Individual Blade Root Control of Helicopter Blade Sailing for Hingeless Shipboard Rotors

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***Abstract* — This paper investigates an individual-blade-root-control approach to the reduction of helicopter blade sailing in hingeless rotors, considering steady flow conditions during engagement shipboard operations and using theoretical aeroservoelasticity principles. The aeroelastic control law synthesis yields a flap-state-feedback individual-blade-root controller for the lift/angle-of-attack compensation whose parameters are associated with the damping/stiffness enhancement of the flapping motion. The simulation results show that the proposed aeroservoelastic controller can obtain blade-sailing reduction of nearly 30% in upward and downward deflections at severe wind-over-deck conditions by using low blade pitch input limits of the actuators. This blade-sailing reduction can prevent tunnel/tail-boom strikes from occurring.**

***Keywords* — Shipboard helicopter, blade sailing, individual blade root control, hingeless rotor, aeroservoelasticity.**

NOMENCLATURE

g = acceleration of gravity
I_B = blade moment of inertia about the center of rotation
K_1, K_2 = State-Feedback Individual-Blade-Root-Control (SF-IBRC) parameters
K_v = ship airwake parameter for the linear gust model
M_{ac} = flapping moment due to the aerodynamic control forces
M_{as} = flapping moment due to the aerodynamic forces
NR = nominal rotational speed
R = rotor radius
r = blade-element radial position
t = time
U_P, U_T = flow velocities at a blade element, perpendicular and tangential to the rotor disk
V_{WOD}, Ψ_{WOD} = magnitude and direction of the incoming wind velocity with respect to ship centerline
V_y, V_z = Wind-Over-Deck (WOD) lateral and vertical velocity components, respectively
β = blade flapping angle
γ = Lock number
θ_u= IBRC blade pitch input angle
μ_{y} = advance ratio parameter ($V_y / (\Omega R)$)
Ψ = rotor blade azimuth
Ω = rotor rotational speed or angular velocity
ω_{nr} = blade non-rotating flapping natural frequency

I. INTRODUCTION

The shipboard helicopter is a key technology for the protection of oceanic resources and littoral defense. Among the main missions are search and rescue, surveillance, transport of troops and materials, anti-submarine warfare and amphibious warfare. The shipboard helicopter may operate from carriers or non-aviation ships, such as frigates. Joint shipboard-helicopter operations, involving Army and Air Force helicopters are also increasingly important. To accomplish its missions, rotor engagement/disengagement operations are often executed in a hostile environment, under high winds and rough sea states. These dangerous conditions are amplified by the ship structure, which generates flow velocity gradients and vortices over the flight deck. Therefore, shipboard helicopter operations are among the most hazardous military operations and the shipboard environment imposes severe restrictions on the missions and determines stringent requirements for the design of aerial vehicles.

The problem of flight in the vicinity of ships is usually called Dynamic Interface (DI) problem [1]. Among the dynamic phenomena in the DI that must be analyzed and controlled, one is especially important for rotary-wing aircraft: *blade sailing*.

Blade sailing is an aeroelastic transient phenomenon characterized by the occurrence of large flapping vibrations, possibly associated with tunnel/tail-boom strikes, due to fluid-structure interactions during engagement or disengagement operations of helicopter rotors under high wind conditions [2]. Considering the ubiquitous use of the shipboard helicopter in critical defense missions, the practical importance of the control of the blade-sailing phenomenon cannot be underestimated. A recent NATO symposium highlights the importance of the study of flow-induced loads and the impact on military applications [3].

Aeroservoelastic strategies, aimed at prescribing a low-vibration behavior for shipboard rotors in the DI by using active controllers, can enhance the survivability of shipboard helicopters and improve the safety of military operations in the hostile maritime environment. The increasing availability and low cost of electronic technology, including microcontrollers, sensors and actuators, stimulate active control research as a reliable substitute for passive control devices, such as dampers, mechanical pitch-flap couplings (δ_3) and spoilers. Previous research on active blade-sailing control includes swashplate-actuation for gimballed rotors [4], use of trailing-edge flaps [5] and active twist [6].

