EXPERIMENTAL IDENTIFICATION OF ROTORCRAFT PILOTS' BIODYNAMIC RESPONSE FOR INVESTIGATION OF PAO EVENTS

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ABSTRACT

This work presents the results of an experimental campaign focused on the characterization of the passive behavior of rotorcraft pilots' biomechanics. Human subjects were subjected to excitation spectra in a flight simulator, recording the motion induced by their limbs' vibrations into the controls inceptors and the limbs' accelerations. Independent excitations in the vertical and lateral direction have been considered. In the first case, measures were related to the motion of the collective lever and of the left arm, while in the second case they were related to the motion of the cyclic stick and of the right arm. The frequency response has been evaluated, and interesting behaviors discussed in view of their relevance in modeling the passive biomechanical behavior of pilots for coupled bio-aeroservoelastic analysis of rotorcraft.

INTRODUCTION

The interaction of the pilot with the aircraft, under specific circumstances, can result in a degradation of the characteristics of the machine in terms of performances and handling qualities. In the worst cases, the pilot can even destabilize the system [1].

An aircraft and its pilot can be viewed as two dynamical systems connected in feedback: the motion of the aircraft stimulates the pilot, which reacts by injecting commands in the flight controls through the inceptors placed in the cockpit. It is well known from control theory that this interconnection may result in an unstable system despite the two subsystems being perfectly stable when considered separately.

In general Aircraft- and Rotorcraft-Pilot Couplings (A/RPCs) are defined as "inadvertent, sustained aircraft oscillations which are consequence of an abnormal joint enterprise between the aircraft and the pilot" [1]. Two different types of phenomena can be observed: the Pilot Induced Oscillations (PIO) and the Pilot Augmented Oscillations (PAO). In the case of PIO the pilot generates a sustained oscillatory motion by an active, although unintended, intervention on the aircraft controls due to an incorrect interpretation of the cues resulting from the motion of the aircraft. In the case of PAO the pilot behavior changes and the oscillations are the results of the passive impedance of the pilot. In practice, the pilot introduces an unintended command because of the cockpit vibration.

The two phenomena are clearly different; they also differ with respect to the range of frequency of interest: the human behaviour is voluntary up to approximately 1Hz, while it is involuntary, thus passive, beyond this limit [2]. A conventionally accepted upper limit for the range of frequencies that can be of interest with respect to 'passive' RPC is 8Hz [3]. Clearly, in this range of frequencies, the pilot interacts with the structural dynamics, and can modify the aeroelastic characteristics of the aircraft.

Experience seems to indicate that the inclusion of fly-by-wire Flight Control Systems (FCS) increased the occurrence of those undesirable phenomena. Unfavorable A/RPCs can affect the operation mission, and sometimes lead to loss of the aircraft [1, 4].

Following a classification introduced in Ref. [3], and mainly based on the characteristic range of frequencies, two classes of A/RPCs have been observed. The first one is in a frequency range up to 1 Hz, where the interactions are dominated by the *active* response of the pilot which is focused on performing the mission task using the physical motion cues to decide the level of corrections that need to be applied. These events are often classified as

PIOs [5].

The second class, in a higher frequency range between 2 and 8 Hz, falls in a bandwidth that cannot be directly controlled by the pilot in an effective manner. In this case, the pilot seated in the cockpit acts as a passive transmitting element for the vibrations of the elastic airframe from the seat to the control inceptor, introducing unintentional high frequency control actions, filtered by the pilot's biomechanical impedance. Thus, the feedback loop between the aircraft and the flight controls is closed by the biomechanical human body response, indicated here as *passive pilot response* to stress the fact that the pilot actions are unintentional. These events are commonly referred in the open literature as PAOs.

In order to investigate the proneness of a new design to PAOs, an appropriate model of the biomechanical response needs to be built. This model must take into account the physiological dynamics of the neuromuscular system of the pilot's limbs. These models are expected to be dependent upon:

- the size of the pilot (weight, height);
- the configuration of the haptic interfaces in the cockpit;
- the posture of the pilot;
- the pilot skills and the control strategy adopted to accomplish the mission task;
- a set of elements correlated to the mental activity of the pilot and the level of workload required by the task, such as the cognitive state, level of awareness, fatigue, anxiety, and more.

This broad class of dependencies is often hidden by the introduction of the concept of 'trigger', or initiation mechanism, which summarizes the external stimuli that may cause the occurrence of a PAO event.

Several pilot models have been developed in the past using cockpit mock-ups [6], simulator tests [2, 7], and in-flight measurements [8]. However, the identification of possible trigger events that affect the response of the pilot requires the development of more detailed models. In turn, they require more information on the response of pilots' limbs to vibrations. Furthermore, to develop a pilot model independent from the configuration of the inceptors, measures directly related to the movements of the pilot's limbs need to be collected.

