NONLINEAR FLAPPING OSCILLATIONS IN HELICOPTER ROTORS

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Abstract

This work presents a study of the nonlinear flapping motion of helicopter rotor blades in hover considering gust effects. The nonlinear differential equation for the flapping motion is obtained and the computational simulations and bifurcation analysis show that above a critical collective pitch angle, large flapping oscillations can occur due to a jump phenomenon, particularly under high winds and with reduced rotational speeds. These large, possibly destructive, oscillations are not predicted by the linear model and may be related to the phenomenon of blade sailing, a common occurrence in naval operations.

Keywords. *helicopter, rotor, flapping, nonlinear, dynamics, oscillations, gust, naval operations.*

Nomenclature

R - rotor radius, m
w - vertical gust velocity, m/s
V_{mw} - mean wind velocity, m/s
α - gust amplitude, m/s
β - flapping angle, rad
γ - Lock number
λ - wavelength, m
λ_1 - nondimensional flapping frequency ratio
v_i - induced velocity, m/s
ϕ - inflow angle, rad
θ_0 - collective pitch angle, rad
Ω - rotor rotational speed, rad/s
p_B, q_B, r_B - components of the blade angular velocity

Introduction

Helicopter response in gusty air has been poorly studied, despite its importance for several applications, particularly in naval operations. Large flapping oscillations in helicopter rotors can occur at low rotational speeds in high winds, a phenomenon called blade sailing (Refs. 1,2). Tail-boom strikes have happened during the startup or shutdown of the rotor system, occasionally yielding severe damage (Refs. 3,4,5). For some naval helicopters, like the H-46 Sea Knight, a relatively small flapping angle is enough to result in blade strike and thus a linear analysis is suitable to study the phenomenon. However, despite the standard low collective and inflow inputs, the coupling with a high amplitude gust at low rotor speeds can amplify the nonlinear structural effects.

This work investigates the resulting nonlinear flapping motion of rotor blades in hover considering gust effects. The aim is to compare the linear model commonly used for small flapping oscillations analysis (Refs. 6,7,8) to a more general nonlinear model for the rotor blades in hover that allows large flapping oscillations to occur due to gusty air and collective pitch command.

The arising of large destructive oscillations in structures due to a gust input is not a new phenomenon. The famous case of the Tacoma Narrows Bridge, not still completely understood, illustrates that the linear approach, based on resonance, may not be the correct explanation for the observed large oscillations. The resonance phenomenon requires stringent conditions of damping and gust/structure frequencies to take place. A recent and more plausible hypothesis is based on the nonlinearity of the system, which obviously cannot be captured by linearizing the model, under the small angle assumption (Ref. 9).

Previous Work

Large flapping oscillations in helicopter rotors have been studied by some researchers (Refs. 1-5). The focus has been the blade sailing, which is an aeroelastic phenomenon affecting helicopter rotors when rotating at low speeds in high wind conditions.

Particularly at low speeds, during startup or shutdown, gusts are of concern since the blade is free to flap and bend in the absence of strong centrifugal forces (Ref. 10).

For very low rotor speeds, the aerodynamic forces are much less than at full rotor speed and the droop stops are of some value. Many rotors have spring-loaded, centrifugally operated droop stops that prevent the blades from going below the rotor hub's height until the rotor speed is near its operating value.

Despite this there have been numerous events where the helicopter blades have actually impacted the helicopter fuselage, which is called "tunnel strikes". Besides the airframe, the flight crew and any personnel working close to the aircraft can be affected. The U.S. Army requires that the rotor can be safely started and stopped in 45-knot winds, while U.S. Navy requires a 60-knot capability (Ref. 10).

The blade sailing phenomenon is particularly applicable to naval helicopters or those operating off exposed sights such as oil rigs (Refs. 1,2).

Naval Helicopters

Naval helicopters, like LYNX, NH90 and EH101, are vertical flight vehicles that operate from the deck of ships like aircraft carriers, frigates and naval amphibious assault vessels. They often operate in bad weather, involving harsh and unstable conditions. Statistically, a helicopter can safely land on a frigate in the North Sea only 10 percent of the time in winter (Refs. 3,4,5).

High winds, the rotor downwash and the turbulent airflow over the ship's superstructure generate an aerodynamic environment that increases the pilot's workload and reduces the operational safety, particularly during helicopter approach, landing and takeoff. These severe conditions affect the control performance, handling qualities and structural limits of the helicopter, yielding the blade strikes.

The occurrence of the large flapping oscillations may be related to resonance due to the matching between the angular frequency of the rotor and the shedding frequency of vortices from the sharp edges of the ship.