The present work investigates a new approach to helicopter blade-sailing reduction based on Rotary-Wing Aeroservoelasticity (RWASE) 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 [7]. The proposed design-oriented RWASE-IBRC approach is aimed at developing a blade-sailing model amenable to [8]:

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(1) Identify the main flow-induced and dynamic loads, as well as the key parameters that govern the flapping vibrations (modeling phase).
(2) Study active IBRC methods for shipboard rotors, in order to reduce the blade-sailing vibrations and enlarge the engagement/disengagement operating envelopes (synthesis phase).
The proposed RWASE-IBRC approach is applied to the reduction of helicopter blade sailing for hingeless rotors, considering steady flow conditions during engagement shipboard operations and using theoretical aeroservoelasticity principles. The aeroservoelastic analysis includes the structural dynamics, a linear aerodynamic model based on the blade-element theory, a vertical velocity gradient modeled as a linear gust for the ship airwake, and a lift compensator based on individual blade root control. Fig. 1 illustrates the proposed blade-sailing aeroservoelastic scheme.

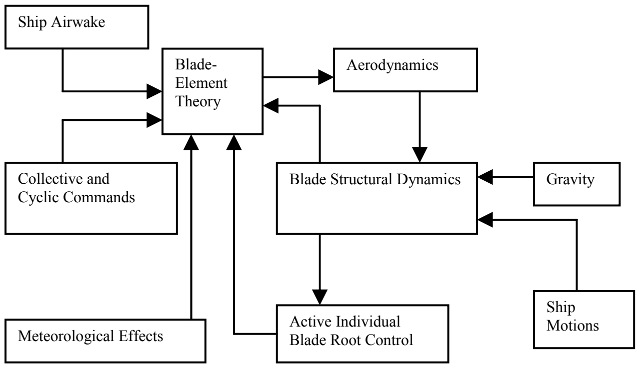

Fig. 1. Blade-sailing aeroservoelastic scheme

Fig. 2 illustrates the proposed blade-sailing feedback control system.

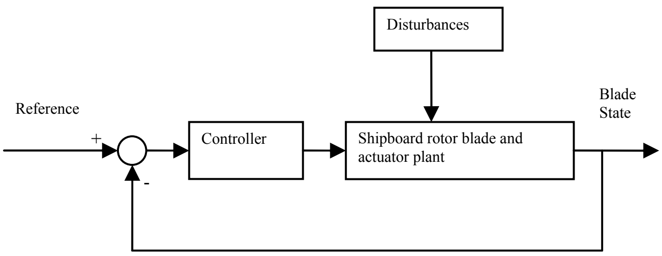

Fig. 2. Blade-sailing feedback control system

Fig. 1 shows that the aerodynamic effects due to the ship airwake, collective/cyclic commands, meteorology, rotor blade motions and active individual blade root control input can be computed according to the blade-element theory, yielding an equivalent angle of attack, which determines the aerodynamic loads. These loads in conjunction with gravity and ship motion effects drive the blade structural response and, thus, the blade controller input.
Fig. 2 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 actuator. The blade controller input is computed according to a state-feedback strategy and generates a compensating aerodynamic moment for flapping 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 the DI.

II. AEROSERVOELASTIC MODELING

For control design purposes, the proposed blade-sailing aeroservoelastic model can be greatly simplified by considering the forces and moments actuating only in the flapping plane. Fig. 3 shows the forces at a blade element for the simplified blade-sailing planar model, according to a frame rotating with the blade.

