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Anti-swing Controller Based on Time-delayed Feedback for Helicopter Slung Load System near Hover

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Abstract: *In this paper, a new anti-swing controller for helicopter slung load system near hover flight is proposed. This controller is based on time-delayed feedback of the load swing angles. The output from this controller is additional displacement that was added to the helicopter trajectory in the longitudinal and lateral directions. Hence, its implementation is simple and it only needs a small modification to the software of helicopter position controller. The parameters of the controllers are determined using the method of particle swarms by minimizing an index, which is a function of the load swing history. The simulation results show the effectiveness of the proposed controller in suppressing the swing of the suspended load and the stabilization of the helicopter.*

Keywords: *Helicopter, Slung load, Particle swarms, Swing.*

LIST OF SYMBOLS AND ACRONYMS

DASC	Time-delayed anti-swing controller
F_{HL}	Force transferred from the load to the helicopter
k_d	Gain of the delayed feedback controller
L	Load cable length
m_L	Load mass
M_{HL}	Moment transferred from the load to the helicopter
N	Number of particles in the PSO
PSO	Particle swarm optimization algorithm
R_H	Hook position vector
R_L	Load position vector
p,q,r	Helicopter angular velocities
V_{max}	Maximum velocity of PSO
u,v,w	Helicopter velocities
x,y,z	Helicopter center of gravity position
ϕ,θ,ψ	Euler angles
ϕ_L, θ_L	Load swing angles
τ_d	Time delay
γ_1, γ_2	PSO learning factors

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INTRODUCTION

Helicopters can be used for carrying heavy loads in civil, military, and rescue operations, where the use of ground-based equipment would be impractical or impossible. In these applications, the external load behaves like a pendulum. If the pendulous motion of the load exceeds certain limits, it may damage the load or threaten the life of the rescued person. Moreover, the external load can change natural frequencies and mode shapes of the low frequency modes of the helicopter. In addition, the aerodynamics of the load may make it unstable in certain flight conditions. These problems slow or even prevent an accurate pickup or placement of the load. Furthermore, it adds extra effort on the pilot.

The dynamics of a helicopter with external suspended loads received considerable attention in the late 1960s and early 1970s. Two reasons for this interest were the extensive external load operations in the Vietnam War, and the heavy-lift helicopter program (HLH). Such concern has been renewed recently with the advances in the modern control technologies (Bisgaard *et al.*, 2006).

Many efforts were done for modeling the slung load and studying its effect on the helicopter dynamics; however, there are relatively few works that discussed the swing control of the helicopter slung (Cicolani and Kanning, 1992). One of the first investigations into automatic control for helicopters with slung loads was conducted by Wolkovitch and Johnston (1965). The single-cable dynamic model was developed in a straightforward application of the Lagrange equations.

Abzug (1970) later expanded on this model to consider the case of two tandem cables. However, his formulation was based on the Newton-Euler equations of motion for small perturbations, separated into longitudinal and lateral sets. Aerodynamic forces on the cables and the load were neglected, as were the rotor dynamic modes.

Briczinski and Karas (1971) involved the computerized simulation of a helicopter and external load in real time with a pilot in the loop. Load aerodynamics was incorporated into the model, as well as rotor-downwash effects in the hover.

Asseo and Whitbeck (1973) on their paper on the control requirements for slung-load stabilization used the linearized equations of motion of the helicopter, winch, cable, and load for variable suspension geometry and then used them in conjunction with modern control theory to design several control systems for each type of suspension.

Cera and Farmer (1974) examined the feasibility of stabilizing external loads by means of controllable fins attached to the cargo. In their simple linear model representing the yawing and the pendulous oscillations of the slung-load system, it was assumed that the helicopter motion was unaffected by the load.

Raz *et al.* (1989) investigated the use of an active aerodynamic load stabilization system for a helicopter slung-load system.

All these studies are based on the classical control techniques. In this paper, a new anti-swing controller for helicopter slung load system near hover flight is used. It is based on time-delayed feedback of the load swing angles (Masoud *et al.*, 2002, Omar and Nayfeh, 2005). The output from this controller was additional displacements that are added to the helicopter trajectory in the longitudinal and lateral directions. Hence, its implementation is simple and it just needed small modification to the software of helicopter position controller. The parameters of the controllers were determined using particle swarms optimization technique by minimizing an index, which is a function of the load swing history.

