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Simulating Flexible Aircraft in a Full Motion Simulator

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Classical flight dynamics analyses and pilot-in-the-loop simulations are traditionally based on rigid-body aircraft models. The assumption of rigid aircraft is acceptable for classical aircraft designs. However, present ecological and economical constraints require modern passenger aircraft to become more efficient and reduce their emissions. This leads to optimized aircraft designs with light structures and high aspect ratios, which exhibit an increased aeroelastic flexibility. These modern more flexible aircraft do not necessarily allow the assumption of rigid-body modeling approaches anymore but require the inclusion of structural flexibility for flight dynamics analyses and handling qualities assessments. This also affects pilot-in-the-loop simulations in a full-motion simulator, where the consideration of structural flexibility is no common practice. The present paper describes the preparation of an extensive simulator campaign with a flexible aircraft. It addresses the question of how to integrate the oscillations resulting from the structural flexibility into the motion filter of the simulator to achieve a realistic feeling of the flexible modes.

I. Nomenclature

$a_{x\,pilot}$	=	body-fixed longitudinal acceleration at the pilot seat
$a_{y\,pilot}$	=	body-fixed lateral acceleration at the pilot seat
$a_{z\,pilot}$	=	body-fixed vertical acceleration at the pilot seat
K	=	wash-out filter Gain
$\dot{p}$	=	roll acceleration
$\dot{q}$	=	pitch acceleration
$\dot{r}$	=	yaw acceleration
x	=	longitudinal direction in body-fixed coordinates
y	=	lateral direction in body-fixed coordinates
z	=	vertical direction in body-fixed coordinates
Θ	=	pitch angle
Φ	=	bank angle

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II. Introduction

New challenges in aviation require new aircraft designs with optimized efficient aerodynamics and new structural designs to achieve the goal of reduced operation costs, fuel consumption and emission. These goals lead to designs with high aspect ratios and light and slender wings of new composite structures. The resulting aircraft configurations show an increased aeroelastic flexibility, which poses new challenges in the aircraft design. One aspect is the influence of the enhanced flexibility on handling qualities of the aircraft. Previous studies [1] showed that structural flexibility can introduce lags to the rigid-body dynamics and lead to the occurrence of Pilot Induced Oscillation (PIO). Furthermore, effects of involuntary passive transmission of structural vibration to the control inceptors of the pilot have been observed for both, aircraft equipped with sidesticks [2] as well as for aircraft with a yoke [3].

Within the research project DinAFlex (Dynamics of Flexible Aircraft), Embraer and the Institute of Flight Systems of DLR (German Aerospace Center) investigated the effect of structural flexibility on handling qualities [4]. Pilot-in-the-loop simulations in the DLR full-motion simulator AVES (Air VEhicle Simulator) represented a major part of the project and delivered important insights about the degradation of the handling qualities due to increased structural flexibility. In order to be able to evaluate these effects it is essential to adequately represent the interaction between the rigid-body aircraft dynamics and the aeroelastic flexibility and provide a realistic impression of the vibrations caused by higher order modes in the cockpit.

The assurance of adequate motion simulation has been a large field of research for motion simulators in the past [5]-[11]. To find the best way to represent the free motion of an aircraft in the limited space of the motion platform is not trivial to solve and different motion cueing algorithms have been developed in the past to address this problem. The motion cueing research focusses in general, however, mainly on the simulation of the rigid-body dynamics of the aircraft. Only very few studies concentrated on the assessment of flexible aircraft in a motion simulator. A simulator study in the NASA Langley Visual Motion Simulator facility [12] was a first approach to investigate the effect of aeroelastic flexibility on handling qualities and showed the degradation of handling qualities with increasing flexibility. A later study in the same simulator [13] investigated the effectiveness of measures to reduce the impact of flexibility on piloting tasks. While these two publications concentrate on the results of the pilot assessment, [14] focusses on the simulation aspect of the flexible aircraft dynamics and describes different approaches to separate rigid and flexible motion and to integrate it into the motion simulation.

The present paper describes the preparation of an extensive simulator campaign for the assessment of the influence of flexible aircraft. It presents the simulator setup with necessary modifications and the experimental setup. The main focus of the paper is the integration of the flexible aircraft dynamics in the motion simulation. Two general concepts of integrating the flexible dynamics have been tested and adjusted in the simulator. Finally, the adjustments were evaluated by a test pilot as well as analyzed in the time and frequency domains.

III. Simulator Campaign

The goal of the simulator campaign was to evaluate the influence of aeroelastic flexibility on handling qualities. The underlying aircraft model is a conceptual medium-range passenger aircraft. The model contains the rigid and flexible aircraft dynamics. The basis of the aircraft model is a nonlinear flight dynamics model with the six-degrees-of-freedom rigid-body equations. It contains an aerodynamic database of the quasi-static aerodynamic characteristics. The flexible dynamics are represented by a linear aeroelastic model of 20-degrees-of-freedom equations in modal basis, considering a limited number of modes with a significant interaction with the rigid-body dynamics. The underlying aeroelastic data set is computed by a rational function approximation of the generalized aerodynamic force and added as incremental forces and moments to the rigid-body model. The flexible modes comprise frequencies up to 10 Hz.

