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DEVELOPMENT OF A TOOL FOR PILOT INDUCED OSCILLATIONS (PIO) TESTING IN FLIGHT SIMULATOR

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Abstract. *PIO (Pilot Induced Oscillations), also known as A-PC (aircraft-Pilot Coupling), is defined as "sustained or uncontrollable oscillations resulting from efforts of the pilot to control the aircraft". Despite being a problem studied for decades, it is still a focus of great interest, since new technologies inserted on flight controls require that this topic be constantly revisited. An important piece of evidence to be considered is that accidents caused by PIO still occur with an undesired recurrence, and still happens in aircraft with a high technological. In order to stimulate and enable research on this phenomenon, the Group of Human Factors in Aviation, of the Department of Aeronautics Engineering from EESC / USP developed a tool to be inserted in the Flight Simulator of the institution, which allows tests with pilots exposed to this phenomenon. The tool consists of a system based on MATLAB®, which presents an artificial horizon and a synthetic task to be coursed by the test pilot. The aircraft dynamics inserted is from the Boeing 747 obtained from the literature. The developed tool permits the test proponent to change the task to be pursued by the pilot and to make changes in the dynamics of the aircraft, allowing to increase or decrease the aircraft proneness to PIO. The used flight simulator has a moving base, as a way to avoid pilot overreaction during tests, as states by the pertinent literature. This work describes the tool developed, enabling the measurement of responses from different pilots subject to various flight conditions and/or tasks that would be unfeasible to be performed on flight tests, given the cost and the risk involved.*

Keywords: *Pilot Induced Oscillations, Flight Simulator, Synthetic Task*

1. INTRODUCTION

The modern tendency for aircraft design has made products increasingly efficient from the point of view of performance, production, maintenance, and operation. To meet this new market demand, the development strategy tends to low stability models inherent to the project. This feature was suppressed by the development of control laws in conjunction with the embedded electronics, through the system known as Fly-by-Wire (FBW), increasing the flight quality, allowing the apparent stability to the pilot, maintaining the efficiency levels expected by the market (Celere, 2008). However, the FBW system architecture can increase the delay between the pilot's command and the effective action of the command surface, making the aircraft more susceptible to PIO.

The best definition for PIO is given by the United States Department of Defense and Published in Mil Standard 1797A, characterizing as sustained and uncontrollable oscillations resulted from a pilot's direct action to control the aircraft (Department of Defense Interface Standard, 1990). Mathematically, the PIO can be characterized by the phase delay between the pilot input in the command and the effective response of the aircraft in the order of 180°. Normally, this phase mismatch effect is given by a high gain piloting, specified by a typical condition of abrupt attitude capture to perform certain tasks or corrections, caused by a "trigger". This term refers to the name given to the pilot's reaction in order to correct any deviation or capture to a given flight condition (Mark, 1998).

The oscillation generated by PIO can be subdivided into two parts: Gross Acquisition and Fine Tracking, which occur at different times during the phenomenon occurrence. The first one is the primary consequence generated after the "trigger" in which the pilot initiates the movement to capture the parameter that the pilot momentarily considered out of the expected position. After correcting this parameter, the second segment (Fine Tracking) begins, where the pilot performs the task of maintaining this capture, performing fine adjustments for some time, leading the aircraft to oscillatory instability (Celere, 2008).

During decades of study of oscillations characterized as PIO, the academic community still considers that there is no method to prove that a given aircraft model is free from PIO susceptibility, so this problem cannot be guaranteed or eliminated in current aircraft. The flight test campaign dedicated to certification for this phenomenon is carried out with some maneuvers defined as a criterion for complying with the requirements from the certification standards (Federal Aviation Administration, 1965). As a practical guide for such compliments, the AC-25-7C is used (Federal Aviation

Administration, 2012). The definition of criteria regarding the tendency to PIO based on the inherent stability of the project is widely studied and proved with the use of flight simulators and prototypes, in which the oscillatory dynamics described is monitored based on the safety criteria imposed by the certifiers (Efremov *et al.*, 1996).