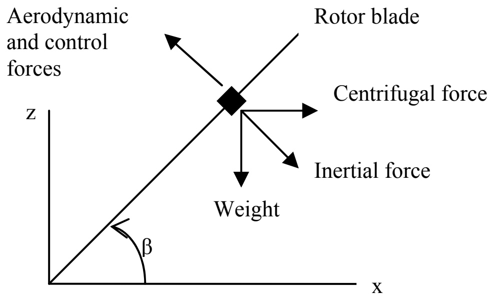

Fig. 3. Forces at a flapping planar blade-element for the proposed blade-sailing model (rotating frame)

The simplified diagram of forces at a planar blade-element in Fig. 3 illustrates the main factors that govern the blade-sailing flapping behavior. Ship motion effects are not included. The resulting moments about the flapping hinge, simply assumed located at the rotating blade root, associated with the stiffness effect of the hingeless blade, determine the flapping tip deflections related to the angle β.

Fig. 4 shows the flow velocity components in the plane of the rotor for the proposed blade-sailing model, considering the WOD conditions.

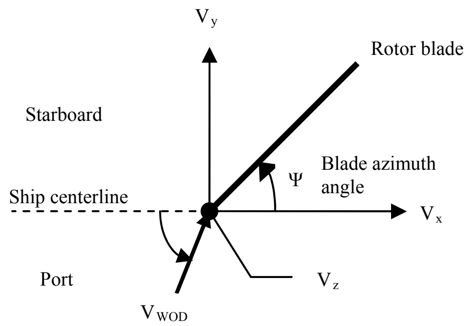

Fig. 4. Flow velocity components for the WOD conditions

The vertical velocity component of the steady flow WOD conditions related to the ship airwake is obtained by considering a linear gust at 270° direction, which is especially associated with large blade deflections [2]:

$$V_z = K_v V_y \frac{r}{R} \sin \Psi \quad . \tag{1}$$

The blade-sailing dynamics for the hingeless blade can be modeled from the moments related to the forces represented in Fig. 3, according to a small-angle approximation:

$$\ddot{\beta} + (\Omega^2 + \omega_{nr}^2)\beta = -\frac{3}{2R}g + (M_{as} + M_{ac})/I_B. \quad (2)$$

The aerodynamic moments due to the considered steady flow conditions can be obtained from the blade-element theory [9] with flow velocity components given by:

$$\begin{aligned} U_T &= \Omega r - V_y \cos\Psi \\ U_P &= r\dot{\beta} + (V_y \sin\Psi)\beta - V_z \end{aligned} . \quad (3)$$

The IBRC compensating aerodynamic moment in (2) is related to the blade pitch inputs from the actuators and it is given by:

$$M_{ac} = I_B \frac{\gamma\Omega^2}{8}\left[1 - \frac{8}{3}\mu_y \cos\Psi + 2(\mu_y \cos\Psi)^2\right]\theta_u. \quad (4)$$

III. AEROSERVOELASTIC CONTROL

The aeroelastic control law synthesis yields a flap-state-feedback individual-blade-root controller (SF-IBRC) for the lift/angle-of-attack compensation associated with the damping/stiffness enhancement of the flapping motion. The blade pitch input is given by:

$$\theta_u = -K_1\beta - K_2\dot{\beta}. \quad (5)$$

The blade-sailing closed-loop dynamics given by (2), (4) and (5) constitutes a time-varying parametric oscillator and it is simulated for a hingeless rotor whose properties are based on the H-46 articulated shipboard rotor [10]. Figs. 5 and 6 show the blade flapping response and the blade pitch control input, respectively, for $K_1 = 4/\gamma$, $K_2 = 2/NR$ and a gust factor $K_v = 0.25$. The actuator inputs are limited to $\pm 6^o$. Tunnel strikes can occur with downward blade deflections of 18%R.

