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Preliminary In-Flight Biomechanic Tests on the BA609 Fly-By-Wire Tiltrotor

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Abstract: This paper presents the results of a preliminary test campaign made on the BA609 tiltrotor for the in-flight measurement of the biodynamic response of the pilot. The objective of the test campaign was to verify the feasibility of this type of measures during flight tests, and to assess the quality of the results that can be obtained. The identification of the biodynamic response of the pilots can be especially useful for the design of Fly-By-Wire rotorcraft where potentially adverse interaction between the aircraft dynamics and the pilot may appear.

1 INTRODUCTION

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]. The past experience seems to indicate that the inclusion of Fly-By-Wire (FBW) Flight Control Systems (FCS) increased the occurrence of such undesirable phenomena. Unfavorable A/RPCs can affect the performance of the aircraft’s mission, and sometimes lead to loss of the aircraft [1, 2].

Following a classification introduced in Ref. [3], 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 to be applied. These events are often classified as Pilot Induced Oscillations (PIOs) [4].

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 Pilot Assisted Oscillations (PAOs).

In order to investigate the proneness of a new design to PAOs, it is necessary to build an appropriate model of the biomechanical response that takes 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 [5], simulator tests [6, 7], and in-flight measurements [8]. However, the identification of possible trigger events that affect the pilots' response requires the development of more detailed models, which in turn 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.

For this reason, the feasibility of measuring the pilot's limbs motion directly during flight tests has been assessed during this work, using several miniature accelerometers with gyro-enhanced Attitude and Heading Reference Systems. Preliminary in-flight experimental tests have been performed with the following goals:

- verify the compatibility of the test equipment with respect to electromagnetic interference;
- verify the flight-worthiness of the set-up;
- verify the freedom of movement of the pilots while performing flight tasks with the sensors attached to their limbs;
- verify the quality of the measures;
- identify possible pitfalls to be avoided in this kind of tests.

The tests have been performed on the BA609 FBW tiltrotor that is currently undergoing flight tests at the AgustaWestland test site in Cameri (NO, Italy). The BA609 is the first tiltrotor that will apply for civil certification. It will be capable of carrying 6–9 passengers and two pilots, with a maximum speed of about 275 KTAS and a maximum takeoff weight of 16800 lbs (see Figure 1). The aircraft adopts the FBW technology and it is totally controlled by a triple redundant FCS with full authority. Particular care has been put in the aeroelastic and aeroservoelastic design of the vehicle in order to provide adequate clearance with respect to the prescribed envelopes both in terms of Speed/Altitude and Gains/Phase margins between structural modes and actuators of rotating and fixed controls band-pass frequencies.

Two flying prototypes are currently undergoing testing: the BA609 prototype number 1 started the test flights in 2003 at the Bell test site in Arlington (TX, US), while ship 2, based at the AgustaWestland test site in Cameri (NO, Italy) made its maiden flight in 2006.

The evaluation of the feasibility of this unusual flight testing on this specific type of aircraft is particularly interesting, because tiltrotor aircraft can fly both in helicopter and in airplane mode. As a consequence, a large variety of different potential PAO mechanism can be evaluated, as testified by Ref. [8], which describes the flight test campaign performed by Bell Helicopter for the V-22 aircraft. In fact, the configuration of the aircraft changes depending on the mode of operation, thus changing the aeroservoelastic properties of the system. Changes in aeromechanical operation mode of the vehicle, in turn, may require changes in the operation mode of the FCS, possibly changing the way the pilot perceives the vehicle. This represents a potential trigger for A/RPC events.

The paper is organized as follow. Section 2 reviews the impact of PAO events on the development of aircraft and especially on tiltrotor. Section 3 presents the details of the performed tests, describing the details of the measurement apparatus and the type of analysis performed. Finally, Section 4 discusses the results obtained.

2 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 YF-12A [9], F-111, Rutan's Voyager [10], C-17A [11] and Boeing 777 [12]. All of them were associated to interaction with fuselage or wing bending modes. Information on rotorcraft PAOs is less widespread. However, as reported for example by Walden [2], a significant

Figure 1: The second BA609 tiltrotor prototype at the AgustaWestland test site in Cameri.

record of occurrences in the past regarded US Navy rotorcraft, including CH-46, UH-60 and SH-60, and CH-53. There are probably more, although not reported in the open literature.

