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Identification of the Movement Algorithm of a Commercial Platform for Helicopter Simulators

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Abstract: The use of flight simulators for pilot training and evaluations is common in the modern aeronautical sector. Whether for airplanes or helicopters, the military and airline companies use this feature to keep their crews operational, safety-oriented and resource-saving. This work presents a proposal for adjusting the washout filter parameters that allows the use of Stewart's platform in helicopter simulators. The identification of the filter parameters was carried out based on tests on an available commercial platform, certified by the company Moog, model MB-E-6DOF/24/1800KG, currently used in the SHEFE helicopter simulator of the Brazilian Army. The work dealt with the physiological aspects of the human vestibular system and its dynamics. Subsequently, the methods for choosing the filter model, and configuration parameters are presented. Three series of tests were carried on the commercial platform and in a real helicopter prepared with special flight test instrumentation. The tests were completed, and the motion platform filter adjustments were made to minimize errors between the movement cues perceived by the pilot in the aircraft and the flight simulator. The errors obtained were below the limits of perception of the human vestibular system. The results of this work will be used as a basis for the development of a national movement platform for another flight simulator in the development phase.

Keywords: Simulator; Washout filter; Helicopter; Stewart Platform, Identification.

1. INTRODUCTION

A certified flight simulator has several interconnected systems. Motion simulators, in addition to mathematical models, have a mechanism capable of reproducing the sensations obtained by the aircraft pilot in the restricted simulation environment.

Most commercial flight simulators are built on a parallel manipulator, called a Stewart platform, which consists of six linear actuators in a hexapod configuration (Eftekhari and Karimpour, 2018). This setup provides six degrees of freedom for the platform.

Figure 1. Hexapod with 6 degrees of freedom.

The goal of any simulator is to provide its users with sensations that make them forget the reality they are living and really believe they are experiencing an alternative reality. To achieve this, the movement mechanism, together with the other systems of the simulator (visual, auditory, etc.) need to stimulate the perceptive abilities of humans (Ellensohn, 2020).

This type of movement system is obtained using the Stewart platform. To control this device, a specific type of algorithm is designed and implemented. They are called, in the literature, Motion Cueing Algorithms (MCA), washout algorithms, or even washout filters (Casas et al., 2018).

The Brazilian armed forces, in their modernization and aircraft acquisition programs, have sought to acquire flight simulators for pilot training. In addition to improving the training of the crew, the simulator brings greater security and a great saving of resources.

One of the products of this initiative is the Squirrel and Fennec Helicopter Simulator (SHEFE). This equipment was developed nationally, with a division of labor between the Army and the national company, Spectra Tecnologia. The only product purchased abroad was the simulator's movement platform. The complete mastery of building a national simulator involves building a movement platform with a functional control system.

This work aims to fill the gap left in the first development with the details of the dynamic characteristics of a moving platform, the construction of a computational model that represents a commercial platform, and the identification of the control parameters of its movement algorithm. For this, a commercial moving platform was used for study and research.

2. APPLIED THEORETICAL FOUNDATION

2.1 Physiological Aspects of Movement

The task of flying is complex, involving the management of multiple sources of stimuli. The pilot has several sensors, which provide information for the perception process. Each of these sensors contributes to the notion of movement, and each sensory system records the stimuli of its domain, as illustrated in Figure 2.

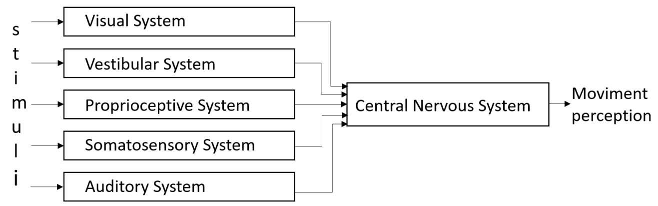

Figure 2. Sensory Systems - (Advani, 1998)

According to Advani (1998), human motion sensors can be classified into two groups:

⋆ Inertial sensors: These record the specific external forces and angular accelerations of the body; and

⋆ Environmental Sensors: These relate to the properties of the external environment.

The synergy of the vestibular, proprioceptive, and somatosensory systems is responsible for inertial sensations, while the visual system has a greater impact on the perception of the environmental movement. Concerning inertial sensors, the vestibular system predominates.

Perception is the process that accompanies the sensation of stimuli, or the acquisition of information from the environment. The lowest detectable levels of sensory inputs are called thresholds. A stimulus less than a sensory threshold is called a sub-threshold and will pass undetected. It is important to note that the threshold of a specific channel can be increased, depending on the task or the workload of the pilot. Thus, larger stimuli will pass unnoticed. This phenomenon is important for flight simulation, as it makes it possible to present low-frequency transient movements to pass undetected in the presence of visual information.