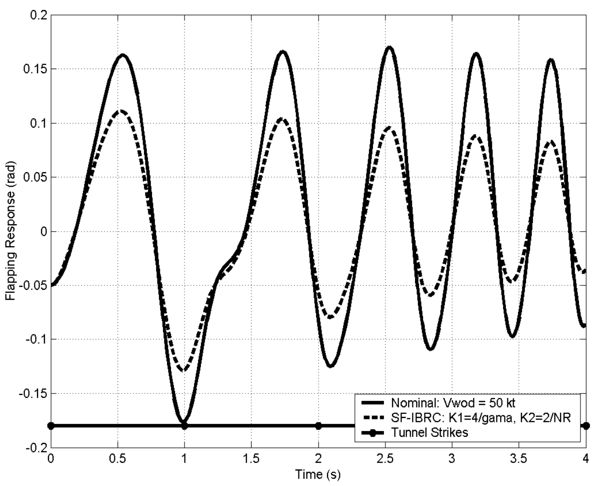

Fig. 5. SF-IBRC – $K_1 = 4/\gamma$ and $K_2 = 2/NR$

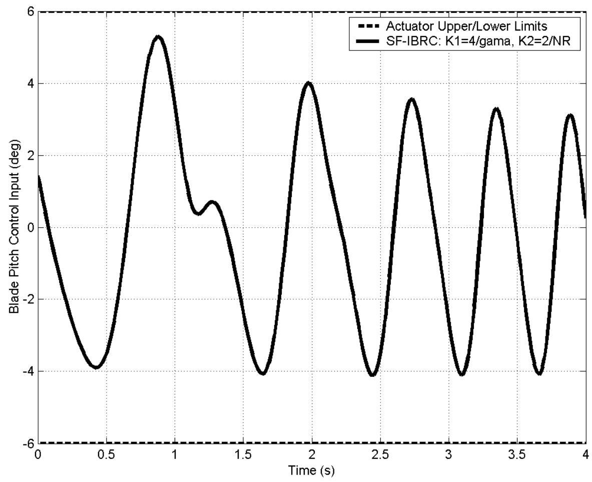

Fig. 6. Control input – $K_1 = 4/\gamma$ and $K_2 = 2/NR$

Figs. 7 and 8 show the blade flapping response and the blade pitch control input, respectively, for $K_1 = 0$ and $K_2 = 7/NR$, in order to investigate the sensitivity of the blade-sailing reduction to the actuator inputs.

