

Voluntary Pilot Action Through Biodynamics for Helicopter Flight Dynamics Simulation

Pierangelo Masarati* and Giuseppe Quaranta†

Politecnico di Milano, 20156 Milan, Italy

and

Andrea Bernardini‡ and Giorgio Guglieri§

Politecnico di Torino, 10129 Torino, Italy

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This work presents the integration of detailed models of a pilot controlling a helicopter along the heave axis through the collective control inceptor. The action on the control inceptor is produced through a biomechanical model of the pilot's limbs, by commanding the activation of the related muscle bundles. Such activation, in turn, is determined by defining the muscle elongations required to move the control inceptor in order to obtain the control of the vehicle according to a high-level model of the voluntary action of the pilot acting as a regulator for the vehicle. The biomechanical model of the pilot's limbs and the aeromechanical model of the helicopter are implemented in a general-purpose multibody simulation. The helicopter model, the biomechanical model of the pilot's limbs, the cognitive model of the pilot, and their integration are discussed. The integrated model is applied to the simulation of simple, yet representative, mission task elements.

Nomenclature

A	=	reference amplitude in vertical maneuver, m	$\hat{H}_{z\theta}(s)$	=	approximated, low-pass filtered vehicle model, m/rad
a	=	nondimensional muscular activation	$H_{\eta z}(s)$	=	biodynamic feedthrough transfer function, rad · s ² /m
a_{ref}	=	nondimensional reference muscular activation	$H_{\theta e_z}(s)$	=	error to control transfer function (voluntary pilot model), rad/m
b_0	=	static gain of involuntary pilot model [see $H_{\eta z}(s)$], rad/m	J	=	inertia of control device, kg · m ²
C_1	=	threshold torque of simplified control inceptor friction model, N · m	ℓ	=	muscle length, m
C_2	=	slope of simplified control inceptor friction model, s/rad	ℓ_d	=	desired muscle length, m
e_z	=	vertical position error ($e_z = z_d - z$), m	ℓ_0	=	reference muscle length, mm
f_m	=	muscle force, N	K_A	=	pilot's gain (Szabolcsi's pilot model), rad/m
f_{m_0}	=	muscle maximum isometric force, N	K_d	=	derivative coefficient of reflexive activation quasi-steady approximation, 1/m
f_1, f_2, f_3	=	nondimensional configuration-dependent contributions to muscle force	K_p	=	proportional coefficient of reflexive activation quasi-steady approximation, s/m
G	=	gearing ratio nondimensional scaling parameter (nominal: 1)	M	=	vehicle mass, kg
G_c	=	gearing ratio between control inceptor and blade pitch rotation, rad/rad	m_e	=	friction moment applied to control inceptor, N · m
g	=	gravity acceleration, m/s ²	P	=	swashplate actuator time constant (first-order approximation), s
$H_{\text{ff}}(s)$	=	feedforward control transfer function, rad/m	s	=	Laplace operator, 1/s
$H_L(s)$	=	loop transfer function	T	=	reference time in vertical maneuver, s
$H_{\text{NMD}}(s)$	=	neuromuscular electromechanical delay transfer function	T_1, T_2, T_3	=	time constants (Szabolcsi's pilot model), s
$H_{z\theta}(s)$	=	control to motion transfer function (vehicle model), m/rad	t	=	time, s
			V_0	=	reference muscle elongation rate, m/s
			v	=	nondimensional muscle elongation rate
			x	=	nondimensional muscle length
			x_{ref}	=	reference nondimensional muscle length
			x_1, x_2	=	x component of muscle insertion point positions, mm
			y_1, y_2	=	y component of muscle insertion point positions, mm
			Z	=	net vertical force (main rotor thrust minus weight), N
			z	=	vertical position, m
			z_d	=	desired vertical position, m
			z_1, z_2	=	z component of muscle insertion point positions, mm
			α_1, α_2	=	low-pass filter coefficients (used with McRuer's crossover pilot model), s, s ²
			$\Delta(\cdot)$	=	finite perturbation operator
			η	=	collective control inceptor rotation, rad
			θ	=	blade collective pitch, rad
			ξ_a	=	swashplate actuator damping factor (second-order approximation)
			ξ_f	=	low-pass filter damping factor
			ξ_p	=	damping factor of involuntary pilot model [see $H_{\eta z}(s)$]
			τ_e	=	equivalent time delay (McRuer's crossover pilot model), s

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*Associate Professor, Dipartimento di Scienze e Tecnologie Aerospaziali, via La Masa 34. Member AIAA (Corresponding Author).

†Assistant Professor, Dipartimento di Scienze e Tecnologie Aerospaziali, via La Masa 34.

‡Graduate Student, Dipartimento di Ingegneria Meccanica e Aerospaziale, corso Duca degli Abruzzi 24.

§Associate Professor, Dipartimento di Ingegneria Meccanica e Aerospaziale, corso Duca degli Abruzzi 24.

ω_a	=	swashplate actuator cut frequency (second-order approximation), rad/s
ω_c	=	crossover frequency (McRuer's crossover pilot model), rad/s
ω_f	=	low-pass filter cut frequency, rad/s
ω_p	=	characteristic frequency of involuntary pilot model [see $H_{\eta\dot{z}}(s)$], rad/s
$(\clubsuit)_{/\clubsuit}$	=	partial derivative of (\clubsuit) with respect to (\clubsuit)

I. Introduction

PILOT/VEHICLE interaction may impact the operation of vehicles as well as the health and even safety of the occupants. This work focuses on specific aspects of pilot/helicopter interaction, addressing diverse fields that include vehicle dynamics and aeroelasticity analysis, pilot biomechanics, and pilot behavioral models. The problem is formalized and analyzed using general-purpose multibody dynamics, which provides the capability to deal with its most important aspects in a monolithic formulation and implementation, with comparable detail levels.

The problem of adverse aircraft–pilot couplings surfaced from the very beginning of human flight, but it only received significant attention starting in the late 1970s [1]. Focus has been mainly placed on adverse effects of voluntary pilot action, the so-called pilot-induced oscillations (PIOs), which are caused by a mismatch between the actual vehicle dynamics and the mental model the pilot uses to anticipate the control action.

However, involuntary interactions may occur as well, often resulting in so-called pilot-augmented oscillations (PAOs). Those phenomena typically occur at frequencies that are too high to be effectively contrasted by the pilot's intentional action on the controls. The involuntary action is a direct consequence of the cockpit vibrations, which are filtered by the human limbs' biomechanics before being involuntarily fed into the control system.

Models of the voluntary pilot action for the investigation of piloted aircraft dynamics date back to the work of McRuer and Jex (see, for example, [2]), with the crossover model. Significant contributions came, for example, from the work of Hess [3] with the structural pilot model, which takes the biomechanics into account in a simplified manner.

Several studies have investigated the effects of fixed-wing aircraft cockpit manipulators while performing compensatory tracking tasks (for example Magdaleno and McRuer [4] and McRuer and Magdaleno [5]). Subsequent work addressed the impact of vibration on pilot control, focusing on the feedthrough of vibration from the pilot to the control inceptors (for example, Allen et al. [6] and Jex and Magdaleno [7]; see also the review by McLeod and Griffin [8], the work by Merhav and Idan [9], and the work of Höhne [10]). The effects of lateral stick characteristics on pilot dynamics were further investigated from flight data by Mitchell et al. [11].

