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Flight Simulator Results Comparing Three Aircraft Configurations: Quasi-Static, Flexible and Extended Flexibility

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Full motion flight simulators are quite commonly used to evaluate handling qualities of an aircraft taking into account its rigid body dynamic model. However, new design, seeking for optimized aerodynamics with high aspect ratios, light and slender wings, has included new issues in handling qualities analysis. In such aircraft, the effect of the aeroelastic modes has a potential to affect its handling qualities characteristics. In this case, these aspects have to be respected in the dynamic model as well as in the flight simulator and the cockpit vibration due to aeroelastic modes must be included in the analysis. In this work the impact of the aircraft flexibility on the handling qualities is investigated. Therefore, an aircraft with significant coupling between rigid body and aeroelastic dynamics is considered. A dynamic model of a flexible aircraft is used, the flight simulator is configured to include the vibration in the cockpit, a dedicated test procedure is proposed, maneuvers with experienced test pilots are executed and the resulting data are analyzed. The pilot evaluation considered the PIO scale. Additionally, to evaluate the aircraft-pilot coupling susceptibility, two additional scales, called Riding Qualities Rating scale (RQR) and Control Inputs Rating Scale (CIR), are introduced. At the end the pilot rates are correlated with the HQ criteria results and remarks made about impact of flexibility on the handling qualities and pilot performance.

I. Nomenclature

AVES = Air Vehicle Simulator
CIR = Control Inputs Rating
HQ = Handling Qualities
IMU = Inertial Measurement Unit
PIL = Pilot-in-the-loop
PAO = Pilot Assisted Oscillations
PIO = Pilot Induced Oscillations
PSD = Power Spectral Density
RQR = Riding Qualities Rating

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II. Introduction

The new scenario for aviation is demanding more efficient aircraft and lower operational cost, translated for the aircraft industry in new structural design and optimized aerodynamics to reduce weight, fuel consumption and drag. These requirements are driving the design to high aspect ratios with light and slender wings of composite structure. However, such requirements have also an undesired side-effect, a more pronounced flexibility of the aircraft, which can cause a coupling of the structural dynamics and the flight dynamics, degrading the flight characteristics of the aircraft. Therefore, it becomes necessary to investigate and to understand the influence of aeroelastic effects on the flight characteristics in order to provide means, in future developments, to mitigate the adverse effects of flexibility on the aircraft design.

As demonstrated by [1], airframe flexibility can introduce lags to the rigid body dynamics that can contribute to the development of the undesired phenomenon of Pilot Induced Oscillation (PIO). Another collateral effect of increasing flexibility is the development of Pilot Assisted Oscillations (PAO), in which structural vibration at the cockpit is passively transmitted to the inceptors by the human pilot in an involuntary way. Even though this phenomenon is more common on rotary-wing aircraft [2], it may happen with fixed-wing aircraft as well. Not only the ones equipped with sidesticks [3], but also with the ones equipped with yoke [4].

This work provides a general description of the model adopted to represent the flexible aircraft, the flight simulator configuration to extend the range of operation to include the effects of the vibration on the cockpit due to the aeroelastic modes, a description of the flight test procedure used to evaluate the flexibility effect in the cockpit, the initial result of the campaign with Pilot-in-the-Loop (PIL) simulations illustrating the metrics and analysis proposed to evaluate the effects of flexibility, and the conclusion about the influence of flexibility on the flight dynamics handling qualities.

III. Aircraft Model

IV.

This work considers an aircraft model which includes the rigid and the flexible dynamics of the aircraft, as shown in Fig. 1. The nonlinear flight mechanics model considers the aerodynamic data bank of the aircraft with the quasi-static characteristic included. This model is based on the six degrees of freedom rigid body equations. The linear aeroelastic model is an n-degree of freedom equation in modal basis, considering a limited number of modes which has some significant interaction with the rigid body,[5]. The aeroelastic data bank is obtained by a rational function approximation of the generalized aerodynamic force provided by NASTRAN. Once the quasi-static characteristic is included in the flight mechanics model, the trim conditions are eliminated of the input signals of the aeroelastic block. Therefore, the aeroelastic model provides incremental forces and moments to be added to the rigid body ones.

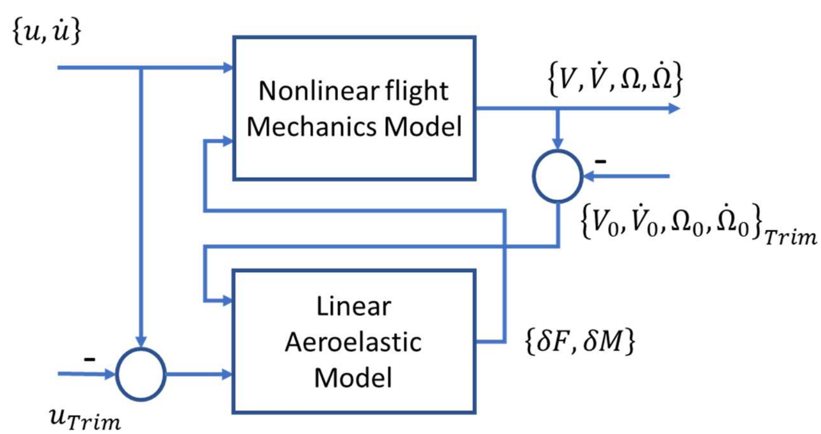

Fig. **1** Flexible aircraft model.

A conceptual aircraft model is used in this work considering three different dynamics. The first one is a '*Quasi-static aircraft*' representing the typical rigid body model considering only quasi-static aeroelastic effects (the linear dynamic aeroelastic model, in Fig. 1, is not considered). The second is a '*Flexible aircraft*' model with feasible case of coupling between rigid and flexible dynamics. This model can be considered as representative for current passenger aircraft with modern design and materials. The third is the '*Extended-flexibility aircraft*' which has a significant coupling between rigid and flexible dynamics, which is assumed to be more flexible than today's aircraft but may be relevant for designs in the near future. This conceptual aircraft is a single aisle in a similar configuration to the Embraer commercial aircraft.

V. Flight Simulator Configuration

The simulator used in this work is the DLR full motion flight simulator AVES (Air VEhicle Simulator) [6]. The AVES is a high-fidelity simulator on an electro-mechanically driven motion system, Fig. 2. It has interchangeable cockpits: an Airbus A320 cockpit, an Eurocopter AC135, and a passenger cabin, whereupon the Airbus A320 cockpit has been used in the simulator experiments. However, it is worthy to emphasize that the conceptual model of the flexible aircraft model used in this work is intended to represent Embraer commercial jets and does not represent anyhow an A320 aircraft.