REVIEW OF PILOT ASSISTED OSCILLATIONS

PAO events have been reported both for fixed and rotary wing aircraft. The peculiar characteristic that allows to identify a PAO event is the major role played in the instability mechanism by the lower frequency flexible modes of the airframe. Several fixed wing aircraft encountered PAO, including: the YF-12A [9], F-111, Rutan's Voyager [10], C17A [11], Boeing 777 [12], all caused by interactions with fuselage or wing bending modes. The information on rotorcraft PAOs are less widespread. However, as reported for example by Walden [4], a significant record of occurrences in the past regarded US Navy rotorcraft, including: CH-46, UH-60 and SH-60, CH-53, and there are probably more not reported in the open literature.

In fact, rotorcraft can be expected to be more prone to PAOs because they are by far less stable than aircraft, and because they are required to fulfill difficult, high workload missions. Typical pilots' biomechanical frequencies (2–6 Hz) lie in a range where modes of flexible airframe, rotors, automatic flight controls, actuator dynamics and drive train system come together. As a consequence, a variety of aeroservoelastic instability phenomena may appear.

The tiltrotor history also catalogs many PAO events, since the early development of the XV-15 technology demonstrator [13]. Several aeroservoelastic pilot-in-the-loop coupling mechanisms where encountered during the V-22 experimental flight tests [8]. The first one was related to a 1.4 Hz lateral oscillation of the fuselage while the aircraft was on the ground. The other was related to high speed in-flight conditions, coupling the lateral and longitudinal pilot response to airframe elastic modes. Tiltrotor industry has been paying significant attention to the problem [8, 14, 15].

DESCRIPTION OF TEST ACTIVITIES

The objective of this work is to obtain a pilot model able to properly reproduce the relationship between the cockpit motion and the involuntary pilot's contribution in the helicopter control inputs and to analyze how the pilot dynamical properties depend on the arms reference position. In particular we focused on helicopter pilots because they are more exposed to vibration than fixed-wing aircraft's pilots.

The passive pilot model has been identified starting from the data measured during a test campaign conducted in the last year, initially within the framework of GARTEUR HC AG-16 [3, 7], and subsequently with partial support from Regione Lombardia and Italian Ministry of University and Research under the PRIN framework.

The experimental tests have been conducted in cooperation with the University of Liverpool, using the Bibby flight simulator. They consist in imposing a motion to the flight simulator and measuring the control sticks rotation. The flight simulator is therefore used as a vibrating platform to excite the human body along different axis, without any visual feedback. During the test a human subject, not necessarily a helicopter pilot, is seated inside the simulator holding a control stick. The subject has not to try to compensate the stick vibration but he has to leave the stick free to vibrate, the only constraint is to try to keep the rotation around the nominal initial position. In order to assist the pilot with this task a display has been created providing the simulator occupant with an indication of all the control sticks positions, useful to compensate any possible drift.

During each experiment also the arm motion has been measured, these biometric measurements have been initially performed by means of three strapdown inertial sensor units placed on the forearm, close to the wrist, on the arm, close to the elbow, and on the upper torso, close to the shoulder.

The experiments has been conducted on three human subjects and the effect on vibration in all the three directions: fore/aft, heave and lateral has been separately investigated. A low pass-filtered random signal has been used as acceleration input imposed on the simulator, characterized by a frequency content limited to 10Hz and an average amplitude of 0.01 g. Figure 1 shows the Power Spectral Density (PSD) of the acceleration measured at the base of the flight simulator; the Root Mean Square (RMS) of the acceleration measured at the base is equal to 0.1108 m/s (about 0.11 g). The same spectrum has been used for vertical, lateral and fore/aft vibration tests.

The interaction with the collective and the cyclic stick has been investigated in separate experiment runs and different reference positions - for the collective, the longitudinal cyclic and the lateral cyclic - have been tested. This allows to obtain a complete

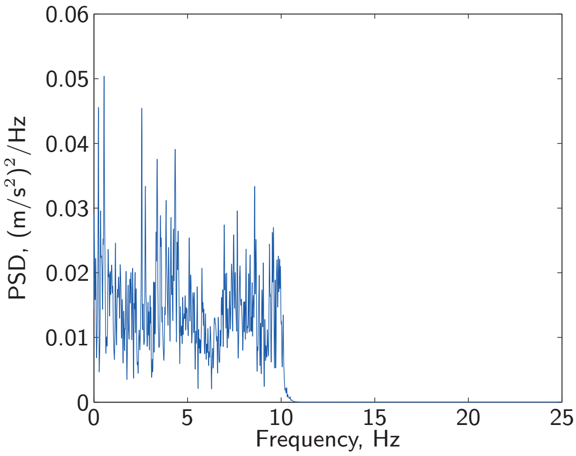


Figure 1: PSD of the acceleration signal measured at the base of the flight simulator.

characterization of the passive behavior of helicopter pilots.