The aircraft model was implemented in the DLR research simulator to study the impact of the flexibility on the aircraft's handling qualities during an extensive simulator campaign with several Embraer test pilots. The applied pilot task and data handling are described in the following sections.

A. Pilot Task

The maneuver considered in this paper is a synthetic task that was developed for the present simulator study. The task consists of combined target values in pitch and bank as illustrated in Fig. 1. The discrete change of the target values is designed in a way to cover gross acquisition with fine tracking tasks and to excite both the rigid and flexible dynamics of the aircraft. The task target values are indicated in the Primary Flight Display (PFD) and shown as a line with triangles at its end points (see Fig. 1, slightly above the horizon). The line indicates target values for pitch and bank. The pilot tries to put a little green aircraft symbol, called birdy here, on the target value line. This line is displayed in green if both target values are captured within a limit of +/- 1° in pitch and of +/- 3° in bank and displayed in red if the pitch or bank angle deviation from the target values is outside these limits. Figure 2 illustrates the modified PFD with the green birdy and the red target line of the synthetic task.

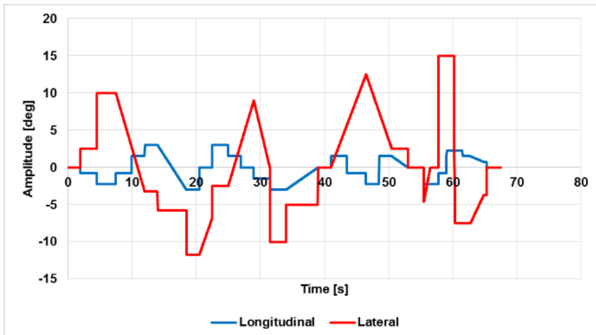

Fig. 1 Targets values of synthetic task.

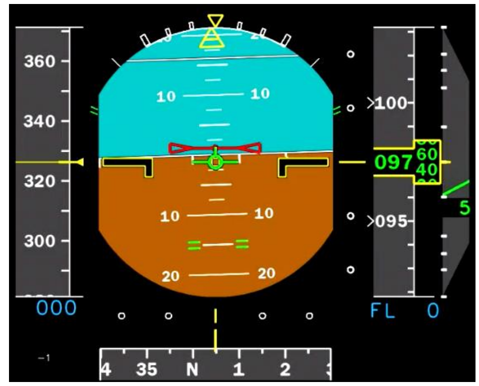

Fig. 2 Visualization of synthetic task in PFD.

B. Experimental Setup

For the final campaign a test matrix with over 400 test points was planned with different trim conditions, aircraft configurations and tasks. In order to allow a broad analysis of the simulator tests, data and video recordings were applied for each test point. All input and output data from the flight mechanical model and the hexapod motion system were recorded as well as a video showing the cockpit interior, an outside view of the simulator, the simulated aircraft motion, and a screen recording of the PFD.

The overall complexity of the trials was high compared to all experiments previously performed on AVES. The parameters that needed to be set up prior to each test point run included the flight mechanical model, motion parameters, pilot tasks, the visual system, and the data recording. The operator further had to carefully follow the test matrix, announce each test point, start the data, video and screen recording, start the simulation, and activate the motion and afterwards do everything in reverse order. Although it was decided to work with two experiment crews (pilot, flight test engineer, operator) in shifts of 90 minutes to counter fatigue and allow rest periods between simulator sessions, it became apparent in the trial's setup phase already that the operator's job was challenging. Operator performance was crucial to the success of the project, but showed to be tedious, error-prone, and therefore needed to be double-checked, especially as there was only little room for repetitions due to the tight scheduling and simulator as well as crew availability. Therefore, automatic proof-checking was deemed mandatory as manual checking was not an option due to the high number of test points to be performed.

An automatic checking process was developed that is shown in Fig. 3 and briefly described in the following. The process had to be initiated by the operator after the completion of a simulator session. The scripted process performed a data post-processing and testing. It was finished at least until the end of the crew's rest period. This allowed the crew to perform necessary repetitions of erroneous test points on their next shift already. The process started with collecting all test data like handling qualities (HQ) ratings and operator notes (also containing the intended test matrix), the data recordings and the video/screen recordings (see step 1 in Fig. 3). The data recordings were then post-processed and combined to a single data file (step 2 in Fig. 3). The resulting data file was then proof-checked with the intended test matrix contained in the operator notes. Test results were written into a report template that used conditional formatting for highlighting test points with discrepancies from the intended test point configuration. This report was checked by the resting crew before entering the simulator for their next shift, advising them which test points had to be repeated (step 3 in Fig. 3). The process concluded by archiving and uploading all data to the project's data storage (step 4 in Fig. 3) from where early analyses on the data could already be performed. The automatic post-processing and validity checking showed to be extremely helpful not only in identifying erroneous test points early, but also showed to be a time saver for the archiving and uploading process. In the final campaign, 456 test points were planned and executed, of which 41 were identified to differ from the intended setup and were therefore repeated. There were also made 23 repetitions upon pilot or engineer request for specific analysis. In total 520 test points were flown in approximately 40 hours of simulator time such that the data validity check process revealed to be a very tool in conducting this extensive campaign.