Rotorcraft/pilot couplings (RPCs) did not receive as much attention in the open literature as their fixed-wing counterpart. This is especially true for involuntary couplings, despite the evidence of occurrences since the 1960s. In 1968, Gabel and Wilson [12] discussed the problem of external sling load instabilities, considering the case of vertical bounce of the sling load interacting with the pilot through the collective control system. In 1992, Prouty and Yackle [13] discussed RPC as a possible cause of an accident that occurred to the AH-56 Cheyenne during its troubled development. In 2007, Walden [14] presented an extensive discussion of aeromechanical instabilities that occurred with several rotorcraft during development and acceptance by the U.S. Navy, including CH-46, UH-60, SH-60, CH-53, RAH-66, V-22, and AH-1. The history of tiltrotor development has seen several PAO events, from the early design and testing of the XV-15 technology demonstrator [15] to the aeroservoelastic pilot-in-the-loop couplings encountered during the development of the V-22 [16]. A complete database of PIO and PAO incidents occurred to fixed- and rotary-wing aircraft is reported in [1].

In the last decade, research efforts flourished in Europe; the coordinated activities of the Group for Aeronautical Research and Technology in Europe Helicopters Action Group-16 [17] and the

Aircraft and Rotorcraft Pilot Couplings-Tools and Techniques for Alleviation and Detection 7th Framework Programme project [18,19] deserve a mention, along with other, independent activities (e.g., [20]).

The present work originates from the need to analyze the behavior of helicopters in interaction with the involuntary action of the pilot. Detailed multibody models of the vehicle and of the pilot's left arm have been developed for this purpose [21] using an original multibody dynamics formulation that is implemented in the free software MBDyn [22,23] and used to numerically characterize the biodynamic feedthrough (BDFT) and neuromuscular admittance of the pilot [24].

The goal of this investigation is to simulate complex aero-mechanical systems and their interaction with the human operator without the undue simplifications that are typically applied in pure flight mechanics analysis, like limiting the helicopter model to rigid blade dynamics and the pilot model to first- or second-order linear approximations of the biodynamics.

The innovative aspect of this work, to the authors' knowledge, is the use of a detailed biomechanical model of the pilot's arm that holds the collective control inceptor to actuate that control device. As a consequence, the voluntary action produced by the behavioral model with the aim of performing a tracking or regulatory task is naturally and intrinsically combined with the involuntary action that results from the environment, significantly from the vibrations of the cockpit. In previous work (e.g., [24]), the involuntary control inceptor rotation resulting from the biomechanical model of the pilot was added to the voluntary contribution before being fed to the control system actuators, bypassing the limbs' neuromuscular dynamics. Such an approach is deemed insufficient because BDFT was experimentally [25,26] as well as numerically [21,24] observed to depend on, among other parameters, the reference position of the control inceptor, which may significantly change as a consequence of voluntary control action. The proposed model fills such a gap, by ensuring consistency between control inputs and overall system configuration.

The work is organized as follows. In the first part, the structure of the piloted simulation problem is introduced, the biomechanical model originally presented in [21] is illustrated, the pilot's voluntary action model and its adaptation to time marching multibody analysis (direct integration of an initial value problem) are discussed, and simple applications of the isolated pilot model are presented. In the second part, the vehicle model and its integration with the pilot model are presented; the coupled model is used to analyze realistic problems.

The proposed approach is rather general, with respect to both pilot and vehicle modeling. Since the objective is the introduction of the voluntary action through the neuromuscular system, the analysis has been simplified by considering only the left arm holding the collective control inceptor, and limiting the overall motion of the vehicle to displacement along the vertical axis, focusing on a vertical maneuver in hover inspired by aircraft design standards.

It is worth noticing that often formulations and software implementations are specialized for given problem types. In the present case, a general-purpose formulation and implementation has been successfully used to model the details of both vehicle aeromechanics and pilot biomechanics, with few straightforward modifications, like user-defined constitutive laws for the muscles.

II. Pilot/Vehicle Modeling

The action of the pilot on the control inceptors originates from the combination of two logically distinct sources, shown in the block diagram of Fig. 1, where $\Delta\theta$ is the control input (the collective control inceptor motion in the present context) and z is the motion of the vehicle (the heave motion in the present context), with z_d being its desired value. One contribution to $\Delta\theta$ is voluntary; in many cases, it can be formulated as an attempt to perform a desired task by cancelling the error between a desired and an actual measure of the state of the vehicle, as perceived by the pilot through appropriate cues (cognitive input). The other contribution is involuntary; it is a

consequence of the acceleration of the cockpit, which is fed through the pilot's body and filtered by the pilot's biodynamics (BDFT).

Both contributions, sent to the vehicle through a suitable control device (e.g., an inceptor), produce a response. Such a response is further interpreted by the pilot to formulate the voluntary action and, at the same time, indirectly produces further involuntary action.

The scheme of Fig. 1 was used in [21,24] to combine the voluntary contribution to the control input that is required to perform a maneuver with the involuntary one. In that model, the motion of the control inceptor caused by the involuntary action was added to a contribution originated by the cognitive action of the pilot. The mixing occurred downstream, as if the latter contribution came from an automatic flight control system.

In reality, however, the voluntary action originates at the pilot's cognitive level and is transformed into the corresponding motion of the control device by the pilot's neuromuscular system, through an appropriate muscular action. Figure 2 schematically illustrates how a neuromuscular model of the pilot action transforms a generic cue (e.g., a visual cue represented by the difference between the desired z_d and the actual position z , as perceived by the pilot) into the muscle elongations ℓ_{i_d} and activations a_i that are required to compensate it.

The function of the block called neuromuscular model can be split in a sequence of tasks:

- 1) The motion $\Delta\eta$ required of the control inceptor to accomplish the target task is determined, according to a mental model of the vehicle dynamics that pilots typically acquire through training and experience.
- 2) The limbs' motion required to produce the desired motion of the control inceptor is determined.
- 3) The muscle action (the elongation ℓ_{i_d} and required force f_{m_i} , or better muscular activation a_i) needed to produce the motion of the limbs is determined.

Usually, biodynamic models of the pilot's limbs produce the actual muscle elongations ℓ_i as functions of cockpit motion \ddot{z} , the so-called BDFT effect. The difference between the desired and the actual elongation of each muscle, and the corresponding activation, produces a change in the muscle force f_{m_i} . To this end, a muscle force model is needed. The Hill-like one proposed in [27] is used in the present work. The combination of synergistic and antagonistic muscle forces produces torques about the motor joints of the pilot's limbs and, in the end, about the hinge of the control device. As a consequence of such torque, the device rotates of an angle $\Delta\eta$, which

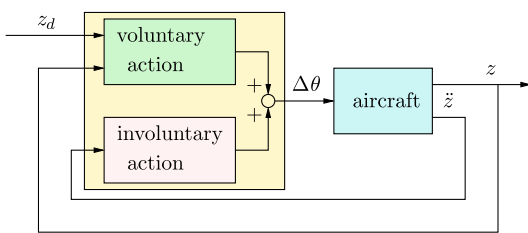


Fig. 1 Abstract pilot model block diagram.

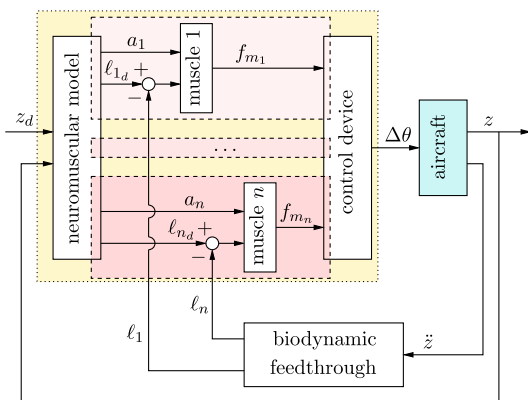


Fig. 2 Neuromuscular pilot model block diagram.

is transformed by the control system (e.g., the control chain, which includes actuators in augmented controls aircraft and may include an automatic flight control system) into the corresponding control input $\Delta\theta$ that is fed to the aircraft. The voluntary and involuntary feedback loops the pilot represents are closed by the resulting aircraft motion in terms of visual cues, exemplified and summarized in this work by the vertical position z , and vibration \ddot{z} .