The history of PIO-related events shows its occurrence even in modern aircraft, such as the divergent oscillation found during the sixth landing of the first JAS 39 Gripen prototype in 1989, where the pilot witnessed intense divergent oscillation at low height, colliding the aircraft wildly with the ground (Gaines, 2014). This event was intensified by strong wind bursts that induced oscillation during landing. In this case, the wind variation was attributed as the “trigger” of the problem. Another recent event related to this phenomenon was experienced during a military in-flight refueling operation with a Boeing C-17 Globemaster operating as the receiver, in 2013. It is worth mentioning that a PIO was identified in a typical operation of this model, alerting that the certification process regarding the PIO does not guarantee the aircraft as being PIO-free. Capture the boom for fuel transfer requires intense pilot control activity to complete the maneuver. Thus, an oscillation with great intensity on the lateral axis was observed during the approach of the aircraft to the tanker. The aircraft in question is an example of multi-mission equipment and had its development process optimized to reduce susceptibility to this phenomenon, designed and certified with a control law created for each type of mission, selected by the pilot. (Iloputaife, 1997).

During the certification process of a new model, some maneuvers are required with the objective of including a "trigger" for PIO excitation, for example, captures on the longitudinal or lateral axis, known as Theta Capture and Bank Capture, respectively. The complete analysis of susceptibility to PIO must be done with several drag configurations, for civil cases with variations of flap and landing gear configuration, and, in military cases, adding variations of external loads. (Hess and Kalteis, 1991)

Another maneuver widely used during the PIO certification campaign is called Offset Landing, which consists of performing a conventional approach to a runway but induced lateral deviation. At a given distance, the pilot starts the correction looking for the center of the runway and tentatively touching the ground in the desired location. This situation induces the pilot to perform the correction quickly, or high gain, due to the need of performing the land at the defined aiming point. Analogous to Offset Landing is the Synthetic Task, where the pilot follows a guide in flight attitude screen. The movement profile of this guide induces the aircraft to perform oscillations that, if supported by the pilot, characterizes a PIO condition. These variations can be longitudinal or lateral with the oscillation profile adapted to the aircraft's dynamic characteristics, providing the analysis of PIO proneness.

The severity of oscillations in a PIO event, are classified using the PIO Rating scale (PIOR) (MIL 1797A - Department of Defense Interface Standard, 1990), shown in Figure 1, which classifies the level of oscillation in a scale from one (lowest oscillation) to six (highest oscillation), based on the opinion of the pilot who performed the maneuver.

