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The role of rotor coning in helicopter proneness to collective bounce

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ABSTRACT

Collective bounce is a rotorcraft–pilot coupling phenomenon caused by vertical vibrations in the aircraft cockpit that are transmitted to the collective lever through the torso, the left arm and the hand of the pilot, and fed back to the rotor through the collective pitch control. This paper shows that collective bounce is rooted in the coupling of the pilot biodynamics with the rotor coning mode. The damping of the coning mode, usually large, introduces significant phase delay in the response to collective pitch. When coupled in feedback with the pilot biodynamics, such delay may lead to marginal stability conditions or even to instability. The basic mechanism of this coupling is shown using simple analytical models, and confirmed using detailed helicopter models. The influence of several design parameters is investigated, and possible means of prevention are briefly discussed.

1. Introduction

ROTORCRAFT, like most vehicles, can be subjected to adverse interaction with the pilot. In fact the pilot, as a consequence of misleading or incorrectly interpreted cues, can move the control inceptors in a manner that produces inadvertent or unintentional commands. These commands, in turn, can produce a behavior of the vehicle that causes further misleading cues, and induce additional adverse input, potentially resulting in unstable events, called Aircraft–Pilot Couplings (APC) in general, and Rotorcraft–Pilot Couplings (RPC) when specifically referred to rotary wing aircraft.

The most renowned and investigated occurrences of A/RPCs are known as Pilot Induced Oscillations (PIO), a name that refers to an oscillatory behavior of the vehicle resulting from commands intentionally introduced by the pilot in response to misinterpreted or contradictory cues. Well-known A/RPCs of different nature are known as Pilot Assisted Oscillations, or Pilot Augmented Oscillations (PAO), where the oscillatory behavior results from involuntary commands produced by the pilot, often caused by vibrations of the vehicle. Although both names have been criticized because they put all the blame on the pilots (McRuer [15]), they highlight an essential feature of the phenomenon, namely its oscillatory nature (Mitchell and Klyde [17]).

PIOs are characterized by voluntary pilot intervention; the pilot "fights" against the aircraft when its behavior contradicts the mental model of the vehicle the pilot formed in his mind. As a consequence, PIOs usually occur in a band of frequencies pilots can normally control. Based on a literature survey, during activity performed under the umbrella of GARTEUR[1] Helicopter Action Group HC AG-16, the upper limit of such band was conventionally placed at 1 Hz [5]. PAOs are characterized by unintentional pilot intervention; the pilot inadvertently feeds undesired controls to the aircraft as a result of the vibrations induced by the interface with the cockpit. The frequency band that characterizes the phenomenon is above that of PIO, where the pilot is no longer capable of intentionally introducing commands, and below an upper limit that was conventionally set at about 8 Hz in [5]. In fact, from that frequency on, the biomechanics of the human body filters out any motion caused by the cockpit.

While PIO and PAO have been investigated in detail in relation to fixed wing aircraft [1,9,36,26], and PIO is receiving considerable attention in relation with rotary wing aircraft [34,24,23], PAO received less attention. This contrasts with the fact that frequencies characteristic of many aspects of rotorcraft aeromechanics — flight mechanics, rotor aeromechanics, airframe, drive train, and engine dynamics — also lie in this range. Several occurrences of PAO in rotorcraft are listed in [25,24]. Noteworthy cases related to US Navy vehicles have been discussed in [35]. A possible case of PAO occurred during the development of the AH-56 Cheyenne compound helicopter is discussed in section "Lesson learned No. 9 (again)" of [28]. PAO events occurred during the development of the V-22 tiltrotor are discussed in [22].

A PAO phenomenon specific of helicopters is the so-called "collective bounce", an RPC caused by vertical vibrations of the cockpit.

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[1] http://www.garteur.org/, last accessed July 2013.

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As a consequence of the most common cockpit and control inceptors layout, the vibrations induce a collective control input as a result of the biodynamics of the pilot's left arm. This, in turn, further excites the vertical vibration by directly inducing a change in rotor thrust along the vertical axis.

Even recently, the National Transportation Safety Board (NTSB) reported accidents occurred after encountering collective bounce (reports[2] SEA08LA043 and ANC08LA083, respectively related to accidents occurred in December 2007 and June 2008). In both cases, a UH-1B was involved, and the probable cause was related to failure of the pilot in controlling the collective bounce. In one case this was accompanied by insufficient collective control friction; in the other by poor maintenance, resulting in loose and worn control system and rotor bearings. The NTSB reports indicate that

> According to the Operator's Manual for the UH-1B helicopter, "Collective bounce is a pilot induced vertical oscillation that may be encountered in any flight condition by a rapid buildup of vertical bounce at approximately three cycles per second. The severity of this oscillation is such that effective control of the aircraft may become difficult to maintain."

