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Executive Summary of the Thesis

Helicopter sensorized inceptors for pilot workload evaluation

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

Author: Davide Pio Loco Zanet
Advisor: Prof. Andrea Zanoni
Co-advisors: Davide Marchesoli, Pietro Ballarin
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1. Introduction

Present-day rotorcraft are the result of the ever increasing needs of operator requirements. Compared to their forerunners, they are faster and more capable but, as a consequence, they are more complex. The rise in complexity can contribute, among the others, to increase the *pilot workload* level. The latter can be a determining factor in helicopter accidents: when a pilot is overwhelmed with excessive workload, the ability to effectively manage the aircraft and respond to changing conditions may be compromised. Moreover, it is commonly agreed that the degree of pilot workload being too low or too high can potentially contribute to the occurrence of Rotorcraft-Pilot-Coupling (RPC) phenomena (Ref. [1]). In this frame, the study of human-rotorcraft interaction has placed a strong emphasis on the development of pilots' workload assessment tools and procedures.

In the thesis work, it is presented the design, the realization and the testing of *light-instrumented* helicopter collective grip and cyclic stick for the gather of real-time information about the pilot action. The word *light* has to be intended in both its English acceptations, being the measurement systems:

- based on an optical principle, i.e., on the light properties;
- non-intrusive, i.e., they neither interfere with the piloting experience nor alter the ergonomics and the perceptible characteristics of the input devices.

2. Collective grip sensor

The grip, 3D-printed, is instrumented with a sensor (OPTical INceptor, OPT-IN) able to capture the pressure introduced by the pilot hand in the inceptor itself, for which a layout re-engineering of an already developed prototype (Ref. [2]) is performed. In Figure 1 is shown the core element of the sensor: a transparent cylinder (1), illuminated by two LEDs placed at the top and bottom facing to each other (2).

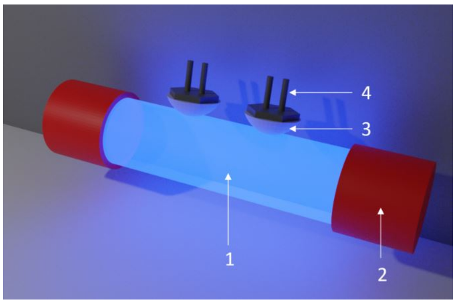

Figure 1: OPT-IN working principle core element

The other elements of the sensor are the individual force transducers (3, 4), that are constituted by a hemispherical-shaped component of transparent elastic material (3), placed in front of a photoresistor (4). The working principle of the sensor relies on the fact that when the hemispherical part is in contact with the cylinder, through the contact area the light reflected in the cylinder is frustrated, allowing it to be transmitted in the hemispheric probe. Since the contact area is proportional to the contact pressure, the sensor is able to produce a signal proportional to the pressure applied by the pilot hands on the control inceptor grip. The photoresistor varies its resistance in response to the quantity of light passing through, which in turn depends on contact area between the hemispheric cell and the cylinder. The load cell is integrated in the handle: some parts of the grip slide with respect to the rest of the grip itself so that, when pressure is applied, they are free to sink by a small amount. Figure 2 shows the grip final prototype.

Figure 2: Final grip prototype picture

3. Collective grip sensor testing

The experimental test-bed for the collective grip sensor is the motion platform of the Department of Aerospace Science and Technology of Politecnico di Milano (DAER). The platform is used to make the tested subject performing tasks which involve the chase of a target both with cyclic and collective inceptors. The pilot shall overlap the dots moving according to the inceptors to the target shown on the screen, which moves following a certain path. The tasks, which last 90 seconds, have different difficulty levels. This is achieved by both changing the platform motion level and by using different error threshold width: during each Mission Task Element (MTE), the dots controlled by the inceptors are green, yellow or red, depending on the level of overlapping between the dots and the targets, resulting respectively in optimal performance, acceptable performance and unacceptable performance. The type of threshold is kept constant in each test and the tested subject is not informed about the type of threshold adopted. Table 1 summarizes the tests performed with the relative platform motion level and threshold used.