Particle swarm optimization (PSO) is a population-based stochastic optimization technique, which is inspired by the social behavior of bird flocking or fish schooling. It shares many similarities with evolutionary computation techniques, such as genetic algorithms (GA) (Kennedy, 1997). The system is initialized with a population of random solutions and it searches for optima by updating generations. However, unlike GA, the PSO has no evolution operators such as crossover and mutation. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles. Compared to GA, the advantages of PSO are that it is easy to implement and there are few parameters to adjust. Moreover, PSO, like all evolutionary algorithms, optimizes a performance index based only on input/output relationships. Therefore, minimal knowledge of the plant under investigation is required. In addition, because derivative information is not needed in the execution of the algorithm, many pitfalls that gradient search methods suffer can be overcome.

MATHEMATICAL MODEL

The helicopter with a slung system can be considered as a multi-body dynamical one. The motion equations of each body may be written separately and then modified by adding the interaction forces between them (Fusato, 1999, Poli and Cromack, 1973).

Modeling the helicopter

In this study, the helicopter was modeled as a rigid body with six degrees of freedom. With Euler angles, the helicopter states are 12, including translational (*u, v, w*) and angular velocities (*p, q, r*), Euler angles (φ, θ, ψ), and helicopter position (*x, y, z*) (Prouty, 2003).

Modeling the slung load

The external load is modeled as a point mass, which behaves like a spherical pendulum suspended from a single point. The cable is assumed to be inelastic and without mass. The geometry and the relevant coordinate systems are shown in Fig. 1. The unit vectors i_H, j_H, k_H of the hook coordinate system always remain parallel to those of the body axis system. The position of the load was described by the two angles θ_L and φ_L, where φ_L is a load angle in the *xz* plane, and θ_L is the load oscillation angle out of the *xz* plane. Therefore, the position vector R_L of the load with respect to the suspension point is given by Eq. 1:

$$\mathrm{R_L} = L\cos(\theta_L)\sin(\phi_L)i_H + L\sin(\theta_L)j_H + L\cos(\theta_L)\cos(\phi_L)k_H \quad (1)$$

The position vector R_H of the hook with respect to the helicopter center of gravity (CG) is given by Fusato *et al.* (1999), as seen in Eq. 2:

$$\mathrm{R_H} = x_H i_H + y_H j_H + z_H k_H \quad (2)$$

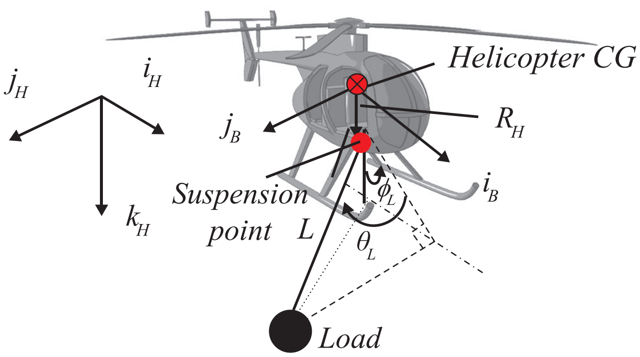

Figure 1. Configuration of helicopter with a slung load.

The absolute velocity V_L of the load is given by Eq. 3:

$$V_L = V_{cg} + \dot{R} + \Omega \times R \tag{3}$$

where,
V_{CG} is the absolute velocity of the helicopter mass center,
$R = R_L + R_H$ is the position vector of the load with respect to the helicopter mass center, and
$\Omega = p\, i_H + q\, j_H + r\, k_H$ is the angular velocity of the helicopter.

The absolute acceleration a_L of the load is (Eq. 4):

$$a_L = \dot{V}_L + \Omega \times V_L \tag{4}$$

The unit vector in the direction of the gravity force is given by Eq. 5:

$$K_g = -\sin(\theta) i_H + \sin(\phi)\cos(\theta) j_H + \cos(\phi)\cos(\theta) k_H \tag{5}$$

Besides the gravity, there is an aerodynamic force applied on the point mass load. Since the analysis in this work was restricted to the helicopter motion near hover, the aerodynamics loads on the load were neglected. The equations of load motion were written by enforcing moment equilibrium on the suspension point, (Eq. 6):

$$R_L \times (-m_L a_L + m_L g k_g) = 0 \tag{6}$$

Equation 6 provides three scalar equations of second orders, only the equations in the x and y directions are retained, which represent the equations of load motion.

