PERFORMANCE ANALYSIS OF A HELICOPTER BLADE-SAILING AEROSERVOELASTIC SYSTEM WITH INDIVIDUAL BLADE ROOT CONTROL AND REVERSE-FLOW EFFECTS

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Abstract. This paper analyzes the vibration-reduction performance of a proposed blade-sailing aeroservoelastic system with individual blade root control (IBRC), including aerodynamic reverse-flow effects. IBRC-based actuation, in the rotating frame, allows the compensation of aerodynamic forces by superimposing a blade pitch angle variation at the blade root to the collective/cyclic commands. The objective is the reduction of flapping deflections and the suppression of tunnel strikes for articulated rotors, considering steady-flow conditions during engagement shipboard operations. The aeroservoelastic modeling includes a nonlinear structural dynamics related to the droop/flap stops, blade-element aerodynamics with reverse-flow effects, a linear gust model for the ship airwake, gravity effects and an active lift compensator. The performance analysis considers a proportional-integral-derivative (PID) individual-blade-root controller with actuator constraints for the lift/angle-of-attack compensation associated with the stiffness and damping enhancement of the flapping oscillator. The closed-loop blade-sailing dynamics constitutes a forced parametric oscillator with nonlinear stiffness and time-varying coefficients and it is simulated for an articulated rotor whose properties are based on the H-46 shipboard rotor. The PID control parameters are varied in order to analyze the effects of the closed-loop stiffness and damping on the alleviation of flapping vibrations. The simulation results show that the proposed PID-IBRC aeroservoelastic system yields tunnel-strike suppression and it is associated with blade-sailing reduction of nearly 50% in upward deflections and nearly 35% in downward deflections for an incoming wind velocity of 45 kt, by using blade-root-actuator limits of ± 6 deg.

Keywords: helicopter blade sailing, individual blade root control, PID control, aeroservoelasticity, reverse flow.

1. INTRODUCTION

Helicopter rotors operating in high winds are subjected to significant flow-induced loads which can yield large vibrations and structural damage. Shipboard helicopters, operating in the hostile maritime environment from frigate-like platforms, are especially susceptible to the phenomenon called blade sailing.

Blade sailing is an aeroelastic transient phenomenon characterized by the occurrence of large flapping vibrations, possibly associated with tunnel/tail-boom strikes (blade-fuselage impacts), due to fluid-structure interactions during engagement or disengagement operations of helicopter rotors under high wind conditions (Newman, 1995).

The blade-sailing control problem has a practical importance due the ubiquitous use of the shipboard helicopter in littoral defense missions (Wall et al., 2005). Aeroservoelastic strategies, aimed at prescribing a low-vibration behavior for rotors operating in high winds, can yield active flow-induced load alleviation by using embedded blade controllers, sensors and actuators integrated according to a feedback control system. Previous research on active blade-sailing control includes swashplate-actuation for gimballed rotors (Keller, 2001), use of trailing-edge flaps (Jones and Newman, 2007) and active twist (Khouli et al., 2008).

Considering that these active control concepts are not fully mature yet, the present work investigates the performance in steady flow of a new approach to helicopter blade-sailing reduction based on Theoretical Rotary-Wing Aeroservoelasticity (RWASE) (Dowell et al., 1995) and Individual Blade Root Control (IBRC). IBRC-based actuation, in the rotating frame, can yield reliable helicopter vibration reduction and allows the compensation of aerodynamic forces by superimposing a blade pitch angle variation at the blade root to the collective/cyclic commands (Haber et al., 2002). The proposed design-oriented RWASE-IBRC approach is aimed at developing a blade-sailing model amenable to (Ramos, 2007) (Ramos et al., 2008, 2009a, 2009b, 2009c):

1. Identify the flow-induced loads that govern the flapping vibrations (aeroservoelastic modeling).
2. Study active IBRC methods for shipboard rotors, in order to reduce the blade-sailing vibrations and enlarge the engagement/disengagement operating envelopes (aeroservoelastic performance analysis).

In this work, a proportional-integral-derivative (PID) individual-blade-root controller is proposed for the active stiffness/damping enhancement of the flapping motion, including aerodynamic reverse-flow effects. The objective is the reduction of flapping deflections and the suppression of tunnel strikes for articulated rotors, considering steady-flow conditions during engagement shipboard operations. The closed-loop blade-sailing dynamics constitutes a pitch-controlled flapping oscillator with nonlinear stiffness and time-varying coefficients and it is simulated for an articulated rotor whose properties are based on the H-46 shipboard rotor. The aeroservoelastic performance analysis focuses on the performance of the proposed PID controller considering the IBRC blade pitch actuator limits.
2. AEROSEROVOELASTIC MODELING

According to the proposed RWASE-IBRC approach, the aeroservoelastic modeling includes a nonlinear structural dynamics related to the droop and flap stops, blade-element aerodynamics with reverse-flow effects, a linear gust model for the ship airwake, gravity effects and an active lift compensator based on PID individual blade root control with actuator constraints. Figure 1 illustrates the proposed blade-sailing aeroelastic feedback control system.