The work presented by Asadi et al. (2015) cites the threshold values for the models of rotational sensation and specific force. The defined values are described in Table 1.

As pointed out by Hosman and Van der Vaart (1978), distractions such as mental tasks and/or tracking tasks can raise the limits to three times.

Table 1. Sensitivity Threshold Values

Parameter	*Pitch*	*Roll*	*Yaw*
Rotational ($degrees/s$)	3.6	3.0	2.6
Parameter	*Surge*	*Sway*	*Heave*
Specifc force (m/s^2)	0.17	0.17	0.28

The sensation of rotational movement can be modeled, according to Gong et al. (2015), by the transfer function presented by the equation (1) in each axis of rotation, with the parameters set out in the Table 2. The sensation of specific force can be modeled by the equation (2) for each axis, and its parameters are described in Table 3.

$$\frac{\hat{\omega}}{\omega} = \frac{p_1 \cdot p_2 \cdot s^2}{(p_1 \cdot s + 1)(p_2 \cdot s + 1)(p_3 \cdot s + 1)} \tag{1}$$

$$\frac{\hat{f}}{f} = \frac{K(\tau_1 s + 1)}{(\tau_2 s + 1)(\tau_3 s + 1)} \tag{2}$$

Table 2. Parameters of the Rotational Motion Sensation Model

Parameter	*Pitch*	*Roll*	*Yaw*
p_1	5.3	6.1	10.2
p_2	30	30	30
p_3	0.1	0.1	0.1

Table 3. Parameters of the Specific Force Sensation Model

τ_1	τ_2	τ_3	K
13.2	5.33	0.66	0.4

2.2 Inverse Kinematics

The manipulator has six actuators connected to the platforms by joints. The joint positions of the lower platform are represented by the vectors B_i, for i = 1,2, ..., 6, in relation to the inertial system (F_I). The joint positions of the moving base are represented by A_i, for i = 1,2, ..., 6, in relation to the reference system (F_S).

The inverse kinematics problem seeks to determine the values of the lengths of the l_i actuators. Figure 3 shows a set of vectors that represent the displacement of the actuator and the position of the connection joints. To solve

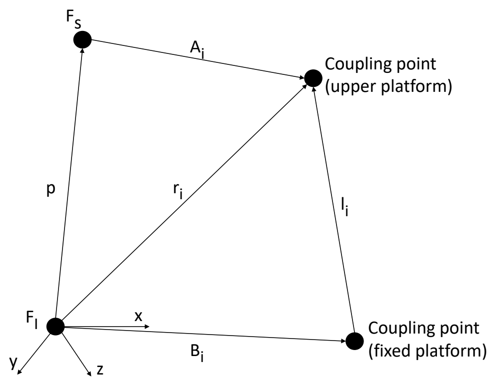

Figure 3. Vectors present in a platform linear actuator

the problem, the values of the vectors $A_i = [A_{ix}\ A_{iy}\ A_{iz}]$, $B_i = [B_{ix}\ \ B_{iy}\ \ B_{iz}]$ and the vector $p = [x\ \ y\ \ z]$, which represents the position of the centroid of the mobile platform, are required as inputs (Ellensohn, 2020). The length of the actuators can be calculated by equation (3).

$$l_i = A_i + p - B_i \tag{3}$$

2.3 Motion Algorithms

Allerton (2009) shows that although Stewart's platform is limited in terms of linear and angular displacements, this platform model has become standard in the simulation industry.

Under certain flight conditions, the application of sustained accelerations would cause the simulator's motion actuators to reach their physical limits of displacement. Thus, to reproduce the movement sensations obtained by the pilot of the aircraft in the pilot of the simulator, there is a movement control algorithm called "washout filter".

The filter works as a transformation from the aircraft's movements to the simulator's movements, taking into account the limitations of displacement of the platform. At the same time, it aims to minimize the error of sensation of movement between the pilot of the aircraft and the pilot in the simulator, as quoted by Becerra (2009).

As illustrated by Figure 4, the washout filter has two inputs and two outputs. The type of entry may vary depending on the algorithm model used. The entry X_1 can represent the specific forces applied to the body or the translational accelerations of the body in the flight deck. The entry X_2 can represent the angular velocities of the aircraft or the Euler angles of the body. The variable Y_1 represents the output of the translation movement, and the variable Y_2 represents the output of the angular movement of the simulator.