Load contributions to helicopter forces

The suspended load introduces additional terms on the rigid body force and moment equations of helicopter motion (Fig. 2). The force F_{HL} that the load exerts on the helicopter is given by Eq. 7:

$$F_{HL} = -m_L a_L + D + m_L g k_g \tag{7}$$

The additional moment M_{HL} is therefore given by Eq. 8:

$$M_{HL} = R_H \times F_{HL} \tag{8}$$

Equations 7 and 8 are derived using Mathematica, which gives highly nonlinear expressions. These equations cannot be used for stability analysis. Therefore, they must be linearized around the trim condition. In order to be able to perform the linearization process, the trim values of the helicopter and the load must be determined.

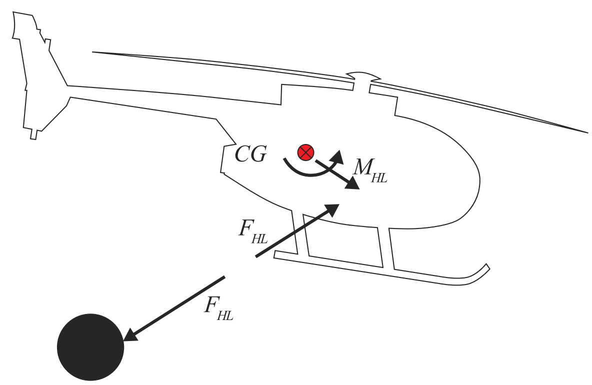

Figure 2. Load contribution to helicopter forces (Fusato *et al.*, 1999).

Linearizing the motion equations

The motion equations obtained were highly nonlinear. We needed to linearize them in order to solve and analyze the helicopter motion. To do that, we used the small-disturbance theory. To apply this theory we assumed that the motion of the helicopter and the load consisted of small deviations about a steady flight condition. After applying the small-disturbance theory, we got the helicopter linearized equations of motion.

The obtained equations were nonlinear and complicated. For the design purpose, these equations are linearized about the hovering conditions. Near hover, the forward speed is nearly zero (i.e. u_o=0). We can also assume that the helicopter roll angle is also zero even with the effect of the load on the helicopter ($\phi_0 = 0$). At this condition, the load trim equations provided the following trim values (Omar, 2005), as in Eq. 9:

$$\theta_{Lo} = 0, \quad \phi_{Lo} = -\theta_o \tag{9}$$

By imposing such results to the linearized load equations, we were able to find the following equations of motion for the load (Eqs. 10 to 12):

$$g\theta_L[t] - g\cos[\theta_0]\phi[t] + y_h\dot{q}[t] + \dot{V}[t] + L\ddot{\theta}_L[t] = 0 \qquad (10)$$

$$\begin{aligned} &L\,\ddot{\phi}_L[t] + g\phi_L[t] + g\theta[t] + (x_h - L\sin[\theta_0])\cos[\theta_0]\dot{p}[t] \\ &+ z_h\sin[\theta_0]\dot{r}[t] + L\cos[\theta_0]\sin[\theta_0]\dot{r}[t] + \cos[\theta_0]\dot{U}[t] \\ &+ \sin[\theta_0]\dot{W}[t] = 0 \end{aligned} \qquad (11)$$

The forces exerted by the load on the helicopter are:

$$\begin{aligned} F_x &= m_L\left(-g\cos[\theta_0]\theta[t] - x_h\,\dot{p}[t] + L\sin[\theta_0]\,\dot{p}[t]\right. \\ &\quad \left. -\dot{U}[t] - L\cos[\theta_0]\ddot{\phi}_L[t]\right) \\ F_y &= m_L\left(g\cos[\theta_0]\phi[t] - y_h\,\dot{q}[t] - \dot{V}[t] - L\,\ddot{\theta}L[t]\right) \\ F_z &= m_L\left(-g\sin[\theta_0]\theta[t] - (z_h + L\cos[\theta_0])\dot{r}[t] - \dot{W}[t]\right. \\ &\quad \left. -L\sin[\theta_0]\ddot{\phi}_L[t]\right) \end{aligned} \qquad (12)$$

