sin \phi_b \cos \theta_b \\ \cos \phi_b \sin \theta_b \sin \psi_b + \sin \phi_b \cos \psi_b & \cos \phi_b \sin \theta_b \sin \psi_b - \sin \phi_b \cos \psi_b & \cos \phi_b \cos \theta_b \end{bmatrix} \]

\[ \Omega_b = \begin{bmatrix} 0 & -\omega_b(3) & \omega_b(2) \\ \omega_b(3) & 0 & -\omega_b(1) \\ -\omega_b(2) & \omega_b(1) & 0 \end{bmatrix} \]
\[ R_{cb} = \begin{bmatrix} 0 & -r_{cb}(3) & r_{cb}(2) \\ r_{cb}(3) & 0 & -r_{cb}(1) \\ -r_{cb}(2) & r_{cb}(1) & 0 \end{bmatrix} \] (6)

**Slung Load Dynamics**

Using Newton’s Second Law we can write the force balance at the slung load CG.

\[ m_{ibb} = F_{aero}^b + W^b - T_{ib} F_R \] (7)

In eqn.7, \( F_R \) contains the reaction forces at the confluence point. By multiplying \( F_R \) with \( T_{ib} \), \( F_R \) is transformed into the slung load body frame. \( F_{aero} \) contains the aerodynamic forces. \( W^b \) contains the gravitational forces acting on the slung load. These forces are written in the slung load body frame as follows:

\[ F_{aero}^b = -\frac{1}{2} \rho S_b |V_b| C_D^b \begin{bmatrix} V_b(1) \\ V_b(2) \\ V_b(3) \end{bmatrix} \] (8)

\[ C_D^b = C_{D_0} + C_{D_\alpha} \alpha_b^2 \] (9)

\[ W^b = m_{ib} g \begin{bmatrix} -\sin(\theta_b) \\ \sin(\phi_b) \cos(\theta_b) \\ \cos(\phi_b) \cos(\theta_b) \end{bmatrix} \] (10)

After substituting eqn.3 into eqn.7 the following equation is obtained:

\[ m_{ib} T_{ib} \dot{V}_c - m_{ib} R_{cb} \dot{\omega}_b + T_{ib} F_R = F_{aero}^b + W^b - m_{ib} \Omega_b \dot{\Omega}_b r_{cb} \] (11)

The corresponding moment equations at the slung load CG are

\[ I_b \dot{\omega}_b + \omega_b \times I_b \dot{\omega}_b = M_c - r_{cb} \times T_{ib} F_R \] (12)

\[ I_b \dot{\omega}_b + \Omega_b I_b \dot{\omega}_b = M_c + R_{cb} T_{ib} F_R \] (13)

In eqn.12, \( M_c \) is the reaction moments acting on point C. Since the slung load is expected to turn in the yaw channel as the helicopter turns, this coupling moment is needed, and modeled as a spring-damper mechanism as follows:

\[ M_c = \begin{bmatrix} 0 \\ 0 \\ K(\psi_p - \psi_b) + C(\dot{\psi}_p - \dot{\psi}_b) \end{bmatrix} \] (14)

Equations 11 and 13 can be written in matrix form as follows:

\[
\begin{bmatrix} -m_{ib} R_{cb} & T_{ib} \\ I_b & -R_{cb} T_{ib} \end{bmatrix} \begin{bmatrix} \ddot{w}_b \\ F_R \end{bmatrix} = \begin{bmatrix} F_{aero}^b + W^b - m_{ib} \Omega_b \Omega_b r_{cb} - m_{ib} T_{ib} \dot{V}_c \\ -\Omega_b I_b \dot{\omega}_b + M_c \end{bmatrix}
\] (15)

Equation 15 represents the resulting slung load model. Here, we solve for \( \ddot{w}_b \) at each simulation time step. Note that \( \dot{V}_c \) is assumed to be known and located at the right-hand side of the equation.
IV. Simulations and Results