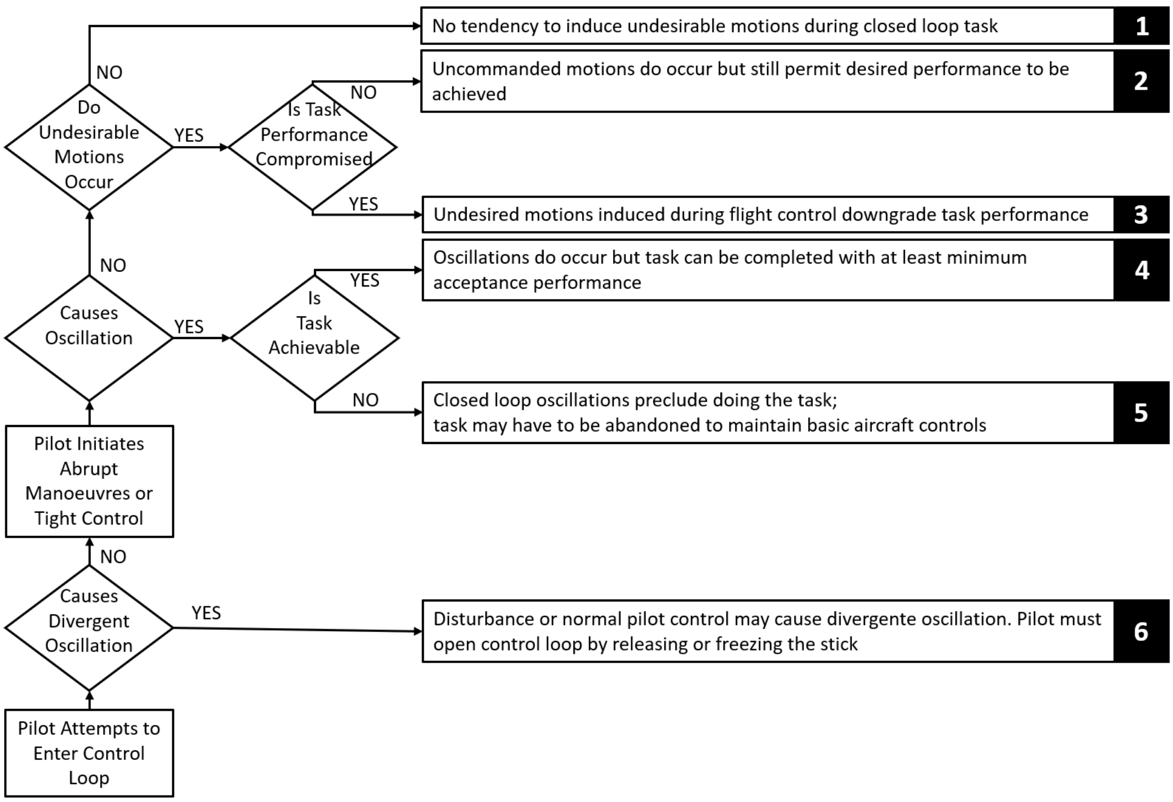


Figure 1. PIO Rating Scale. Adapted from Weingarten and Chalk (1981).

In PIOR scale analysis, oscillations classified as 5 or 6 have divergent characteristics, leading the aircraft and crew to unsafe conditions, possibly allowing structural damage or material and personal loss. Despite it, the academic study of these conditions is necessary for the phenomenon comprehension. In this way, the use of the flight simulator as a data generator tool is fundamental for the development of research in the field of flight quality.

The Department of Aeronautics Engineering from EESC-USP has been dedicated to the study of PIO (Moura *et al.*, 2018a; Moura *et al.*, 2018b), studying the phenomenon in all possible conditions, including those that are not feasible in flight tests, as previously described. To enable it, a moving-based flight simulator is used, together with a group of test pilots from the Brazilian aeronautical industry.

As a complement to this platform, it is necessary to create a tool that integrates several important characteristics, allowing the PIO tests in different conditions of tasks and susceptibilities. This tool, to be effective must be flexible in order to have a set of parameters easily changed and the data have to be analyzed quickly, allowing maneuvers validation in real-time.

2. OBJECTIVES

Given the above, the objective of this work is the development of a computational tool capable of being embedded in the flight simulator, which allows (i) the variation of the aircraft dynamics, increasing or decreasing its susceptibility to PIO through software; (ii) the application of synthetic tasks for the pilot, in order to provoke “triggers” that can put him in PIO condition; (iii) flexibility for these tasks, which can easily change its profile, and (iv) preliminary real-time analysis of data collected at each test.

3. METHODOLOGY AND MATERIALS

For the construction of the test platform proposed, a MATLAB® routine was built and loaded into the flight simulator of the Department of Aeronautics Engineering from São Carlos School of Engineering.

The flight simulator consists of a moving base equipment with a Stewart Platform, already used for several other research and teaching activities. Figure 2 shows an external view of the simulator, which was fully developed within the Department.

Figure 2. Flight Simulator from the Department of Aeronautics Engineering at USP São Carlos.

Its equipment includes a Hotas Warthog commercial flight control system and two monitors: one for the external view and the other for the emulation of the instrument panel. The synthetic task for the pilot, the product of this work, can be available on any of the two monitors.

