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Preliminary Study on Helicopter Ground Resonance Phenomena

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ABSTRACT
Helicopters are rotor-equipped aerial vehicles capable of hovering and executing maneuvers in multiple directions (forward, backward, lateral) by altering the plane of rotation of their rotors. However, this rotary design inherently introduces mechanical, dynamic, and aerodynamic challenges. Ground resonance, arising in articulated and soft in-plane rotor systems, is a dynamic instability where the in-plane movements of helicopter blades couple with the fuselage's corresponding in-plane motions. This instability is termed 'ground resonance' because it specifically arises when the helicopter is on the ground and is investigated as self-excited vibration. This study evaluates ground resonance in helicopters during the initial design phase and examines strategies to mitigate it.
Keywords-Dynamic Model, Ground Resonance, Helicopter

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I. INTRODUCTION

The first articulated helicopters were produced in the early 1920s. The flapping hinge allows the helicopter blade to freely execute flap motions, thus preventing high bending moments at its root. This flapping movement of blade within the rotating rotor system, leading to significant Coriolis forces. Due to the increased Coriolis forces, lead-lag hinges were implemented at the blade roots. Furthermore, another hinge providing third-axis rotation for blade pitch adjustments was added to the blade roots [1]. Fig.1 schematically illustrates these hinges.

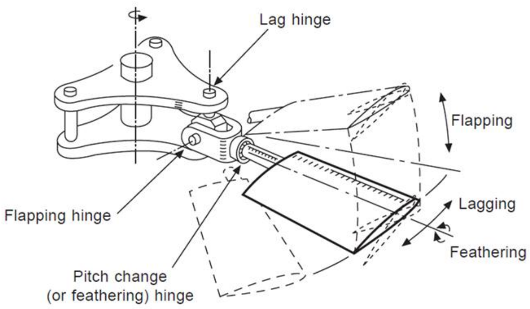

Figure 1 Representation of blade hinges [1]

Increasing degrees of freedom in helicopter blades generates various instability issues. Ground resonance, the central focus of this article, is recognized as a type of coupled rotor-fuselage instability.

II. GROUND RESONANCE MODEL

In a simplified ground resonance model of a helicopter with articulated rotors, the model's degrees of freedom are combination of certain rotor modes within the rotor's plane of rotation and the fuselage's in-plane modes of vibration. When considering the fuselage's modes within the rotor's plane of rotation, its movements are pitching and rolling motions. Analyzing rotor modes reveals that certain modes induce a displacement of the rotor's center of mass relative to its rotational axis. Rotor modes that do not cause displacement of the rotor's center of mass relative to its rotational axis are illustrated in Fig.2.

Phase shifts in the in-plane blade motions can, in certain scenarios, contribute to the displacement of the rotor's center of mass from its rotational axis. In this scenario, blade inertial forces excite the helicopter fuselage. When the rotor's center of mass displacement during rotation aligns with the rotor's rotational direction, this mode described as progressive lag mode (Fig.3.a) When it does not align, the mode described as regressive lag mode (Fig.3.b). Ground resonance can arise when the frequency of the regressive lag mode and the helicopter fuselage's frequency coincide at a specific rotor speed. To prevent the instability arising from ground resonance, damping must be added to both the blades and the fuselage.

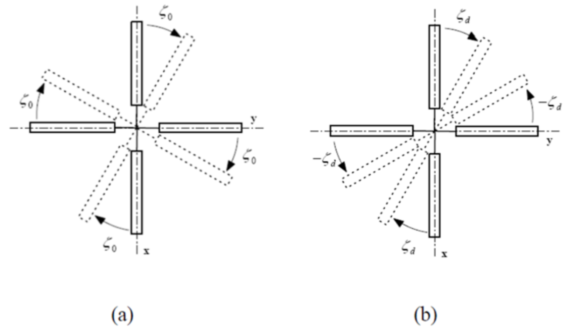

Figure 2 Mode shapes of the rotor a) Rotor collective mode b) Rotor scissor mode [2]