A. Integrating the Models

The slung load dynamics given in eqn.15 and the helicopter math model exported from Heli-Dyn+ are combined in the Matlab/Simulink environment. In order to combine the two models, the required signals are connected. The exported model from Heli-Dyn+ is able to take external forces and moments on its center of gravity. Therefore, reaction forces $F_R$ are calculated using eqn.15 and are added to the helicopter as external forces at its CG, and so are the reaction moments $M_R$. $F_R$ and $M_R$ are transformed into the helicopter body axis:

$$ M_R^H = -T_p T_b^T M_c $$

(16)

Here, $T_p$ is the transformation matrix which can transform a vector defined in the inertial frame to the helicopter body frame. Since $F_R$ is defined in the inertial frame, the following transformation is also needed before inputting $F_R$ into the helicopter CG:

$$ F_R^H = T_p^T F_R $$

(17)

The interaction from the helicopter to the slung load is apparent in eqn.15. The velocity and acceleration at the connection point is required. As a result the accelerations and velocities of the body frame of the helicopter CG are re-calculated for the point of connection of the load. Since eqn.15 require these variables to be defined in the inertial frame the following transformations are done:

$$ \dot{V}_c = T_p^T \dot{V}_c^H $$

(18)

$$ V_c = T_p^T V_c^H $$

(19)

As a result the helicopter and slung load models exhibit component interaction. Modeling block diagram, including the interaction between helicopter model and slung load dynamics can be found in Figure 5.

Figure 5. Simulation Block Diagram
B. Matlab/Simulink Environment

The simulation block diagram shown in Figure 5 is modeled in MATLAB/Simulink (Fig. 6). In Fig.6 the blue subsystem block represents the helicopter model exported using Heli-Dyn+. The yellow subsystem block is the 3-DOF slung load model given in Equation 15. And the orange blocks are inner and outer loop controller algorithms developed to perform desired maneuvers.

Figure 6. Simulink Environment for Helicopter, Slung Load and Controller Algorithms

C. Simulation Results

Before exporting the helicopter model into MATLAB, the UH-1H model is trimmed using the trim function of Heli-Dyn+. Simulations 1, 2 and 3 are started from a 60 knots trimmed flight condition. The forth one, is started from a 18 knots trim condition.

In simulations-1 and 2, trimmed model is accelerated and decelerated using appropriate references to the autopilot. New steady states of the slung load and the helicopter are obtained (Figures 7 and 9). Reaction forces and moments acting on the helicopter during these maneuvers are shown in Figures 8 and 10.

In the third simulation, an input in the lateral channel is given to the trimmed model by applying a roll angle reference to the roll autopilot. Roll, pitch and heading responses can be seen in Figure 11. Note that especially in yaw channel, slung load turns as helicopter turns. This response can be altered by changing the spring and damper constants of the coupling moment in yaw channel given in Eqn. 14. Reaction forces and moments acting on the helicopter during the third maneuver are shown in Figure 12.

In simulation-4 both roll and pitch references are given to the controller. Roll and pitch reference signals can be seen in Figure 13. Responses of the helicopter and the slung load are presented in Figure 14.

An in-house built animation environment is used to visualize the dynamic interaction between the two dynamics. Time response taken from Simulink is given to that animation environment. In Figures 15 and 16, pictures of animation environment is presented.
V. Conclusions

This paper presents results on the modeling and simulation of a helicopter-slung load using Heli-Dyn+. The modeling required minimal effort and was quick in execution.

References

10 www.mathworks.com
15 www.flightgear.org
Figure 8. Simulation-1, Reaction Forces and Moments acting on Helicopter CG

Figure 9. Simulation-2, Longitudinal Parameters
Figure 10. Simulation-2, Reaction Forces and Moments acting on Helicopter CG

Figure 11. Simulation-3, Long./Lat. Parameters
Figure 12. Simulation-3, Reaction Forces and Moments acting on Helicopter CG

Figure 13. Simulation-4, Pitch and Roll Reference Commands
Figure 14. Simulation-4, Maneuver Response

Figure 15. Helicopter-Slung load Animation, Side View
Figure 16. Helicopter-Slung load Animation, Back View