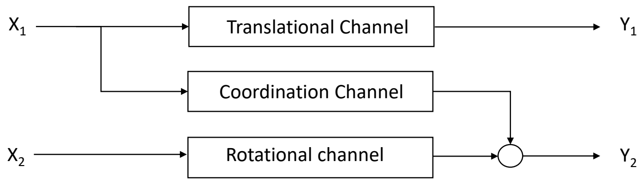

Figure 4. Washout filter model

The translational channel has the purpose of dimensioning the input signal and filtering it to pass only the high frequency components, due to the movement base not being able to reproduce the low frequency signals without reaching its structural limits of displacement.

The sustained translational inertial acceleration is felt by the pilot as a long-term change in the magnitude and direction of the specific force, in the absence of rotational motion. This cannot be simulated by translational motion due to displacement limits on Stewart platforms. However, it is possible to change the direction of the specific steady-state force experienced by the pilot in the simulator by tilting the cab. As this process cannot change the long-term magnitude of the specific force vector, it is an approximation to the desired effect. This process is called the tilt coordination channel.

The purpose of this tilt coordination mechanism is to generate the necessary tilt angles of the simulator to reproduce the specific sustained forces. That is, it guides the gravity vector in the simulator in the same way to the pilot, as the specific low frequency force in the aircraft, thus allowing the sustained accelerations to be simulated. As Nahon and Reid (1990), as this feature is not available in the vertical direction, pilots usually complain about the lack of sustained changes in the vertical load.

Figure 5 illustrates the principle of tilt coordination for longitudinal accelerations. The left head, representing the pilot in the aircraft, needs to be moved horizontally to perceive acceleration, while the right head, representing the pilot in the simulator, simply remains in an inclined position. The visual stimulus reinforces that stimulus, making the sensation more real for the pilot.

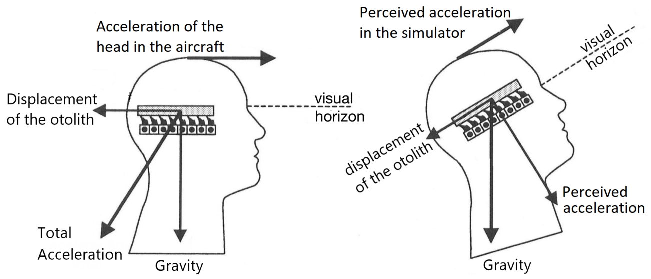

Figure 5. Coordination channel principle. (Weiß, 2006)

The rotation channel scales and filters the input signal (ω_{AA}) to let the high frequency components pass, in the same way as the translational channel. The output of this channel represents the dimensioned angular velocity, to simulate the angular velocities of the simulator.

Several models of washout filters have been developed over the years. The best known are the classical, optimal, and adaptive models.

According to Nahon and Reid (1990), an ideal movement platform control algorithm must contain the following characteristics: 1 - It must be able to achieve good pilot evaluations and potential for future improvements; 2 - It must be easy to adjust; 3 - Must have fewer differential equations and high execution speed.

The comparison of requirements with the aforementioned algorithm models shows that the first requirement can be achieved by any of the algorithms, with changes in the parameters. However, the algorithms have different characteristics for the other requirements.

Although the optimal control algorithm appears to fulfill the second requirement, it does not occur transparently. In comparative terms, the classical algorithm is the one with the easiest parameter adjustment, followed by the other algorithms (Grant and Reid, 1997).

The complexity of the algorithms, in terms of the number of differential equations required for the real-time solution, is smaller in the classical model and larger in the adaptive model. This number has a close relationship with the computational processing time required to complete an iteration using this algorithm.

In terms of ease of use, the classical algorithm is transparent, while the others are more difficult to make any adjustments. This criterion is an indication of how easily the designer can predict changes in the free parameters of the algorithm that would result in the necessary change of movements in the simulator. Thus, it can be seen why the classical filter is the most used in the simulation industry, as mentioned by Pouliot et al. (1998).

Comparing the desirable characteristics of the washout filter and the characteristics of each algorithm model, it is concluded that the classical algorithm is the best in terms of simplicity, ease of adjustment, and processing speed. In addition, as verified by Pouliot et al. (1998) and Houck et al. (2005), its performance remains effective in relation to other filter models.

Thus, the classical washout filter will be used in the development of this work to identify the commercial platform.

2.4 Classical Washout Algorithm Model

With more details of those presented in Figure 4, the classical algorithm is shown in Figure 6. According to the figure, the inputs of the algorithm are specific forces and the angular velocities in the three axes of the aircraft.