Rotorcraft can be expected to be more prone to PAO because they are by far less stable than aircraft, and because they are required to fulfill difficult missions usually characterized by high workload. Typical pilots' biomechanical frequencies (2–6 Hz) lie in a range where modes of flexible airframe, rotors, automatic flight control system, actuator dynamics and drive train system come together. So, a variety of aeroservoelastic instability phenomena may show up. Also the tiltrotor history catalogs many PAO events, since the early development of the XV-15 technology demonstrator [13]. Several aeroservoelastic pilot-in-the-loop coupling mechanisms were encountered during the V-22 experimental flight tests [8]. One was related to a 1.4 Hz lateral oscillation of the fuselage while the aircraft was on the ground. Another one was related to high speed in-flight conditions, when the lateral and longitudinal pilot response coupled to airframe elastic modes.

3 EXPERIMENTAL APPROACH

The preliminary assessment of the feasibility of biodynamic in-flight tests was performed on the second BA609 prototype, which is currently undergoing an extensive flight test program in Cameri. The test program, not specifically related to this work, includes: the expansion of the flight envelope, the evaluation of load levels and vibration survey, and the investigation of high angle of attack and buffet conditions.

In order to minimize the impact of the activity presented in this work on the scheduled flight tests, no specific tests for pilot biomechanics have been designed. On the contrary, the required instrumentation was simply placed on the pilots during the execution of already scheduled flight tests that could present interesting features from a pilot biomechanics point of view.

For this reason, a preliminary selection of possible tests that may meet the requirements of biodynamic identification was made. Focus was placed primarily on the *collective dwell* tests. They consist in exciting the aircraft by a signal fed into the collective control of the rotors, with frequencies close to those of the lowest airframe modes, while the aircraft is hovering.

This approach had several drawbacks, including the lack of specific excitation signals tailored for biodynamic identification, the lack of exact time synchronization between the signals acquired by the sensors mounted on the aircraft and the biodynamic sensors applied on pilots, and presented practical issues, like the need to check and start data acquisition during pre-flight operations, since no access to the data recording system was possible neither on board nor remotely. However, these issues were considered non critical, given the preliminary stage of the investigation. It was decided to perform measures on the biodynamic response of the arm used to control

Figure 2: MTi sensor set-up on the pilot's left arm and forearm.

Figure 3: Verification of the ability to perform all arm movements while the MTi sensors were on.

the collective stick, in order to compare the results with other already acquired by Politecnico di Milano during flight simulator experiments made using the University of Liverpool's flight simulator [7, 14]. Those tests were not related to the BA609, but rather focused on a generic conventional rotorcraft configuration.

3.1 APPARATUS AND MEASUREMENTS

Two MTi strapdown sensors, manufactured by XSens [15], were applied to the left arm and forearm. The MTi are miniature strapdown devices that output the acceleration and the rate of turn along three body-fixed orthogonal axes. Additionally, a built-in integration algorithm uses the output of a magnetic field sensor to resolve the sensor orientation. One of the MTi sensors was placed close to the elbow and the other close to the wrist, using fabric hook-and-loop fasteners, as shown in Figure 2. Special care was taken to verify the ability of the pilot to perform all arm movements that may be required during a flight without any impediment, Figure 3. Additionally, to ensure the safety of the setup, it was verified that the fasteners were sufficiently loose to warrant the ability for the pilot to escape from the cockpit without getting entangled with sensor cables. The two MTi sensors were connected via USB ports to a laptop, based on an Intel Core2 CPU @ 1.66 MHz with Linux OS, dedicated to biodynamic data recording. The PC power supply was provided by a standard set of batteries. To increase the endurance, the hard disk drive was disconnected and all data was recorded on a USB pen drive. This guaranteed more than 3 hours of data recording. All MTi data were collected with a sampling rate of 100 Hz.