However, when the rotor is prone to large flapping deflections, the nonlinear effects become relevant and resonance may not be the unique explanation for the large flapping motion observed in practice. Bifurcation, limit cycles and chaos must also be taken into account.

Sensitive dependence on initial values and strong change of flapping behavior according to several varying parameters are conditions that must be evaluated through analytical and numerical tools.

The nonlinear theory based on a topological approach is still poorly understood and used by engineers. Except possibly for limit cycle oscillations (Ref. 11), concepts like attractors, bifurcations and Lyapunov exponents are nearly absent of the aeronautical research, even about helicopter rotor dynamics, which is inherently nonlinear.

The engineering analysis based on Computational Fluid Dynamics (CFD) and Wind Tunnel tests is very important, but the tools of the bifurcation and chaos theory can shed light on the complex dynamics of naval helicopters, driving and complementing the experimental work. The investigation and understanding of the nonlinear aeroelastic phenomena related to helicopter operations in a hostile wind environment can determine operational and design modifications for improved safety and autonomy.

Integrated Model for Rotor Dynamics with Aerodynamic Gust Disturbance

The aerodynamics and structural dynamics of the rotor, linked to an autopilot used to trim the system, may be represented by Fig. 1 (Refs. 12,13):

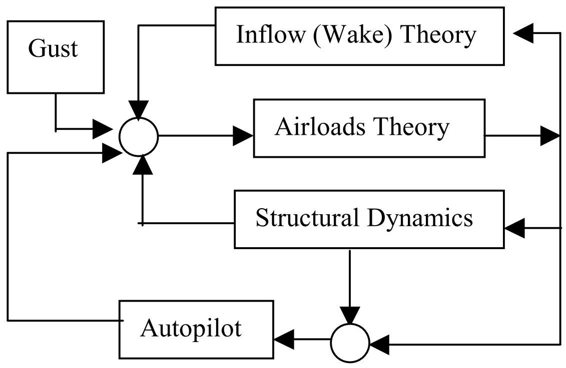

Figure 1. Structure-Aerodynamics-Control Interactions

The airloads theory relates the velocity field about the section to the lift, drag and pitching moment. The induced flow theory links the rotor airload distribution to the inflow velocity distribution at the rotor disk. The structural model relates the rotor airloads to the blade motions. The autopilot provides the collective and cyclic control inputs required for the desired flight condition, specified by hub thrust, roll and pitch moment coefficients.

The pilot must keep a trimmed flight condition in an aeroelastic context and, thus, an aeromechanical control problem must be resolved (Ref. 12).

Aiming to consider a possible aerodynamic disturbance, like a vertical gust or turbulence, the integrated rotor model includes this external effect on the velocity distribution. The resulting airloads (lift and pitching moment) can produce significant deviations from the specified hub thrust, roll and pitch moment coefficients, possibly preventing the autopilot from keeping the planned set-points and trajectories and, thus, increasing the pilot workload.

Nonlinear Flapping Model with Gust Effects

The flapping degree of freedom of helicopter rotors was introduced to isolate the problem created by the advancing and retreating sides, associated to the dissymmetry of lift in forward flight (Ref. 7).

The flapping, lagging and torsional degrees of freedom of the flexible rotor interact nonlinearly and a lot of work has been dedicated to analyze these couplings (Ref. 11).

According to the integrated model in Fig. 1, the aerodynamic loads are dependent on the structure deformation (Ref. 14). However, the structure is also dependent on the aerodynamic environment and gusty air can produce large deflections, amplifying the nonlinear effects.

In order to study the flapping behavior in gusty air and analyze the nonlinear effects, the rotor is assumed to be fully articulated, operating in a hovering state with no translational velocity. The rotor blade is assumed to be rigid and the nonlinear flapping model is derived using the blade element theory (Ref. 8).

The flapping model includes a simplified sinusoidal vertical gust and collective pitch inputs with constant inflow, neglecting the couplings with the other degrees of freedom.

Initially it is important to identify the sources of the flapping nonlinearities and the conditions under which these nonlinearities are significant.