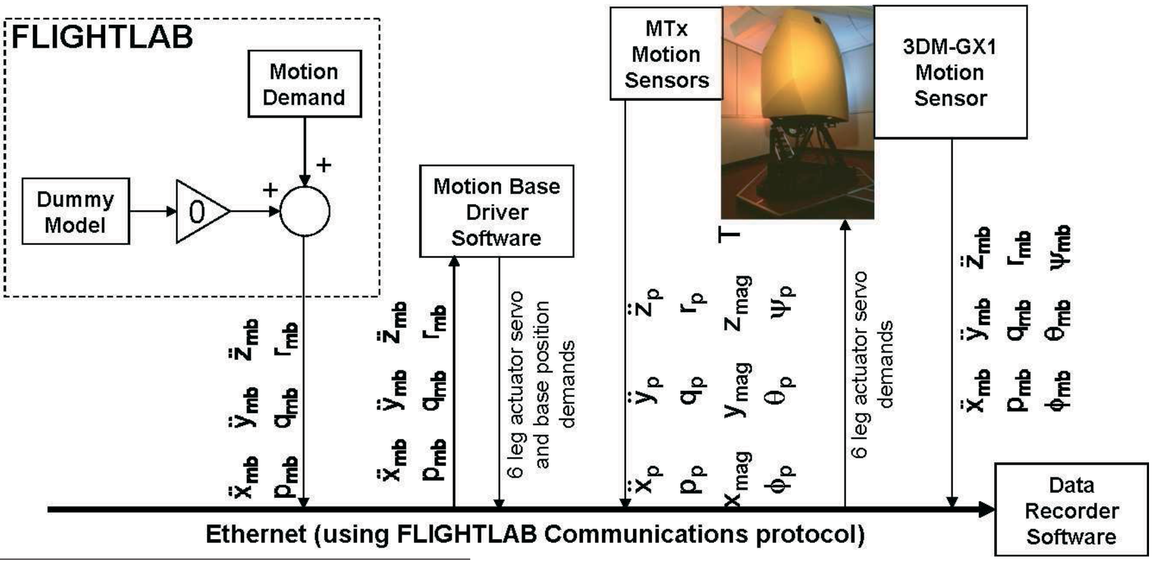
Previously obtained results show that, regardless the cockpit acceleration direction and the control stick, the pilot dynamics can be modeled by a fourth order transfer function with two complex conjugated poles in the excited range of frequency [16, 17].

This can be considered an enhancement of the existing passive pilots models, like the model proposed by R. Mayo [2] where the pilot is model by a second order transfer function or the model proposed by the authors [16] where only the relationship between the vertical acceleration and the collective rotation has been investigated, because the range of frequency of interest was extended, resulting in the evidence of a higher frequency pole not present in Mayo's model.

The effect of different arm reference positions has been investigated as well: it appears to modify the amplitude and phase of the limbs' response, so also the cockpit configuration and the pilot task can have an effect on the adverse coupling between the helicopter and the pilot.

Experimental Set-Up

The testing was conducted at The University of Liverpool's (UOL) Flight Science and Technology (FST) Research Group's Bibby flight simulation laboratory. The primary research tool available to FST is a six visual channel flight simulator mounted upon a six-axis motion base, Figure 2. This facility is described in its original form in Ref. [18]. The pri-



Notation

x	x measurement axis of motion sensor
y	y measurement axis of motion sensor
z	z measurement axis of motion sensor
p	roll rate
q	pitch rate
r	yaw rate
ϕ	roll angle
θ	pitch angle
ψ	yaw angle
T	temperature

Subscripts

mb	of the simulator motion base
p	of the pilot/simulator occupant
mag	magnetic field

Figure 3: Schematic diagram of experimental set-up.

mary modelling tool used to generate research vehicle model's is Advanced Rotorcraft Technologies' (ART) FLIGHTLAB software (Ref. [19]). This interfaces with ART's PILOTSTATION software to provide the motion cueing to the simulator pilot. The usual use to which the simulator is put requires the development of an air-vehicle model of the desired fidelity. However, the operation of that model, including the use of motion cueing and the subsequent recording of test data is all handled automatically by the facility hardware and software. The proposed experimentation required that new capabilities be developed (or procured) to achieve the test objectives, viz:

1. develop a method to drive the existing motion system without reference to a specific vehicle model;
2. measure the input demands to the motion system;
3. measure the angles, rates and accelerations of the simulator pod (i.e. the motion stimulus to the simulator occupant);
4. measure the resultant pilot's arm motion, and
5. capture all of the experimental data from the various sources of measurement.

Figure 3 shows schematically how these objectives were achieved. To achieve capability 1, a dummy FLIGHTLAB model was created whose motion-demand outputs were all set to zero. The desired input to the motion base was then injected via the simulation model's control system, the output of which was directed to the six motion system data latches that are the 'input' to the motion base control software. To achieve the second capability requirement, a new version of the motion-base controller software was created to broadcast the inputs and outputs of the latch filters. To measure the motion of the