All software components, including the display systems and the simulation framework, of the simulator are in-house developments of DLR, which allows high flexibility and easy modifications. The aircraft model is a Matlab Simulink® model, which is integrated in the simulation framework and can easily be adjusted, like in the present simulator campaign by varying the flexibility level within the aircraft model. The visual system of the simulator consists of 9 LED projectors, with a total field-of-view of 240° x 95°. The 14 t motion system allows accelerations of 0.6 - 0.8 g, velocities of 1 m/s and travelling distances of 1 m. Frequencies are limited up to 10 Hz.

Fig. 2 Aves picture.

Even though it was known that the AVES is in principle able to simulate motions up to 10 Hz, it had only been used to simulate rigid body aircraft before and the present campaign has been the first time a flexible aircraft has been simulated on the motion platform. Before the actual campaign several preceding motion tests have been performed to assure that the flexible modes can be adequately represented by the simulator. For this purpose, the Objective Motion Cueing Test (OMCT), which is often used to get an objective evaluation of the motion performance, and which is included in relevant certification standards like the FAA AC120-40 [7], is extended to 10Hz. The results show that the AVES is principally able to fulfill the requirements of the OMCT to adequately simulate motions up to 10 Hz. However, it has to be kept in mind that the OMCT is originally not designed for frequencies above 2.5 Hz, which are however the most relevant frequencies for the present studies. Consequently, the preceding motion tests did not only focus on the OMCT but also comprised a comparison of the frequency response (in form of PSD) of the motion with the one of the models for the relevant tasks and verify that the relevant frequencies are adequately modeled.

To set up the configuration of the motion algorithm, some tests with pilots were performed to evaluate the overall effect of motion in the simulator. These tests used the same maneuvers proposed in the test procedure for the final campaign. The final configuration was selected by PSD comparison of the motion platform with the aircraft dynamics and pilot subjective evaluation. As a result, the accelerations that are sent to the motion algorithm are thereby split into two parts, the rigid body components and the accelerations resulting from the flexible aircraft model. The rigid body motion is fed through the regular motion algorithm by Moog with high-pass filters with the following setup of parameters:

- X-axes: gain 0.6 and bandwidth of 3 rad/s
- Y-axes: gain 0.2 and bandwidth of 1 rad/s
- Z-axes: gain 0.8 and bandwidth of 4 rad/s

The additional accelerations resulting from the flexible deformation of the aircraft are not fed through the motion cueing algorithm but are sent directly to the motion by a so-called buffet channel. Extensions pre-test with pilot evaluations led to a single gain for the buffet channels in all three axes x, y, and z:

- Buffet channel gains (x, y, z) of 0.4.

Fig. 3 shows the comparison of the frequency responses of the model and the motion platform exemplarily for the z acceleration. The solid lines in blue and green represent accelerations at the pilot seat calculated in the dynamic aircraft model. The blue line is the rigid body component and the green line the flexible component. The overall acceleration in z direction at the pilot seat would thus be the sum of the blue and green solid line. The red dashed line is the acceleration of the motion platform, measured by an IMU (inertial measurement unit) attached to the motion frame. It can be noticed that the motion platform adequately represents the accelerations that are commanded by the aircraft model.

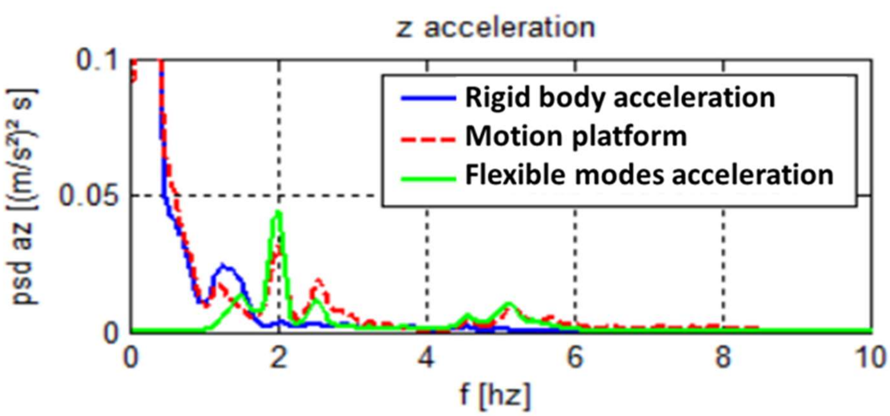

Fig. 3 PSD of vertical acceleration at the pilot seat

VI. Test Procedure

The evaluation of aircraft handling qualities characteristics is based on the guidance of AC 25-7D [8], and other maneuvers based on EMBRAER previous experience.

The following tasks were considered for the handling qualities evaluation in the dedicated simulator test campaign:

- Offset Landing.
- Synthetic Tasks (Pitch and Bank), known as Fine Tracking Tasks.
- Close Formation Flight.

These tasks demand different levels of effort from the pilot. The synthetic task has a characteristic of high precision and small command deflections by the pilot. On the other side, the offset landing requires large pilot inputs with sufficient precision to align with the runway. In the middle there is the close formation task, with intermediate characteristics of precision and command deflection.

The synthetic Task considers both pitch and bank targets. Continuous and discrete tasks are used to stir up the frequency of the rigid and the flexible dynamics. They also combine gross acquisition with fine tracking periods. For this maneuver, a dedicated PFD is provided to include the synthetic task symbology. An illustration of the tasks and PFD is shown in Fig. 4.