The simulator also has an instructor station, where it is possible to evaluate the test data, emulate fails, vary aircraft parameters, among other possibilities. Figure 3 shows the system architecture

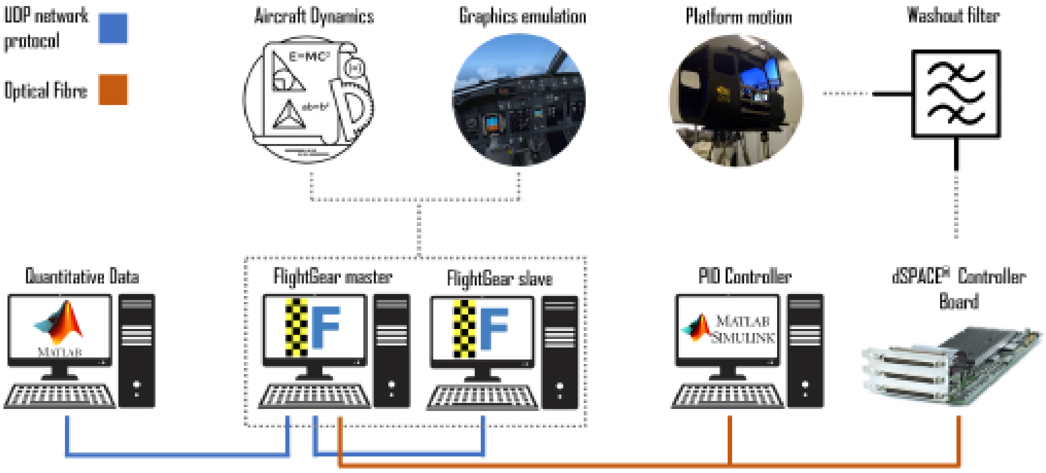


Figure 3. Flight Simulator system architecture.

4. DEVELOPMENT

Due to the need of simulating the pilot's complete experience, the instrumentation and avionics of the aircraft must be considered as faithfully as possible. Therefore, a graphical interface capable of updating the artificial horizon without significant delays for the human pilot, which considers the Nyquist frequency for the dominant mode of study (short period), as well an ambient visually similar to reality, are fundamental requirements for immersion in the experiment and obtaining conclusive results.

The architecture of the tool follows Figure 4, whose parts are detailed separately.