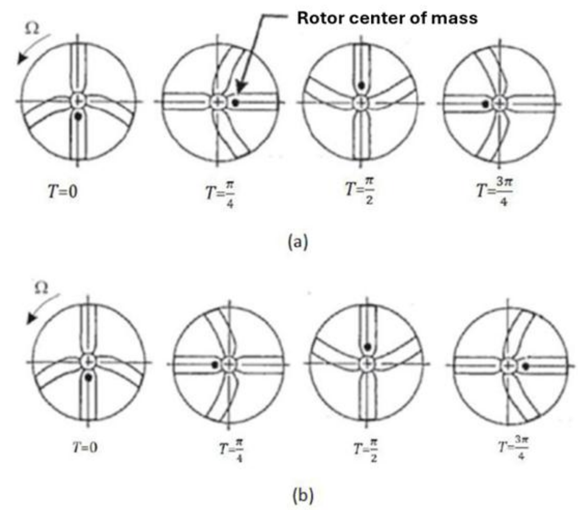

Figure 3 Mode shapes in which the center of mass of the rotor shifts from the rotor's axis of rotation a) Progressive lag mode b) Regressive lag mode [2]

Ground resonance model that includes two fuselage degrees of freedom is shown in Fig.4. while one of blades model that is embedded in the ground resonance model is shown in Fig.5. In Fig.5. **e** represents the distance of the in-plane hinge from the rotor's axis of rotation, **r** denotes the distance of the blade's center of mass from the in-plane hinge, ψ_k is the azimuth angle, and ζ_k indicates the small angular motion of the blade around the in-plane hinge.

In a mathematical model constructed in this way, the two fuselage modes are independent of the rotor speed, while frequency of rotor modes given in Fig.3. change with the rotor speed. Fuselage and rotor modes frequencies with respect to rotor speed are shown in Fig.6. The regressive lag mode and fuselage modes overlap at points B, C and D. At points C and D fuselage modes and rotor modes are coupled and ground resonance may occur.

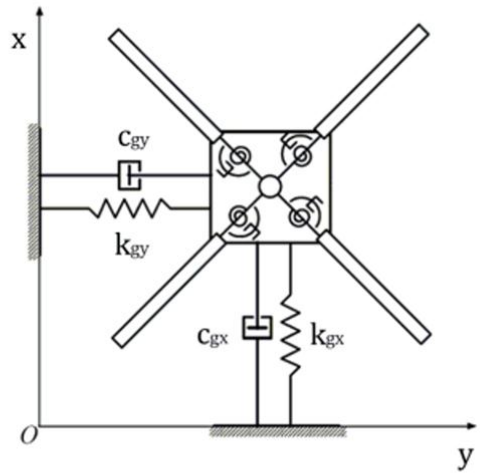

Figure 4 Four-degree-of-freedom ground resonance model [3]

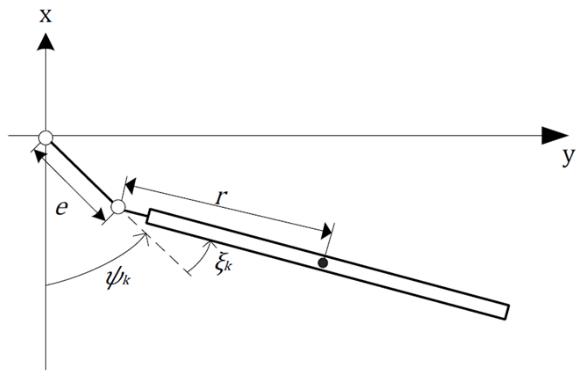

Figure 5 Embedded blade model

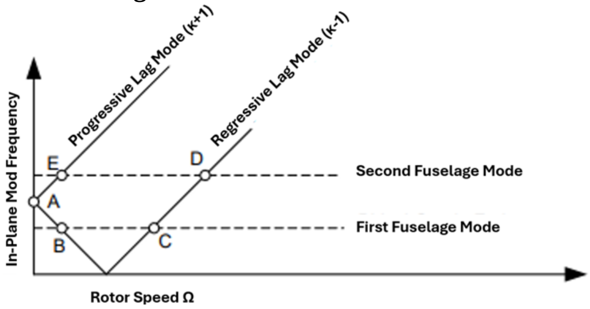

Figure 6 In-plane frequencies of a hingeless soft in-plane rotor as a function of rotor speed

The equation of motion of ground resonance model which is shown in Fig.4. can be expressed as equation (1). Details on the derivation of the equations and related parameters can be found in [2]. When the equations are examined, it can be seen thatthesystem of equations depend on the rotor speed. By solving the eigenvalue problem for each rotor speed, the natural frequencies of the system at each rotor speed can be calculated and its stability can be assessed to determine how much damping should be added.