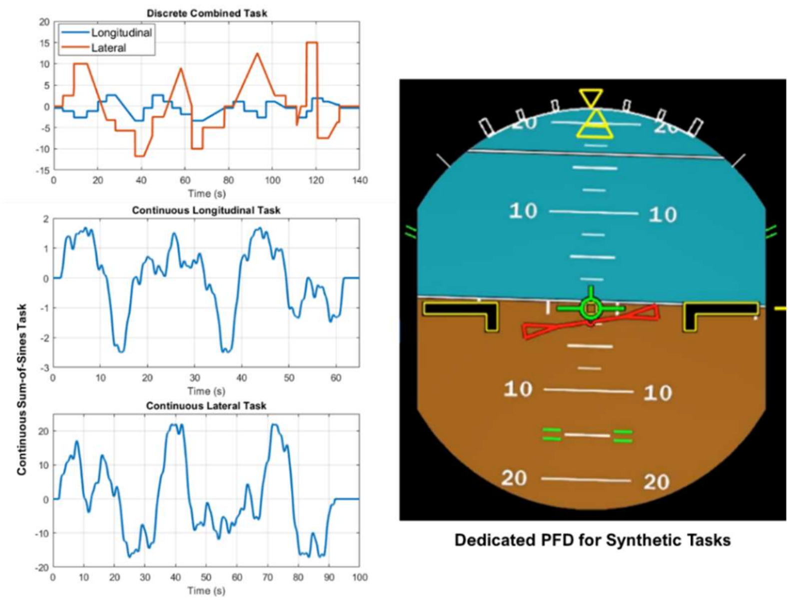

Fig. 4 Synthetic task schematics

Close formation flight test points were performed considering another aircraft as a leader (or reference) aircraft with which the pilot must align the aircraft. Two different tasks are considered: alignment behind the leader and with the leader's wingtip. Visual reference in the leader aircraft is used to guide the pilot: the alignment of the landing gear wheels for the task behind the aircraft and the alignment of the wingtip with the front door, as shown in Fig. 5. The test is performed considering different turbulence levels to act as a disturbance to be counteracted. It must be noted that no wake vortex of the leader aircraft is considered. The major target is to verify the effects of the flexibility on the pilot commands to keep the aircraft alignment, while keeping tight control in the stick.

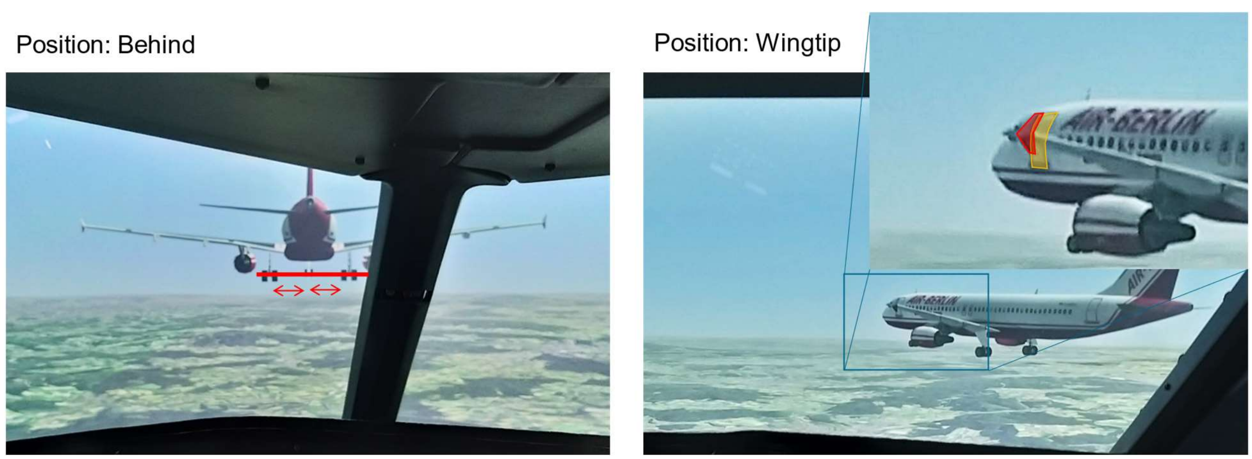

Fig. 5 Close formation flight demonstration.

Offset landings are performed for landing configurations. For this maneuver a rectangle, that is offset to the runway centerline is provided as a visual cue target for the pilot to cross and, immediately, perform the offset correction to align with the runway centerline while aiming for the touchdown point.

Fig. 6 Offset Landing view with offset rectangle

During all tasks, the pilots were asked to answer three rating scales used to evaluate the aircraft-pilot coupling susceptibility. They are the PIO scale and two additional scales for evaluation of flexible aircraft, proposed by Raney et al [9]. These scales are the Riding Qualities Rating scale (RQR) and Control Inputs Rating Scale (CIR), intended to evaluate the effect of the cockpit vibrations on the pilot commands. These scales are presented in the Appendix.

VII. Test Results

A total of 461 simulator test runs were performed with 4 pilots, covering the 3 tasks (synthetic task, formation flight and offset landing) and 9 trim conditions for the 3 models, with some additional cases including turbulence (light and moderate) and some repetitions. The overall statistics of the complete test campaign is shown below in Fig. 7. Rating '1' and '2' represent most of the cases, which are the cases meaning an acceptable response. For rating '3' the pilots consider a small degradation in their commands that compromises the task. In case of rating above '3' pilots reduce the gain mostly due to vibration during the task.

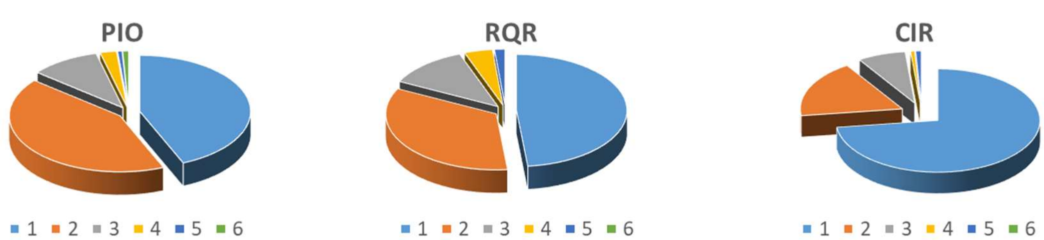

Fig. 7: General result for scale ratings.

Comparing the aircraft models, Fig. 8, the degradation of the ratings from the Quasi-Static to the Extended-flexibility models becomes evident. . Comparing the RQR results for Quasi-Static, Flexible and Extended-Flexibility models, a degradation of the ratings is noticeable due to the vibration effects. The effects of vibration are less evident in the pilot CIR ratings. It seems like the RQR rating is more prone to pilot evaluation of vibration effects in the cockpit. However, it must be considered that pilots are not so familiar with these rating scales.