Figure 1 shows a feedback control system perspective, where the rotor blade loads due to aerodynamic effects, gravity and ship motions are viewed as disturbances to the plant constituted by the blade itself and its individual root actuator. The blade control (IBRC) input is computed according to a PID strategy and generates a compensating aerodynamic moment for the flapping stiffness/damping enhancement and vibration reduction. The choice of an individual blade control approach is due to the very different aerodynamic conditions that a blade experiences while rotating in high wind conditions.

2.1. Structural modeling: droop/flap-stop effects

The articulated-rotor blade-sailing dynamics is given by (Ramos, 2007) (Ramos et al., 2009a):

\[
\ddot{\beta} + \Omega^2 \beta + \sigma(\beta) = -\frac{3}{2R} g + \frac{M_{\text{as}} + M_{\text{ac}}}{I_b} \tag{1}
\]

where

\[
\sigma(\beta) = \omega_{nr}^2 (\beta - \beta_{FS}), \text{if } \beta > \beta_{FS} \\
\sigma(\beta) = 0, \text{if } \beta_{DS} \leq \beta \leq \beta_{FS} \\
\sigma(\beta) = \omega_{DS}^2 (\beta - \beta_{DS}), \text{if } \beta < \beta_{DS} \tag{2}
\]

In Eqs. (1) and (2), \(\dot{\beta}\) is the blade flapping angle, \(\Omega\) is the rotor rotational speed, \(\sigma(\beta)\) is the nonlinear stiffness function related to the droop/flap-stop effects, \(R\) is the rotor radius, \(g\) is the acceleration of gravity, \(I_b\) is the blade moment of inertia about the center of rotation, \(M_{\text{as}}\) is the moment due to the aerodynamic forces related to the ship airwake, collective/cyclic commands and rotor blade motions, \(M_{\text{ac}}\) is the moment due to the aerodynamic PID-IBRC active control forces, \(\omega_{nr}\) is the blade non-rotating flapping natural frequency, \(\beta_{DS}\) is the blade droop stop angle, and \(\beta_{FS}\) is the blade flap stop angle.

2.2. Aerodynamic modeling: blade-element theory with reverse-flow effects

Considering the large reverse-flow region at the retreating side of the rotor disk, due to the high wind velocities in conjunction with the low rotational speeds during rotor engagement/disengagement, the aerodynamic moments given in (Ramos et al., 2009a) must be corrected for the retreating blade motion based on (Johnson, 1994). The corresponding aerodynamic moments are given by:
\[ M_{ax} = M_{ai} + M_{anw} + M_{a\beta} + M_{az} \]  \hspace{1cm} (3)

where:

\[
\begin{align*}
M_{ai} &= I_{b} \frac{2 \Omega^2}{8} \left[ -1 + \frac{8}{3} (\mu \cos \Psi) + 2 (\mu \cos \Psi)^2 - \frac{2}{3} (\mu \cos \Psi)^3 \right] \theta_i \\
M_{anw} &= I_{b} \frac{2 \Omega^2}{8} \left[ -1 + \frac{1}{2} (\mu \cos \Psi) + \frac{1}{3} (\mu \cos \Psi)^2 - \frac{1}{15} (\mu \cos \Psi)^3 \right] \theta_{n} \\
M_{a\beta} &= I_{b} \frac{2 \Omega^2}{8} \left[ -1 + \frac{4}{3} (\mu \cos \Psi) - \frac{2}{3} (\mu \cos \Psi)^3 \right] \dot{\beta} = -I_{b} [c_{\beta}(t) - \Omega^2] \\
M_{az} &= I_{b} \frac{2 \Omega^2}{8} \left[ -1 + \frac{4}{3} (\mu \cos \Psi) + \frac{2}{3} (\mu \cos \Psi)^3 \right] \left[ V_{zg} + \frac{4}{3} - 2 (\mu \cos \Psi) + \frac{4}{3} (\mu \cos \Psi)^3 \right] V_{zu} \\
\end{align*}
\]  \hspace{1cm} (4)