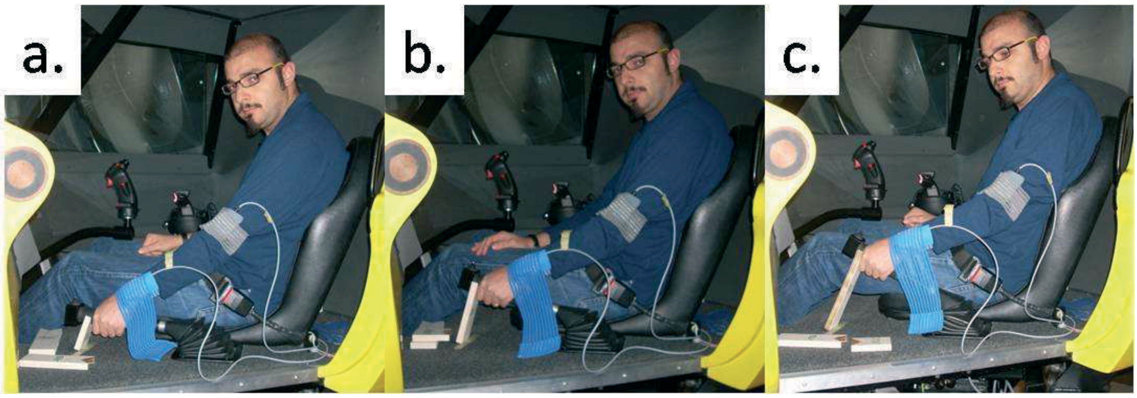


Figure 4: Nominal collective lever start positions: (a) 10%; (b) 50% and (c) 90% of full scale rotation.

Figure 2: Bibby Flight Simulator

motion-base itself, a MicroStrain 3DM-GX1 motion sensor was rigidly connected to the flight simulator. To measure the motion of the pilot limbs, XSens MTi sensors were fixed using fabric hook-and-loop fasteners, as shown in Figure 4. The MTi are miniature devices that output the acceleration and the rate of turn along three orthogonal axes. Additionally, a built-in integration algorithm uses the output of a magnetic field sensor to produce the sensor orientation. All data were collected with a sampling rate of 100 Hz.

For all of these sensors, data acquisition software had to be customized to broadcast the measured data. Finally, a set of software had to be developed to capture and save all of the data being broadcast across the simulation facility Ethernet.

Test Procedure: Collective Lever

With the hardware and software configured as described above, the human subject was seated in the simulator cockpit. The MTi motion sensors were attached to the left arm and shoulder as described earlier. A typical arrangement is shown in Figure 4(a), although this early picture does not show the sensor located near the shoulder. The controls (longitudinal and lateral cyclic stick, collective lever, rudder pedals) were set to their nominal start positions, the occupant locked into the pod and the motion platform raised. The excitation for the current test point was applied and the results recorded for later analysis. Figure 4 shows the three nominal collective positions.

The majority of the test points required the collective lever forces to be switched off. The ideal situation was one of zero friction. In practice, this was not possible with the simulator hardware and the best that could be achieved was that the collective lever forces were set to the minimum available. This initially presented an issue in that, with the stick forces switched off, the collective became ‘floppy’ and had to be physically held in the desired start positions. However, it was important that any collective and hence arm vibration were restricted to be approximately around this nominal start position during a given test. To assist with this task, a pilot display was created as shown in Figure 5. The display provided the simulator occupant and opera-

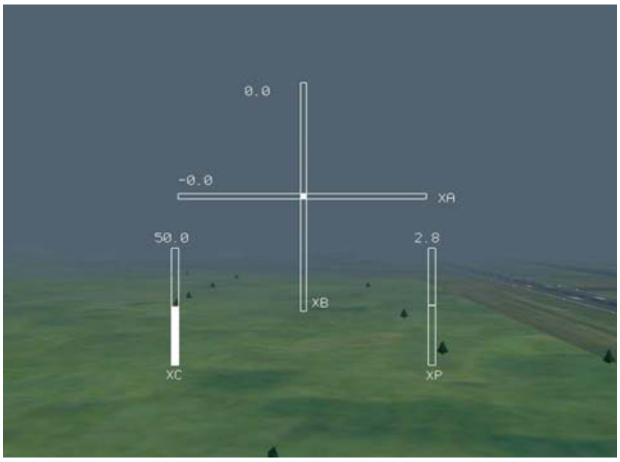


Figure 5: Control inceptor position display.

tors with an indication of all of the control inceptor positions. The left-most symbol shows collective lever position, the central cross-shaped symbol shows longitudinal and lateral cyclic position and the right-most symbol shows rudder pedal position. The occupant was instructed to keep the collective lever close to the reference position using the display as a guide. No specific precision was required for this task, in order to avoid significant muscular activation transients.

Test Procedure: Cyclic Stick

The MTi motion sensors were attached as described earlier, but to the right arm and shoulder. No picture is available because the simulator provides no visual access from the right side. Reference positions of 0 and $\pm 35\%$ of the maximum range allowed by the inceptor were considered. Two sets of tests have been conducted. During one set, the retention spring was disconnected from the inceptor, resulting in a 'floppy' behavior. During the other set, the retention spring was connected, requiring the pilots to apply a significant load to hold the stick in the $\pm 35\%$ positions.

RESULTS

All the recorded signal were conditioned during the post-processing phase by using low-pass Butterworth filters, with the pass-band below 25 Hz, before being used for the identification. The transfer functions shown in the next section have been identified using a spectral analysis method based on the Blackman-Tukey algorithm [20] with a frequency resolution equal to 1Hz. A smaller frequency resolution can be useful when the transfer function contains very sharp peaks, but it increases the uncertainty. However, since the pilot biodynamic response is characterized by significant damping [2, 16], no sharp peaks are expected. For this reason a higher frequency resolution was considered adequate.