The moments in the *x-y-z* directions are (Eq. 13):

$$M_x = m_L\begin{pmatrix} -gy_h\sin[\theta_0]\theta[t] - gz_h\cos[\theta_0]\phi[t] + y_h z_h\dot{q}[t] \\ -y_h(z_h + Ly_h\cos[\theta_0])\dot{r}[t] + z_h\dot{V}[t] - y_h\dot{W}[t] \\ +Lz_h\,\ddot{\theta}_L[t] - Ly_h\sin[\theta_0]\ddot{\phi}_L[t] \end{pmatrix}$$

$$M_y = m_L\begin{pmatrix} -gz_h\cos[\theta_0]\theta[t] + gx_h\sin[\theta_0]m_L\theta[t] - x_h z_h m_L\dot{p}[t][t] \\ +Lz_h\sin[\theta_0]\dot{p}[t] + x_h z_h\dot{r}[t] + Lx_h\cos[\theta_0]\dot{r}[t] - z_h\dot{U}[t] \\ +x_h\dot{W}[t] - Lz_h\cos[\theta_0]\ddot{\phi}_L[t] + Lx_h\sin[\theta_0]\ddot{\phi}_L[t] \end{pmatrix}$$

$$M_z = m_L\begin{pmatrix} gy_h\cos[\theta_0]\theta[t] + gx_h\cos[\theta_0]\phi[t] + x_h y_h\dot{p}[t] \\ -Ly_h\sin[\theta_0]\dot{p}[t] - x_h y_h\dot{q}[t] + y_h\dot{U}[t] - x_h\dot{V}[t] \\ -Lx_h\,\ddot{\theta}_L[t] + Ly_h\cos[\theta_0]\ddot{\phi}_L[t] \end{pmatrix} \qquad (13)$$

These equations are linear and can be formulated in a state space form. If we define the load state vector as $x_L = [\dot{\phi}_L \quad \dot{\theta}_L \quad \phi_L \quad \theta_L]^T$, the load equations in state space can be written as Eq. 14:

$$E_L x = A_L x \qquad (14)$$

where,
x is the state vector for the load and the helicopter (i.e., $x = [x_H \quad x_L]$).

Similarly, the effect of the load on the helicopter force terms can be written also as Eq. 15:

$$\begin{bmatrix} F_{HL} \\ M_{HL} \end{bmatrix} = E_{HL}\dot{x} + A_{HL}x \qquad (15)$$

The linearized equations of helicopter motion and the load can be written in the following state space forms (Eq. 16):

$$\dot{x} = \begin{bmatrix} \dot{x}_h \\ \dot{x}_L \end{bmatrix} = Ax + B\eta \qquad (16)$$

PROPOSED ANTI-SWING CONTROLLER

The configuration of the proposed controller is shown in Fig. 3. It consists of two control systems: a tracking and an anti-swing one.

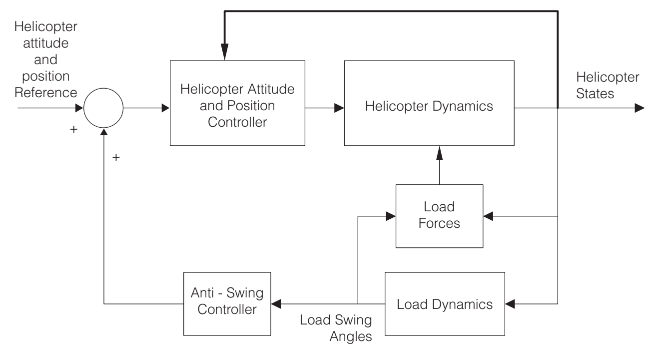

Figure 3. Configuration of the proposed anti-swing controller.

We needed to design a tracking controller for the helicopter to follow the trajectory generated by the anti-swing controller. Therefore, the controller design of the whole system could be divided into two stages. In the first one, the tracking controller for the helicopter alone was designed by neglecting the effect of the slung load on the helicopter dynamics. The function of this controller is to stabilize the helicopter and to follow the trajectory generated by the anti-swing controller. In the second stage, the whole system is integrated by augmenting the dynamics of the controlled helicopter with the dynamics of the slung load. Then, the proposed anti-swing controller is added to the integrated system, and the performance of the whole system is evaluated. The optimal parameters of the anti-swing controller are determined based on minimizing the history of the load swing.