A. Biomechanical Model of Pilot

The biomechanical model of the pilot arm originally developed and presented in [21,24] is briefly recalled in this section for completeness. The pilot's left arm is modeled using four rigid bodies that represent the humerus, the radius, the ulna, and the hand grasping the control inceptor. A sketch of the model is provided in Fig. 3.

The humerus is connected to the seat by a spherical hinge to model a pilot tightly buckled by seat belts with shoulder harnesses. The ulna and the radius are connected to the humerus respectively by a revolute joint and a spherical joint to model the articulation of the elbow. An inline joint prescribes that the distal ends of radius and ulna move along a line. The carpal complex connecting the hand to the radius is modeled by a universal joint. The hand is rigidly connected to the control device, to simulate the firm grasp of the pilot (such assumption is a simplification that represents a limit case for an interaction that is not easily quantifiable; see, for example, [28], Sec. 13.4.1). The rigid bodies are connected by 25 muscle bundles (see Table 1 for details), modeled using deformable rod elements with a constitutive law discussed later. Data used in this work refer to a person of 70 kg body mass and 170 cm height (between 15% and 25% percentile for an adult male [29]). More details on the model, including dimensions, masses, and muscle properties can be found in [21,24,27,30,31].

Each rod defines a tension force between two points rigidly offset with respect to the bodies they connect. The force depends on the length and elongation rate of the rod. Specific constitutive properties have been developed, based on the simplified Hill-type muscle model proposed in [27].

According to [27], the force of the i th muscle is formulated as

$$f_{m_i} = f_{m0_i} [f_1(x_i) f_2(v_i) a_i + f_3(x_i)] \quad (1)$$

where $x_i = \ell_i / \ell_{0i}$ and $v_i = \dot{\ell}_i / V_{0i}$ are the nondimensional muscle elongation and elongation rate, the former referring to a specific reference length of the muscle and the latter to a common conventional reference velocity [27]; a_i is the nondimensional activation parameter, constrained by $0 \leq a_i \leq 1$.

The reference activation of the muscles is computed by solving the cascaded problem discussed in [21,32]. An underdetermined inverse kinestatics problem is solved first, to find the configuration of the limbs that complies with the boundary constraints and minimizes some ergonomics cost function (usually consisting of maximizing the distance from extreme joint positions). An inverse dynamics problem is then solved to find the joint torques that guarantee the equilibrium

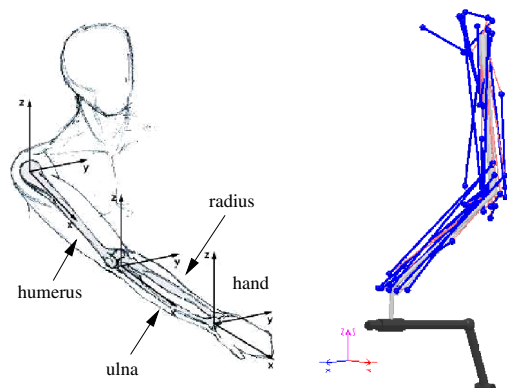


Fig. 3 Multibody model of the arm holding the collective control inceptor.

Table 1 Arm muscles' properties: reference length (ℓ_0), max isometric force (f_{m0}), and coordinates of insertion points 1 and 2 ($x_1, y_1, z_1; x_2, y_2, z_2$)

Muscle number	Muscle name	ℓ_0 , mm	f_{m0} , N	x_1 , mm	y_1 , mm	z_1 , mm	x_2 , mm	y_2 , mm	z_2 , mm
1	Coracobrachialis	197	242.5	20	30	35	174	21	0
2	Deltoid: anterior fascicles	179	1142.6	35	25	35	136	-12	10
3	Deltoid: middle fascicles	159	1142.6	35	-22	20	136	-24	18
4	Deltoid: posterior fascicles	148	259.9	-35	10	0	136	-24	18
5	Latissimus dorsi	380	1059.2	-65	110	-290	75	25	9
6	Pectoralis major	147	1270.3	45	110	10	36	0	25
7	Supraspinatus	108	487.8	-36	80	35	-32	2	-13
8	Infraspinatus	111	1210.8	-32	80	-40	-26	0	-20
9	Biceps brachii caput longus	388	624.3	0	-15	10	34	16	0
10	Biceps brachii caput brevis	324	435.6	20	30	25	3	16	0
11	Triceps brachii caput longus	290	798.5	-35	20	-20	-15	0	-22
12	Anconeus	55	350.0	300	-5	-12	-14	7	-11
13	Triceps brachii caput laterale/mediale	211	1248.6	112	0	-28	-27	0	-6
14	Brachialis	140	987.3	196	-8	16	17	15	5
15	Brachioradialis	306	261.3	246	-7	0	238	-18	13
16	Pronator teres	148	566.2	270	33	-7	55	-18	12
17	Flexor carpi ulnaris	317	128.9	265	27	-5	5	30	23
18	Extensor carpi ulnaris	290	93.2	269	-27	-5	5	30	-18
19	Extensor digitorum	387	100.7	269	-20	-20	8	0	-16
20	Flexor digitorum superficialis	380	226.6	275	27	-10	7	18	26
21	Flexor carpi radialis	307	74.0	275	27	-7	3	-20	32
22	Extensor carpi radialis	305	405.4	245	-20	0	5	-23	-11
23	Pronator quadratus	33	75.5	200	7	14	236	27	23
24	Supinator	61	476.0	13	17	-8	28	13	-24
25	Abductor pollicis longus	202	59.5	115	-21	-5	3	-18	23

of the system. Since the inverse dynamics problem is overdetermined in terms of muscle forces, the force required of each muscle to provide the previously estimated joint torques is computed by minimizing the activation of the muscles, $\min_{a_i} \sum_i a_i^2$, constrained by $0 \leq a_i \leq 1$. As an example, the muscular activations required to hold the collective control inceptor at 10, 50, and 90% are reported in Fig. 4. Some of the muscle bundles only activate for specific reference configurations; some do not activate at all, suggesting that in the given configuration they should push rather than pull to contribute to the required joint torques. However, all of them may be needed when reflexive activation and cognitive action are considered, as is detailed later.

As discussed in [21,24], based on considerations made by Stroeve [33], a simple quasi-steady approximation of the reflexive contribution to the activation based on the muscle length and elongation rate is considered,

$$a_i = a_{i_{ref}} - K_p(x_i - x_{i_{ref}}) - K_d v_i \quad (2)$$

where, as discussed later, the reference length $x_{i_{ref}}$ is modified to produce the control inceptor motion requested by the voluntary pilot model. The use of a quasi-steady approximation is justified by the consideration that the dynamics of muscular activation is characterized by relatively high frequencies (time constants between 10 and 40 ms [34]) compared to the mechanical phenomena under consideration, which occur well below 10 Hz.

In [24], a relation between the approximate reflexive activation parameter K_p and the task a pilot is performing was established by comparing the results obtained from the numerical model and corresponding experimental results presented by Venrooij et al. in [35]. In that experiment, pilots were asked to perform a position task (PT), consisting in keeping the control inceptor in a prescribed position as accurately as possible, resisting forces; a relax task (RT), consisting of loosely keeping the control inceptor about a prescribed

position; and a force task, consisting of yielding to forces without trying to keep the inceptor in a specific position.