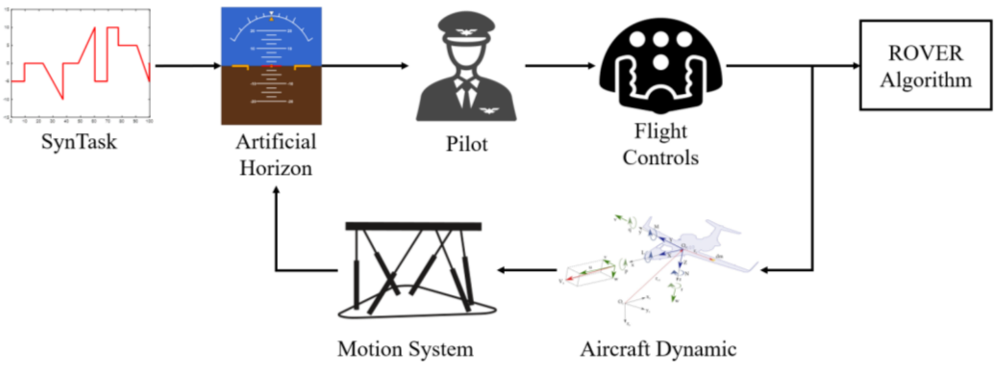
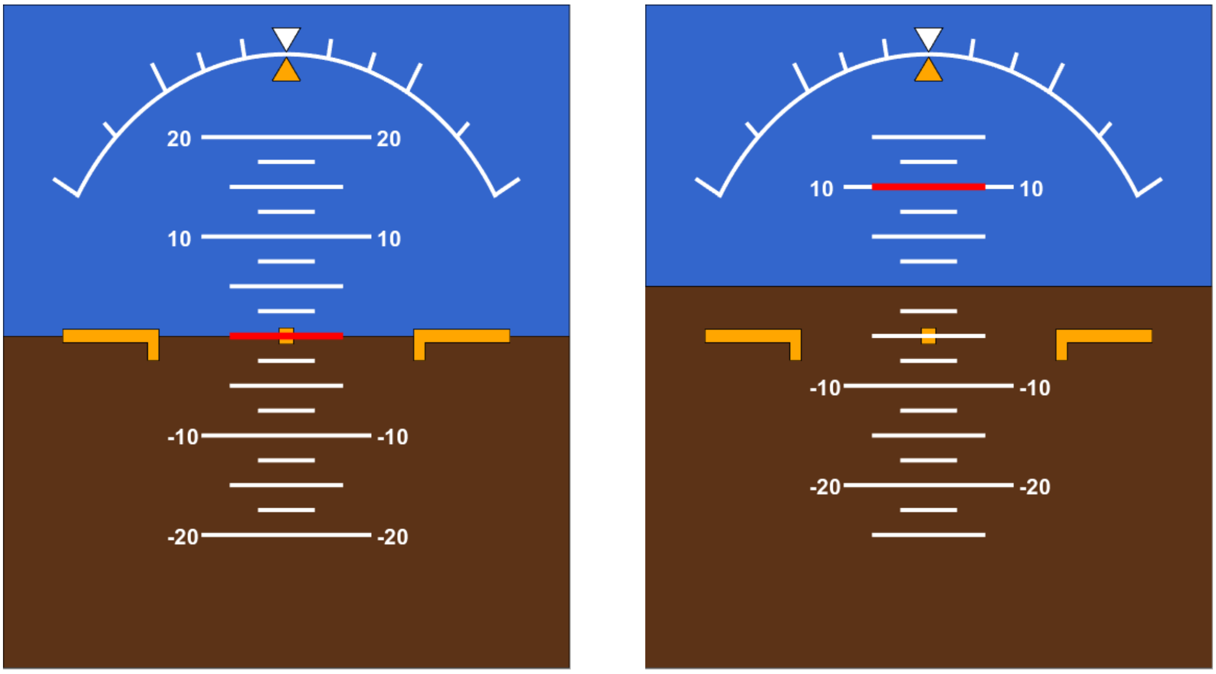


Figure 4. Embedded system architecture.

4.1 Synthetic Task (SynTask)

The routine has the flexibility of choosing the profile of synthetic tasks applied to the pilot. It allows the insertion of discrete tasks or continuous ones, in the form of functions (sinusoid or sum of several sinusoids, for example). The synthetic task (SynTask) is previously generated to have characteristics capable of evidence PIO when the pilot has the function of following it quickly and with “high gain”. The task is represented by a movable red bar, while the pitch angle is indicated by the position of a "rotated L" (lateral) and a square (central) marking, with the attitude of the aircraft being of interest for longitudinal movements, faithful to a real aircraft. The condition referring to Figure 5a is the initialization of the experiment, and their position properties are updated, as in Figure 5b, according to the sampling frequency. This parameter is essential to define the discrete transfer functions and the difference equations necessary for updating digital systems.



(a) (b)

Figure 5. Artificial horizon, in initial condition (a), and during a test, performing a longitudinal task (b).

4.2 Artificial Horizon

The developed interface consists of an artificial horizon (Figure 1) similar to an aircraft Primary Flight Display, using the MATLAB® tool, designed for communication on a local server, given the need for high updating of both the aircraft dynamics and the graphical interface. For such communication, there is a UDP protocol (User Datagram Protocol) that transmits the desired parameters (commanded pitch angle and synthetic task) to the computer responsible for updating the graphical interface.

4.3 Pilot and Flight Controls

The pilot presented in the system architecture refers to the human pilot, which is being tested during the simulation. The flight commands correspond to those present in the flight simulator, already detailed in section 3 of this text.