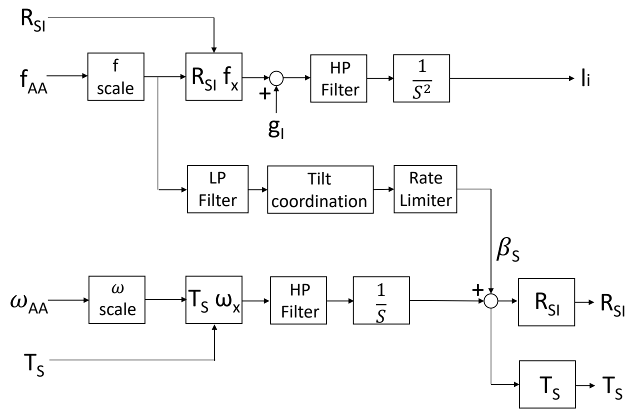

Figure 6. Classical Algorithm Model

As developed by Grant and Reid (1997) and Asadi et al. (2015), the high-pass filters present in the classical algorithm can assume, for the translational and rotational channels, the transfer function presented by the equation (4).

$$\frac{s^2}{s^2 + 2\zeta\omega_n + \omega_n^2} \tag{4}$$

The low-pass filter, used in the tilt coordination process, is modeled according to the transfer function shown by equation (5).

$$\frac{\omega_n^2}{s^2 + 2\zeta\omega_n + \omega_n^2} \tag{5}$$

3. TEST METHODOLOGY

The commercial platform in use in the SHEFE simulator is a Moog MB-E-6DOF/24/1800KG. This platform is capable of handling a gross moving load of 1,800 kg and is comprised of six 24 inches (60.96 cm) stroke electric actuators. To identify the dynamic response of the commercial platform, three tests were performed.

The procedure for the first test is illustrated in Figure 7. The input signal was inserted by the control system (Moog explorer). Through this system, it was possible to separate the output signals from the movement algorithm (position variations of the actuators) and the platform output signals, which are their angular positions, displacements, and translational velocity on the XYZ axes.

The filter output data was used as the input of the computational model of the commercial platform. This model was built based on the physical characteristics of the movement system. Its mass characteristics and inertia data were calculated using drawing in the software Catia V5. As a result of the computational model, there is the "simulated output". In the end, the data of the real and simulated outputs are compared to validate the computational model of the platform.

With this test, it was possible to create an adjusted computational model of the moving platform capable of being used in the other phases of the identification of the washout algorithm. The second test has the purpose

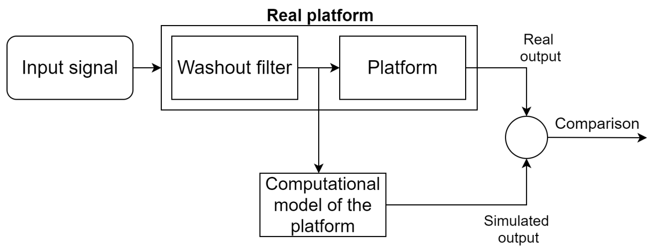

Figure 7. Platform test model

of adjusting the washout filters to reproduce the Moog platform.

The schematic shown in Figure 8 illustrates the method for this test (Harparan and Malmström, 2018). With the same excitation signal being used at the entrance of the commercial platform and in the computational model, the "real" and "simulated" outputs were obtained, respectively for each model. The outputs were compared to analyze the existing variations. Research carried out by Schroeder

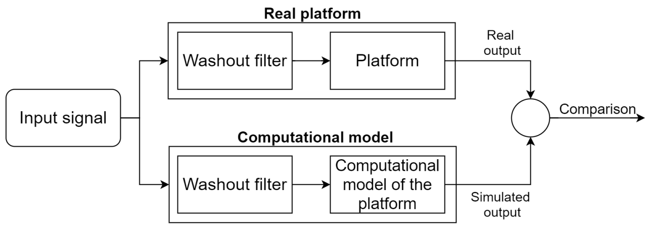

Figure 8. Washout filter test model

(1999) has shown that the most significant maneuvers to activate the pilots' sensations of movement are:

- ⋆ Longitudinal acceleration;
- ⋆ Lateral acceleration; and
- ⋆ Vertical acceleration.

Still, it concludes that the rolling and yaw maneuvers are not as important as the translations. In particular, yaw maneuvers do not seem to be useful in improving performance or reducing workload.

Therefore, in tests 1 and 2, longitudinal, lateral, and vertical variations were performed on the commercial platform.