Each task required human operators to attain different levels and combinations of muscular activation. The PT required a significant amount of reflexive activation in addition to the reference amount required to counteract the own weight of the arm, whereas the other tasks required a much lower level of reflexive activation. High reflexive activation can be intuitively associated with pilot's reactivity and promptness in responding to perturbations and external stimuli in general. BDFT appears to be most prone to causing RPCs when the reflexive muscular activation related to PT is considered [24,36]. Indeed, it has been assessed that reflexive activation parameters associated with less aggressive pilot behavior (e.g., RT) lead to a less prompt and slightly more damped response. For this reason, only the parameters related to PT are used in the coupled pilot/vehicle analyses presented in this work.

In [25], Mayo reported significant dependence of BDFT gain on collective inceptor reference position; no attempt was made at transfer function identification parameterized in the inceptor position. In [26], Masarati et al. presented experimental BDFT frequency responses and reported significant dependence of gain and poles of identified pilots' BDFT transfer functions on the collective inceptor reference position. Specifically, the frequency and the damping factor reduced when the collective was increased. In [24], Masarati and Quaranta, using the same biomechanical model discussed in the present work, obtained numerical trends in BDFT that were consistent with those of [26] and were subsequently extended by Zanlucchi et al. [37]. These considerations support the opportunity to preserve consistency between the control input and the actual position of the control inceptor.

B. Cognitive Pilot Model

According to the block diagram of Fig. 5, the voluntary control of the pilot is

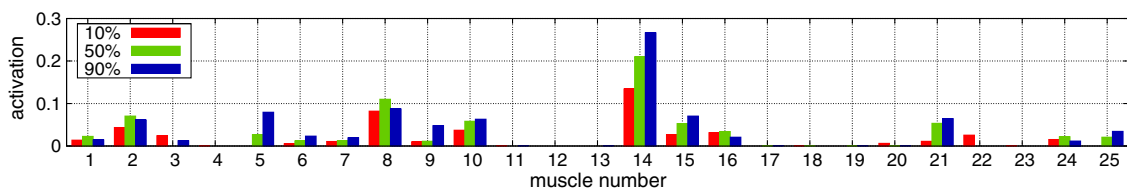


Fig. 4 Muscular activation parameters for 10, 50, and 90% collective control device reference position (muscles numbered according to Table 1).

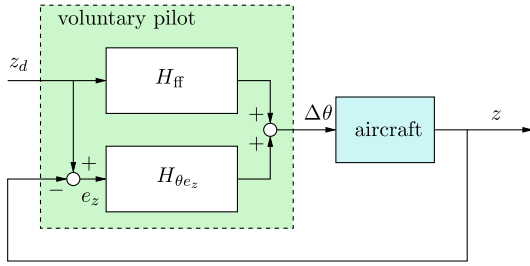


Fig. 5 Voluntary pilot model block diagram.

$$\Delta\theta = H_{\theta e_z}(s)(z_d - z) + H_{ff}(s)z_d \quad (3)$$

The function $H_{\theta e_z}(s)$ encompasses the strategy elaborated by the pilot acting as a regulator to cancel the error $e_z = z_d - z$ between the desired z_d and the actual position z . The function $H_{ff}(s) \approx \hat{H}_{z\theta}^{-1}(s)$ represents a feedforward contribution based on an approximated inverse model of the vehicle's response to the controls, low-pass filtered to only account for the vehicle behavior in the pilot's bandwidth. Both functions express the mental model of the vehicle upon which the pilot's control action is based.

For the vertical axis in hover, the simplest model within the pilot's bandwidth that can be obtained from the linearization of the equilibrium equation along the vertical axis is

$$M\ddot{z} = Z_{jz}\dot{z} + Z_{j\theta}\Delta\theta \quad (4)$$

where M is the mass of the helicopter and Z is the net vertical force component, i.e., thrust minus weight, with $Z_{j\theta} > 0$ (thrust changes according to the collective control) and $Z_{jz} < 0$ (velocity perturbations cause opposite thrust perturbations). The approximate transfer function is

$$\hat{H}_{z\theta}(s) = \frac{Z_{j\theta}/M}{s(s - Z_{jz}/M)} \quad (5)$$

where Z/M is the net specific force perturbation (dimensionally an acceleration). The inverse of Eq. (5) must be low-pass filtered by a filter at least of the third order to obtain a strictly proper function [38]. Some simple antiwindup strategy has been considered to limit the phenomenon when tracking a rapidly changing desired position, by saturating the accumulated integral of the error. These aspects are not described in detail as they are considered inessential with respect to the main topic of the work.

In the present work, two simple voluntary pilot feedback functions have been initially considered. The first one is based on McRuer's crossover model [2]. The model results from the observation that for a broad variety of simple tasks the loop transfer function $H_L(s) = H_{z\theta}(s)H_{\theta e_z}(s)$ can be approximated by an integrator and a time delay in the vicinity of the crossover frequency of the function ω_c , namely,

$$H_L(s) = H_{z\theta}(s)H_{\theta e_z}(s) = \frac{\omega_c}{s} e^{-s\tau_e} \quad (6)$$

According to this model, and considering the approximated vehicle transfer function $\hat{H}_{z\theta}(s)$ of Eq. (5) under the assumption that it captures the behavior of the vehicle in the vicinity of the crossover frequency, the pilot feedback function is

$$H_{\theta e_z}(s) \approx \hat{H}_{z\theta}^{-1}(s) \frac{\omega_c}{s} e^{-s\tau_e} = \frac{s - Z_{jz}/M}{Z_{j\theta}/M} \omega_c e^{-s\tau_e} \quad (7)$$

To be usable in a time marching simulation, such a model needs to be made strictly proper by adding a low-pass filter at least of second order, which is characterized by two poles,

$$H_{\theta e_z \text{ filtered}}(s) = \frac{\alpha_2}{s^2 + \alpha_1 s + \alpha_2} \frac{s - Z_{jz}/M}{Z_{j\theta}/M} \omega_c e^{-s\tau_e} \quad (8)$$

that for $0 < \alpha_1 \leq 2\sqrt{\alpha_2}$ (i.e., when they are complex conjugated) produce a cut frequency $\sqrt{\alpha_2}$ slightly higher than ω_c .

The second voluntary pilot feedback function is the one derived from the work of Szabolcsi [39] and used in [40],

$$H_{\theta e_z}(s) = K_A \frac{(T_3 s + 1)}{(T_1 s + 1)(T_2 s + 1)} e^{-s\tau_e} \quad (9)$$

According to [40], the parameters of the model are 1) K_A , the pilot's gain; 2) T_1 , the lag time constant, describing "the ease with which the pilot generates the required input"; 3) T_2 , the neuromuscular lag time constant; 4) T_3 , the lead time constant, which represents the ability of the pilot in predicting the behavior of the vehicle within the pilot's bandwidth; 5) τ_e , a time delay that represents the time that lapses between the sensing of a cue and the voluntary reaction of the pilot.

Note that Eq. (9) of the second model has the same structure of Eq. (8) of the first one, with $K_A = -\omega_c Z_{jz}/Z_{j\theta}$, $T_3 = -M/Z_{jz}$, and $T_1 + T_2 = 1/\alpha_2$, $T_1 T_2 = \alpha_1/\alpha_2$. In practice, the model of Eq. (9) gives a specific physical meaning to the poles of the low-pass filter, purposely introduced in Eq. (8) to make it suitable for time marching analysis, which are assumed to be real rather than complex conjugated.

The pole characterized by T_2 in the model of Eq. (9) plays the role (and is a gross approximation) of the low-pass filtering effect of the pilot limbs' biomechanics (it is worth noticing that in the original work of Szabolcsi [39] an alternative second-order approximation was proposed using two complex-conjugate poles; a similar approach was proposed by Hess [3] in his fundamental work on the structural pilot model). Clearly, in the present work, such a role is played by the detailed biomechanical model of the pilot.