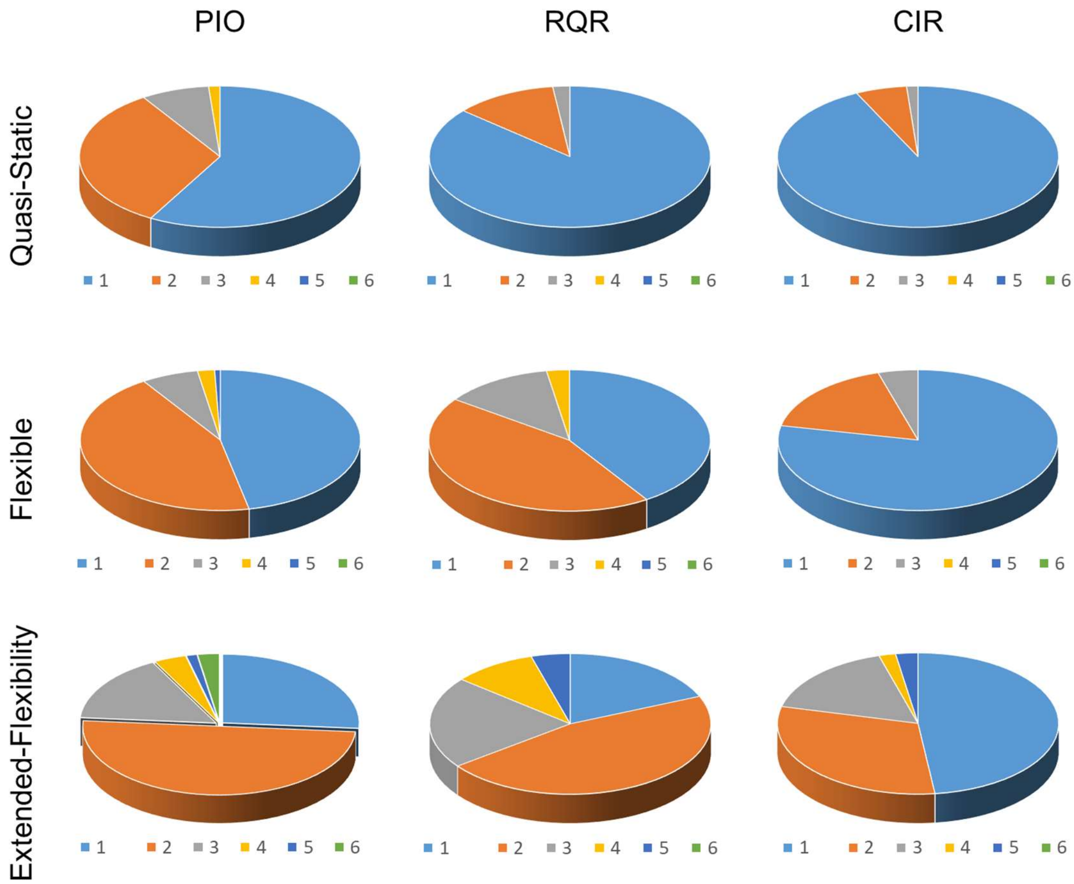

Fig. 8: Pilot rating statistics according to aircraft model.

The test data were analyzed in both time and frequency domain to correlate flexibility with pilot handling qualities. As a huge set of data was generated only an outline of the analysis is presented in the following. Starting with the synthetic task, the time response of a combined task in the lateral axis is shown in Fig. 9. The green and yellow regions define the tolerance of 3 degrees for 'Desired' and 5 degrees for 'Adequate' response. Based on this result, it is possible to evaluate the task adherence looking at the dispersion of the response for 'Quasi-Static', 'Flexible' and 'Extended-Flexibility' models in relation to the reference 'TaskPlay'. The analysis shows a noticeable degradation in the response as the 'Extended-Flexibility' model exceeds the green region more than the others.

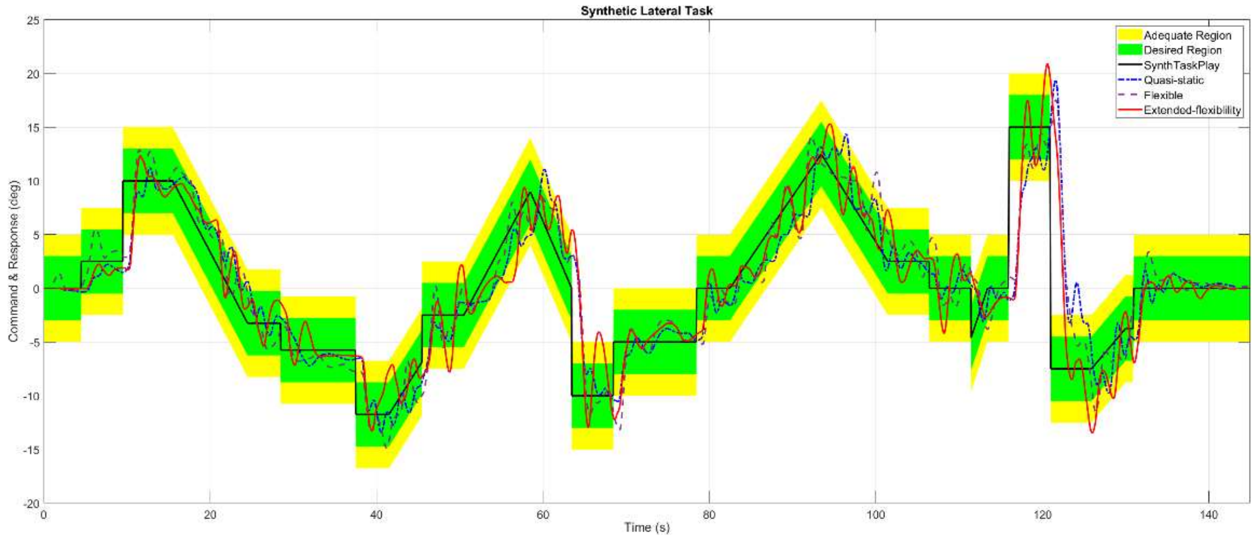

Fig. 9 Time domain analysis for synthetic task.

Additional indication of degradation is shown by the distribution analysis in Fig. 10 where the histogram and a fitted normal probability distribution of the error between the command and aircraft response are shown. For instance, in this illustrated case, the dispersion of the distribution increases from ‘Quasi-Static’ to ‘Extended-Flexiblility’ model. This evaluation corroborates the pilot rating given in Table 1 for this test. There is no complaint from the pilot about CIR, however PIO and RQR ratings change according to the increase in the spread of tracking error shown by the increased dispersion of the distribution for rising flexibility.

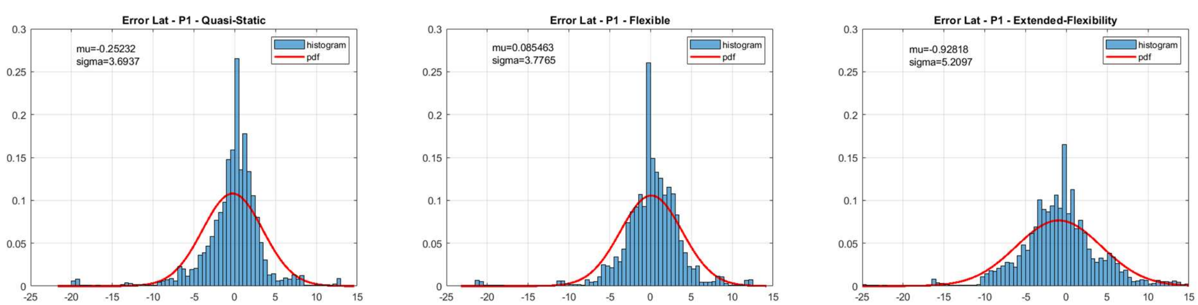

Fig. 10 Histogram plot of task error for the three model tests.