Additional signals were already taken directly from the measurement instrumentation placed in the aircraft cockpit. In particular, the signals coming from the vertical accelerometer placed under the pilot's seat, and those

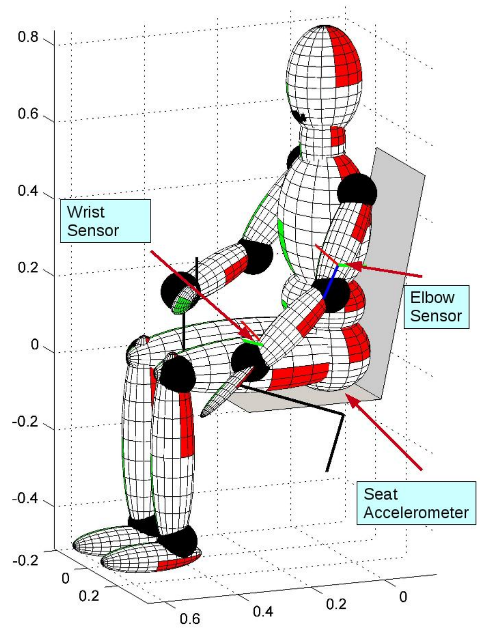

Figure 4: Sketch of the global sensors set-up in the cockpit.

related to the motion and acceleration of the control sticks were used. However, these signal could not be perfectly synchronized with those coming from the MTi sensors. As a consequence, some uncertainty in the phase between aircraft and pilot sensor signals affected the correlation of the recorded data. A sketch of the global set-up is shown in Figure 4.

A preliminary on-ground test was performed to check the absence of electromagnetic interference between the test instrumentation and the avionics and existing test equipment of the aircraft. As expected, the MTi sensors heading was significantly affected by the electromagnetic fields in the cockpit, confirming that the orientation outputs were not reliable. For this reason, only the MTi signals in the vertical direction were considered, since that direction could be easily discriminated according to the mean value of the acceleration.

No special excitation was scheduled in the range of frequencies typical of pilot's biodynamics. As a consequence, the only excitation for the biomechanical identification came from the natural vibrations of the airframe generated during flight.

3.2 TEST CONDITIONS

The measurement apparatus described in the previous section was used during two flight tests. During the first one, high and low g symmetric maneuvers were performed. The results obtained in this case confirmed the functioning of the measurement system. However, the amplitude of the excitation in the bandwidth of interest for biodynamic identification was not sufficient to carry out any reliable identification process.

The second flight test considered was a collective dwell during hover flight, with different levels of friction in the collective stick. In this case a specific excitation close to 3 Hz applied by means of the rotors collective was scheduled, yielding quite interesting results.

3.3 ANALYSIS OF THE DYNAMIC RESPONSE

All the recorded signals were conditioned during the post-processing phase by means of low-pass Butterworth filters, with pass-band below 25 Hz, before being used for the identification. The transfer functions shown in

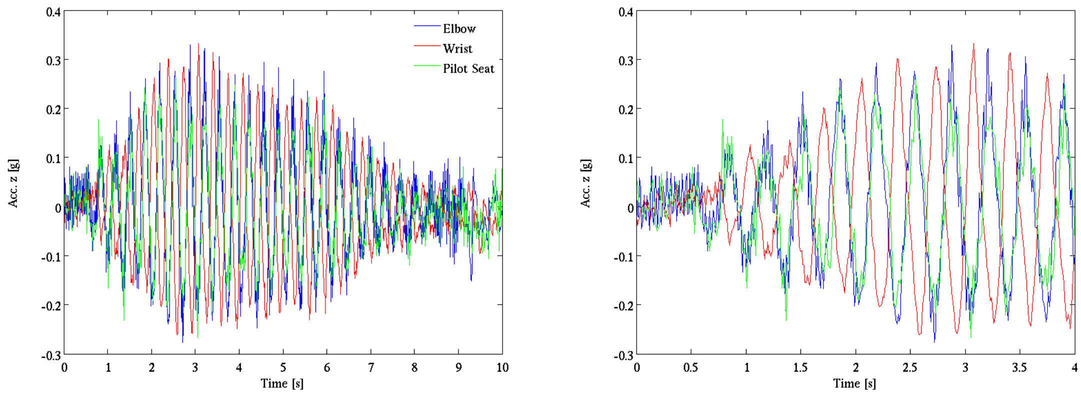

Figure 5: Accelerations measured during the collective dwell test at maximum stick friction; on the right, a zoom of the first 4 s.