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$$\begin{bmatrix} M_{gx} & 0 & 0 & -\frac{mrb}{2} \\ 0 & M_{gy} & \frac{mrb}{2} & 0 \\ 0 & \frac{mrb}{2} & \frac{b}{2}I & 0 \\ -\frac{mrb}{2} & 0 & 0 & \frac{b}{2}I \end{bmatrix} \begin{Bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\xi}_c \\ \ddot{\xi}_s \end{Bmatrix} + \begin{bmatrix} c_{gx} & 0 & 0 & 0 \\ 0 & c_{gy} & 0 & 0 \\ 0 & 0 & \frac{b}{2}c_\xi & \frac{b}{2}(2I\Omega) \\ 0 & 0 & -\frac{b}{2}(2I\Omega) & \frac{b}{2}c_\xi \end{bmatrix} \begin{Bmatrix} \dot{x} \\ \dot{y} \\ \dot{\xi}_c \\ \dot{\xi}_s \end{Bmatrix}$$

$$+ \begin{bmatrix} k_{gx} & 0 & 0 & 0 \\ 0 & k_{gy} & 0 & 0 \\ 0 & 0 & \frac{b}{2}[k_\xi + \Omega^2(mer - I)] & \frac{b}{2}c_\xi\Omega \\ 0 & 0 & -\frac{b}{2}c_\xi\Omega & \frac{b}{2}[k_\xi + \Omega^2(mer - I)] \end{bmatrix} \begin{Bmatrix} x \\ y \\ \xi_c \\ \xi_s \end{Bmatrix} = 0$$

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} \qquad (1)$$

In the early design phase of aerospace projects, these blade parameters can be estimated. The fuselage parameters used in these equations are the equivalent mass and stiffness of the fuselage in rotor plane. Therefore, in order to be used in mathematical model of helicopter ground resonance, the equivalent mass and equivalent stiffness values of the helicopter fuselage are required.

To calculate the equivalent mass and equivalent stiffness of the helicopter fuselage, a certain amount of mass is added to the rotor center in the Finite Element (FE) model of the helicopter, and the change in natural frequency is analyzed. Based on this analysis, the equivalent mass and stiffness values of the fuselage can be determined [4]

Let the natural frequency of a selected mode of the helicopter be ω and the equivalent mass at the rotor center be Meff. When an additional mass of δm is added to the rotor center, if the new natural frequency of the helicopter fuselage is ω2, then the new equivalent mass can be considered as Meff2=Meff+δm. Repeating the same process for another additional mass results in the graph shown in Fig.7. The equivalent stiffness Keff is calculated from the slope of Fig.7. Keff represents the equivalent stiffness of the helicopter fuselage at the rotor center for the selected mode. Finally, Meff can be calculated since Keff and 1/ ω^2 are known.

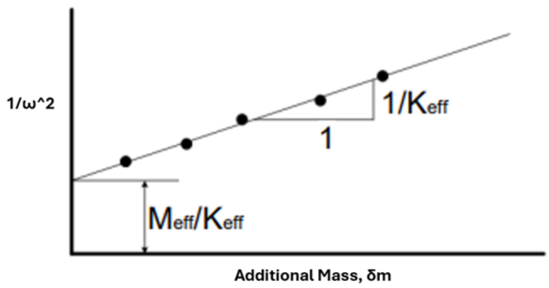

Figure 7 Equivalent mass and stiffness calculation

By substituting the obtained values into equation (1), the preliminary analyses can be performed. As an example, the graphical representation of the frequencies at different rotor speeds for the ITU-HTH helicopter's ground resonance model and the real roots obtained from the eigenvalue problem are shown in Fig.8 and Fig.9, respectively.

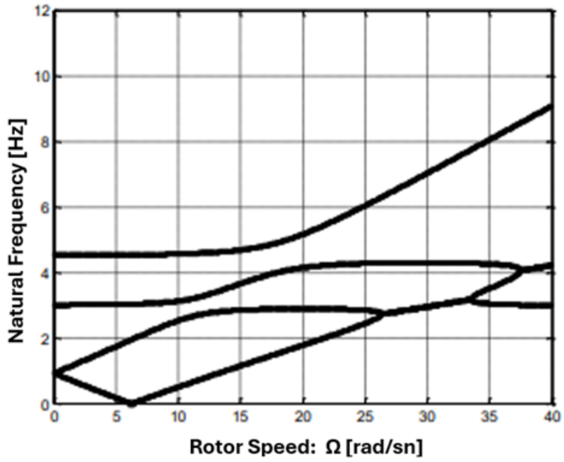

Figure 8 Frequencies of the ground resonance model of ITU-HTH in an empty condition

