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Designing anti-swing fuzzy controller for helicopter slung-load system near hover by particle swarms

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ABSTRACT

A new control system is proposed for the helicopter-slung load system near hover flight. It consists of two controllers: tracking and anti-swing. The anti-swing controller is fuzzy based and its outputs are additional displacements that are added to the helicopter trajectory in the longitudinal and lateral directions. Hence, its implementation is simple; it just needs a small modification to the software of the helicopter position controller. The rules of the anti-swing controller are derived to mimic the performance of a time-delayed feedback controller. The distribution of the fuzzy membership functions is optimally tuned using the method of particle swarms. The function of the tracking controller is to stabilize the helicopter and track the trajectory generated by the anti-swing controller. The simulation results show the effectiveness of the proposed controller in stabilizing the helicopter slung load system and suppressing the load oscillation. Moreover, the proposed fuzzy controller has better performance compared with the time-delayed feedback controller and the classical PD fuzzy controller.
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1. Introduction

Helicopters can be used in carrying heavy loads in civil, military, and rescue operations where the use of ground-based equipments would be impractical or impossible. An unmanned small-scale helicopter can be used also in landmine detection application by suspending the mine detection equipment as a slung load underneath a low-cost model helicopter [3,4].

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.

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. This interest has been renewed recently with the advances in the modern control technologies.

A lot of 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 with slung loads [8]. One of the first investigations into automatic control of this system was conducted by Wolkovitch and Johnston in 1965 [22]. The single-cable dynamic model was developed in a straightforward application of the Lagrange equations. Abzug [1] 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 [6] involved the computerized 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. Asseo and Whitbeck [2] in their paper on the control requirements for sling-load stabilization used the linearized equations of motion of the helicopter, winch, cable, and load for variable suspension geometry and were then used in conjunction with modern control theory to design several control systems for each type of suspension. Gera and Farmer [7] 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. Rosen et al. [19] investigated the use of active aerodynamic Load Stabilization System for a helicopter sling-load system.

Hamers and Bouwer [10] developed the flight director concept to give the pilot a convenient aid to damp the load pendulum motion and to allow maneuvering without exciting oscillatory load modes. A flight test was carried by Hamers et al. [11] to demonstrate the effectiveness of this technique.

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Nomenclature

F_{HL}	force transferred from the load to the helicopter
FLC	fuzzy logic control
GA	genetic algorithm
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 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 particles
u, v, w	helicopter velocities
x, y, z	helicopter CG position
ϕ, θ, ψ	Euler angles
ϕ_L, θ_L	load swing angles
τ_d	time delay
γ_1, γ_2	PSO learning factors

Recently, Bisgaard et al. [5] used the time-delayed feedback of the load swing angles to suppress the oscillation of the slung load in helicopter operations. Actually, this time-delayed anti-swing controller was successfully designed and applied experimentally on gantry, rotary, and tower cranes [14,16]. The same concept of using the time-delayed feedback signals was used also for suppressing the vibration of structural systems [15].

Fuzzy logic was first proposed by Lotfi Zadeh, in a classical paper published 1965 [23]. Zadeh showed that fuzzy logic is the foundation of any logic, regardless of how many truth values it may have. Fuzzy logic control (FLC) is the most active area of fuzzy logic application. The research started by Mamdani and his students in 1965 by applying fuzzy control to steam engine [13]. Since that time, many researchers and applications are carried on different process. It was shown in these works that FLC is robust with respect to the variation in the system parameters.

These unique characteristics of FLC motivate us to propose it as an anti-swing controller for the helicopter slung load system. FLC was already used for designing autopilot systems for helicopter and for controlling the oscillation of loads carried by ground cranes [16]. However, according to the author's knowledge, no trial was made to use FLC for controlling helicopters with slung loads.

In this paper, a simple procedure is proposed to control a helicopter carrying a slung load through two consecutive stages. In the first stage, a tracking controller is designed to control the helicopter alone near its hover operation which is usually available in standard autonomous helicopters. The main contribution of this paper comes from the second stage in which the helicopter and the slung load are integrated then a new fuzzy-based anti-swing controller is designed to suppress the oscillations of the slung load. The outputs from this controller are additional displacement that is added to the helicopter trajectory which should be followed by the tracking controlled designed in the first stage. Using this concept, the anti-swing control problem is converted to a trajectory tracking problem. Therefore, the proposed anti-swing controller can be integrated with the existing helicopter position controller with minor modifications to the helicopter control software program.

Usually, FLC is designed by trial and error which consumes time and effort. In this paper, we propose a new procedure for designing such controllers. The rules of FLC are generated to mimic the performance of the time-delayed feedback controller. Moreover, the distributions of the membership functions are optimally tuned using the particle swarms optimization technique by minimizing an index which is a function of the history of load swing.

The paper is organized as follows: The mathematical model of the helicopter and the suspended load is derived in Section 2, the procedure of designing the proposed control system is given in Section 3, the particle swarm optimization algorithm is illustrated in Section 4 followed by the simulation results in Section 5 and Section 6 concludes the paper.

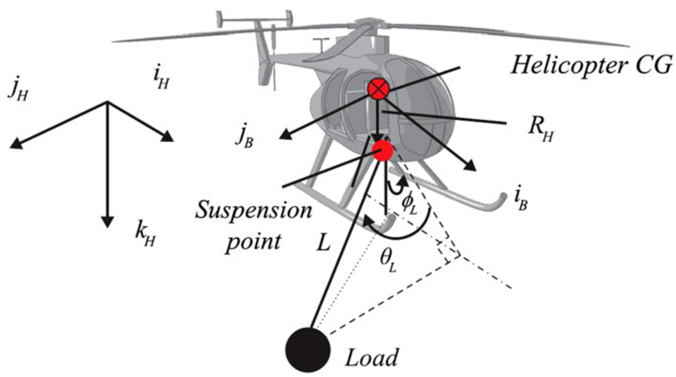

Fig. 1. Configuration of helicopter with a slung load.

2. Mathematical model

The helicopter with a slung system can be considered as a multi-body dynamical system. The equations of motion of each body can be written alone and then modified by adding the interaction forces between them [9,17].

2.1. Modeling the helicopter

In this study, the helicopter is modeled as a rigid body. With Euler angles, the helicopter states are twelve; translational positions (x, y, z), translational velocities (u, v, w), angular velocities (p, q, r), and Euler angles (ϕ, θ, ψ). The linearized equations of motion of the helicopter can be written as

$$\dot{x}_H = A_H x_H + B_H \eta \tag{1}$$

where x_H is the helicopter state vector which can be expressed as $x_H = [x\ y\ z\ u\ v\ w\ p\ q\ r\ \phi\ \theta\ \psi]^T$ and η is the helicopter input vector which include the pitch (longitudinal stick), roll (lateral stick), yaw (pedal), and collective control inputs [18,21].

2.2. Modeling of the slung load

The external load is modeled as a point mass that behaves like a spherical pendulum suspended from a single point. The cable of length L is assumed to be inelastic and with no 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 is described by the two angles ϕ_L and θ_L, where ϕ_L is load angle in the xz plane while θ_L is the load oscillation angle out of xz plane. Therefore, the position vector R_L of the load with respect to the suspension point is given by

$$R_L = L\cos(\theta_L)\sin(\phi_L) i_H + L\sin(\theta_L) j_H + L\cos(\theta_L)\cos(\phi_L) k_H \tag{2}$$

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