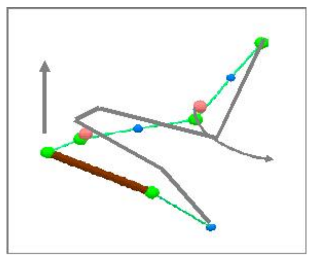

Figure 6: Kinematics of the movement of the left arm holding the collective stick.

the next section have been identified using a spectral analysis method based on the Blackman-Tukey algorithm [16, 17] with a frequency resolution of 1 Hz. A fine frequency resolution can be useful if there are very narrow peaks in the transfer function, but it increases the uncertainty. However, since the pilot biodynamic response is characterized by a significant damping [7, 14], no sharp peaks are expected, so a coarse frequency resolution was considered adequate.

4 DISCUSSION

This section presents the results obtained during the second flight test, since these are the most significant. Two hover tests with a different level of friction in the collective control lever were performed. Figure 5 shows the time histories of the three accelerometers in the vertical direction, associated to the motion of the wrist, elbow and pilot seat, during the first collective dwell test with a higher level of friction. The synchronization between the wrist and elbow signal is correct, since both signals were acquired by the same system. However, the correct alignment of these two signals with the one that measures the acceleration of the pilot's seat was affected by an uncertainty of about 1 s. It was decided to arbitrarily align the pilot's seat acceleration signal with that of the elbow. Looking at the zoomed time window on the left of Figure 5, it is clear how the accelerations of the wrist and of the elbow are nearly in phase opposition. This is consistent with the kinematics of the arm that holds the collective stick: Figure 6 clarifies how, when the wrist rises, the elbow is constrained to move on a descending, almost circular trajectory.

Figure 7 shows the Fast Fourier Transform (FFT) of the three signals, highlighting the fact that the excitation on the pilot's seat dominated by a 3 Hz peak, as expected. As a consequence, frequencies close to 3 Hz should be considered as those for which more reliable information can be inferred. This is confirmed by the corresponding plot of Figure 8, which illustrates the coherence between the pilot's seat vertical acceleration and those of the wrist and elbow, close to 1 in the vicinity of 3 Hz. Figure 9 shows the results of the application of the spectral analysis to identify the transfer functions between the seat and the pilot's arm acceleration signals. Whenever the value of the transfer functions is above one, there is an amplification of the acceleration transmitted through the pilot's

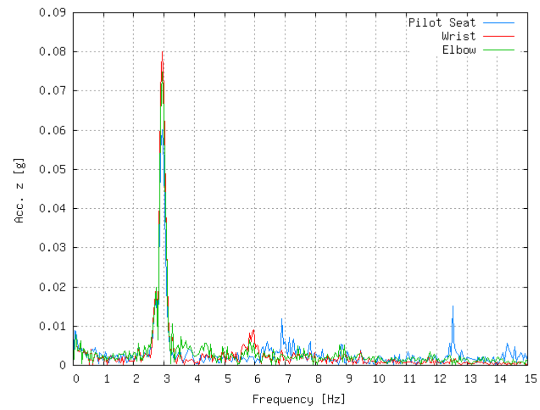

Figure 7: FFT of the signals acquired during the collective dwell with high friction.

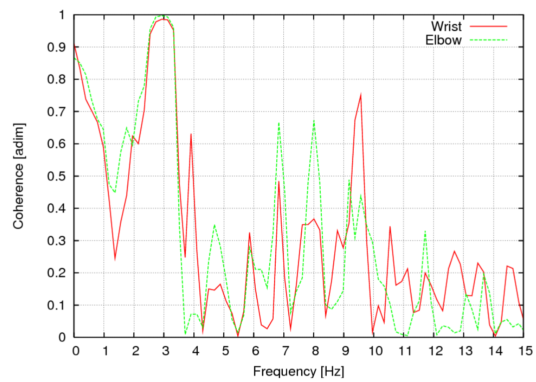

Figure 8: Coherence between the pilot's seat vertical acceleration and those of the wrist and elbow acquired during the collective dwell with high friction.

body. On the contrary, whenever the value is below one, the acceleration transmitted is attenuated. At the wrist there are two bands of amplification: one between 2.5 and 3.5 Hz, and another one slightly below 6 Hz. The first resonance band is consistent with the findings of other authors [6, 7, 14]. The amplitude in this first resonance band is slightly lower than those reported by Mayo [6]. The second resonance is in a region without an appreciable excitation level. However, the presence of a second resonance peak in the pilot's response is consistent with the recent findings reported in Refs. [7, 14]. A similar behavior is shown by the elbow transfer function, with lower amplitudes.