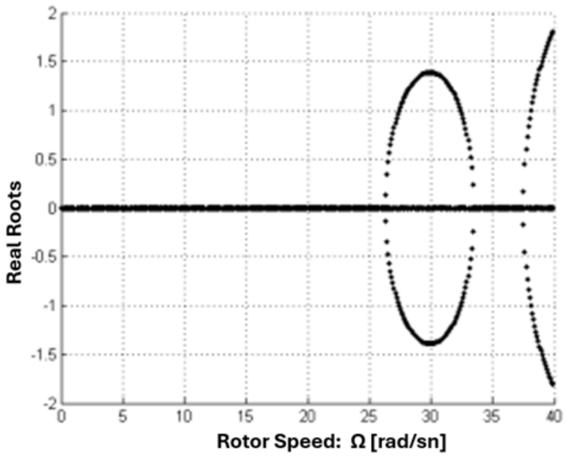

Figure 9 Real roots of the calculated eigenvalues for ITU-HTH in an empty condition

III. REQUIRED DAMPING

As previously mentioned, damping must be added to both the blades and the fuselage to prevent ground resonance. The damping values required to prevent ground resonance instability can be determined according to the Deutsch criterion [5]. The expression of Deutsch criterion is presented in equation (2).

$$\zeta\zeta_c = \frac{b}{4}\left(\frac{\omega}{\Omega}\Big/\left(1-\frac{\omega}{\Omega}\right)\right)s_\xi^2\omega^2 \tag{2}$$

In equation (2), **b** represents the number of blades, while **ω** represents the natural frequency of the fuselage, which is also equal to the frequency of the regressive lag mode at the rotor speed where the coincidence occurs. Additionally, **Ω** refers to the rotor speed at which the coincidence takes place, ζrepresents the damping ratio of the blade, and ζ_c represents the damping ratio of the helicopter fuselage. Moreover, $\mathbf{S}_\zeta$ is defined as the first mass moment of inertia with respect to the equivalent hinge offset of the blade.

The multiplication of the blade and fuselage damping ratios calculated according to the Deutsch criterion for ITU-HTH is presented in Table 1.

Table 1 Product of blade and fuselage damping ratios based on the Deutsch criterion

Fuselage Mode	Product of Fuselage and Blade Damping Ratios (%)
I. Fuselage Mode (Empty)	0.0226
II. Fuselage Mode (Empty)	0.0436
I. Fuselage Mode (MTOW)	0.0110
II. Fuselage Mode (MTOW)	0.0295

When the fuselage and blade damping are determined to satisfy these multiplication results, the real roots of the model as a function of rotor speed are presented in Fig.10. It can be observed that all real roots are negative, indicating the absence of any instability.

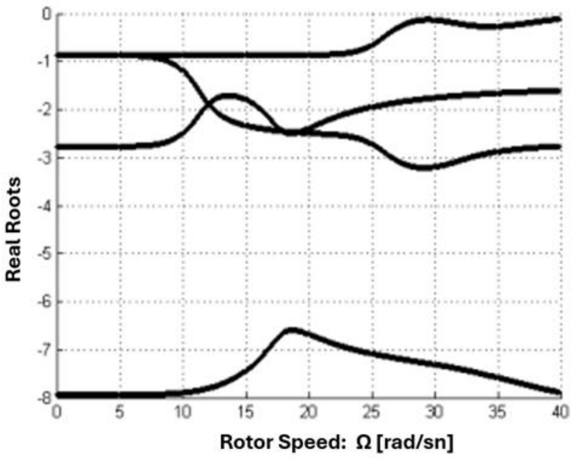

Figure 10 Real roots of the ground resonance model of ITU-HTH. (Deutsch Criterion)

To eliminate ground resonance instability, Done [6] proposed a criterion similar to the Deutsch criterion for determining the additional damping required for the helicopter fuselage and blades, as expressed in equation (3).

$$\zeta\zeta_c = \mu\kappa_c^2/8\kappa(1-\kappa_c) \tag{3}$$

where,

$$\mu = \frac{b}{2}m_b/(M_{eff}+bm) \tag{4}$$

$$\kappa_c = {}^{\omega}/_{\Omega} \tag{5}$$

$$\kappa = 1-\kappa_c \tag{6}$$

In Done's Equation **b** represents the number of blades, $\mathbf{m_b}$ denotes the mass of the blade, and $\mathbf{M_{eff}}$ represents the effective mass of the helicopter fuselage. Additionally, **ω** corresponds to the natural frequency of the fuselage, while **Ω** denotes the rotor speed. In this context, $\boldsymbol{\kappa_c}$ represents the natural frequency of the helicopter fuselage normalized with respect to the rotor speed, whereas **κ** denotes the natural frequency of the helicopter blade normalized with respect to the rotor speed.