To design the tracking controller, we assumed that the reference trajectory for the helicopter states is x_{ref}, then, the error signal is $e = x_{Href} - x_H$. Using state feedback technique, the helicopter control input can be written as Eq. 17:

$$\eta = K(x_{Href} - x_H) \qquad (17)$$

The feedback gain matrix K was chosen such that the error history is minimum. The feedback gain (K) can be determined using the linear quadratic regulator technique (LQR), which depends on minimizing a quadratic function that can be written as Eq. 18:

$$Indx = \int_0^{t_f} (e^T Qe + \eta^T R\eta)dt \qquad (18)$$

Since the goal was to minimize the error signal, Q is chosen with high gains compared to R. After determining K, the helicopter state space model can be rewritten as Eq. 19:

$$\begin{aligned}\dot{x}_H &= (A_H - B_H K)x_H + B_H K x_{Href} \\ &= A_c x_H + B_c x_{Href}\end{aligned} \qquad (19)$$

Equation 19 indicates that the reference states become the new inputs for the helicopter.

In the second stage, the anti-swing controller was designed. After modifying the helicopter dynamics by incorporating the stability and tracking controller, the effect of the load swing forces were added to the state space model in Eq. 16. Before this step, we needed to express Eq. 19 in terms of the total state vector, which include the helicopter and the load states. In this case, the helicopter dynamics can be written as Eq. 20:

$$\begin{aligned}\dot{x}_H &= [A_c \;\; 0]\begin{bmatrix} x_H \\ x_L \end{bmatrix} + [B_c \;\; 0]\begin{bmatrix} x_{Href} \\ 0 \end{bmatrix} \\ &= A_1 x + B_1 x_{ref}\end{aligned} \qquad (20)$$

The slung load effect modifies the forces and moments equations in the helicopter equations of motion. Recalling Eq. 16, the forces and moments from the slung load can be written as Eq. 21:

$$\begin{bmatrix} F_{HL} \\ M_{HL} \end{bmatrix} = E_{HL}\dot{x} + A_{HL}x \qquad (21)$$

Adding such forces to the helicopter dynamics, the new model can be written as Eq. 22:

$$\begin{aligned}\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} \dot{x}_H \\ \dot{x}_L \end{bmatrix} &= \left(\begin{bmatrix} A_1 \\ [0]_{4\times16} \end{bmatrix} + \begin{bmatrix} [0]_{3\times16} \\ A_{HL} \\ [0]_{7\times16} \end{bmatrix}\right)x + \begin{bmatrix} [0]_{3\times16} \\ E_{HL} \\ [0]_{7\times16} \end{bmatrix}\dot{x} + \begin{bmatrix} B_1 \\ [0]_{4\times12} \end{bmatrix}x_{ref} \\ E_H\dot{x} &= A_2 x + E_2\dot{x} + B_2 x_{ref}\end{aligned} \qquad (22)$$

The load dynamics can be written as Eq. 23:

$$E_L\dot{x} = A_L x \qquad (23)$$

By adding Eq. 22 and 23, we could obtain the final state space model for the combined systems (helicopter and slung load), as in Eq. 24:

$$\begin{aligned}(I - E_2 + E_L)\dot{x} &= (A_2 + A_L)x + B_2 x_{ref} \\ \dot{x} &= (I - E_2 + E_L)^{-1}(A_2 + A_L)x + (I - E_2 + E_L)^{-2}B_2 x_{ref} \\ \dot{x} &= A_f x + B_f x_{ref}\end{aligned} \qquad (24)$$

The anti-swing controller for the in-plane and out-of-plane motions can be expressed as Eq. 25:

$$\begin{aligned}x_S &= k_{dx} L\phi_L(t - \tau_{dx}) \\ y_S &= k_{dy} L\theta_L(t - \tau_{dy})\end{aligned} \qquad (25)$$

where,

x_s and y_s are additional displacement that are added to the helicopter trajectory in the longitudinal and lateral directions, respectively;

k_d is the feedback gain, and

τ is the time delay introduced in the feedback of the load swing angles.