Table 1 Pilot ratings for the synthetic task.

Model	PIO	RQR	CIR
Quasi-Static	1	1	1
Flexible	1	2	1
Extended-Flexibility	3	4	1

In the frequency-domain a scalogram, [10], is used to assess the evolution of the signal power spectrum along the time. The scalogram of the roll stick and the y-acceleration in the cockpit are shown in Fig. 11. In the figure, the plot on top shows the time evolution of the signal, the right plot is the power spectral density function, and the center plot shows the power spectrum evolution over time. It exemplifies how to extract relevant information from data. This figure shows regions in the time history where frequencies related to flexible modes appears in both signals. It is an indication that the acceleration in the cockpit feeds through pilot to stick, suggesting a mechanism of coupling between pilot and aircraft.

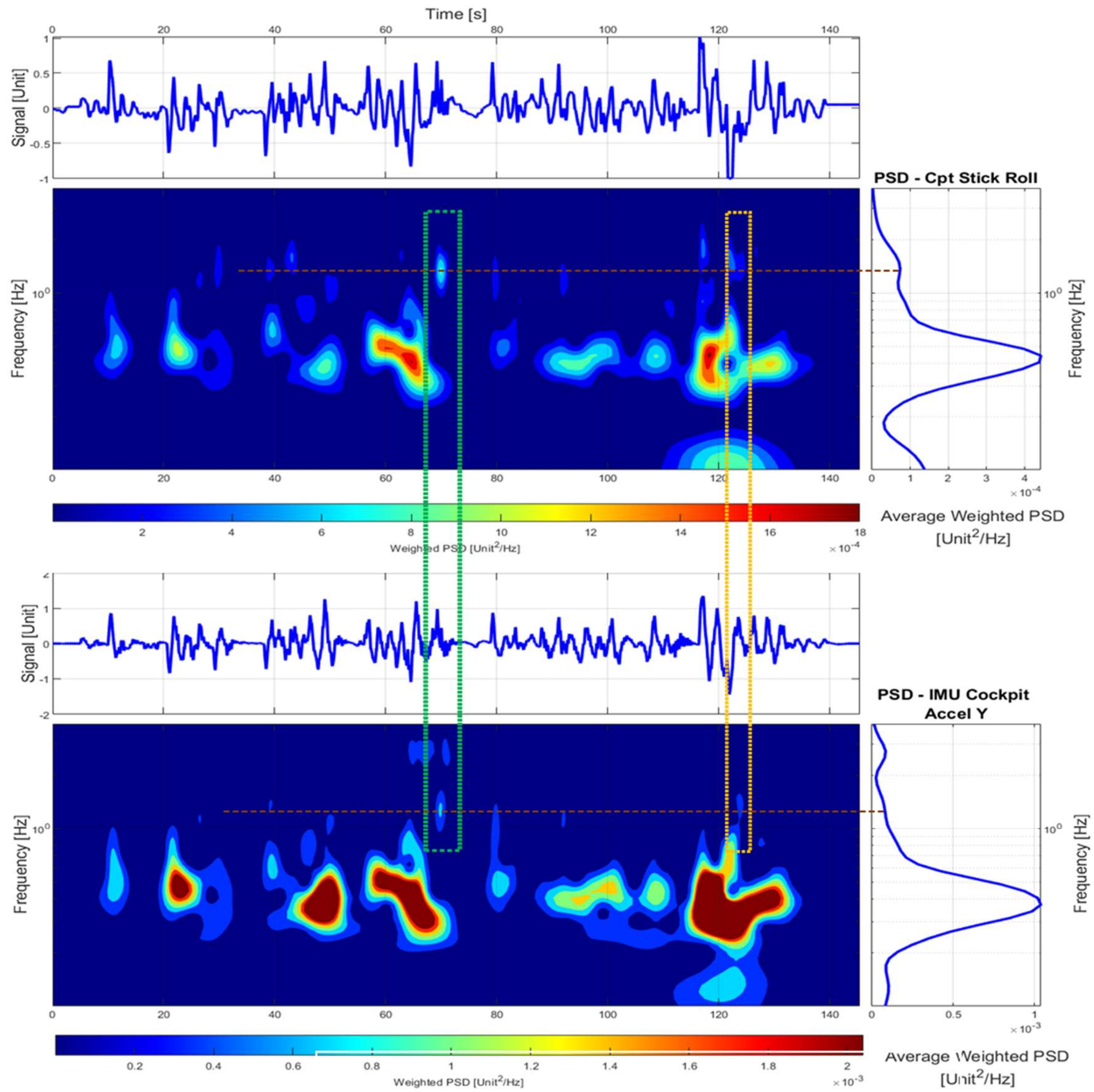

Fig. 11 Scalogram plot of synthetic combined task for lateral axis.

The power spectrum density function, shown in Fig. 12, is also used to evaluate the characteristics of the three models. The cockpit acceleration is depicted for longitudinal and lateral maneuvers for continuous and discrete synthetic tasks. In the two plots, the discrete task shows how the energy of the pilot excitation decreases as frequency increases, while the continuous task keeps a certain level of energy for the bandwidth of the harmonics of the reference task. Another relevant observation is the change in the pilot handling technique from the Quasi-Static to the flexible models in the longitudinal response. In this case, the normal acceleration signal for both, continuous and discrete tasks, has a peak in the region of 3 rad/s for the Quasi-Static case. Because of the presence of vibration in the cockpit due to flexible dynamics the pilot changes his command technique. The lateral response shows a peak in the frequency region of the flexible modes in the lateral response. Therefore, the aircraft is more susceptible to flexible modes in the lateral response for the synthetic task runs, as also observed in the scalogram.