4.4 Aircraft Dynamics

For the simulations, the dynamics of the Boeing 747-200 aircraft in cruise flight condition, at 40000ft and Mach 0.8 is used, obtained from Etkin and Reid (1996).

For some tests performed, it is necessary to increase or decrease the susceptibility of the system to the PIO phenomenon. In this way, it is possible to change some stability derivatives in order to change this behavior.

The study by Moura *et al.*, 2018a provides which derivatives should be changed and the values to be used. This methodology has already been applied for other purposes in the simulator, according to Bidinotto *et al.* (2021).

4.5 Stewart Platform

The flight simulator movement is given by a Stewart Platform. Static tests for PIO evaluation do not generate consistent results, according to studies by Chase (1967), since the pilot's vestibular system has a great influence on his response and performance on flight controls. Thus, the platform previously detailed must be always operational during tests.

4.6 ROVER

The ROVER algorithm (Realtime Oscillation Verifier), proposed by Mitchell and Arencibia (2004) will be implemented in the work monitoring 4 parameters: amplitude and frequency of the angular pitch rate, the amplitude of the pilot's command signal, and the phase difference between these two signals. In this way, four monitoring flags for these variables are created, which will be assigned the value 10 (for easy visualization on the graph) when all of them cross the limits established in Table 1. The values presented were established based on the work of Liu (2012) and Johnson (2002) and based on initial simulations performed. The algorithm allows changes in these values if it is convenient for the simulation.

Table 1. Used threshold for ROVER algorithm.

Parameter	**Threshold**
Peak-to-peak amplitude of pitch rate (q)	> 6°/s
Pitch rate frequency	0.85 a 10 rad/s
Peak-to-peak amplitude of pilot command (δ_p)	> 1.0 (50% of total amplitude from previous cycle)
Phase difference	> 40°

4.7 Simulation Parameters

The simulation uses a sampling/update rate of 40Hz, therefore, frequencies below 20Hz do not have aliasing and this limit includes the short period frequencies in commercial aircraft. Regarding the parameters corresponding to the human operator, this limit value is higher than the frequency related to the human reaction time, thus it does not interfere negatively in decision making due to latency, which could generate inconsistencies between the vestibular and visual systems of the human pilot.

Figure 6 illustrates an example of qualitative comparison for a step response. The error due to the sampling operation is null for step inputs, with the retention operation performed by the zero-order holder (ZOH), conveniently chosen due to the nature of the physical system (aircraft and pilot set), as well as the signal input, the synthetic task (primarily step-type signs). The discrete transfer function is then used to obtain the difference equation through the inverse Z transform, being implemented to carry out the experiments.

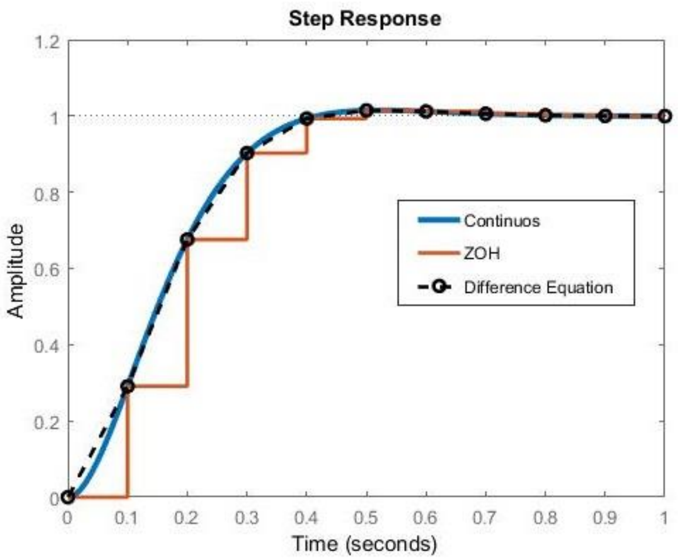


Figure 6. Data discretization for digital signal.