The computed product of the damping ratios is presented in Table 2. When compared to the values calculated using the Deutsch criterion, equation (4) predicts lower damping values

Table 2 Product of blade and fuselage damping ratios based on the Deutsch criterion

Fuselage Mode	Product of Fuselage and Blade Damping Ratios (%)
I. Fuselage Mode (Empty)	0.0152
II. Fuselage Mode (Empty)	0.0243
I. Fuselage Mode (MTOW)	0.0082
II. Fuselage Mode (MTOW)	0.0127

When the damping calculated using Done's equation is added to the ground resonance model of ITU-HTH, the real values of the eigenvalue problem for each rotor speed are shown in Fig. 11. It is observed that the real roots are positive at rotor speeds where the coincidence occurs. Nevertheless, small real roots indicate that the instability is minimal.

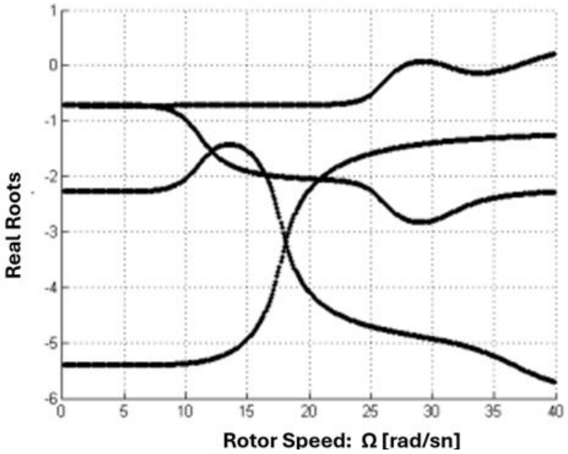

Figure 11 Real roots of the ground resonance model of ITU-HTH (Done Criterion)

Another method that provides more accurate results is to test every combination of added damping values for the blade and helicopter fuselage at each rotor speed and check whether the system remains stable.

To compare the methods used for determining the required damping, the results obtained from different approaches can be presented in the same graph. In Fig.12, the damping ratios required to eliminate ground resonance instability are plotted together.

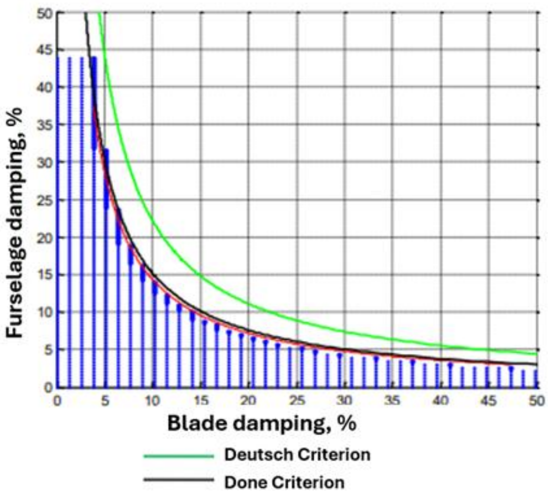

Figure 12 Comparison of required damping for stability in ground resonance.

IV. CONCLUSION

In this study, a mathematical model for ground resonance that can be established in the early stages of a helicopter development process is presented. Using this model, the calculation of the damping to be added to the blades and fuselage has been discussed, and subsequently, the damping ratios calculated by different methods have been compared. Thus, a simple and effective method for determining the damping to be added to the blades and fuselage to prevent ground resonance in the early stages of helicopter design is proposed. In future studies, the damping ratios calculated using more detailed and comprehensive models can be compared with the results obtained in this study, and improvements to the simple model can be suggested. In the final stage, comparing the damping ratios verified by ground resonance tests with those calculated using simple models in this study will be crucial for evaluating the effectiveness of the proposed simple model.

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