The results obtained during the second collective dwell test with lower friction in the collective mechanism are shown in Figure 10. Figure 11 shows the corresponding coherence between the pilot's seat vertical acceleration and those of the wrist and elbow. Figure 12 shows the transfer function identified from the measured vertical acceleration of the pilot's seat and of the wrist. These results are consistent with the ones obtained during the first test, at least in the 2.5–3.5 Hz range.

A final analysis was performed using the signals recorded during the final approach performed before landing. In this case there is a broader range of excitation frequencies input by the airframe vibrations, with lower amplitude, as shown in Figure 13. Figure 14 shows the corresponding coherence between the pilot's seat vertical acceleration and those of the wrist and elbow. Figure 15 shows the transfer function identified from the measured vertical acceleration of the pilot's seat and of the wrist. The results in the 2.5–3.5 Hz range are again consistent with those obtained during the previous tests (Figure 10). A higher amplification factor is shown in the 3.5–5 Hz range. However, the level of excitation does not allow to consider this information sufficiently reliable.

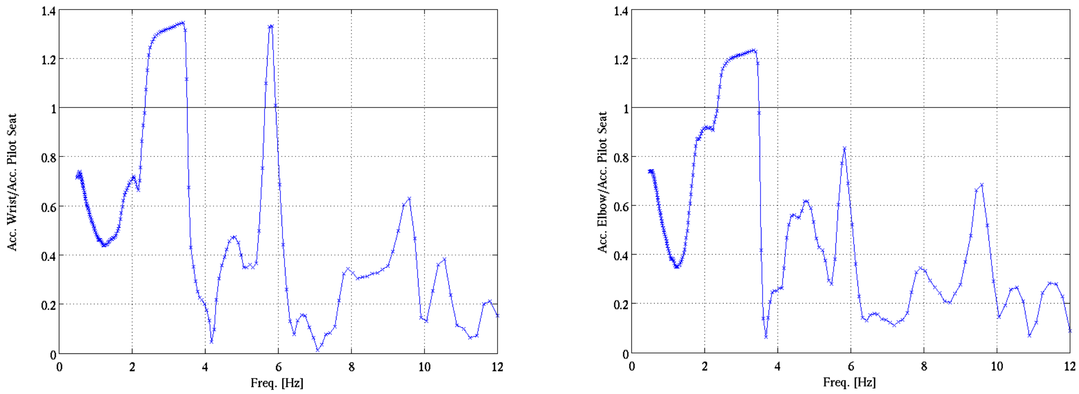

Figure 9: Transfer function between vertical acceleration of the pilot's seat and those of the wrist (left), and of the elbow (right) from signals measured during the collective dwell with high friction.

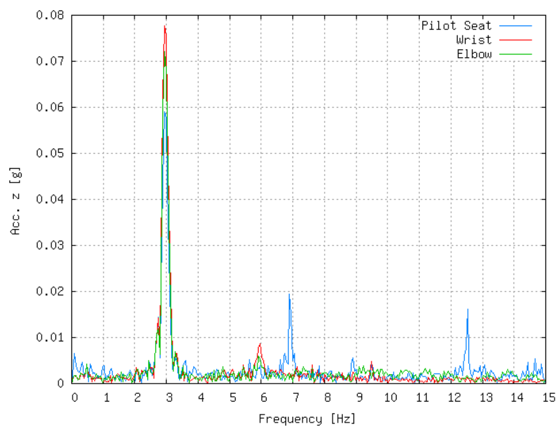

Figure 10: FFT of the signals acquired during the collective dwell test with low friction.

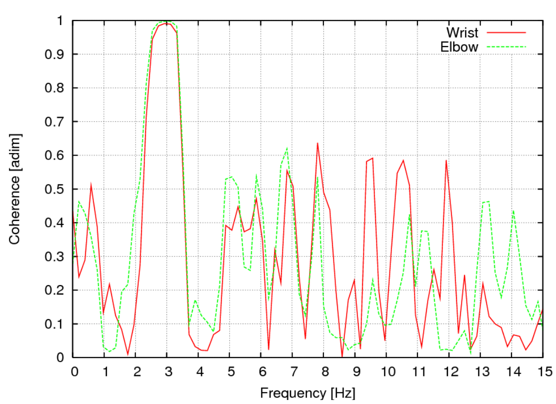

Figure 11: Coherence between the pilot's seat vertical acceleration and those of the wrist and elbow acquired during the collective dwell with low friction.