Table 1: Physical characteristics of the tested subjects.

Label	Weight, kg	Height, m
Pilot 1	70	1.81
Pilot 2	74	1.78
Pilot 3	67	1.65

Three different subjects were tested. Their physical characteristics are summarized in Table 1. During this first campaign, 69 tests, differing in the subject, control stick type, position and condition, have been performed. Only the most significant results, related to a small subset of the performed tests, are presented in the following.

Collective Lever

Figure 6 shows the frequency responses of the acceleration relative to the flight simulator moving reference frame, measured during a heave excitation test with all pilots holding the collective lever across 50% positioning. The responses look somehow similar; however, each pilot shows a peculiar behavior. All pilots have a significantly damped main resonance peak at the shoulder, between 4 and 6Hz. The lighter pilot presents the higher frequency, suggesting that this effect may be dominated by the whole body, or torso, oscillation due to the joint effect of the elasticity of the seat and the body elastic and viscous forces. The high phase delay close to the peak — about 180 degrees — suggests that this effect may not be ascribed only to the elastic deformation of the seat, and the internal forces yielded by the human body must be significant.

Looking at the elbow and the wrist, the differences increase. The shorter pilot shifts toward a lower frequency resonance peak, close to 3.5 Hz. The other two present a similar behavior before the main peak, but the first pilot presents a sharper peak, especially at the elbow, while the second shows a sort of plateau of high relative acceleration after the peak. These differences, especially between pilots 1 and 2, whose physical characteristics are somehow closer, may reveal a different muscular activation state. Additionally, a possible nonlinear constitutive law, typical of reflexive muscular behavior [21] may be responsible for such large plateau like the one shown by pilot 2. For pilot 3, instead, the arm acts like a notch filter that tries to cancel the shoulder resonant peak close to 6Hz.

In any case, from 2.5Hz to at least 5Hz — up to 7Hz for the taller pilots — the acceleration of the seat seems to be amplified by the vibration of the body when transmitted to the collective lever, with a significant phase delay.

Figure 7 shows the response in terms of relative acceleration at the wrist for different reference positions of the collective lever. For both pilots the lower amplification factors are obtained at 90%. However, the first pilot shows a larger variability than the second one. This result suggests again that the main difference should be related to muscular activation rather than to the relative geometrical position of the different limbs.

Cyclic Stick

Figure 8 shows the lateral acceleration at the different sensors on the right arm, for a lateral imposed acceleration, when the control stick is 'floppy', i.e. no retention spring is connected.

Here the amplification appears at a lower frequency, compared with the collective level cases, and appears to be mainly due to the arm vibration, with a slight influence of the vibrations of the torso. In fact, Pilot 1 and 2 present an amplification between 1Hz and 2.7Hz, while the shorter pilot presents a slightly larger amplification range, with a peak shifted at a higher frequency, close to 3Hz.

It is very interesting to compare the behavior shown in Figure 8 with that shown in Figure 9, which presents the relative acceleration for the cases with a retention spring on the stick. In this case pilots 1 and 2, that have a lower peak for the free stick, show a interaction with the retention spring that causes a sharp increase of the amplitude peak close to 2Hz. Pilot 3, that has a higher peak frequency with the free stick, does not show any significant change in the response.

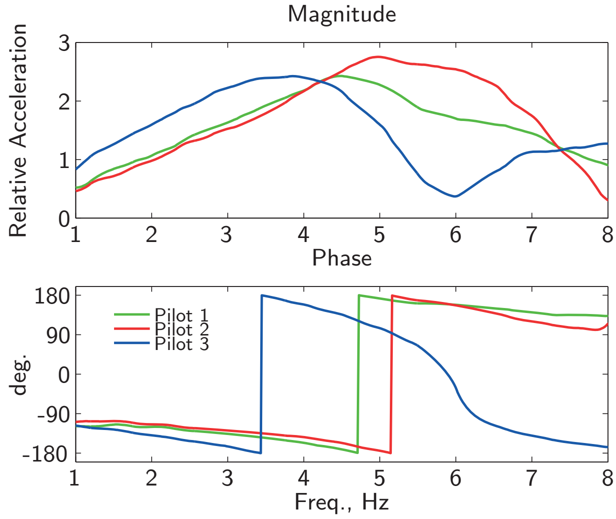
The change of reference position for the case of the free control stick, does not produce any significant modification of the response, as shown by Figure 10. However, with the retention spring there is a drastic change of behavior (Figure 11), which can be ascribed to the change in muscular activation. In fact, a significant load was required by the pilots to keep the control stick at $\pm 35\%$. In this case, too, as shown for the collective lever, the muscular activation of the pilot limbs may be responsible of a change in the pilot biodynamic response.

It is worth noticing that such a high load required to hold the stick in the desired position is unrealistic during regular flight, as a pilot would trim it out. However, it might be required during maneuvers and transients in general. The resulting significant change of passive biodynamic behavior may thus alter the overall stability of the rotorcraft, and become a potential trigger of a PAO event.