Test	Motion RMS	Threshold
1	-	Wide
2	-	Narrow
3	1.0 m/s^2	Narrow
4	1.5 m/s^2	Narrow
5	1.0 m/s^2	Wide
6	1.5 m/s^2	Wide

Table 1: Test summary table

In Figure 3 is reported, for each test, the grip average pressure exerted by the tested subject. The first two tests have been performed with the motion at rest, hence the workload level is lower if compared with the other ones. The results of tests 3 and 4 show that the pilot workload level is higher with respect to the one of the tests without motion. Moreover, it is possible to see that the grip average pressure for the test with higher RMS of the motion is higher than the one with lower RMS. Similar considerations apply to the results of the last two tests and in particular it is possible to see that, being their threshold wider with respect to the previous two tests, the average grip pressure is lower with respect to the one of the tests 3 and 4.

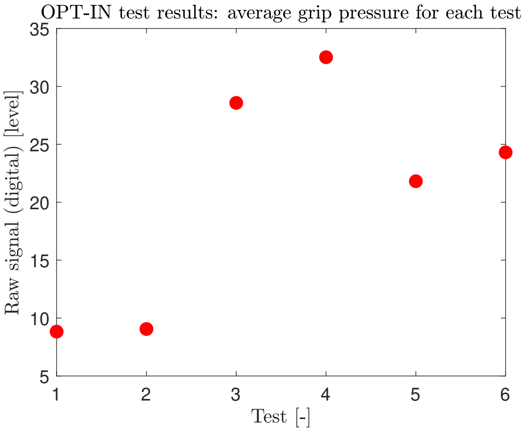

Figure 3: OPT-IN results: average grip pressure for each test

To have an indication of the accuracy with which the tested subject followed the target, Figure 4 and Figure 5 show, for each test, the comparison between the time histories of the target, which has a sinusoidal trend over time, and the input.

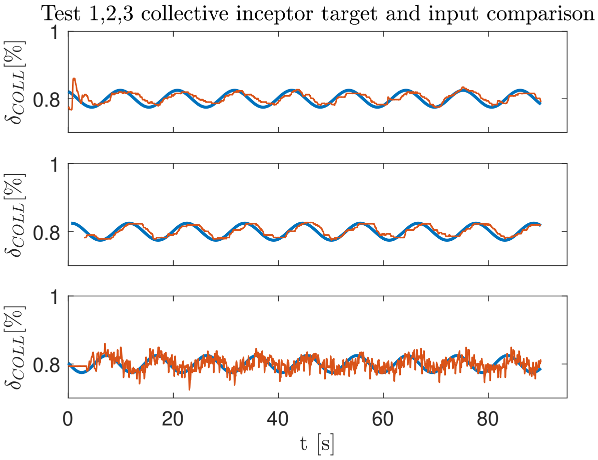

Figure 4: Comparison between the time histories of collective inceptor target (blue) and input (red) for the tests 1-2-3

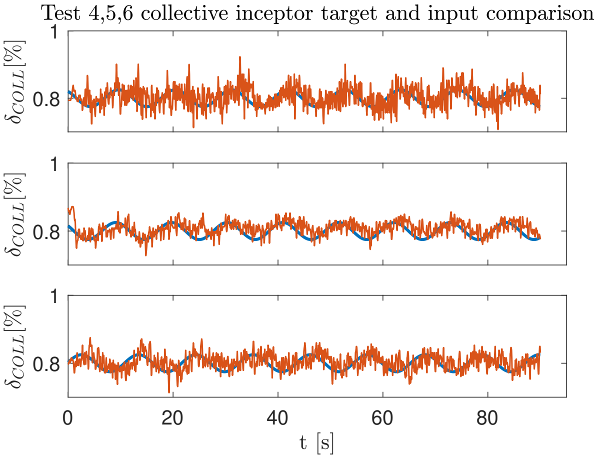

Figure 5: Comparison between the time histories of collective inceptor target (blue) and input (red) for the tests 4-5-6