The Nyquist frequency was used to define the discretization frequency of the transfer functions involved, with a value greater than thirty times the bandwidth of the used system, with the short period mode being used as the basis for establishing this frequency value. The chosen value was 200 Hz, paying attention to the need of been a multiple of the artificial horizon update frequency, in such a way that the discretization does not impact significantly the phase delay and the interface is updated correctly with the current value, to not generate latency for the pilot in the test.

5. PRELIMINARY RESULTS

As the proposed methodology for longitudinal PIO results analysis, the pitch angle (θ) is the main variable shown, since it serves as a reference for the synthetic task, as well as the classification according to ROVER criteria.

Thus, Figure 7 shows the result of a test performed, where the pre-established discrete synthetic task is defined as "Pitch task", is performed by the pilot, whose signal is classified as "Model" and the classification in PIO condition or not is the curve called ROVER, which assumes a value equal to 10 when the aircraft is in PIO condition, and equal to 0 when it is not.

In the graph, it is easily observed that, in the regions where ROVER assumes a value equal to 10, the model presents more accentuated oscillations. The routine also provides the parameter "PIO Level", which is the percentage of time during the test in which the ROVER parameter assumed a value of 10 (therefore the pilot-aircraft system was coupled in PIO condition).

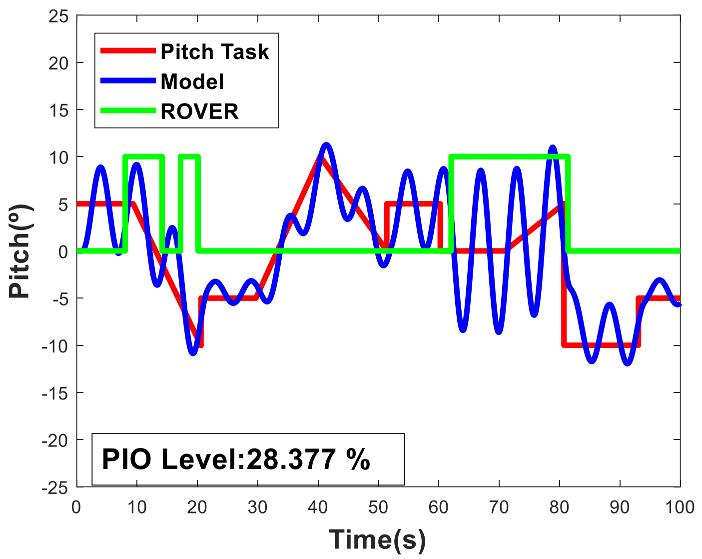
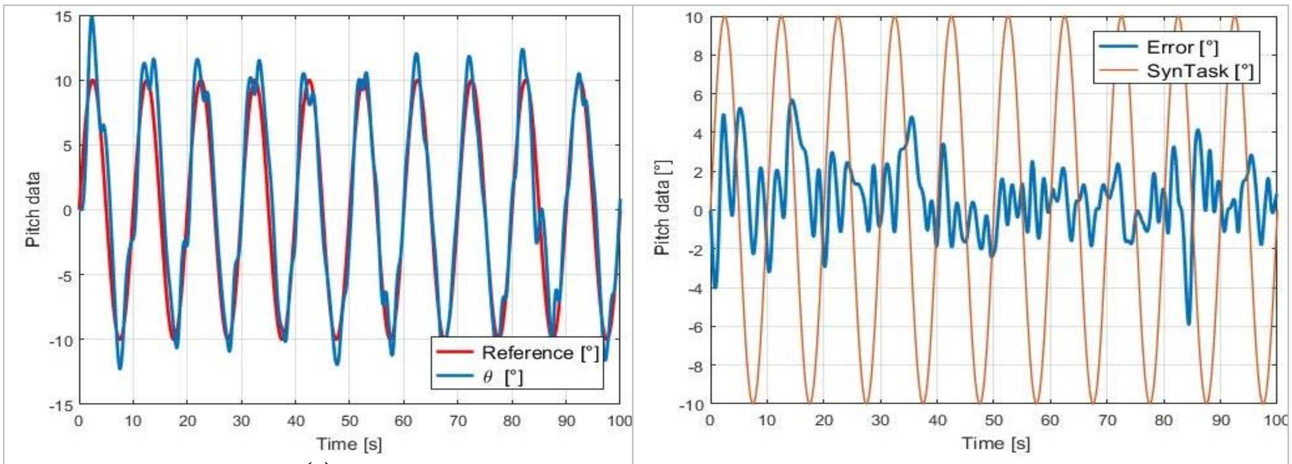


