Active Control of Helicopter Ground Resonance with Lead-Lag Actuators

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Abstract- The coupling between the low frequency lead-lag motion of rotor blade and the frequency of fuselage is the phenomenon of ground resonance. This mechanical instability can lead to the total destruction of the aircraft if the vibrations are not reduced in time. Differential equations of motion of the simple ground resonance model are derived by using the Lagrange method. Five degrees of freedom coupled rotor/fuselage model with lead-lag actuators in the root of each blade is simulated. Fuzzy Logic Controller is used for the purpose of suppressing the ground resonance. The results show that existence of the active lead-lag control system prevents the ground resonance from happening while the helicopter is in touch with the ground.

Keywords- Helicopter ground resonance, lead-lag, coupled rotor/fuselage model, Fuzzy Logic, vibration control

1. Introduction

Helicopter vibration control studies in passive, semi-active and active control methods have drawn great attention from researchers due to the vibration effects on ride comfort, fatigue life of structural components and reliability of equipment attached to the helicopter [1-4]. Generally, rotary wing aircraft vibration level is higher than the fixed wing aircrafts. The main reason of the fuselage vibrations of a helicopter is the main rotor forces caused by the varying aerodynamic conditions on rotor blades and the inertia forces produced by the flap (out-of-plane) and lag (in-plane) degrees of freedom (DOF) of the rotor blade [5].

Besides the in-flight vibrations, a type of unstable fuselage vibrations called ground resonance may take place during take-off or landing phases. Not requiring the existence of aerodynamic forces, ground resonance may happen with the coupling of in-plane main rotor hub motion and low frequency lag mode of the blades for both articulated and hingeless rotors when the helicopter landing gear or skids are touching the ground. In other words, ground resonance is the result of unbalanced forces in the main rotor disc due to the change in the rotor center of gravity. The frequency of the unbalanced force couples with the natural frequency of the structure, mostly with the roll frequency of the fuselage.

Coleman has presented the earliest important ground resonance theory in a rotary wing aircraft with hinged blades [6]. Byers and Gandhi have used vibration absorbers embedded in the rotor blade to passively augment the rotor lag damping [7]. They have showed that the radial type absorber in blade is more effective than the chordwise absorber. Another passive nonlinear vibration absorber has been used to control helicopter ground resonance instability [8]. They have introduced a helicopter model consisting of a fuselage with lateral translation freedom and of four blades with a chordwise absorber attached on each blade. Wei and Pinqi have applied a semi-active adaptive control strategy for the helicopter ground resonance by controlling the output damping force of magnetorheological (MR) lag damper [9]. The damping force of MR damper is controlled by applying electrical current to the damper. Helicopter ground resonance is modelled, ignoring the effect of aerodynamic force, as a coupled fuselage with two translation freedoms and rotor system with three rigid blades. Similar to this study, Warrier and Ali have also developed a nonlinear semi active control strategy to prevent the ground resonance phenomenon by using MR damper [10]. Kessler and Reichert have actively controlled lead-lag damping with simple lead-lag feedback of an hingeless and isolated rotor blade model with flap, lag and pitch DOFs in hover and forward flight conditions [11]. Kunz has obtained a solution to the fully nonlinear equations for the ground resonance problem and has stated the requirement of nonlinear consideration for the rotor system that does not require lag dampers [12]. In addition, Zhu et al. have investigated the effects of nonlinearities on ground resonance considering the nonlinear dynamic characteristics of the landing gear wheel, landing gear shock absorber and rotor lead-lag dampers [13]. Sanches et al. have studied the ground resonance phenomenon for isotropic and anisotropic rotor configurations and analyzed the effect of asymmetries in the variation of in-plane lead-lag stiffness on individual blade of main rotor system [14]. They also have used the method of multiple scales by considering the helicopter as a parametrically excited system [15].

In this study, a coupled rotor/fuselage model is derived. Blades only have the lead-lag degree of freedom and the fuselage only has a translational degree of freedom. An active Fuzzy Logic control strategy is developed to suppress the ground resonance using the lead-lag actuators.

2. The helicopter ground resonance model

Simplified ground resonance model is developed for a helicopter with 4-bladed main rotor [6, 16, 17] as illustrated in Figure 1. All blades are elastomechanically same (isotropic rotor). The rotor aerodynamics, flap and pitch motions of blades, longitudinal motion of fuselage and the offset between the main rotor rotation axis and the lag hinge axis are not considered in order to concentrate to the ground resonance phenomenon. The fuselage model is consisting of the rigid mass M, linear spring with stiffness coefficient kf, viscous damper with the damping coefficient cf, and representing the roll motion of the fuselage on the landing gear or skids. Each blade is modeled by a concentrated and equal mass m at the distance L from the rotation axis O. Torsion spring with stiffness coefficient kb and viscous damper with the damping coefficient cb are assumed at the blade root where there is articulation between the main rotor hub and the lag hinge that provides blades to move in the plane of the rotor disk. The system has five degrees of freedom with one lateral translational motion of the fuselage y and four rotational lag motion of the blades β1, β2, β3, β4.