For both models, the time delay has been approximated using a second-order Padé form,

$$e^{-s\tau_e} \cong \frac{1 - (\tau_e/2)s + (\tau_e^2/12)s^2}{1 + (\tau_e/2)s + (\tau_e^2/12)s^2} \quad (10)$$

and the whole transfer function has been transformed in the time domain in the form of a linear, time invariant state-space system that produces the desired intentional control inceptor rotation as a function of the altitude error. Given the clear similarity between the two models, only results obtained with the crossover model are presented in the following.

More sophisticated voluntary pilot models can be used, for example when specific tasks need to be addressed (e.g., models derived from Gray's work on boundary avoidance task [41–43]). The previously discussed simple models are preferred in this context since the focus is on producing the effect of the pilot's intentional behavior throughout the same detailed biomechanical model that is used to simulate the involuntary behavior. However, the opportunity to take into account a voluntary change in control strategy and/or an involuntary change in biodynamic properties of the limbs triggered by a change in control demand of the task will be investigated in the future as a potential source of RPC.

C. Pilot Voluntary Action Through Biomechanical Model

The voluntary action of the pilot defined by Eq. (3) in terms of blade collective pitch as a function of the desired and actual states of the vehicle must be transformed into appropriate commands to the muscles by means of a neuromuscular model.

Consider a linear map between the collective control perturbation $\Delta\eta$ and the muscle elongation perturbations $\Delta\ell$,

$$\Delta\ell = \ell_{j\eta} \Delta\eta \quad (11)$$

In the simplest case, a (linear) mapping can be defined between the rotation of the collective control inceptor η (the control throw) and the static blade collective pitch rotation θ , namely

$$\Delta\theta = G_c \Delta\eta \quad (12)$$

(in the case at hand, $G_c \approx 0.5$ rad/rad, since a typical control inceptor end to end rotation is about 35 deg, whereas the blade collective pitch range is between 16 and 20 deg).

A more realistic model also considers the dynamics of the control system actuators. In this work, they are approximated using either first- or second-order low-pass filters, e.g.,

$$\Delta\theta = G_c \frac{1}{1 + ps} \Delta\eta \quad (13)$$

with a time constant p of about 0.012 s, or

$$\Delta\theta = G_c \frac{1}{1 + 2\xi_a s/\omega_a + (s/\omega_a)^2} \Delta\eta \quad (14)$$

with a cut frequency ω_a of about 12 Hz and a damping factor ξ_a of about 0.4.

In advanced rotorcraft, a sophisticated flight control system may further modify the pilot controls before feeding them to the actual pitch control mechanism. Although the details of such systems are beyond the scope of the current work, a net effect they could have on the pilot's commanded control is a further delay of up to 100 ms caused by the digital filtering and processing of the control inceptor motion [1,44]. Such a delay may play a critical role in reducing the phase margin of the closed loop system.

The blade collective pitch demand can be mapped onto the corresponding muscle elongation perturbation demand,

$$\Delta\ell = \ell_{/\eta} \frac{1}{G_c} \{ [H_{\theta_{e_c}}(s) + \hat{H}_{z\theta}^{-1}(s)] z_d - H_{\theta_{e_c}}(s) z \} \quad (15)$$

The actual muscle elongation demand is filtered by a low-pass filter that includes an electromechanical delay of about 50 ms, $H_{\text{NMD}}(s)$ (values between 10 and 120 ms are reported in the literature; see, for example, [45]).

The filtered muscle elongation demand is added to the reference muscle elongation used in the quasi-steady approximation of the reflexive activation of Eq. (2), which becomes

$$a_i = a_{i_{\text{ref}}} - K_p [x_i - x_{i_{\text{ref}}} - H_{\text{NMD}}(s) \Delta x_{i_{\text{ref}}}] - K_d v_i \quad (16)$$

The modified reference length is used to produce the control inceptor motion requested by the voluntary pilot model.

Rather than resorting to a complex inverse model of the pilot biomechanics, given the simplicity of the specific problem, a numerical linearization has been considered. The approach used in this work assumes that only small perturbations of the limbs' motion about a steady reference configuration are required, involving a limited amount of muscular activation.

The value of $\ell_{/\eta}$ is computed according to the following procedure:

- Prescribe a small rotation $\Delta\eta$ to the control inceptor.
 - Measure the length change of each muscle $\Delta\ell_i$.
 - Measure the activation change of each muscle Δa_i .
- The force change in each muscle is

$$\Delta f_{m_i} = f_{m0_i} [f_1(x_{i_{\text{ref}}} + \Delta x_i)(a_{i_{\text{ref}}} - K_p \Delta x_i) + f_3(x_{i_{\text{ref}}} + \Delta x_i) - f_1(x_{i_{\text{ref}}})a_{i_{\text{ref}}} - f_3(x_{i_{\text{ref}}})] \quad (17)$$

considering that in isometric conditions $v_i = 0$ and $f_2(0) \equiv 1$. Assuming the elongation change Δx_i is small enough that a local linearization of $f_1(x)$, $f_3(x)$ is an acceptable approximation, the force perturbation becomes

$$\Delta f_{m_i} = f_{m0_i} \{ [f_1/x a_{i_{\text{ref}}} + f_3/x - f_1(x_{i_{\text{ref}}})K_p] \Delta x_i - f_1/x K_p \Delta x_i^2 \} \quad (18)$$

Consider now a change of reference length such that $\Delta\ell_{i_{\text{ref}}} \equiv \Delta\ell_i$; thus, $\Delta a_i = \Delta a_{i_{\text{ref}}}$, since the reflexive change of activation is zero. Then, the change of muscle force is

$$\Delta \tilde{f}_{m_i} = f_{m0_i} \{ (f_1/x a_{i_{\text{ref}}} + f_3/x) \Delta x_i + [f_1(x_{i_{\text{ref}}}) + f_1/x \Delta x_i] \Delta a_{i_{\text{ref}}} \} \quad (19)$$

If the change of reference length (and of reference activation) is applied to an otherwise unloaded arm, assuming that the change of configuration is small enough, no first-order change of muscular force is needed. As a consequence, $\Delta \tilde{f}_{m_i} \approx 0$, which requires a change of reference activation

$$\Delta a_{i_{\text{ref}}} \approx - \frac{f_1/x a_{i_{\text{ref}}} + f_3/x}{f_1(x_{i_{\text{ref}}} + \Delta x_i)} \Delta x_i \quad (20)$$

This implies that when the simple reflexive model of Eq. (2) is considered for the muscular activation, to prescribe a rotation of the control inceptor, both the desired reference length of the muscles $\Delta\ell_{i_{\text{ref}}}$ and the corresponding reference activation $\Delta a_{i_{\text{ref}}}$ must be modified accordingly.

D. Basic Voluntary/Involuntary Pilot-Control Device Interaction Re-sults

BDFT has been estimated using system identification from detailed multibody simulation. According to functions proposed in the literature, either identified from experiments [25,26] or from numerical models [24], the BDFT between the collective control inceptor motion and the acceleration of the cockpit can be represented by a second-order low-pass filter,

$$H_{\eta z}(s) = \frac{b_0 \omega_p^2}{s^2 + 2\xi_p \omega_p s + \omega_p^2} \quad (21)$$

In the case of the PT pilot, with the collective control inceptor held about the 50% position, the function (shown in Fig. 6) is characterized by a natural frequency $\omega_p = 16.7$ rad/s (2.66 Hz), a damping factor $\xi_p = 0.251$, and a static gain $b_0 = 1.47$ rad/m.