The final test was carried out with the insertion of flight test data in an AS355-F2 helicopter. With these flight test data, it was possible to make fine adjustments to the rotational channels of the washout filter. The flight was planned to make sinusoidal inputs with low, medium, and high frequency longitudinal cyclic control at a speed of 80 kt and the indicated pressure altitude of 5,000 ft.

The helicopter had an Aydin Vector PCU-816-I flight test instrumentation and an ATD-800 digital recorder. The instrumentation provides 30 parameters including information from the anemometric system, the basic static pressure - or PB - the basic dynamic pressure - or qb of the co-pilot (2P) and the *air data boom*, which provides, through transducers installed in the left side rack, the basic static (pbboom) and dynamic (qbboom) pressures in the boom, the impact temperature and the angles of attack (α_g) and skidding (β_g) from *girouette*.

4. RESULTS AND DISCUSSION

4.1 Platform test

As a result of the first test, modeling the movement platform, the curves are shown in Figures 9 to 11. It can be seen that the simulated data, in red, present values similar to the real values, in black.

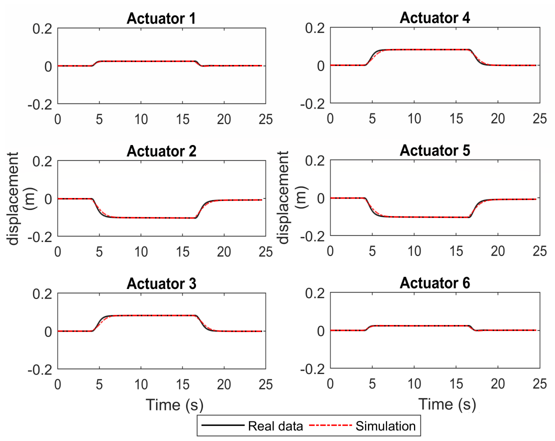

Figure 9. Platform test results - longitudinal test

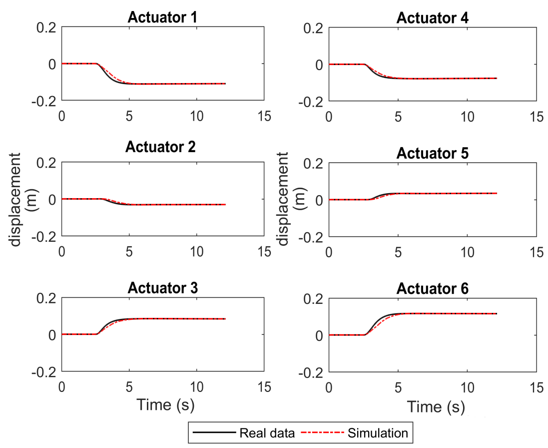

Figure 10. Platform test results - lateral test

Thus, with the adjustments in the model and the insertion of the physical parameters of dimension, mass, inertia matrix, and tuning of the PID controls, the results obtained showed that the behavior of the computational model can represent the movement platform in the other filter adjustment tests washout. All outputs obtained by the commercial movement platform were reproduced by the computational model. The stationary values obtained by

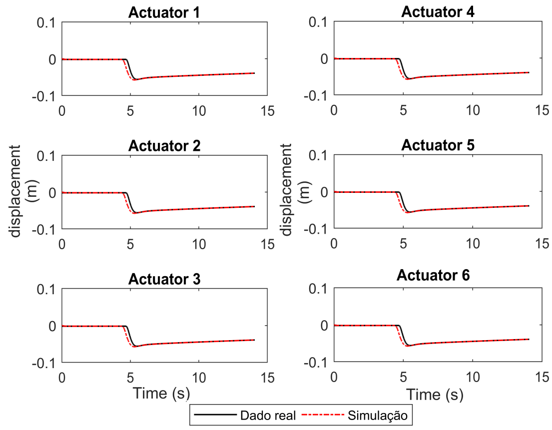

Figure 11. Platform test results - vertical test

the simulation had the same indices as the actual data of the platform. A maximum relative error of 15% was obtained in the transition of the movement for a period of time smaller than 0.5 seconds.

4.2 Washout filter test

The second test sequence was obtained with the adjustments made to the washout filter. The adjustments were performed in the longitudinal, lateral, and vertical order. The results of the longitudinal test are shown in Figures 12 and 13.