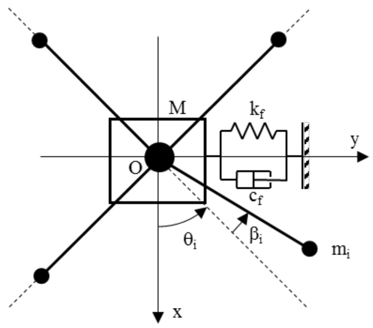

Figure 1: Simplified mechanical system representing helicopter ground resonance model

Rotational velocity of the main rotor is the constant **Ω** and the angular position of each blade for the zero lag angle βi is

$$\theta_i(t) = \Omega t + \varphi_i \quad (1)$$

where $\varphi_i = (\pi/2)(i-1)$ for *i*=1,2,3,4.

Cartesian coordinates for the position of each blade may be written as

$$r_x = L\cos(\theta_i + \beta_i) \quad \text{and} \quad r_y = y + L\sin(\theta_i + \beta_i) \quad (2)$$

Then the velocity of each blade may be found as

$$v_i = \sqrt{\left(-L(\Omega + \dot{\beta}_i)\sin(\Omega t + \varphi_i + \beta_i)\right)^2 + \left(\dot{y} + L(\Omega + \dot{\beta}_i)\cos(\Omega t + \varphi_i + \beta_i)\right)^2}. \quad (3)$$

Here, over-dot notation is used to denote the differentiation with respect to time.

The total kinetic energy of the system T, the potential energy of the system V, and the dissipation function are written as

$$T = \frac{1}{2}M\dot{y}^2 + \sum_{n=1}^{4}\frac{1}{2}m_n v_n^2, \quad V = \frac{1}{2}k_f y^2 + \sum_{n=1}^{4}\frac{1}{2}k_b\beta_n^2,$$
$$D = \frac{1}{2}c_f\dot{y}^2 + \sum_{n=1}^{4}\frac{1}{2}c_b\dot{\beta}_n^2 \quad (4)$$

Substituting Equation (4) into Lagrange equation

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_j}\right) - \frac{\partial T}{\partial q_j} + \frac{\partial V}{\partial q_j} + \frac{\partial D}{\partial \dot{q}_j} = Q_j \quad (5)$$

where are generalized coordinates and are the generalized forces, yields

$$(M + 4m)\ddot{y} + c_f\dot{y} + k_f y + mL\sum_{n=1}^{4}\left(\ddot{\beta}_i\cos(\Omega t + \varphi_n + \beta_i) - (\Omega + \dot{\beta}_n)^2\sin(\Omega t + \varphi_n + \beta_i)\right) = Q_f \quad (6)$$

$$mL^2\ddot{\beta}_i + c_b\dot{\beta}_i + k_b\beta_i + mL\ddot{y}\cos(\Omega t + \varphi_i + \beta_i) = Q_i$$

for *i*=1,2,3,4. (7)

3. Fuzzy Logic Controller Design

Fuzzy Logic Controller is used in wide range of vibration control applications [18, 19]. In this study, a Fuzzy Logic approach is suggested to generate a control signal for the actuators which are located at each blade root. Main objective of the controller is to control the lag angle of each blade to prevent a ground resonance from happening during both take-off and landing. Fuzzy inputs are error 'e' which is the change of lag angle from blade's rest position and the error change 'de' which is the derivative of error. Membership functions of inputs and the output are all normalized in the interval of $[-1, 1]$ as shown in Figure 2 where the set of linguistic variables for the error input is {N, Z, P}, error change input is {N, Z, P} and the output is {NB, NS, Z, PS, PB}. Here, NB, NS, Z, PS and PB refer to negative big, negative small, zero, positive small and positive big, respectively.

Fuzzy inputs are scaled with normalization factor to the membership function intervals before the fuzzification. Fuzzy output is multiplied with denormalization factor to the desired control signal after the defuzzification processes. Fuzzified inputs are processed in the fuzzy interface engine and the fuzzy output is derived with the defuzzification processes by using the rule base of fuzzy logic controller which is given in Table 1.