Data have been obtained by applying a random vertical acceleration, band-pass filtered in the 1–10 Hz range, to the multibody model of the pilot's arm. The transfer function estimated from the input and the resulting collective control inceptor rotation is labeled "estimated." The corresponding identified transfer function is labeled "identified"; the formula is that of Eq. (21). The analogous function obtained from the response to limited amplitude harmonic excitation is labeled "harmonic."

The subsequent applications verify how the actual rotation of the control inceptor, sketched in Fig. 7, resembles the demanded one.

The result is shown in Figs. 8 and 9. Figure 8 shows the actual motion when a large step input (6 deg) is demanded. Figure 9 shows the actual motion when the the collective control inceptor rotation measured during flight simulator tests originally presented in [46] is demanded. The neuromuscular model is able to accurately track the

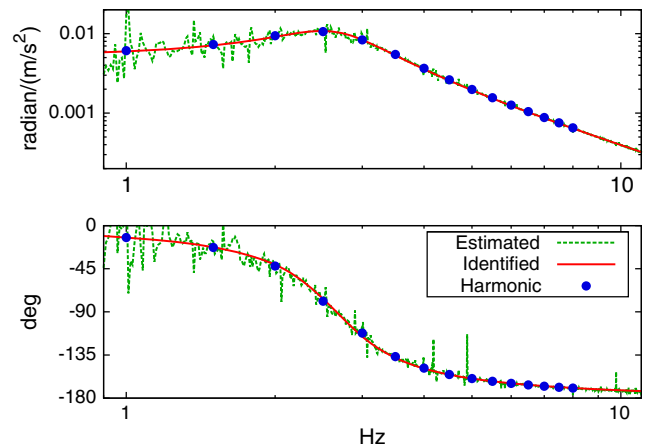


Fig. 6 Biodynamic feedthrough: transfer functions estimated, identified, and obtained using harmonic excitation.

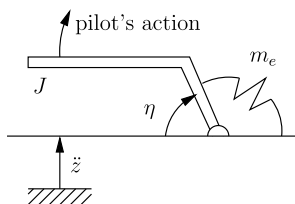


Fig. 7 Sketch of collective control device.

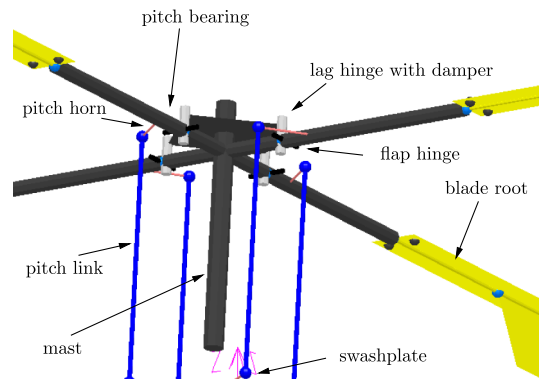


Fig. 10 Detailed view of the main rotor hub.

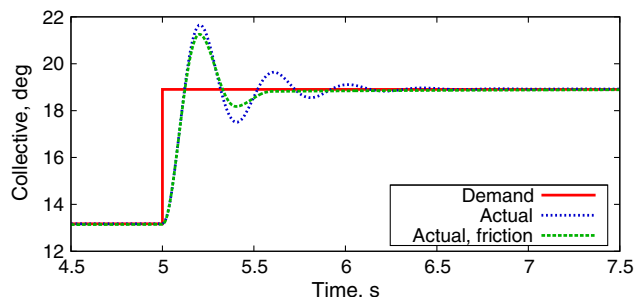


Fig. 8 Step input: collective control inceptor demanded and actual rotation.

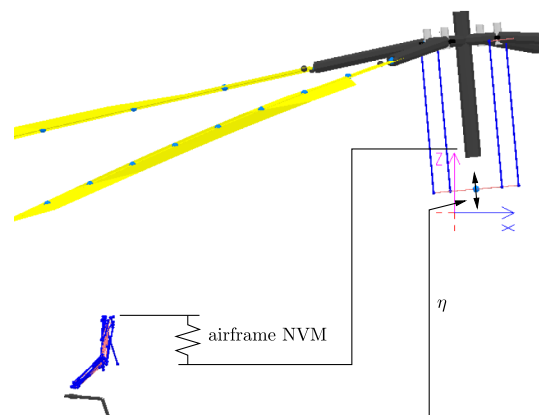


Fig. 11 Multibody model of the main rotor and pilot.

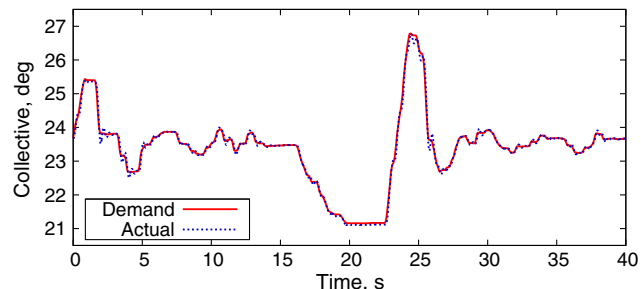


Fig. 9 Input from measured data: collective control inceptor demanded and actual rotation.

motion demand, with minimal delay and small, damped oscillations occurring when the input variation is excessively abrupt. In Fig. 8, the curve obtained with a loose inceptor, i.e., without any reaction moment, is labeled “actual.” Additionally, the curve labeled “actual, friction” illustrates the response obtained also considering a moment of the form

$$m_e = -C_1 \tanh(C_2 \dot{\eta}) \quad (22)$$

that contrasts the rotation of the control inceptor, emulating the friction that often characterizes the collective control inceptor, with $C_1 = 0.3 \text{ N} \cdot \text{m}$ and $C_2 = 300 \text{ s/rad}$.

III. Analysis of Piloted Vehicle Model

This section presents the analysis of a detailed multibody model of a vehicle controlled by the previously described pilot model. Both models are developed within the same multibody analysis following a monolithic approach.

A. Aeromechanical Model of Vehicle

A multibody model of a generic medium-weight helicopter, with articulated main rotor, has been developed using the free general-purpose multibody solver MBDyn [23]. The aeromechanical data of the helicopter is loosely related to that of the Sud Aviation (now Airbus Helicopters) SA330 Puma. The multibody model was presented first in [47], where it was correlated to an independently developed model based on the same data, and on limited experimental data. The same model was used in [24], where the involuntary biomechanics of the pilot was used to analyze the effect of BDFT.

The choice of this specific helicopter was dictated by the broad availability of aeroelastic data in the open literature. The aeromechanical model is briefly described in the following for completeness and to give the reader an indication of its complexity and detail.

The aspects of the vehicle that, according to [48], are essential for aeroelastic RPCs have been considered. The main rotor aeroelasticity is modeled in detail. The structural dynamics of the four rotor blades are described using the original geometrically exact beam formulation presented in [49]. Each blade is modeled using five three-node beam elements.

Figure 10 shows a detail of the rotor hub. The root of each blade is connected to the hub by a sequence of revolute hinges that reproduce the exact kinematics of the lag and flap hinges and of the pitch bearing. A rigid body that can lag (i.e., rotate about an axis that is parallel to the rotation axis of the rotor) is connected to the rotor hub for each blade. A linear viscous element models the viscous damper that acts between the lagging body and the hub. Another revolute hinge models the connection between the rigid body that can flap (i.e., rotate about an axis that is orthogonal to both the blade and the rotation axes) and the lagging body of each blade. The root of the blade is connected to the flapping body by a third revolute hinge that models the bearing that allows the pitching of the blade. The root of

Table 2 Parameters of the voluntary pilot model

Symbol	Value	Units
M	7345.0	kg
$Z_{f\dot{z}}/M$	-0.8	s^{-1}
$Z_{f\theta}/M$	113.0	$\text{m} \cdot \text{s}^{-2} \cdot \text{rad}^{-1}$
ω_e	1.0	$\text{rad} \cdot \text{s}^{-1}$
τ_e	0.38	s
$\omega_f = \sqrt{\alpha_2}$	3.10	$\text{rad} \cdot \text{s}^{-1}$
$\xi_f = a_1/(2\omega_f)$	$1/\sqrt{2}$	n.d.