A change in collective pitch essentially results in a very quick change in thrust, since the dynamics of the aerodynamics may be regarded as fast in relation with the frequency that characterizes the phenomenon, usually below 1/rev (once per revolution). A thrust change, in turn, produces a vertical acceleration. If the pilot's biomechanics, at least in part, transforms this acceleration into a rotation of the collective inceptor, inducing a further change in rotor blade collective pitch, a feedback loop appears, that may lead to collective bounce.

One may be tempted to explain the phenomenon directly through such mechanism. However, this work shows that a key role in emphasizing collective bounce is played by the collective flap, or coning, rotor mode. Helicopter rotor blades are allowed to flap, namely move out of the rotor disk plane by either rotating about a hinge orthogonal to both the blade and the rotor axis and located close to the blade root (articulated rotors), or by bending a flexural element that connects the blade root to the hub (hingeless rotors). As a consequence of such displacement, the blade is in equilibrium about the flap hinge under the aerodynamic and centrifugal loads, relieving the blade itself from carrying lift to the hub in form of bending moment. Perturbations of such equilibrium result in flapping dynamics characterized by a natural frequency close to (and usually slightly higher than) the rotor angular velocity, and by significant damping provided by the aerodynamics, since the local angle of attack of the blades is modified by the flapping velocity. When all blades flap simultaneously, the rotor coning mode occurs. This mode is known to be highly damped (between 35% and 50%, with notable exceptions), which implies limited amplification, if any, even at resonance. What makes the coning mode dominate the proneness to collective bounce is actually the phase delay introduced in rotor thrust by this mode, something not acknowledged so far, to the authors' knowledge.

A simple analytical model of the problem is presented in Section 2. The model points out the dependence of collective bounce on the interaction between the biomechanics of the pilot and the rotor coning mode. Specifically, the role of the phase lag introduced by rotor coning in the loop transfer function between the blade collective pitch and the involuntary pitch control induced by the vertical acceleration of the helicopter as a consequence of biodynamic feedthrough is highlighted. How effectively the minimal model captures the essence of the problem, compared to more sophisticated aeromechanics models, is discussed in Section 3, along with an exhaustive discussion of the sensitivity of the phenomenon to the most important parameters of the problem. Possible means of prevention are briefly discussed in Section 4.

[2] http://www.ntsb.gov/aviationquery/, last accessed July 2013.

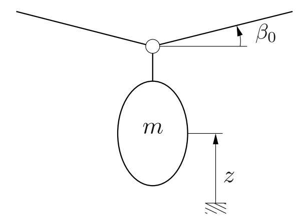

Fig. 1. Sketch of the minimal analytical model of the helicopter associated with pure heave (z) and collective coning (β_0) motion.

2. Analytical model

In hover, rotors respond to changes in blade collective pitch with collective flap motion. This motion is called the rotor blade coning motion, and is described by the collective flap angle β_0. The basics of rotor blade flapping coupled with helicopter vertical motion in hover are briefly reviewed in this section. The objective is to formulate the equations of motion that characterize the helicopter dynamics that may be relevant for the involuntary interaction with the pilot during collective bounce.

A simplified model is developed, sketched in Fig. 1, which consists of the vertical motion of the entire helicopter and the rotor coning motion. The model is drastically simplified, since it neglects the details of the rotor hub geometry and kinematics (for example the pitch–flap coupling, which provides an aerodynamic contribution to the equivalent stiffness of blade flapping), the drive train dynamics (which in principle could interact with collective flap and pitch motion), and many details of basic rotor aerodynamics like inflow, twist, tip loss, etc., that may be significant in performance analysis but are considered inessential for the desired perturbative model, or require not readily available or easily accessible information. Specifically, inflow dynamics has been neglected from the beginning to avoid excessive complication of the analytical model, and the validity of the assumption has been verified later using numerical models obtained from comprehensive rotorcraft analysis.

2.1. Basic blade flapping dynamics

A rotorcraft in hover is considered. For simplicity, the model consists of rigid, articulated blades whose motion relative to the hub is restricted to flapping, with null flap hinge offset; the effect of the offset on blade dynamics is recovered using an equivalent flap spring of stiffness $k_\beta = \Omega^2 I_\beta(\nu_\beta^2 - 1)$, such that the nondimensional natural flap frequency of the isolated rotor in vacuo is ν_β. Inflow, tip losses, root cut-out and pre-twist are neglected for simplicity, since in this context they would only introduce a correction of the resulting coefficients without altering the key relationships between the parameters that characterize the motion. The relative participation of aerodynamic and inertial forces is described by the Lock number,

$$\gamma = \frac{\rho a c R^4}{I_\beta}, \tag{1}$$

where ρ is the air density (international standard atmosphere (ISA) was considered in this work), a is the lift curve slope, c is the chord, R is the rotor radius, and I_β is the flap inertia moment. In a general discussion of rotor aeromechanics, the perturbative flap angle β, pitch angle θ and vertical motion z would be expressed as functions of their azimuthal harmonic decomposition.