and

\[
\begin{align*}
\theta_i &= \theta_{35} + \theta_{ls} \sin \Psi + \theta_{1c} \cos \Psi - \frac{3}{4} \theta_{n} \\
V_{zg} &= K_{v} V \sin \Psi \\
V_{zu} &= 0
\end{align*}
\]  \hspace{1cm} (5)

where \( \gamma \) is the Lock number (relation between aerodynamic and inertial forces) (Johnson, 1994), \( \mu \) is the advance ratio parameter for a lateral starboard side wind velocity \( V_{y} \), and \( \varphi(t) \) is the time-varying blade azimuth angle. The parameters \( \theta_{35}, \theta_{ls}, \theta_{1c} \), and \( \theta_{n} \) are, respectively, the blade collective, longitudinal cyclic, lateral cyclic, and the linear built-in twist angles. The terms \( M_{ai}, M_{anw}, M_{a\beta}, M_{az} \) are, respectively, the aerodynamic moments due to the blade pitch input, to the blade built-in twist, to the blade flapping rate, to the blade flapping angle, and to the wind-over-deck (WOD) vertical velocity, which is determined by the gust factor \( K_{v} \). The aerodynamic moments associated with the flapping angle and rate in Eq. (4) introduce time-varying coefficients on the blade-sailing Eq. (1).

The verification of the obtained blade-sailing model given by Eqs. (1) to (5) is carried out by comparison with the results given in (Geyer et al., 1998) from a model validated with experimental data, by using a fourth-fifth order Runge-Kutta numerical simulation (Ramos et al., 2009a). The helicopter rotor parameter values for the verification task and the control performance simulations are shown in Tab. 1. The adopted rotor parameters and the rotational speed profile are based on the characteristics of the H-46 Sea Knight helicopter (Keller, 2001). The gust factor \( K_{v} \) is equal to 0.25.

| \( \gamma \) (Lock number) | 7.96 |
| \( \Omega_{0} \) (nominal rotor rotational speed) | 27.65 rad/s |
| \( V_{y} \) (lateral WOD velocity) | - 45 kt |
| \( V_{x} \) (longitudinal WOD velocity) | 0 kt |
| \( R \) (rotor radius) | 25.5 ft |
| \( \omega_{nr} \) (blade non-rotating flapping frequency) | 6 rad/s |
| \( \beta_{DS} \) (droop stop angle) | - 0.54° |
| \( B_{FS} \) (flap stop angle) | 1.5° |
| \( \theta_{35} \) (collective pitch angle) | 3° |
| \( \theta_{ns} \) (built-in twist angle) | - 8.5° |
| \( \theta_{1s} \) (longitudinal cyclic angle) | 2.5° |
| \( \theta_{1c} \) (lateral cyclic angle) | 0.0693° |
3. AEROSERVOELASTIC PERFORMANCE ANALYSIS

3.1. Aerodynamic control moments

Aerodynamic moments can be designed for the reduction of blade-sailing vibrations by using active control methods. As mentioned in the introduction, previous researches on blade-sailing active control were based on swashplate-actuation for gimballed rotors (Keller, 2001), use of trailing-edge flaps (Jones and Newman, 2007) and active twist (Khouli et al., 2008).

The new active control approach proposed in this work for articulated shipboard rotors is based on Individual Blade Root Control (IBRC) actuation (Haber et al., 2002). A variable length rod, constituted by a hydraulic actuator, is linked to the swashplate, in order to allow a blade pitch control input to superimpose the collective and cyclic commands. The hydraulic actuators replace the rigid pitch links of the helicopter control system, yielding IBRC motions, which can reduce rotor vibration. Accelerometers and strain gauges can be used for sensing and approximate calculation of the blade flapping angle and angular velocity, based on the blade tip motion.

The IBRC method is associated with the rotating frame, allowing the generation of compensating aerodynamic moments according to the individual behavior of each rotor blade. This characteristic is especially important for articulated rotors because droop/flap-stop impacts and tunnel/tail-boom strikes are the main concern about blade-sailing occurrences.