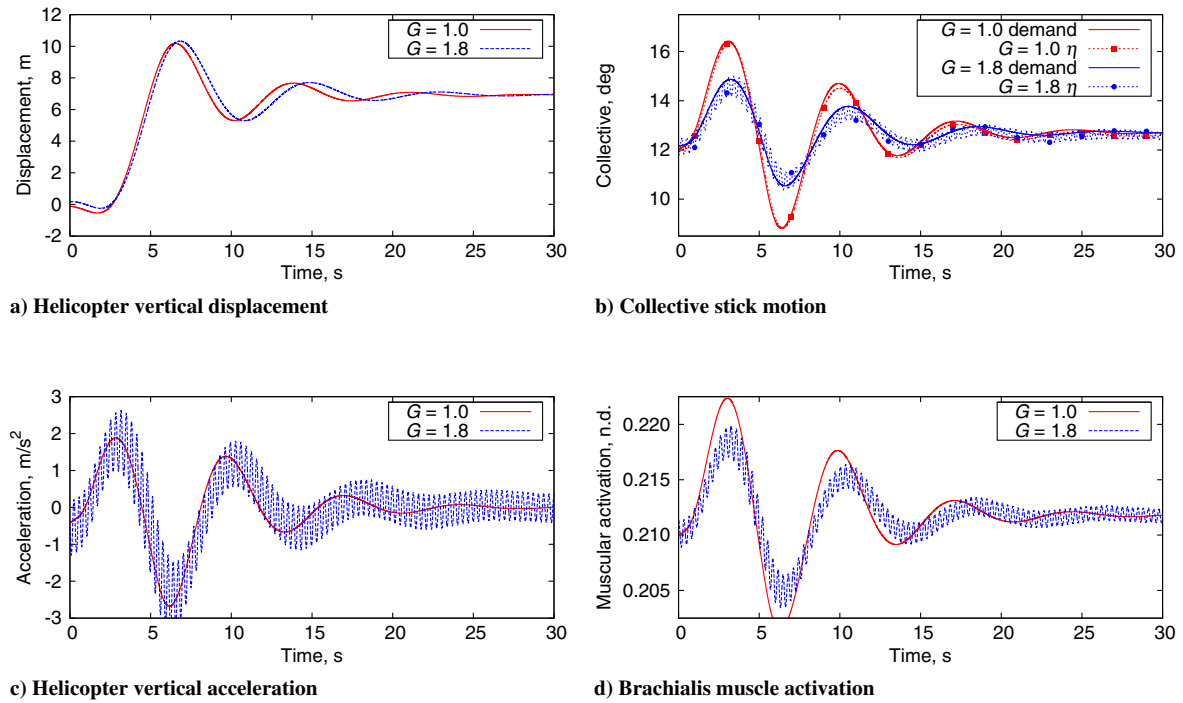


Fig. 12 Helicopter vertical maneuver: loose control inceptor.

the blade, right after the pitch bearing, is also connected to the rotating swashplate by a pitch link, namely, an elastic rod loosely directed along the rotation axis of the rotor and offset from the blade axis, that transmits the pitch control to the blade, also accounting for the mechanical compliance of the pitch control mechanism.

The main rotor is connected to a component mode synthesis model of the airframe by a joint that prescribes the angular velocity of the hub. The fixed part of the swashplate, including the linear actuators that command its position and orientation, is also connected to the airframe model. The airframe model is made of a rigid body that accounts for the rigid-body dynamics of the vehicle and up to eight normal vibration modes (NVMs).

The motion of selected points, namely, the connections with the main and tail rotors and the locations of the pilot and copilot seats, is described in terms of their location in the reference model and their participation to those NVMs. The NVMs in the band of frequencies of interest (up to about 30 Hz) and with appreciable modal participation of the main rotor and crew seats have been chosen. The frequency of the lowest structural mode is about 6.8 Hz; the first mode with significant airframe bending in the vertical direction is at about 8.0 Hz.

The airframe dynamics are completed by simple look-up-table aerodynamics of the tail surfaces. The tail rotor aeromechanics is approximated by a lumped lateral force of which the magnitude depends on the related collective pitch control and on the normal component of the velocity at the center of the rotor.

B. Results of Coupled System Analysis

The proposed model of the joint voluntary and involuntary pilot action has been integrated in the coupled helicopter/pilot model, as shown in Fig. 11. The airframe is modeled using normal vibration modes. Only the location and the modal displacement of selected nodes (pilots' seats, main and tail rotor attachments, and aircraft center of mass) were available.[†] The shoulder and the collective control inceptor are hinged to the seat node by a spherical and a revolute hinge, respectively; the corresponding muscle bundles are connected to the seat node accordingly. The rotation of the collective

control inceptor is logically fed into the swashplate actuators as actuator displacement demand.

In the present analysis, the rigid-body motion of the helicopter is only allowed along and about the vertical axis. Such a restriction has been introduced because only the left arm is modeled, the one that commands the collective control inceptor and thus directly determines the vertical thrust produced by the rotor.

The intentional action of the pilot has been modeled using McRuer's crossover model. The parameters of what corresponds to the pilot's mental model of the helicopter are listed in Table 2 (adapted from [50] with reference to the IAR330, a heavy version of the SA330), along with those of the pilot (from [2]) and of the low-pass filter, a second-order low-pass Butterworth filter with the cut frequency set to 3.1 rad/s.

Figure 12 presents the results of the simulation of a task inspired by the vertical maneuver specified in the U.S. Army rotorcraft handling qualities performance design specification, ADS-33E-PRF [51]. During the maneuver, the pilot changes the altitude of the helicopter by 25 ft (about 8 m), starting and ending in hover condition, to rapidly unmask an attack/scout helicopter or to assess the heave axis controllability of a utility/cargo helicopter with precision station keeping. Since the specification only prescribes the purpose of the maneuver, the desired trajectory of the aircraft is arbitrarily chosen as a vertical motion $z_d = [1 - \cos(\pi t/T)]A/2$ with $T = 5$ s and $A = 25$ ft, for $0 \leq t \leq T$.

In the following, the gearing ratio is modified to act as a sort of a physical feedback gain. Rather than changing G_c , an amplification factor G is considered, such that $\Delta\theta = GG_c\Delta\eta$, with $G = 1$ corresponding to nominal gearing ratio. Figure 12a compares the vertical displacement of the helicopter with nominal and nearly doubled gearing ratio ($G = 1.8$); the latter makes the coupled vehicle/pilot system barely stable. Figure 12c shows the vertical acceleration of the helicopter. Figure 12b shows the collective control inceptor rotation demand and the actual rotation after the action of the biomechanical model. Note that when the gearing ratio is increased from 1.0 to 1.8 the inceptor rotation demand reduces by a factor $1/G = 5/9$, since the maneuver requires the same amount of blade pitch rotation, which is obtained with a smaller rotation of the control inceptor. Figure 12d shows the muscular activation of the brachialis muscle (which is significantly involved in the flexure of the elbow; see Table 1). The brachialis muscle shows the largest activation level for this specific maneuver.

[†]Representative airframe data were only available through private communications; as such, they are not reported in detail. It is understood that the exact values are not critical for the relevant aspects of the analysis.