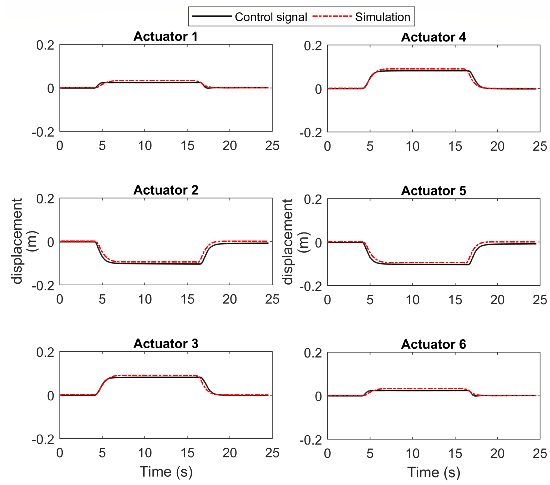

Figure 12. Washout filter test results - longitudinal mode - displacements of the actuators

The displacements of the actuators, shown in Figure 12, also show that the real and simulated signals are almost coincident. The difference is 9 millimeters, causing an angular difference in the platform of 0.2 degrees. Figure 13 shows the comparison between the acceleration perceived by the pilot in the aircraft and the flight simulator. It is possible to notice that in the longitudinal axis the sensations are identical. However, although there is a difference in the simulated sensation on the vertical axis (z), this value is below a pilot's sensitivity threshold, thus, this variation goes unnoticed.

The result in the lateral test are shown in Figures 14 and 15. The excitation signal applied to the commercial

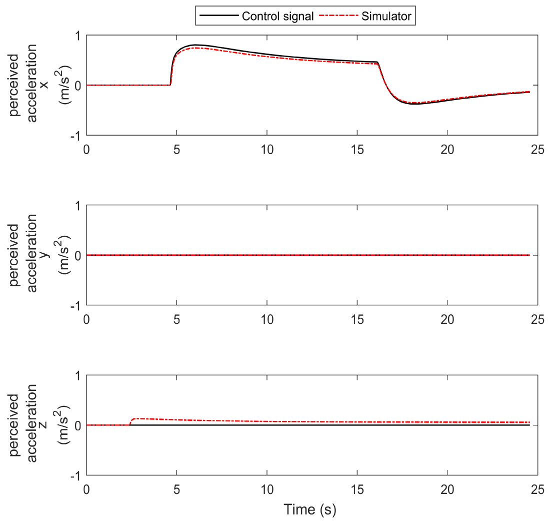

Figure 13. Washout filter test results - longitudinal mode - perceived acceleration

platform is a step-type acceleration with an amplitude of 1 m/s^2, only on the y-axis.

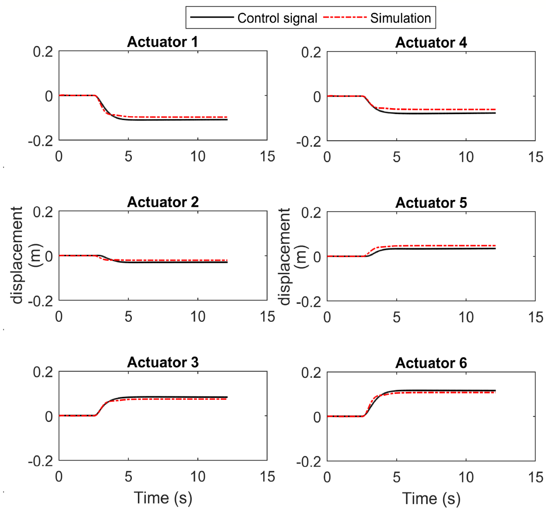

Figure 14. Washout filter test results - lateral mode - displacements of the actuators

The result presented shows that the displacements obtained by the computational model were compatible with those obtained by the commercial platform with a washout filter. The difference is 12 millimeters, causing an angular difference in the platform of 0.18 degrees in rolling axes.

According to the Figure 15, the difference between the accelerations perceived on the y-axis is 0.12 m/s^2, not influencing the differentiation for the pilot, between the movements in the aircraft and in the simulator, that is, are below the sensitivity thresholds. On the z-axis, there is no movement prediction. The residual signal that appears on this axis has an amplitude of 0.13 m/s^2, therefore lower than the sensitivity threshold of 0.17 m/s^2.