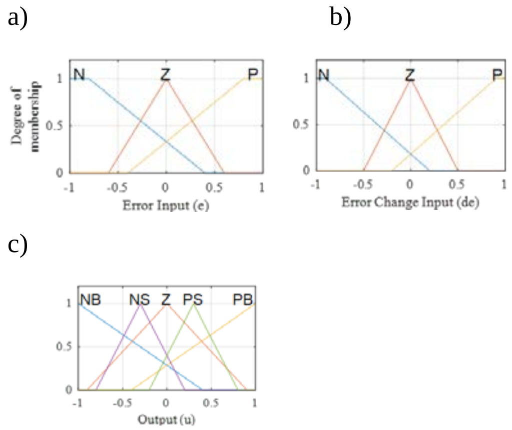

Figure 2: Membership functions for the first input (a), second input (b) and output (c)

Table 1: Fuzzy Control Rule Table

	de		
e	**N**	**Z**	**P**
N	PB	PS	Z
Z	PS	Z	NS
P	Z	NS	N

4. Numerical Results and Discussion

Lead-lag hinges between the hub and blades are primarily designed to mitigate the high forces acting on the blade root by ensuring in-plane blade movement. However, during the take-off and landing of the helicopter, blade lagging may prompt ground resonance at low main rotor speeds. An external disturbance such as an impulse from ground to the helicopter skids or landing gear during landing or as an aerodynamic force on the blades may cause blade lagging.

Fuzzy Logic controller is tested for two cases in the coupled helicopter rotor/fuselage model by using MATLAB/Simulink. Model parameters used in numerical simulations of the model in Equations (6) and (7) are given in Table 2. Throughout the simulations the rotor velocity is taken equal to the ground resonance frequency [16] and given as

$$\Omega = \sqrt{\frac{k_f}{M+4m} + \frac{k_b}{mL^2}} \quad . \tag{8}$$

Table 2: Parameters of helicopter ground resonance model [17]

Parameter	Value	Parameter	Value
Stiffness coefficient of fuselage k_f	2.7275×10^4 N/m	Fuselage mass M	2902.9 kg
Damping coefficient of fuselage c_f	1.091×10^3 Ns/m	Blade mass m	31.9 kg
Stiffness coefficient of blade k_b	1.0313×10^3 Nm/rad	Blade length L	2.85 m
Damping coefficient of blade c_b	41.252 Nms/rad		

For the first case (Case I), an initial perturbation to the fuselage, which represents the force arising when the helicopter touches the ground, excites the system. In the second case (Case II), an initial perturbation to the rotor blade which represents the aerodynamic forces acting on the blades, excites the system. Figure 3 shows the time responses of the fuselage translational motion and rotational motion of the first blade for an initial perturbation to the fuselage. In the beginning of the simulation, coupling between the fuselage and blades is observed and then oscillations gradually increase to an unstable condition for the uncontrolled system. In the Fuzzy Logic controlled system ground resonance is suppressed. Figure 4 shows the time response of the fuselage translational motion and rotational motion of the first blade for an initial perturbation to the blade. Because of the fact that the actuators are placed in the root of blades, vibration attenuation of blades is better than the vibration attenuation of fuselage.

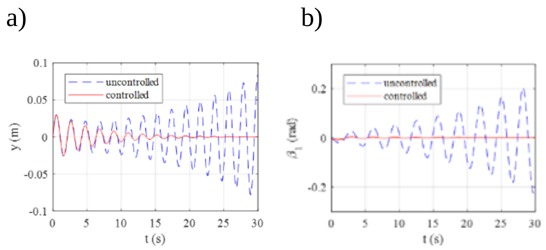

Figure 3: Fuselage translational displacement (a), first blade rotational displacement (b) for Case I

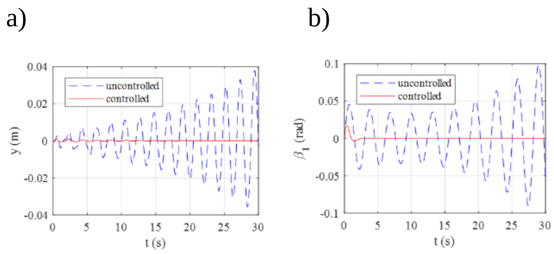

Figure 4: Fuselage translational displacement (a), first blade rotational displacement (b) for case II

5. Conclusion

An active Fuzzy Logic controller is presented to suppress the helicopter ground resonance. Actuators are placed at the root of each blade to control the lead-lag angle of the blades. Without a controller any disturbance to the system from the fuselage or from the blade causes instability when the rotor speed is equal to the ground resonance frequency. However active controller successfully diminishes the vibrations in a short time. According to the results in the case of initial fuselage perturbation, reduction of vibrations takes much time against the case of initial blade perturbation. This is due to the fact that the objective of the controller is not to reduce the translational displacement of the fuselage but is to reduce the rotational displacement of the blade. Further studies may be conducted by adding another input for the fuselage displacement to the Fuzzy Logic controller to reduce fuselage vibrations faster in the case of the fuselage disturbance.

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