These parameters are chosen to maximize the damping of the slung load system by minimizing the following index, which is expressed in terms of the time history of the load swing (Eq. 26):

$$ISH = \int_0^{t_f} (\theta_L^2 + \dot{\theta}_L^2 + \phi_L^2 + \dot{\phi}_L^2)dt \qquad (26)$$

PARTICLE SWARM ALGORITHM

PSO simulates the behaviors of bird flocking. If we suppose the following scenario: a group of birds is randomly searching food in an area. There is only one piece of food in the area being searched. The birds do not know where the food is. However, they know how far the food is in each iteration. Therefore, what is the best strategy to find food? The effective one is to follow the bird that is nearest to the food (Kennedy, 1997).

PSO learned from the scenario and used it to solve the optimization problems. In PSO, each single solution is a ‘bird’ in the search space, which is called ‘particle’. All particles have fitness values that are evaluated by the fitness function to be optimized, and they have velocities that direct the flying of the particles. The particles fly through the problem space by following the current optimum particles.

PSO is initialized with a group of random particles (solutions) and then it searches for optima by updating generations. In every iteration, each particle is updated by following the two 'best' values. The best values represent the lowest ones for the objective function since our problem is a minimization problem. The first one is the best solution (fitness) that it has achieved so far and it is called pbest. Another best value that is tracked by the PSO is the best value, obtained so far by any particle in the population. This best value is a global best and called gbest. After finding the two best values, the particle updates its velocity and positions following Eqs. 27 and 28:

$$v_i(k+1) = v_i(k) + \gamma_{1i}(p_i - x_i(k))\gamma_{i2}(G - x_i(k)) \quad (27)$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (28)$$

where,
v is the particle velocity, and
x is the current particle position (solution);
γ's are weighting parameters that control the performance of the PSO algorithm (Shi and Eberhart, 1998).

The pseudo code of the procedure is as follows:

Randomly initialize N particles
Do
For each particle
Calculate fitness value (i.e. objective function)
If the fitness value is better than the best fitness value (pBest) in history,
set current value as the new pBest
end
End
zChoose the particle with the best fitness value of all the particles as the gBest
For each particle
Calculate particle velocity according equation (27)
Update particle position according equation (28)
End
While maximum iterations or minimum error criteria is not attained

NUMERICAL RESULTS

We chose the Chinok helicopter in this study since the aerodynamics derivatives near hover was available in Stuckey (2001). Without loss of generality, we assumed the following data for numerical simulation.

The tracking controller was as in Eq. 29:

$$K = 10^3 I, \ \ Q = I \quad (29)$$

The load was as in Eq. 30:

$$L = 15ft, \ \ x_h = y_h = z_h = 0, \ \ m_r = 0.5 \quad (30)$$

To choose the control parameters of the time-delayed anti-swing controller (DASC), we assumed that $k_{dx} = k_{dy}$ and $\tau_{dx} = \tau_{dy}$ in order to enable us to obtain a map that represents the relationship between the damping of the load swing and the parameters of the anti-swing controller. To get this map, we assumed that the load swing was 20 degrees for the load swing angles and the remaining states for the helicopter and the load were zeros. We used the reciprocal of the swing index IHS as an indication of the level of damping as shown in Fig. 4. This map also shows the ranges of the control parameters that stabilized the system.

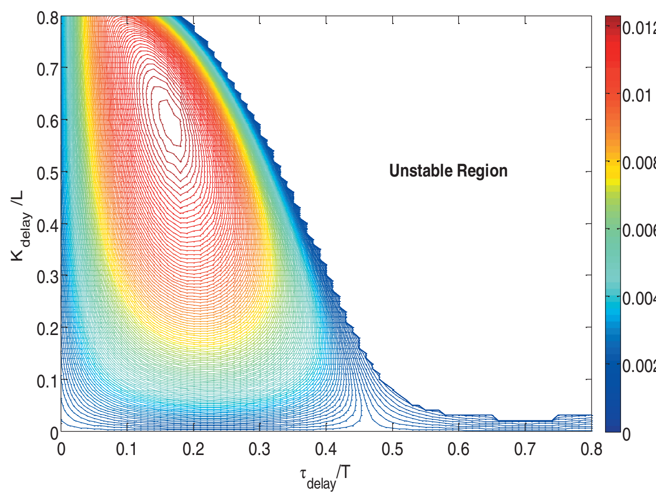

Figure 4. Damping map of the load swing (1/ISH) using DASC.