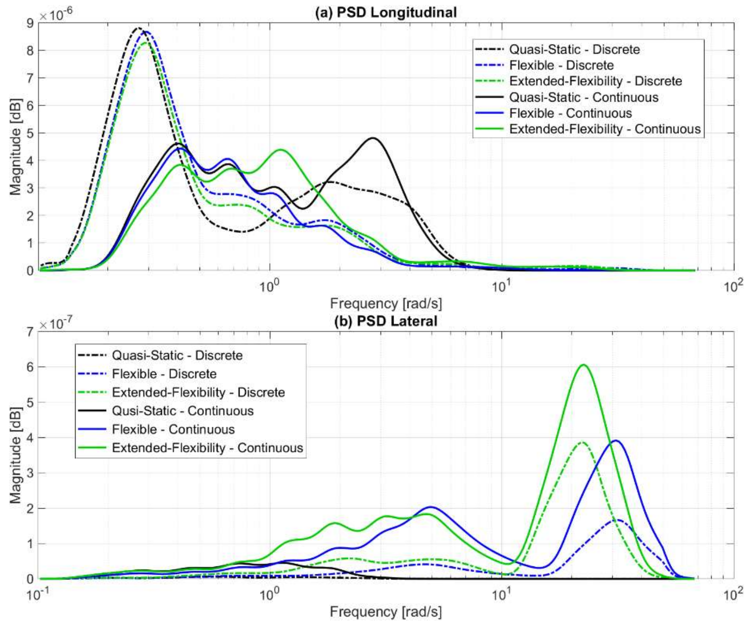

Fig. 12 PSD for synthetic task acceleration: (a) Longitudinal, (b) Lateral.

Considering the close formation flight task, the pilot was asked to perform small and large deviations from reference and to recover the formation. The scalogram of Fig. 13 illustrates the frequency spectrum excited by pilot commands and the resulting roll rate power level. The scalogram clearly shows the frequencies excited by the pilot-induced deviations from the formation position (perturbation) and the subsequent reacquisition of this position.

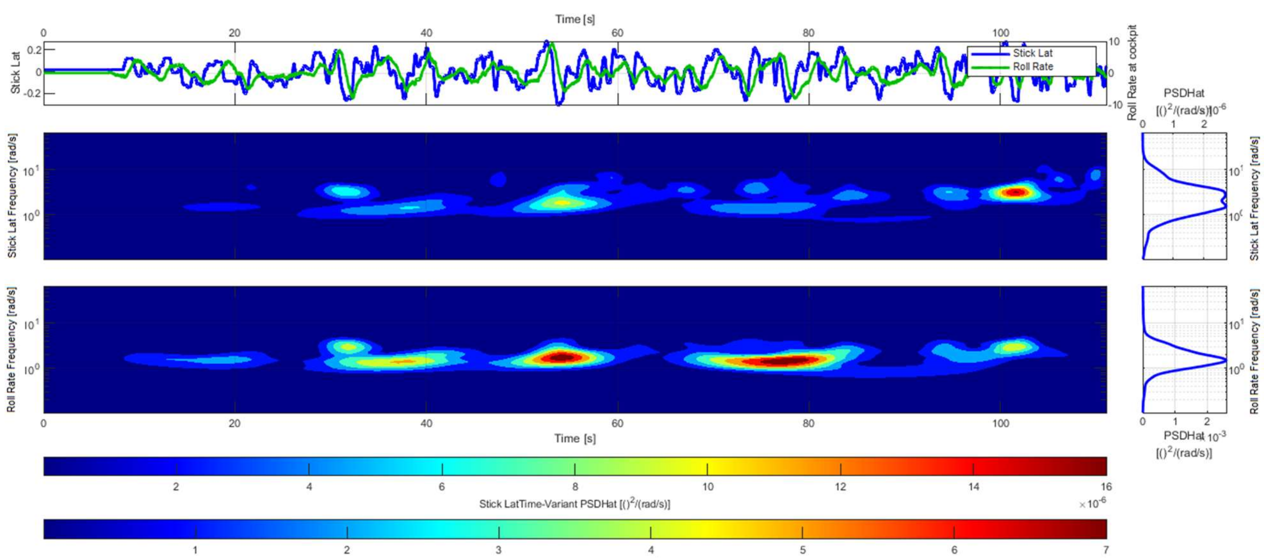

Fig. 13 Scalogram for lateral axis, behind the leader position.

Turbulence was also included in the task, exciting the flexible modes in a persistent way and demanding more effort from the pilot. The power spectrum depicted in Fig. 14, of other test case, shows the effect of turbulence perturbation in the modes corresponding to the rigid body dynamics. Also, interesting to note is increasing turbulence levels also excite a flexible mode, as can be seen in the small peak in the high frequency range.

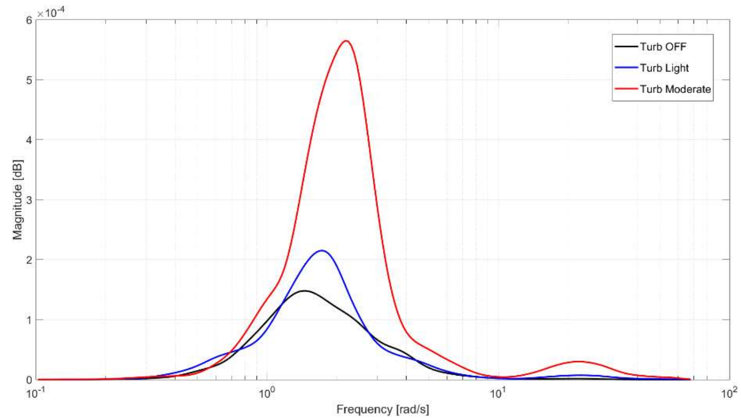

Fig. 14 PSD for longitudinal accelerations at the cockpit, turbulence level comparison.

The IPPP (Input Power Peak – Phase lag), [11], is another criterion used to compare the pilot execution of the tasks for the three models. Basically, it computes an input signal (stick displacement) and an output (pitch and roll rates) and calculates the phase lag between both signals and associates it with a measure of power in the signals. PIO signature is represented by high power associated with a phase lag close to –90deg.The IPPP plots, Fig. 15, show the largest dispersion in peak power of the longitudinal response and higher values of phase in the lateral response for the Extended-Flexibility model. This response tendency is consistent for most of the formation flight tests. The phase lags observed are small, indicating no tendencies for PIO. All the results corroborate with the pilot correspondent ratings in Table 2, with the worst ratings occurring for the Extended-Flexibility, in which highest phase lags were indeed observed.