In order to accomplish this, the equation of motion of the rotor blade about the flapping axis must be obtained. Using the Newtonian approach and Euler's equations based on a blade-body axis system and considering the blade as a very slender rod, the angular acceleration of the blade about the flapping axis y is given by (Ref. 8):

$$\alpha_y = \frac{dq_B}{dt} - p_B r_B \qquad (1)$$

where

$$\begin{aligned} p_B &= \Omega \sin\beta \\ q_B &= -d\beta / dt \\ r_B &= \Omega \cos\beta \end{aligned} \qquad (2)$$

Therefore the angular acceleration of the blade about the y axis is:

$$\alpha_y = -\frac{d^2\beta}{dt^2} - \Omega^2 \sin\beta\cos\beta \qquad (3)$$

The Equation (3) determines the flapping nonlinearity, which is significant only for large angles. However, this condition is typical for blade sailing phenomenon and thus the linear approximation is not applicable.

The inflow angle for a radial blade element located at distance r from the rotor hub obtained in Ref. 8, made up of the effect of induced velocity (downwash) and the induced angle due to flapping velocity, can be modified by including gust effects, as follows:

$$\phi = \frac{r\dfrac{d\beta}{dt} + v_i - w}{\Omega r} \qquad (4)$$

where ϕ is the new inflow angle, assumed to be relatively small.

Therefore, the nonlinear differential equation for the flapping motion in hover with gust effects is:

$$\frac{d^2\beta}{dt^2} + \frac{\gamma\Omega}{8}\frac{d\beta}{dt} + \lambda_1^2\Omega^2 \sin\beta\cos\beta = \\ = \left(\frac{\gamma\theta_0}{8} - \frac{\gamma v_i}{6\Omega R}\right)\Omega^2 + \frac{\gamma\Omega}{6R} w \qquad (5)$$

The gust effects are modeled by a simplified vertical sinusoidal wave actuating uniformly over the rotor blades (Ref. 15):

$$w = \alpha \sin\left(\frac{2\pi}{\lambda} V_{mw} t\right) \qquad (6)$$

This gust model is far from the complex air wake patterns that exist in a real environment, particularly over ships (Ref. 16), but it allows a preliminary study of the fluid-structure-pilot nonlinear interactions in dangerous situations.

The term $\lambda_1^2\Omega^2 \sin\beta\cos\beta$ of the Equation (5) represents the nonlinearity of the flapping motion and it is usually approximated by the term $\lambda_1^2\Omega^2\beta$ for small amplitude oscillations (Refs. 6,7,8). While this approximation seems reasonable for stability analysis purposes around an equilibrium position, the gust response may require a nonlinear analysis considering the possibility of the arising of large oscillations.

Simulation of the Nonlinear Flapping Equation

A common approach for rotor stability analysis is to find the equilibrium points using the complete nonlinear equations and then linearize the equations around these points. However, though commonly assumed, this static nonlinear approach may not be adequate for response problems, for, in fact, the modeling requires the use of non-homogeneous differential equations with forcing terms that interact in a complex way.

Therefore, the aeroelastic investigation developed in the present work uses the fully nonlinear model describing the dynamic flapping behavior and is based on the Runge–Kutta simulation of the Equation (5). Fig. 2 shows the differences between the solutions predicted by the nonlinear model and the linear one, for the following set of parameters and inputs:

$$\begin{aligned} &R = 5.7m \\ &\gamma = 8 \\ &\Omega = 10 rad/s \\ &\lambda_1 = 1 \\ &\theta_0 = 4\deg \\ &v_i = 0 m/s \\ &\alpha = 21 m/s \\ &\lambda = 15m \\ &Vmw = 3m/s \end{aligned}$$

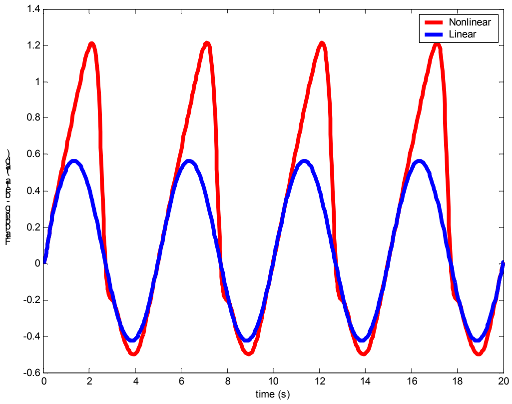

Figure 2. Nonlinear and linear gust / collective pitch response.

The low rotational speed used in the simulation represents a condition of startup or shutdown of the rotor system, when the centrifugal force is small. This condition is also associated with a low stiffness of the rotor blades. The simulation considered a high amplitude sinusoidal gust input, thus generating a large aerodynamic force. The combination of low stiffness, large aerodynamic force and nonlinear effects gave rise to the excessive flapping of the rotor blades shown in Fig. 2. Possibly this nonlinear phenomenon is present in some blade sailing occurrences.