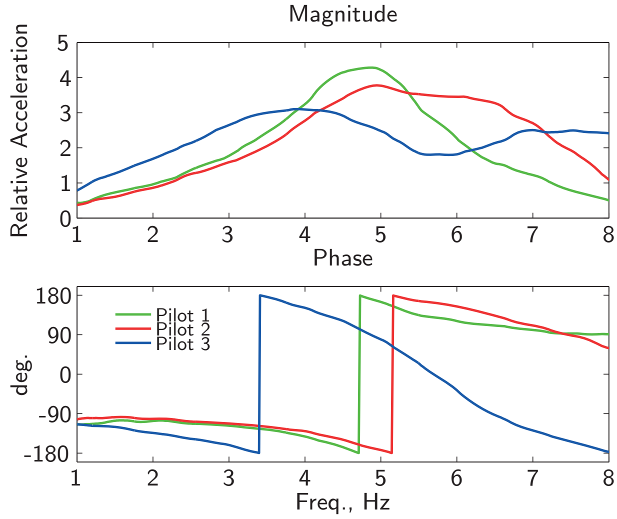
CONCLUDING REMARKS

The paper presented the results of a test campaign conducted in a flight simulator to address the passive biodynamic response of helicopter pilots. The frequency response of multiple human subjects to base motion in the vertical and lateral directions has been measured in terms of collective and cyclic control inceptors motion and pilot's limbs accelerations. A significant dependence on the configuration of the limbs, resulting from the requirement to hold the inceptors at different reference positions, has been observed. Measurements related to lateral excitation also show a significant dependence of the behavior on the muscular activation required to react the load provided by retention springs. These factors are believed to have some potential influence on triggers for PAO events.

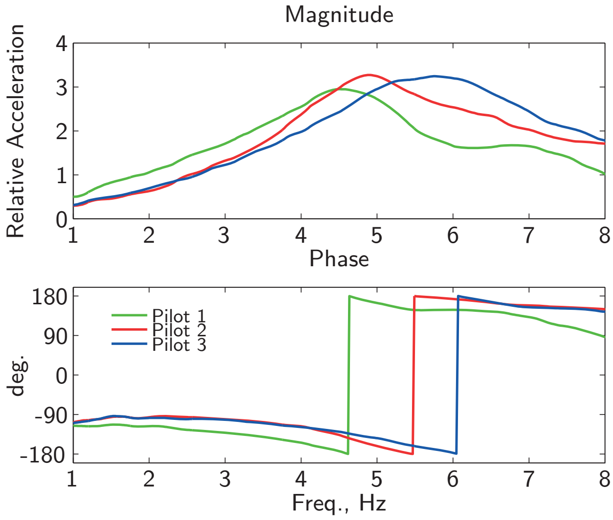
Future activity will address the development of pilot models for aeroservoelastic simulation of rotorcraft. The database gathered with these experiments will be instrumental for the identification of the constitutive properties of the pilot's articulations in realistic configurations, and for their validation. Furthermore, additional experiments involving real helicopter pilots performing simple yet realistic flight tasks with different levels of difficulty have been already performed and are currently being analyzed.