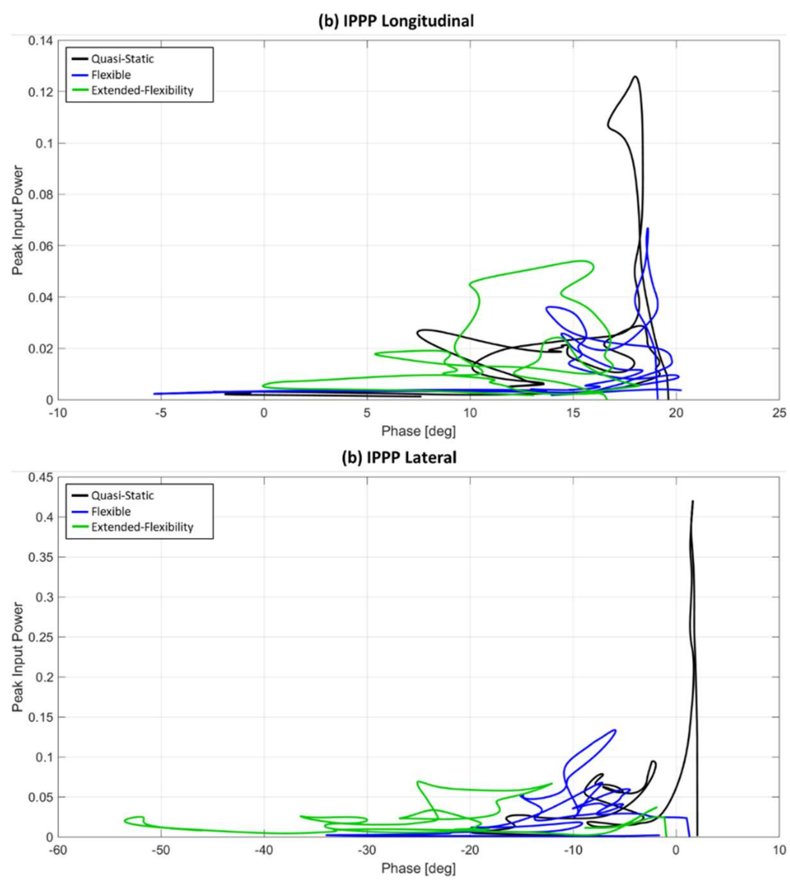

Fig. 15 IPPP for formation flight (a) Longitudinal (b) Lateral

Table 2 Pilot ratings for the Formation Flight, no turbulence.

Model	PIO	RQR	CIR
Quasi-Static	1-2	1	1
Flexible	1-2	1	1
Extended-Flexibility	2-3	2	2

The offset landing is the task which demands the largest inceptor commands in a short time interval. It allows to investigate the effects of flexibility due to large and fast commands. The scalogram in Fig. 16 illustrates the power increasing with time in the stick command and the resulting roll rate, as the aircraft is getting closer to the landing and the final effort to align with the runway after the aircraft crosses the reference rectangle.

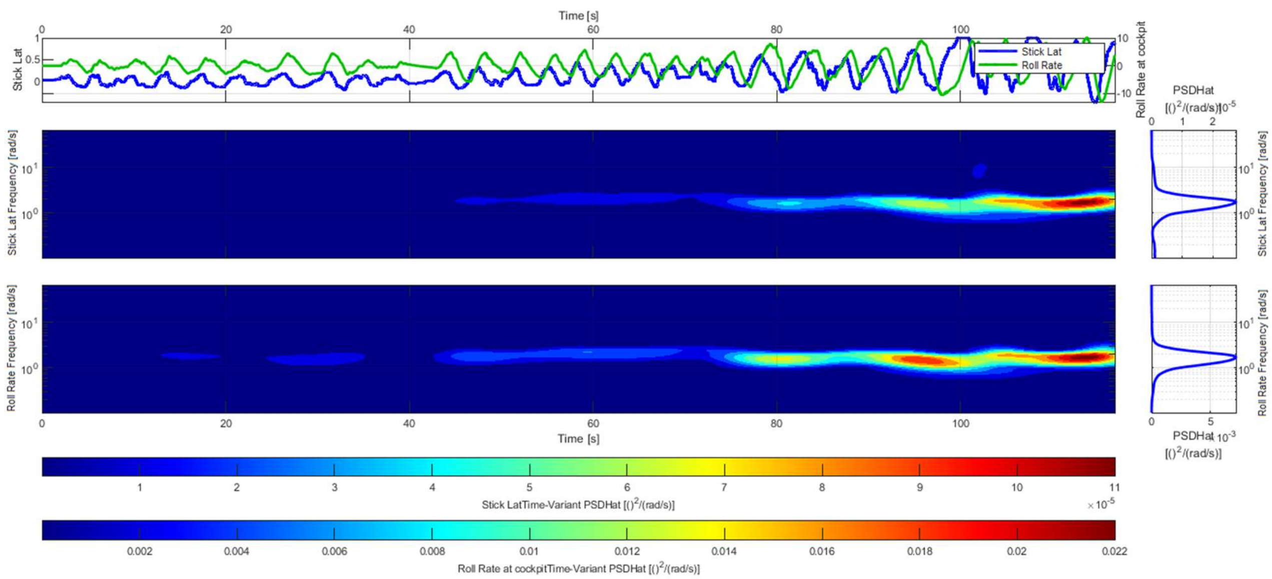

Fig. 16 Scalogram for lateral axis, offset lading.

For the offset landing, the most critical characteristic to investigate is PIO. In this case the IPPP shows very specific results with larger phase deviations than the other tasks. As illustrated in Fig. 17, the longitudinal responses are close for all cases, with average phase variation between 0 to -60 degrees and average peak not greater than 0.04 even for the Extended-Flexibility cases (exception for P1 – Extended-Flexibility). The lateral response reaches phase values up to -80 degrees and, with peaks greater than 0.1, for all pilots in the Extended-Flexibility cases, corresponding to the PIO signature. It confirms that the oscillations observed in the lateral axis are indeed a PIO. The fact that only the Extended-Flexibility model presented PIO indicates a possible problem that more flexible aircraft may have to deal with. Finally, these results are also in accordance with the ratings given by the pilots in Table 3.