A linear model can be used to study this phenomenon if relatively small flapping angles are considered. However, for large angles the nonlinearity becomes important and a new class of phenomena can occur, including bifurcations and, possibly, chaos.

Bifurcation Analysis

Approximating the term $\lambda_1^2\Omega^2 \sin\beta\cos\beta$ in Equation (5) by $\lambda_1^2\Omega^2(\beta - 2\beta^3/3)$, valid for the considered range of the flapping angles (0 to 1 rad), a nonlinear Duffing-type model is obtained, as follows:

$$\begin{aligned} &\frac{d^2\beta}{dt^2} + \frac{\gamma\Omega}{8}\frac{d\beta}{dt} + \lambda_1^2\Omega^2(\beta - 2\beta^3/3) = \\ &= \left(\frac{\gamma\theta_0}{8} - \frac{\gamma v_i}{6\Omega R}\right)\Omega^2 + \frac{\gamma\Omega}{6R}w \end{aligned} \qquad (7)$$

Equation (7) can be written in the general form:

$$\begin{aligned} &\frac{d^2\beta}{dt^2} + a\frac{d\beta}{dt} + b\beta + c\beta^3 = \\ &= B_0 + B_1\sin\omega t = f(\theta_0, w) \end{aligned} \qquad (8)$$

A first approximate solution is given by:

$$\beta(t) = C_0 + C_1\sin(\omega t + \sigma) \qquad (9)$$

Substituting (9) in (8) and using the method of harmonic balance (Refs. 17,18), the result is a system of algebraic equations involving C_0, C_1, σ:

$$\begin{aligned} &C_1(-\omega^2 + b + 3cC_0^2 + 3cC_1^2/4) = B_1\cos\sigma \\ &-a\omega C_1 = B_1\sin\sigma \\ &C_0(b + cC_0^2 + 3cC_1^2/2) = B_0 \end{aligned} \qquad (10)$$

The flapping response given by (9) and (10) exhibits the nonlinear behavior called *jump phenomenon*, related to a cycle bifurcation (Ref. 19). This occurrence is due to the multi-value solutions of C_1 for a particular B_0. Two limit cycles with different stability properties coexist for some values of the control parameter (collective pitch command theta0).

Fig. 3 shows the *jump phenomenon* related to the Duffing-type Equation (7).

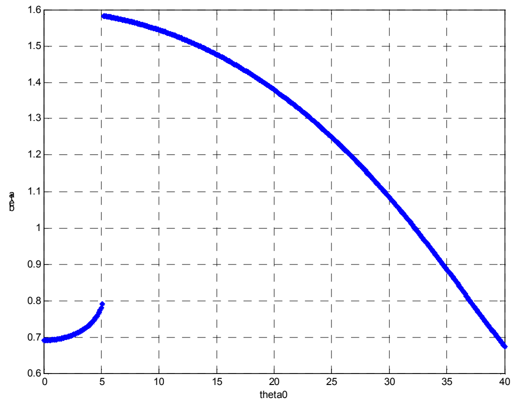

Figure 3. Bifurcation diagram for beta (flapping amplitude) varying according to the control parameter theta0 (collective pitch command).

Discussion of the Analysis Results

The large damping, approximately equal to γ/16 (γ range is, typically, from 5 to 15), prevents large flapping oscillations from occurring in normal conditions, which is a highly desirable property.

However, the computational simulations and the bifurcation analysis show that a combination of low rotational speeds, low gust frequencies and large gust amplitudes can give rise to large, possibly destructive, flapping oscillations if the collective pitch is commanded above a critical angle. This *jump phenomenon* is inherent to nonlinear systems and is not predicted by the linear model. Fig. 2 shows the large difference between the flapping amplitudes predicted by the two models.

The origin of the discrepancies between the two models is that the principle of superposition does not apply for the nonlinear flapping and, thus, the gust and collective pitch input contributions are not additive, yielding the large oscillations.

Therefore the reduction of excessive tip deflections by increasing the blade collective pitch setting as suggested in Refs. 3-5 should be carefully analyzed, taking into account the possible onset of the *jump phenomenon*.

The analysis of the Equation (5) reveals that a helicopter rotor, as a nonlinear dynamic system, may be extremely sensitive to a gust input, despite the large flapping damping. Probably a careful nonlinear analysis validated by experimental results will be particularly important for naval operations, where high winds are common.

Future work includes a nonlinear analysis of the coupling of the flapping motion with the other degrees of freedom, particularly the torsional motion, including gust effects. Eventually, this aeroelastic coupling may constitute itself as the basis for a control method to reduce rotor oscillations.

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