As expected, in the first two tests, that are without platform motion, the input follows the target with a relative small error. The comparison between tests 3 and 4 shows that, fixed the threshold type, the oscillations of the input are larger in the case with larger motion RMS (test 4). The same applies to the comparison between tests 5 and 6, that show oscillations with smaller amplitude if compared respectively to tests 3 and 4. This is due, other than the wider thresholds used for tests 5 and 6, to a "learning process" of the tested subject, which during test 4 declared that an improvement of the performance was obtainable by relaxing the arm muscles rather than stiffen them. In Figure 6 is reported a comparison between the OPT-IN results and the aggression parameter relative to the collective control input, which is a workload index defined as (Ref. [3]):

$$A(\delta) = \frac{1}{T} \int_{t}^{t+T} |\dot{\delta}| dt \qquad (1)$$

where T is the time interval used for the parameter calculation, considered equal to the whole acquisition time in the present analysis, δ is the collective control input and $\dot{\delta}$ its time derivative. It is possible to appreciate a strict correlation between the two, indicating that the OPT-IN outputs can be effectively considered a measure of the pilot workload level.

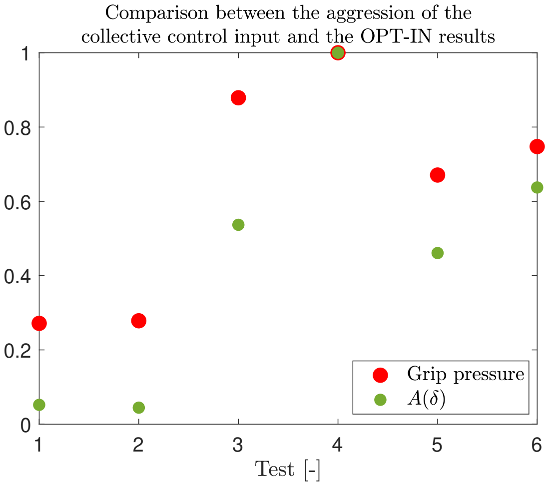

Figure 6: Comparison of the OPT-IN measurement with the aggression parameter

4. Cyclic stick realization

The cyclic inceptor stick, made of carbon fiber-reinforced composite material, is equipped with FBG (Fiber Bragg Grating) sensors able to measure the deformation induced by the pilot control actions and, in turn, the loads applied to the inceptor. The sensors working principle relies on the measure of the frequency shift of the light passing through the optical fiber in which they are embedded as consequence of the external phenomena to which the latter is subjected. One of the main advantages of the use of a carbon fiber composite material for the stick realization is the weight saving: considering the stick isolated, the weight saving amounts to 92% with respect to the weight of the same stick made of steel. The weight saving does not merely reduce to the one of the stick itself, but also to the lumped masses that are needed below the inceptor elbow to make the inceptor balanced, i.e., such to have its center of gravity on the elbow itself. The sensors embedded on the stick, if properly calibrated, allow the measure of the force applied by the pilot without the use of a load cell, which is not usually present in production helicopters. The force measurement allows the computation of the Biodynamic Feedthrough (BDFT), which is one of the pilot-vehicle interaction index, in a modified fashion:

$$\tilde{H}_{BDFT}(s) = \frac{F(s)}{\ddot{x}(s)} \tag{2}$$

being F the force introduced in the stick and $\ddot{x}$ the vehicle acceleration. The computation of $\tilde{H}_{BDFT}$ is particularly useful in case of a high level of friction present in the controls. In this case, the motion of the inceptor is small and typically highly non-linear, while the force applied by the pilot is not. From the technological point of view, the stick is realized, other than by the use of appropriate mould-counter mould, by the employment of a soluble mandrel. The latter is used to wrap the pre-preg layers on its surface, minimizing the overlapped regions and thus allowing a superior control over the thickness of the final product, which is crucial for the FBG sensors positioning. A picture of the stick after the autoclave cycle is reported in Figure 7.

Figure 7: Stick after the autoclave cycle

5. Cyclic stick sensors calibration

A calibration procedure is carried out for the FBG sensors, of which Figure 8 reports a summary scheme.