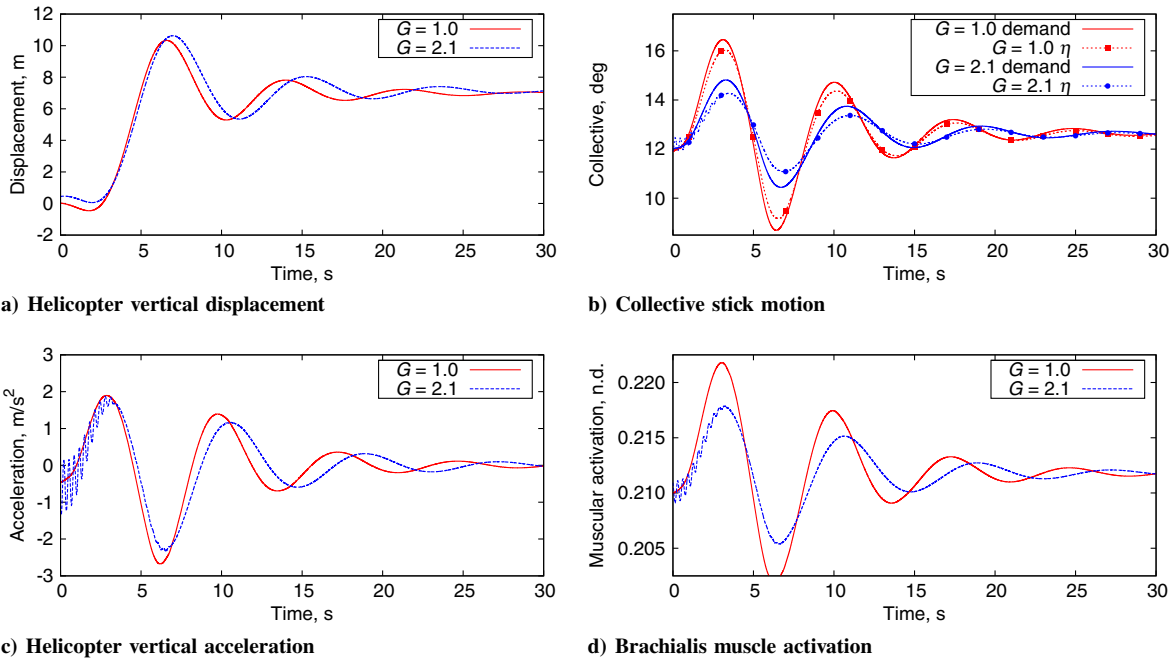


Fig. 13 Helicopter vertical maneuver: control inceptor with emulated friction.

Figure 13 is similar to Fig. 12; only, in this case, the control inceptor is not loose. On the contrary, friction is emulated according to Eq. (22), with $C_1 = 0.3 \text{ N} \cdot \text{m}$ and $C_2 = 300 \text{ s/rad}$. The trends are quite similar. The main difference, when $G = 1.0$, is that the presence of emulated friction increases the difference between the demanded and the actual control inceptor rotation (Fig. 13b vs Fig. 12b). Another important difference is that with emulated friction the coupled pilot/vehicle system remains stable at a value of G about 15% higher than in the case of loose control.

Figure 14 shows the vertical acceleration of the helicopter during a short transient before the maneuver is initiated, after the system has been perturbed impulsively. The figure shows that for nominal gear ratio ($G = 1.0$) the oscillations associated with the interaction between the main rotor coning mode (a major factor in collective bounce, as pointed out in [52]) and the pilot biodynamics quickly vanish. For $G = 1.8$, the oscillations persist, whereas for $G = 2.0$, they diverge. Moreover, the frequency of the oscillations slightly increases with G , from about 2.9 Hz with 10% damping for $G = 1.0$ to about 3.1 Hz and slightly negative damping for $G = 2.0$. Such an increase is mainly a consequence of the fact that the coupling of the pilot's limb biomechanics (of which the pole is at about 2.6 Hz) with the main rotor coning aeromechanics (at about 4 Hz) increases with G .

Figure 15 is analogous to Fig. 14, with emulated friction instead of the loose control inceptor. It shows that the presence of friction makes the coupled system stable for larger values of G (about 15% larger). Also, for G set to the nominal value of 1.0, the initial oscillations triggered by the impulsive perturbations vanish more quickly.

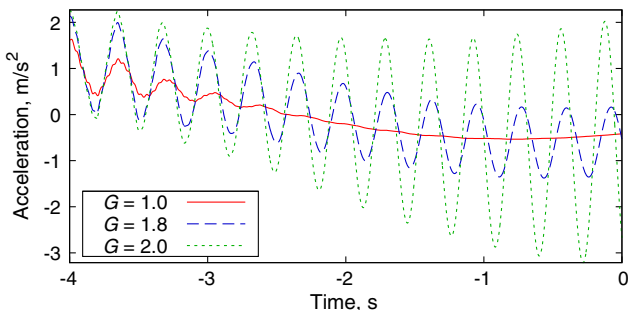


Fig. 14 Helicopter vertical acceleration after impulsive perturbation: loose control inceptor.

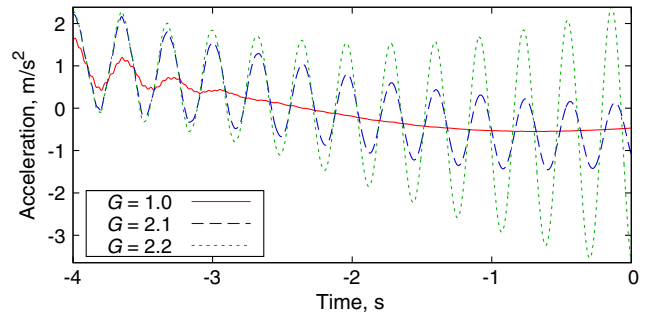


Fig. 15 Helicopter vertical acceleration after impulsive perturbation: control inceptor with emulated friction.

This section showed how the introduction of the pilot's voluntary action by means of the biomechanical model of the arm preserves consistency between the position of the inceptor, which determines the input of the control system, and the biodynamic feedthrough characteristics of the pilot. As discussed previously, there is indirect numerical and experimental evidence that such consistency can play a role in determining the actual BDFT. Further investigation is needed to determine its importance, with the ultimate goal of contributing to practical procedures to define pilot BDFT envelopes, boundaries, and most critical operating conditions, to support the development of rotorcraft that are RPC free by design.

Thorough validation of the biomechanical model is needed to improve its reliability in predicting biodynamic feedthrough. Other directions for improvement encompass statistical considerations on intersubject (e.g., height and weight) as well as intrasubject (reflexive activation and control inceptor configuration) variability of biomechanical properties. Finally, the same analysis should be formulated for the right arm holding the cyclic control inceptor.

IV. Conclusions

This work presented the analysis of the pilot interaction with the aeromechanics of a helicopter in relation with hover and precision repositioning maneuvers along the vertical axis. The voluntary action of the pilot that determines the collective pitch control was formulated using McRuer's crossover model, a simple behavioral model that characterizes the control of simple tasks by human subjects. Such an action was transformed into the actuation of the

collective control inceptor by prescribing the corresponding desired muscle elongation in a detailed biomechanical model of the pilot's left arm. The desired elongation of each muscle is tracked using a quasi-steady approximation of the muscular activation that simulates response to reflexive stimuli. The coupled pilot/vehicle model is formulated and applied to the simulation of standard maneuvers. The results showed that the proposed biomechanical model can be successfully used to transform the voluntary action of the pilot in realistic motion of the control inceptors. As a consequence, when that signal is used as input of the control system, consistency is preserved between the control input and the configuration of the pilot's arm, providing consistent feedthrough of cockpit vibrations to the control system.

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