Figure 7. Simulation result.

Still, as a way to validate and provide preliminary results in real-time after each test, the routine present in the tool provides the dispersion of the data obtained by the pilot and the error between the commanded attitude and the synthetic task. Figure 8a shows a test performed with a synthetic task given by a continuous function (sinusoid), and figure 8b shows the error at each moment of the simulation. The tests are carried out at 200 Hz sampling, as detailed previously.



(a) (b)

Figure 8. Sinusoid Synthetic Task performed (a) and instant error during simulation (b).

Figure 9 shows the dispersion data for this same simulation. The 45-degree straight line shows the ideal representation if the pilot's command perfectly followed the proposed synthetic task. The more distant the points from thins line, the greater the dispersion, and the bigger the proneness to the PIO occurrence during these tests. For purposes of illustration, the dispersion data presented in the figure are discretized to a 10 Hz sampling.

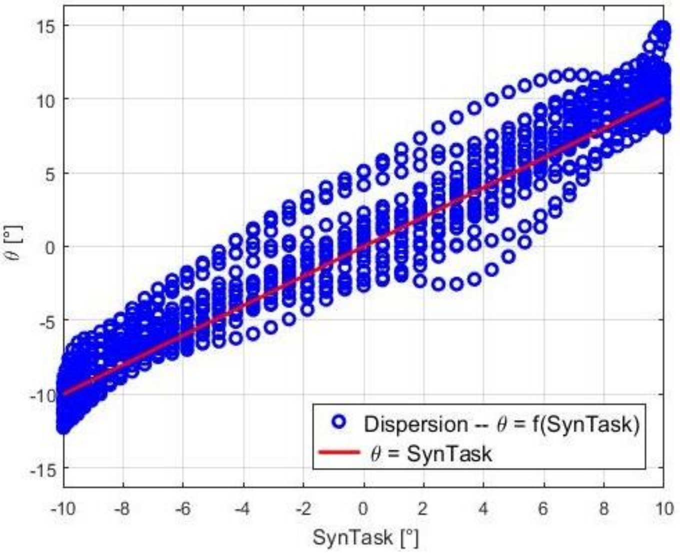


Figure 9. Dispersion observed during the test using sinusoid Synthetic Task.

6. CONCLUSIONS

This work carried out the development of a computational tool that, combined with the use of the Flight Simulator existing in the Department of Aeronautics Engineering at USP-São Carlos, allows the test of human pilots subjected to conditions prone to PIO occurrence.

As desired, this tool proved to be effective and has important characteristics, such as flexibility, since it allows changing the dynamics of the tested aircraft and the synthetic task imposed on the pilot; safety, as it allows testing in critical PIO conditions, which are not feasible in a flight test, as well as the “triggers” for creating an environment conducive to the appearance of the phenomenon; representativeness, since, according to the subjective opinions of pilots exposed to the tests, the dynamics of the system well represented a real aircraft; and practicality, as it presents ease in the preliminary analysis of tests, providing in real-time some important parameters, as well as the validation of the performed test.

As future work, tests will be carried out with pilots subject to PIO in different conditions, as well as their reaction to this phenomenon, in order to contribute to the design of future aircraft, contributing to flight safety in modern aerial vehicles, especially those with using of FBW flight commands.

7. ACKNOWLEDGEMENTS

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