The test with vertical variation, that is, on the z-axis (heave), was carried out to verify the behavior of the washout filter concerning maneuvers with translational

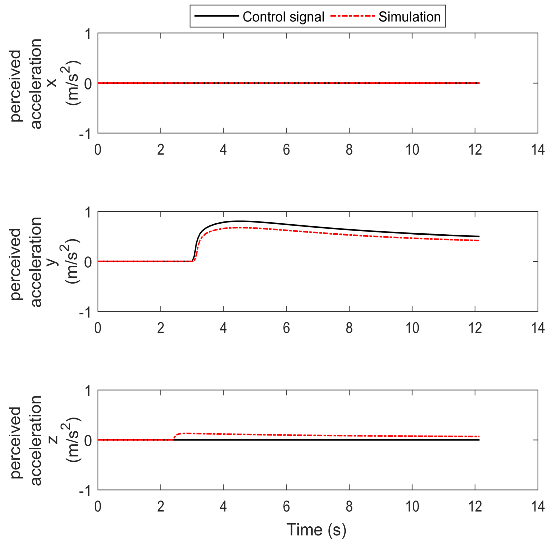

Figure 15. Washout filter test results - lateral mode - perceived acceleration

accelerations on this axis, such as vertical ascents and descents.

The excitation signal is a step type with an amplitude of 2 m/s^2, applied only on the z-axis. The results are shown in Figures 16 and 17.

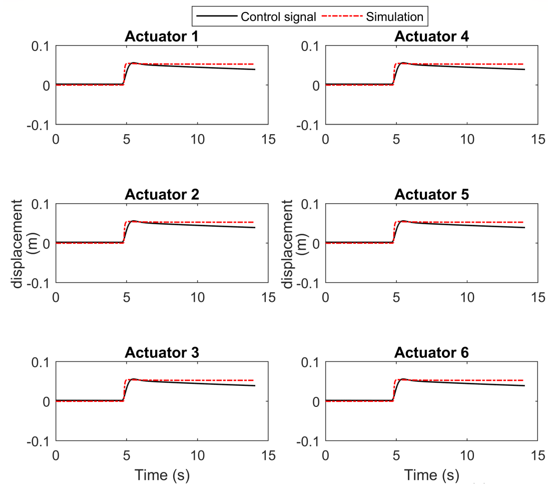

Figure 16. Washout filter test results - vertical mode - displacements of the actuators

The displacement graph of the actuators shows that there was a synchronization of the movements of the actuators. In other words, they all went up with the same amplitude, so that there were no angular variations. It can be seen that the final position of the commercial platform was slightly different from that of the computational model. The maximum relative error obtained at the end of the movement reaches 20%. This is explained as a function of the platform algorithm returning to the initial position after the stimulus. In the simulation, the stimulus was maintained until the end of the evaluation time.

Figure 17 illustrates the acceleration perceived by the pilot in the aircraft and the simulator. The difference between the sensations obtained between the pilot of the aircraft

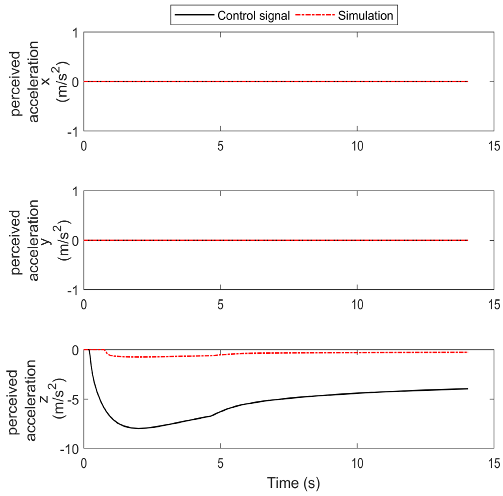

Figure 17. Washout filter test results - vertical mode - perceived acceleration

and the simulator is great. This characteristic is expected for this type of movement since there is no way to simulate the gravity vector in purely vertical displacement. As seen previously, the tilt coordination channel acts only on the x and y axes.

4.3 Flight test evaluation

The tests were closed with the insertion of real flight test data in the computational model, to verify whether the responses obtained followed the aircraft's behavior and the sensations obtained would be consistent.

The test maneuvers started with longitudinal cyclic command variations. Such excitation movements caused the aircraft to have a longitudinal oscillatory dynamic behavior, whose period decreases along with the test point. Small amplitude oscillations on the lateral axis were verified during the excitation signal. The results of the excitations on the aircraft and the post-filtering data are shown in Figures 18 to 20. The dynamic responses of the aircraft