The highest damping level can be achieved at the following values (Eq. 31):

$$k_d = k_{dx} = k_{dy} = 0.67L, \tau = \tau_{dx} = \tau_{dy} = 0.19T_L \quad (31)$$

where, $T_L = 2\pi / \sqrt{g/L}$ is the period of oscillation of the suspended load.

To get the optimal values of the four parameters that minimize the swing index *ISH*, we used the method of particle swarms. The following values were used for the PSO code (Eq. 32):

$$N = 30, \quad V_{\max} = 2, \quad \gamma_1 = \gamma_2 = 1 \quad (32)$$

The evolution of the swing index ($1/ISH$) at each iteration is showed in Fig. 5. The optimal parameters obtained using this technique were as in Eq. 33:

$$k_{dx} = 0.658L, \quad \tau_{dx} = 0.188T_L$$
$$k_{dy} = 0.824L, \quad \tau_{dy} = 0.175T_L \qquad (33)$$

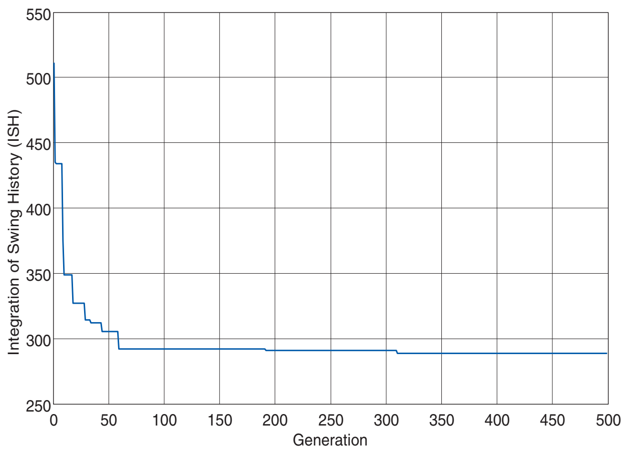

Figure 5. Evolution of the PSO code.

The minimum value for *ISH* corresponding to these parameters was found to be 288, while it was 294 when we assumed the same gains for the longitudinal and lateral motions. This result is expected since we have more freedom than the case when we have only two parameters.

The time history of the helicopter CG, suspended load swing angles, and the Euler angles are shown in Figs. 6 to 9, using the optimal gains obtained from PSO. These figures show the effectiveness of the proposed controller in suppressing the load swing. The anti-swing controller perturbs the helicopter form its initial position, but it returns it back due to the stability of the whole system. The maximum deviation in helicopter position is nearly 5 ft, which can be considered small. However, this value can be more decreased by choosing small values of the anti-swing gain (k_d), without significant decrease in the level of swing damping. The damping map can help in choosing the value of such gain. As shown in the map, with $K = 0.3$ and $\tau = 0.2$, we can get high level of damping, which is comparable to that one obtained using the optimal gains but with small value for the traveling distance of the helicopter. The value of *ISH* recorded in this case is 420.

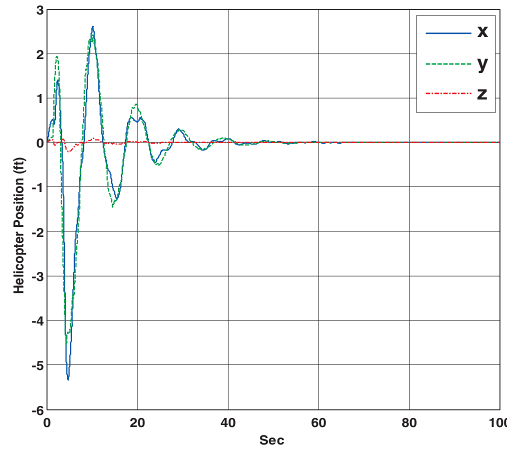

Figure 6. Time history of the helicopter CG using DASC with the optimal gains.