The aerodynamic moments associated with an angle-of-attack/lift compensation due to an IBRC pitch input \( \theta_u \) in the rotating frame, are given by:

\[
M_{ac} = \frac{1}{2} \rho V^2 \left[ 1 - \frac{8}{3} \left( \mu_c \cos \Psi \right) + 2 \left( \mu_c \cos \Psi \right)^2 \right] \theta_u, \text{ for the advancing blade motion}
\]

\[
M_{ac} = \frac{1}{2} \rho V^2 \left[ 1 - \frac{8}{3} \left( \mu_c \cos \Psi \right) + 2 \left( \mu_c \cos \Psi \right)^2 - \frac{2}{3} \left( \mu_c \cos \Psi \right) \right] \theta_u, \text{ for the retreating blade motion}
\]

Substituting the ship airwake and the IBRC aerodynamic moments, given by Eqs. (3) and (6), respectively, into Eq. (1), yields:

\[
\ddot{\beta} + c_{\beta}(t) \dot{\beta} + c_{\beta}(t) \beta + \sigma(\beta) = u(t) + x_0(t)
\]

\[
u(t) = \frac{M_{ac}}{I_B}, \quad x_0(t) = \frac{M_{aw} + M_{aw} + M_{ac}}{I_B} - \frac{3}{2} \frac{g}{R}
\]

where \( c_{\beta}(t), c_{\beta}(t) \) are the damping and stiffness time-varying coefficients in Eq. (4), respectively, \( \sigma(\beta) \) is the nonlinear stiffness function related to the droop/flap-stop effects, \( u(t) \) represents the active IBRC input and \( x_0(t) \) represents the exogenous inputs due to the pilot commands, to the blade twist, to the ship airwake and to gravity. According to Eq. (7), the single-degree-of-freedom blade-sailing behavior is governed by a nonlinear ordinary differential equation with time-varying coefficients.

3.2. PID-IBRC active controller design and simulation

The active aeroelastic controller design is based on the obtained blade-sailing model, considering a nominal steady-flow condition associated with tunnel-strike occurrences for the H-46 shipboard helicopter (blade tip deflections greater than 18%R). The proposed IBRC-based actuation in the rotating frame can modify the angle of attack and, hence, the lift conditions at the blade sections, by superimposing a blade pitch input at the root to the collective/cyclic commands. This control input is applied only during rotor engagement/disengagement operations and it is set to zero at hover or forward flight conditions, therefore, the flight dynamics is not affected by IBRC. The active lift compensation can be associated with the stiffness and damping enhancement of the flapping motion by using a PID control law, according to the feedback control scheme illustrated in Fig. 1. Therefore, the blade pitch control input \( \theta_u \) is given by:

\[
\theta_u = -K_p \beta - K_i \int \beta \, dt - K_d \dot{\beta}
\]
where $K_p$, $K_i$, and $K_d$ are the proportional, integral and derivative PID-IBRC parameters, respectively. The tuning of the control parameters is carried out according to enhanced damping (derivative/integral actions) and natural frequency (proportional action) characteristics for an approximate closed-loop flapping oscillator with constant coefficients. The behavior of the closed-loop time-varying blade-sailing system for a choice of control parameters is verified through numerical simulations (Ramos et al., 2009a). Figures 2 and 3, obtained from these numerical simulations, show the blade flapping response and the blade pitch control input, respectively, associated with PID-IBRC effects. The designed controller yields a significant blade-sailing reduction without actuator saturation (control inputs are limited to ± 6 deg).

![Blade Flapping Response](image1)

Figure 2. Flapping response – $K_p = 4.4/\gamma$, $K_d = 2.6/\Omega_0$, $K_i = -0.01*\Omega_0$

![Blade Pitch Control Input](image2)

Figure 3. Blade pitch control input – $K_p = 4.4/\gamma$, $K_d = 2.6/\Omega_0$, $K_i = -0.01*\Omega_0$
4. CONCLUSIONS

1. Despite the hub restraints, uncontrolled shipboard articulated rotors are subjected to tunnel strikes at severe steady-flow wind-over-deck conditions.
2. The blade-sailing aeroservoelastic model is a nonlinear parametric PID pitch-controlled flapping oscillator.
3. A PID individual-blade-root controller (active blade pitch control with a PID-IBRC strategy) can yield active lift compensation by enhancing the stiffness and damping of the flapping oscillator without rotor design changes.
4. The tuning of the PID control parameters according to desirable stiffness/damping properties can be achieved from numerical simulations considering the IBRC actuator constraints. The PID-IBRC parameters depend mainly on the Lock number and on the rotor nominal rotational speed.
5. The performance analysis results from the numerical simulations show that the proposed helicopter blade-sailing aeroservoelastic system using a PID-IBRC strategy yields tunnel-strike suppression and blade-sailing reduction of nearly 50% in upward deflections and nearly 35% in downward deflections at severe steady-flow wind-over-deck conditions without actuator saturation (limits of ± 6 deg).
6. Future work will involve the modeling of IBRC sensor/actuator behavior, the design of suitable filters, and the study of optimal/robust IBRC-based (active blade pitch control) strategies for blade-sailing mitigation in high winds.

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6. REFERENCES


7. RESPONSIBILITY NOTICE

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