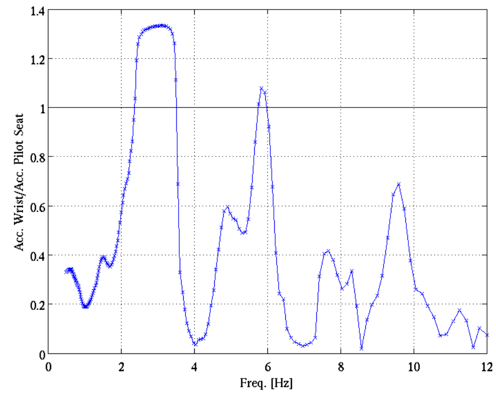

Figure 12: Transfer function between the vertical acceleration of the pilot's seat and that of the wrist, identified from signals acquired during the collective dwell test with low friction.

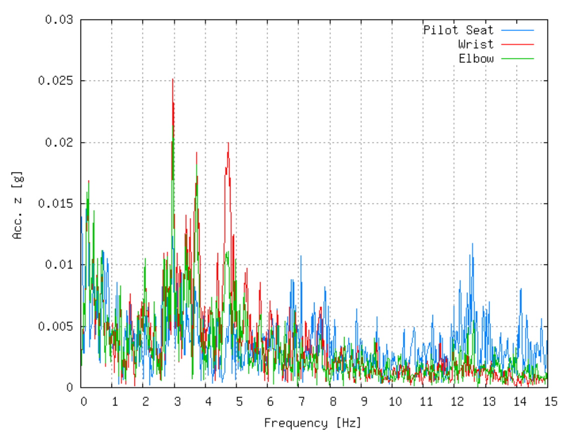

Figure 13: FFT of the signals acquired during the final approach before landing.

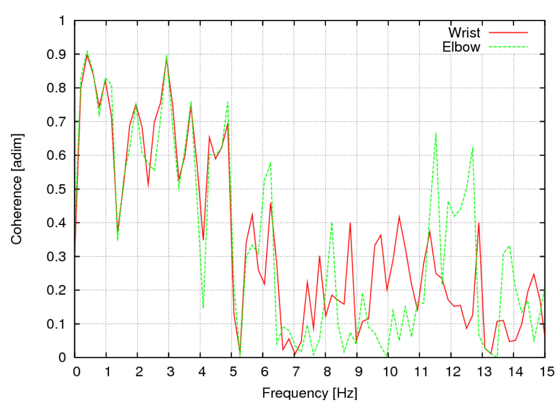

Figure 14: Coherence between the pilot's seat vertical acceleration and those of the wrist and elbow acquired during the final approach before landing.

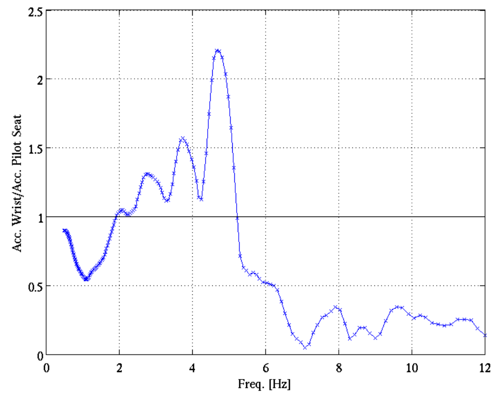

Figure 15: Transfer function between the vertical acceleration of the pilot's seat and that of the wrist, identified from signals acquired during the final approach before landing.

5 FINAL REMARKS

A preliminary in-flight test campaign for the identification of the biodynamic response of the pilot was performed on the BA609 tiltrotor. The tests made confirmed the possibility to perform this kind of measurements during regular flight tests. The obtained results are encouraging and in line with those that can be found in the open literature. However, reliable results are expected to be obtained only when a dedicated biodynamic test campaign is designed and performed. This will allow to ensure better synchronization between the different acquired signals, and to design an appropriate excitation in the 1–10 Hz frequency range. Furthermore, a preliminary assessment of the biodynamic response of the pilot by ground tests will support the interpretation of the results obtained in flight and will shed some light on the identification of possible triggers of PAO events.

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