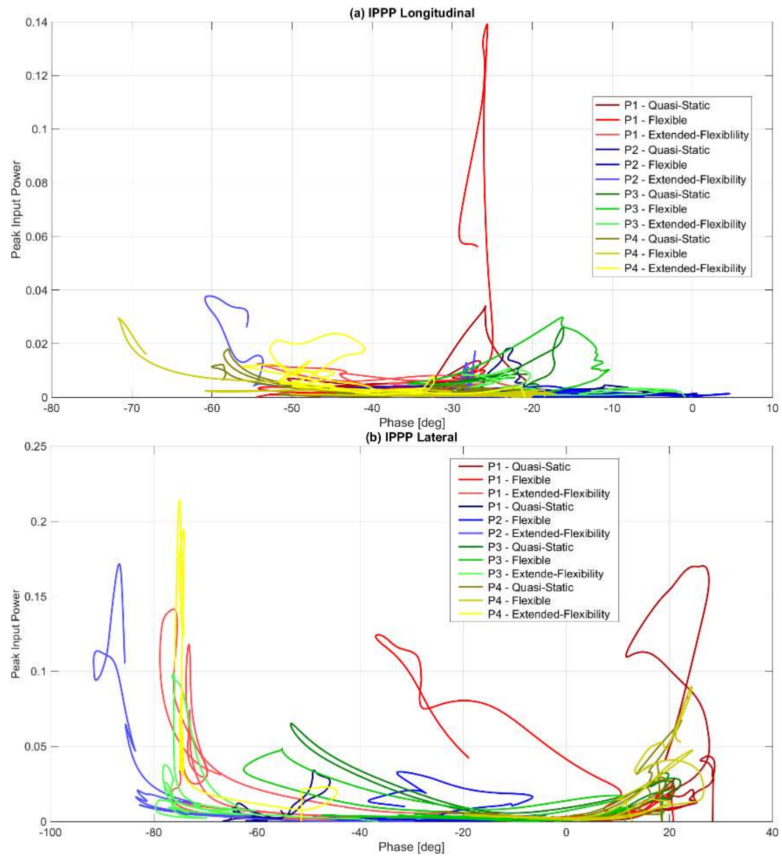

Fig. 17 IPPP for offset landing (a) Longitudinal (b) Lateral

Table 3 Pilot ratings for the Formation Flight, no turbulence.

Model	PIO	RQR	CIR
Quasi-Static	1-2	1	1
Flexible	2	1-2	1
Extended-Flexibility	4-6	4-5	3-5

VIII. Conclusion

Three aircraft models were tested in a full motion simulator to investigate the impact of the flexible dynamics on pilot handling qualities. The results of the pilot ratings of each test were correlated with some metrics in the time and frequency domain. Examples of application of these metrics were presented explaining what information each one can provide. Both pilot ratings and metrics analysis demonstrate the degradation of the pilot performance from the Quasi-Static to Extended-Flexibility models. Only a general overview of the analysis was presented in this work. Preliminary analysis shows evidence of potential coupling in some tests and requires further investigation. This further analysis will verify in detail if there is a way to demonstrate the pilot-aircraft coupling phenomena. A thorough analysis of the data is planned for future works to identify the occurrence of pilot-aircraft coupling phenomenon.

Appendix

Three rating scales were used by the pilots for test evaluation. The first of which is the standard PIO rating classification, as shown in Fig. 18.

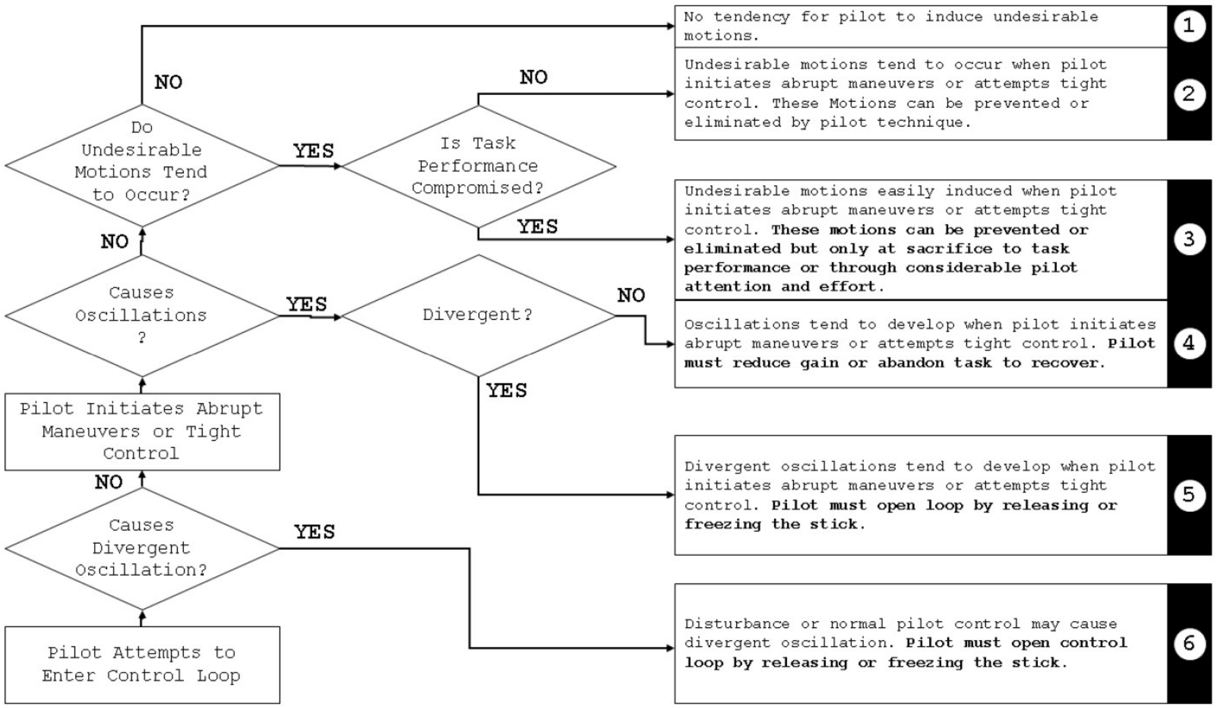

Fig. 18 - PIO Rating Scale

With the same motivation of having a more precise pilot opinion about aircraft vibration in the cockpit, as allowed by the PIO scales, Raney et al [9] proposed two evaluation scales called Riding Qualities Rating Scale (RQR) and Control Inputs Rating Scale (CIR) as shown in Table 1 and Table 2 respectively. These scales were proposed to evaluate how flexibility and biodynamic coupling could affect the handling qualities characteristics of the aircraft.

Table 1 - Riding Qualities Rating Scale

Description	Rating
Cockpit vibrations do not impact ride quality.	1
Cockpit vibrations are perceptible but not objectionable, no improvement necessary.	2
Cockpit vibrations are mildly objectionable, improvement desired.	3
Cockpit vibrations are moderately objectionable, improvement warranted.	4
Cockpit vibrations are highly objectionable, improvement required.	5
Cockpit vibrations cause abandonment of task, improvement required.	6

Table 2 - Control Inputs Rating Scale

Description	Rating
Pilot does not alter control inputs as a result of aircraft flexibility.	1
Pilot intentionally modifies control inputs to avoid excitation of flexible modes.	2
Cockpit vibrations impact precision of voluntary control inputs.	3
Cockpit vibrations cause occasional involuntary control inputs.	4
Cockpit vibrations cause frequent involuntary control inputs.	5
Cockpit vibrations cause sustained involuntary control inputs or loss of control.	6

Acknowledgments

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