(a) Wrist

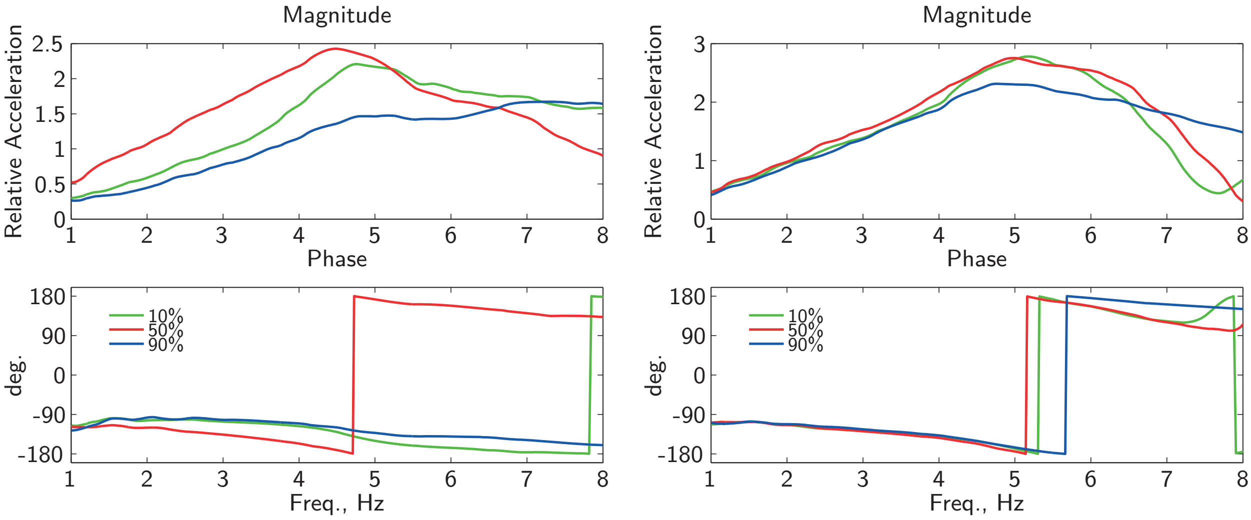


(b) Elbow



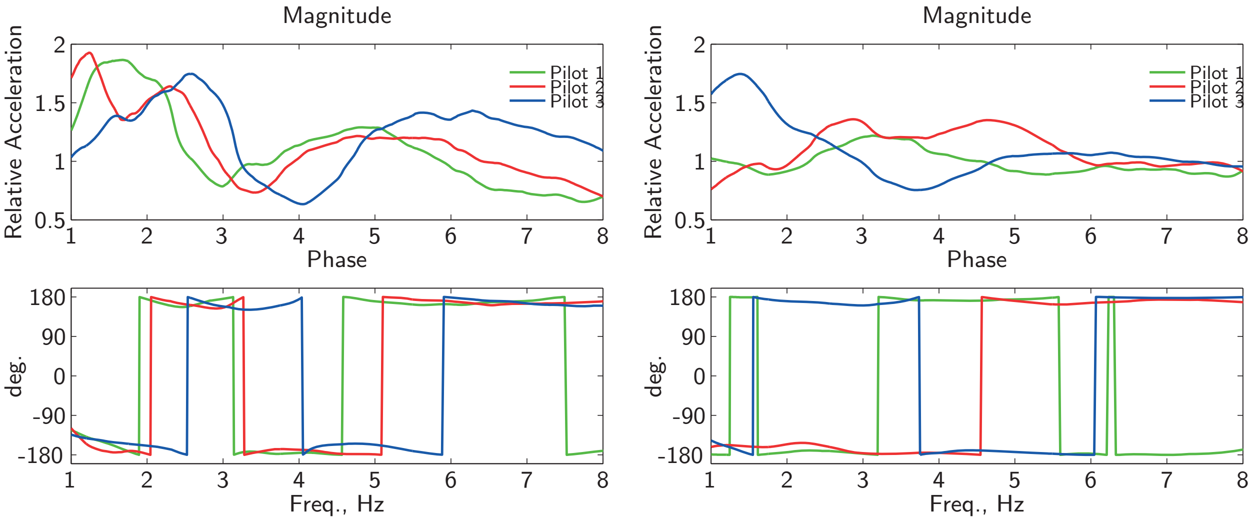
(c) Shoulder

Figure 6: Frequency response of the vertical acceleration relative to the flight simulator reference frame measured on pilot limbs. The input is the vertical acceleration of motion-base; the collective lever reference position is 50%.



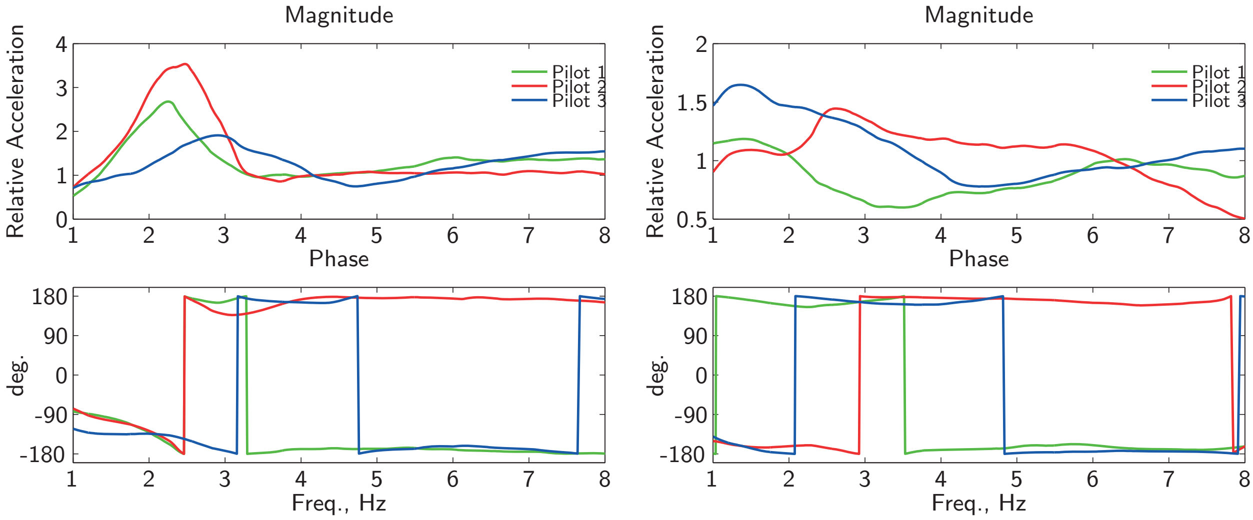
(a) Pilot 1 (b) Pilot 2

Figure 7: Frequency response of the vertical acceleration relative to the flight simulator reference frame measured on pilot limbs for different reference positions of the collective lever. The input is the vertical acceleration of motion-base.