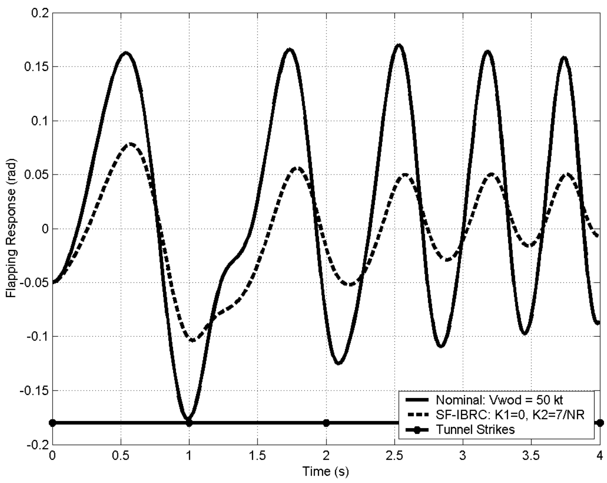

Fig. 7. SF-IBRC – $K_1 = 0$ and $K_2 = 7/NR$

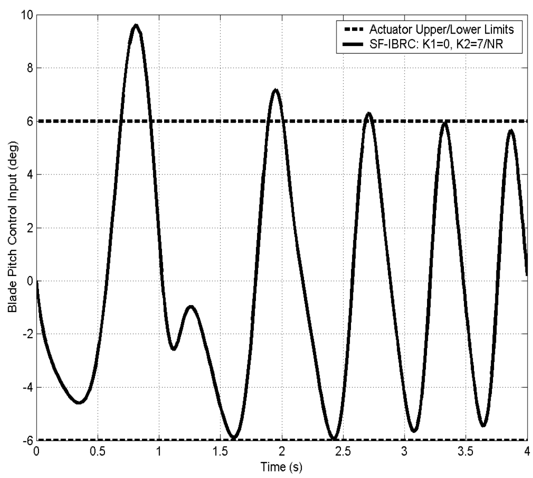

Fig. 8. Control input – $K_1 = 0$ and $K_2 = 7/NR$

IV. CONCLUSIONS

The simulation results show that the proposed aeroservoelastic SF-IBRC method can yield blade-sailing reduction of nearly 30% in upward and downward deflections for hingeless shipboard rotors at severe wind-over-deck conditions, by using low blade pitch inputs of the IBRC actuators. This blade-sailing reduction can prevent tunnel/tail-boom strikes from occurring.

The blade-sailing reduction is very sensitive to the IBRC actuator constraints, thus, the relaxation of the considered limits can strongly improve the alleviation of the flapping vibration effects, and can yield tunnel/tail-boom-strike suppression at severe steady flow conditions.

Future work will involve the study of the performance of the proposed SF-IBRC scheme in unsteady flow considering ship motion effects.

REFERENCES

[1] RHOADES, M.M.; HEALEY, J.V. Flight deck aerodynamics of a nonaviation ship. *Journal of Aircraft*, v. 29, n. 4, p. 619-626, Jul.-Aug. 1992.

[2] NEWMAN, S.J. The Verification of a Theoretical Helicopter Rotor Blade Sailing Method by Means of Windtunnel Testing. *The Aeronautical Journal of the Royal Aeronautical Society*, v. 99, n. 982, p. 41-51, Feb. 1995.

[3] WALL, A.S.; ZAN, S.J.; LANGLOIS, R.G.; AFAGH F.F. A Numerical Model for Studying Helicopter Blade Sailing in an Unsteady Airwake. In: FLOW-INDUCED UNSTEADY LOADS AND THE IMPACT ON MILITARY APPLICATIONS – NATO SYMPOSIUM, April 2005. *Proceedings*, 2005.

[4] KELLER, J.A.; SMITH, E.C. Active Control of Gimballed Rotors Using Swashplate Actuation During Shipboard Engagement Operations. *Journal of Aircraft*, v. 40, n. 4, p. 726-733, Jul.-Aug. 2003.

[5] JONES, M.P.; NEWMAN, S.J. A Method of Reducing Blade Sailing through the Use of Trailing Edge Flaps. In: AMERICAN HELICOPTER SOCIETY ANNUAL FORUM, 63., 2007. *Proceedings*, 2007.

[6] KHOULI, F.; WALL, A.S.; LANGLOIS, R.G.; AFAGH F.F. Investigation of the Feasibility of a Proposed Hybrid Passive and Active Control Strategy for the Transient Aeroelastic Response of Helicopter Rotor Blades During Shipboard Engage and Disengage Operations. In: AMERICAN HELICOPTER SOCIETY ANNUAL FORUM, 64., 2008. *Proceedings*, 2008.

[7] JACKLIN, S.A. *et al*. Full-Scale Wind Tunnel Test of An Individual Blade Control System For a UH-60 Helicopter. In: AMERICAN HELICOPTER SOCIETY ANNUAL FORUM, 58., Montreal, Canada, 2002. *Proceedings*, 2002.

[8] RAMOS, R. L. C. B.; *Aeroservoelastic Analysis of the Blade-Sailing Phenomenon in the Helicopter-Ship Dynamic Interface*. Thesis (D.Sc.) – Technological Institute of Aeronautics, Brazil, 2007.

[9] JOHNSON, W. *Helicopter Theory*. [S.l.]: Dover, 1994, p. 1-767.

[10] KELLER, J.A. *Analysis and control of the transient aeroelastic response of rotors during shipboard engagement and disengagement operations*. Thesis (PhD) - The Pennsylvania State University, 2001.