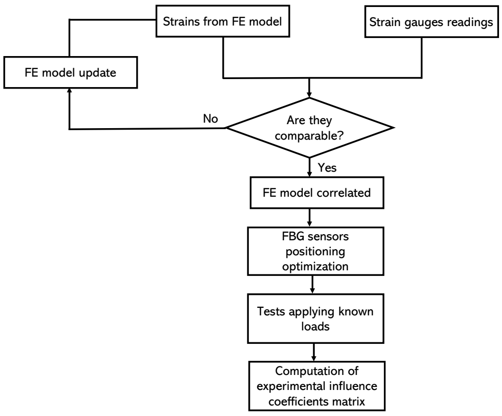

Figure 8: Calibration process summary scheme

The stick is instrumented with some strain gauges, which readings resulting from the application of known loads to the stick are compared to the ones coming from a Finite Element (FE) model of the test setup. If the comparison is not successful, an update of the FE model is required, otherwise the latter can be considered correlated. The FE model is used to perform the optimization of the FBG sensors positioning, which is carried out by the use of a genetic algorithm. Experimental tests on the stick containing the sensors are performed by applying known loads and by reading the sensors measurement, obtaining the experimental influence coefficients matrix (Ref. [4]). This is possible by making the hypothesis of linearity, thanks to which the relationship between the strains measured by the two FBG sensors and the applied loads can be expressed as:

$$\boldsymbol{\epsilon} = \mathbf{K}\mathbf{P} \tag{3}$$

where:

- $\boldsymbol{\epsilon} = \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix}$ is the vector containing the two FBG sensors outputs for the considered loading condition;
- $\mathbf{K} = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix}$ is the matrix of the influence coefficients;
- $\mathbf{P} = \begin{Bmatrix} F_{lat} \\ F_{long} \end{Bmatrix}$ is the vector containing the applied loads.

The cyclic inceptor is subjected to longitudinal forces, to lateral ones and to any combination of them. During the calibration process is necessary to reproduce these loading conditions and to do that the stick is clamped to a wall. To test the pure longitudinal force loading condition, since the load is applied by exploiting gravity, the stick geometry leads to the necessity to use an ad hoc setup, shown in Figure 9 (together with the one used to test the pure lateral force loading condition).

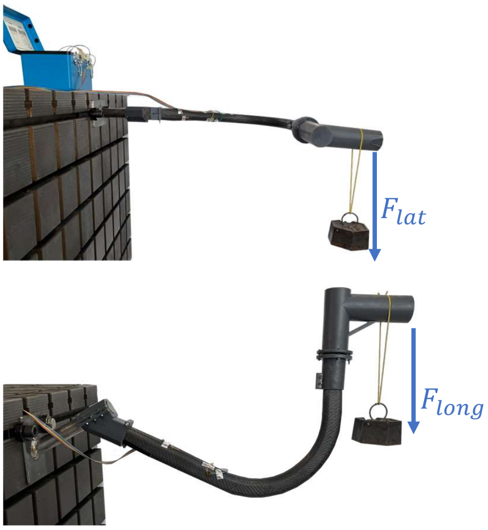

Figure 9: Test setup

6. Conclusions

Even though more tests on more subjects should be performed to draw solid conclusions, the trend of the average grip pressure for each test is well correlated to the one of other consolidated pilot workload indicators, as the aggression. A relevant outcome from the tests performed with the motion platform is the finding that a relaxation of the arm muscles can help to counteract the vibrations induced by the vehicle to the pilot, which in turn translated in a better target tracking performance. The novel cyclic inceptor stick realization technique has revealed to be successful, except for the mandrel dissolution process. The use of a sodium hydroxide solution with a higher concentration might be the answer to this issue. Despite that, the use of the mandrel allowed to have a good control thickness, that is crucial for the sensorization of the stick itself. The results obtained for the tests with the FBG sensors allowed to successfully accomplish the calibration process. The results of the optimization of the FBG sensors position carried out using the genetic algorithm has revealed to be fully satisfactory. Thanks to the genetic algorithm, the measure of two FBG sensors is well better than the one obtained with four strain gauges, for which a qualitative positioning based on the FE model results has been performed. As the collective grip sensor, the sensorized cyclic stick can be considered a tool for the pilot workload evaluation, that will be employed in the motion platform.

References

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