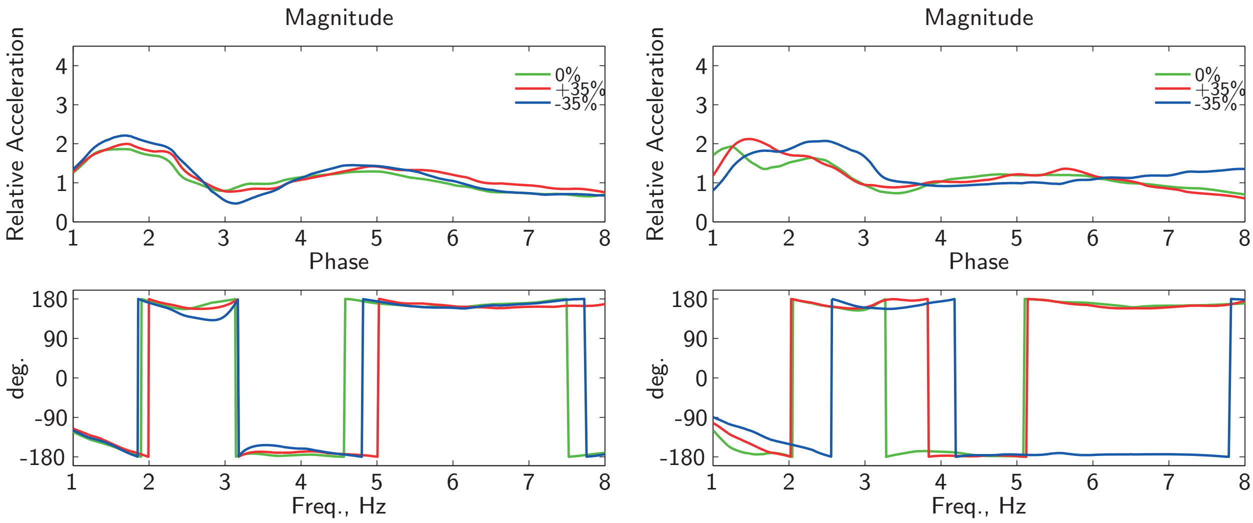
(a) Wrist (b) Shoulder

Figure 8: Frequency response of the lateral acceleration relative to the flight simulator reference frame measured on pilot limbs. The input is the lateral acceleration of motion-base; the cyclic stick is free to move and the reference position is 0%.



(a) Wrist (b) Shoulder

Figure 9: Frequency response of the lateral acceleration relative to the flight simulator reference frame measured on pilot limbs. The input is the lateral acceleration of motion-base; the cyclic stick is attached to a retention spring and the reference position is 0%.



(a) Pilot 1 (b) Pilot 2

Figure 10: Frequency response of the lateral acceleration relative to the flight simulator reference frame measured on pilot limbs for different reference positions of the cyclic stick. The input is the lateral acceleration of motion-base; the cyclic stick is free to move.

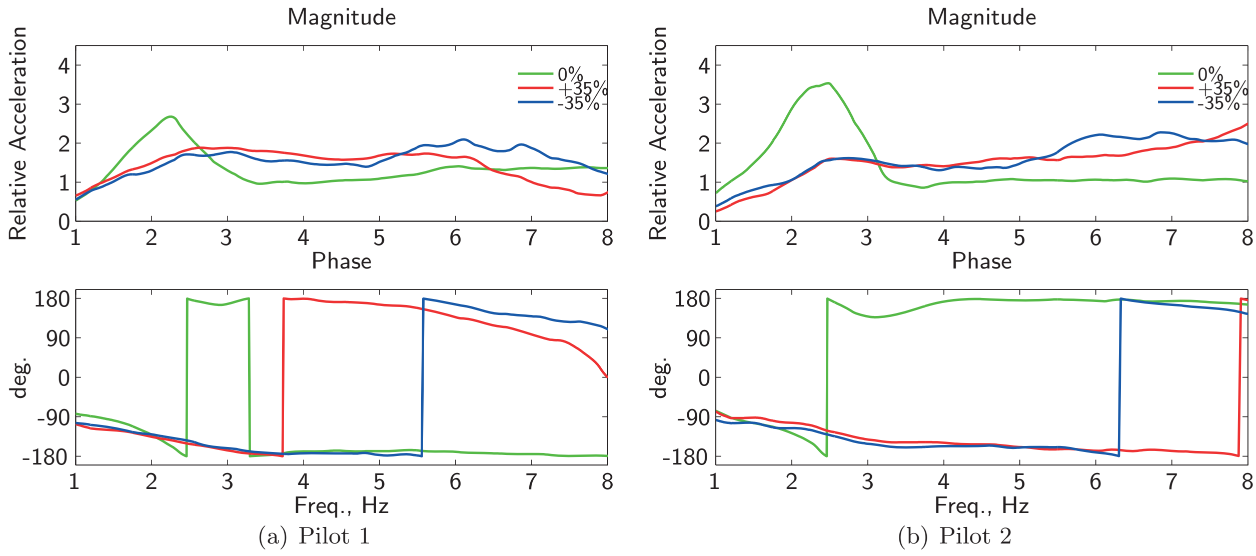


Figure 11: Frequency response of the lateral acceleration relative to the flight simulator reference frame measured on pilot limbs for different reference positions of the cyclic stick. The input is the lateral acceleration of motion-base; the cyclic stick is attached to a retention spring.

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