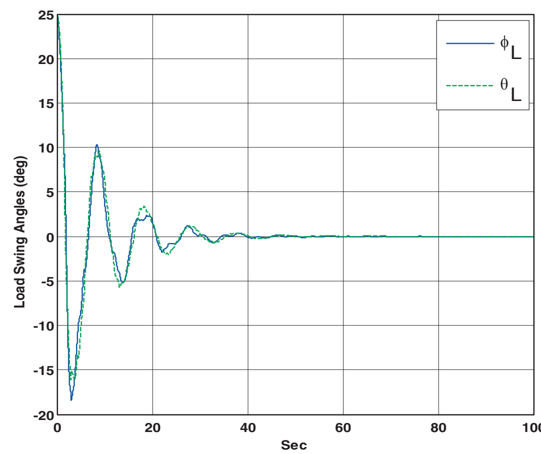

Figure 7. Time history of the load swing angles using DASC with optimal gains.

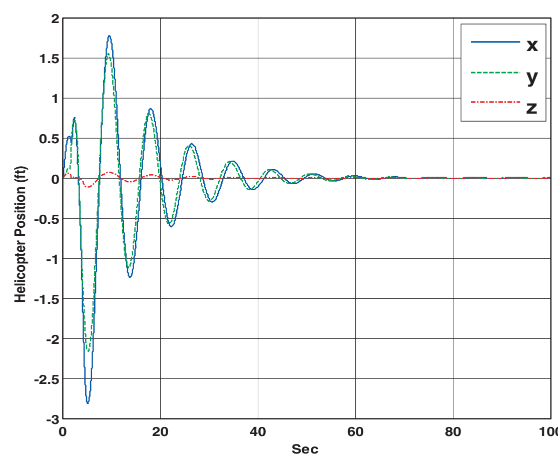

Figure 8. Time history of the helicopter CG using DASC with $K_d = 0.3$ and $\tau = 0.2T_L$.

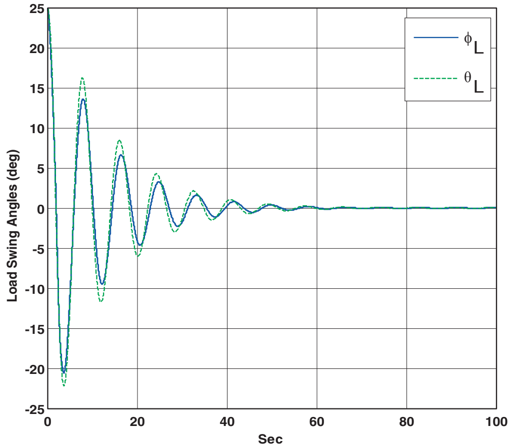

Figure 9. Time history of the load swing angles using DASC with K_d=0.3 and τ_d=0.2T_L.

Robustness

It can be shown by simulation that the designed system is robust with the changes of the load mass as indicated in Table 1. Moreover, the control parameters of the controller are functions of the load cable length. This robustness is due to the integration of the tracking controller, which is based on LQR technique and the time-delayed anti-swing controller.

Table 1. Performance of DASC with variation of load weight.

m_r	0.3	0.5	0.7	0.9
ISH	339	288	251	221

Table 2. Performance of DASC with variation of the suspension point location.

Location	x_h = 2, y_h = 0, z_h = 1	x_h = 2, y_h = 0, z_h = 2	x_h = -2, y_h = 0, z_h = 1	x_h = -2, y_h = 0, z_h = 2
ISH	267	272	320	316

CONCLUSIONS

A new anti-swing controller for helicopter slung load system near hover flight was proposed. This controller was based on time-delayed feedback of the load swing angles. The output from this controller was an additional displacement, which was added to the helicopter trajectory in the longitudinal and lateral directions. Hence, its implementation is simple and it only needs a small modification to the software of helicopter position controller.

To implement the proposed anti-swing controllers, a tracking controller for the helicopter was designed using the LQR technique. The function of the tracking controller is to stabilize the helicopter and track the trajectory generated by the anti-swing controller.

A map that represents the level of damping achieved by the proposed anti-swing controller was constructed as function of the controller parameters. To consider the coupling between the in-plane and out-of-plane load swings, the PSO algorithm was used to get the optimal gains for controlling the swing of both motions. The simulation results show the effectiveness of proposed controller in suppressing the load swing. For initial disturbance of the load swing angles, the anti-swing controller makes the helicopter slightly moves from its rest position to damp the swing motion, then it returns the helicopter back to its nominal position due to the stability of the whole system and the damping added to the load swing by the time-delayed anti-swing controller. The parameters of the controller can be chosen to keep the helicopter deviated from hovering position within acceptable limits.

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