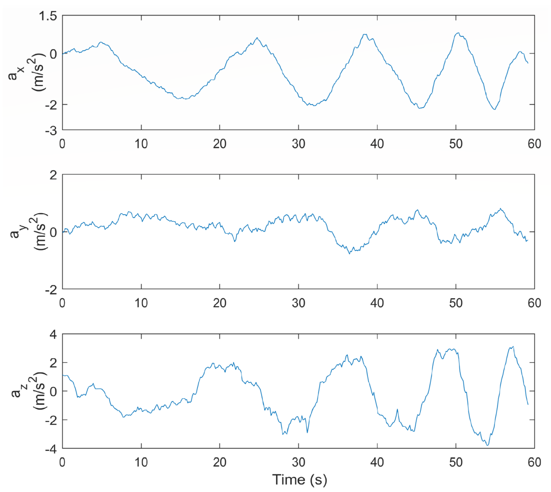

Figure 18. Flight test evaluation inputs

are shown in figures 18 and 19, with the outputs of translational accelerations and angular velocities on each axis,

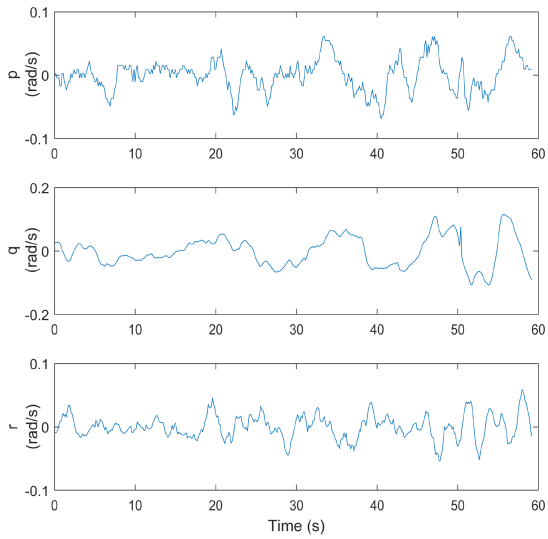

Figure 19. Flight test evaluation inputs

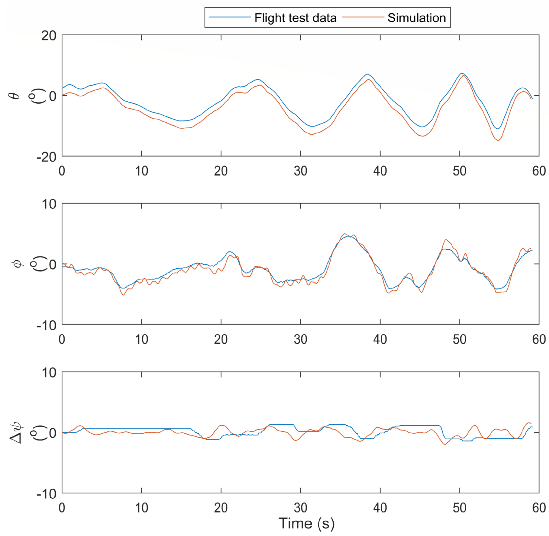

Figure 20. Flight test evaluation results

respectively. These responses were used as inputs for the computational model of the platform with a washout filter.

Figure 20 illustrates the comparisons between the actual flight test data and the model simulated data. The angular variations obtained by the aircraft and the movement platform are shown.The maximum difference obtained between the simulation and the actual flight for the pitch angle was 3 degrees. For the roll and yaw angles, the differences were 0.6 and 1 degree, respectively. The answers are following the inputs of the computational model (accelerations and angular velocities).

5. PLATFORM WASHOUT FILTER IDENTIFICATION

Based on the adjustments made and the results presented, it was possible to establish the final values for the parameters of the washout filter that reproduced the behavior of Moog's commercial movement platform.

The final parameters are shown in Table 4.

Table 4. Adjusted Parameters for the Washout Filter

Filter / Channel	Natural frequency	Damping coefficient
High pass Translational	$\omega_{n_x} = 2.95$ $\omega_{n_y} = 7.05$ $\omega_{n_z} = 7.05$	$\zeta = 1.0$
Low pass Coordination	$\omega_{n_x} = 2.95$ $\omega_{n_y} = 7.05$	$\zeta = 1.0$
High pass Rotational	$\omega_{n_\phi} = 2.45$ $\omega_{n_\theta} = 2.06$ $\omega_{n_\psi} = 1.85$	$\zeta = 0.9$

6. CONCLUSIONS

This work aimed to present the kinematic characteristics of a moving platform and the process of identifying the parameters of a possible movement algorithm of the commercial platform Moog MB-E-6DOF / 24 / 1800KG, used in the SHEFE helicopter simulator of the Brazilian Army.

The results obtained showed that the applied methodology was able to obtain a good approximation for the computational model of the moving platform and, later, with the classic model of the washout filter, in all axes of operation of the moving platform.

Based on the results presented, the choice of the filter model and the adjustments made were successful in reproducing the movements of the commercial platform.

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