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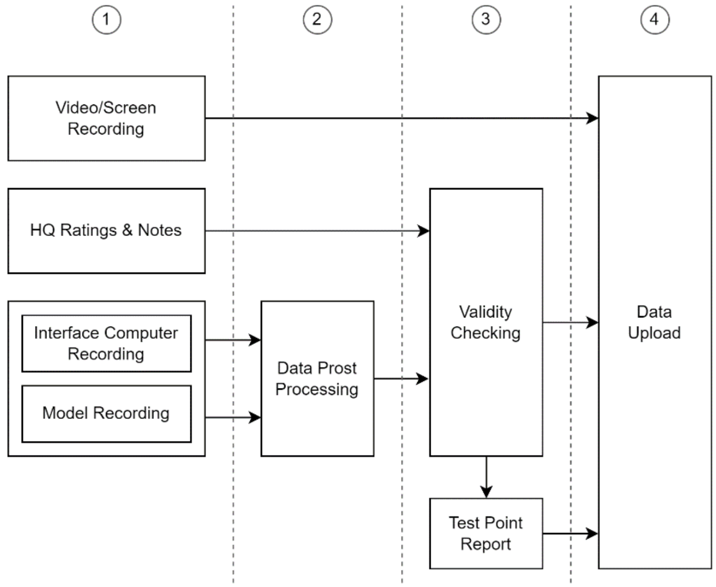


Fig. 3 Schematics of the data validity check process.

IV. Full-motion Simulator AVES

C. General Simulator Characteristics

The DLR simulator AVES, shown in Fig. 4 is a research simulator facility that is operated by the DLR Institute of Flight Systems since 2013 [1]. AVES comprises two platforms to simulate airplanes and helicopters: a fixed-base and a full-motion simulation platform, each with its dedicated projection system with a field of view of 240° x 95°. The motion platform is an electro-pneumatic six-degrees-of-freedom hexapod motion system whose motion cueing algorithm can be specifically tuned. This was paramount to the study described in this paper. Both platforms can be equipped with different cabs that can be exchanged due to a roll-on roll-off cab exchange system. Currently, three modules are available: An Airbus Helicopters H135 cockpit, a generic passenger cabin and an Airbus A320 cockpit. Currently, a second fixed-base platform as well as cockpit of a Dassault Falcon 2000LX being operated as DLR's new research aircraft ISTAR are being added to the AVES.

All of the aircraft specific simulation modules as well as the real-time simulation framework have been developed in-house at DLR and are completely customizable. For the presented study the motion platform was equipped with the Airbus A320 cockpit. During the trial's setup phase the cockpit of the A320 had to be adapted to be comparable to Embraer's simulator with which a complementary study was performed within the DinAFlex project. This adaptation included modifying the active sidesticks' force/deflection curve and the PFD with a possibility to display synthetic pilot tasks and creating a generic engine display.

Fig. 4 DLR full motion flight simulator AVES.

D. Motion Drive Algorithm

Flight simulation is the attempt to perform a real flight in a nutshell in a way that the pilot does not notice the illusion of the artificial reality reproduced around him. For most simulation components this is technically possible, e. g. by using the same avionic components so the pilots have the visual and haptic perception in the simulated cockpit as in the aircraft. For motion simulation things are more difficult due to the fact that accelerations and forces of the freely moving airplane cannot identically be reproduced within the space envelope of a standard motion platform, which has usually a range of less than 2 m in each direction. This problem is tackled by the Motion Drive Algorithms (MDA). MDAs are parts of the control algorithm running the motion systems and fulfill the task to translate the simulated aircraft accelerations into a movement of the simulator cabin. As it is obviously not possible to move the simulator cabin in the same way as the aircraft, a wash-out filter with a set of high and low pass filters manipulates the aircraft movements. In general, one can say that short accelerations can be reproduced more or less the same way as in reality while long-lasting accelerations have to be reproduced by changing the attitude of the simulator in a way the pilot does not notice, e. g. a take-off run can be simulated by pitching up the simulator cabin. The last method is called tilt-coordination and implies some problems concerning the realism of flight simulations with respect to human motion perception.

The problem starts where the change of an acceleration calls for a rotation of the simulator cabin that is noticeable by the simulator crew. In this case a trade-off needs to be found between the accurate reproduction of the acceleration leading to a noticeable rotation and an unnoticeable rotation leading to a perceived translational acceleration while the rest of the simulated environment shows something different. This situation may lead to medical issues like motion sickness that have a strong influence on the success of a simulator session. Another constraint is the fact that the tuning of an MDA has to guarantee that no platform boundaries (accelerations, velocities, angles) will be hit during the later use of the simulator. This leads to a situation where for a single flight phase the response of the motion systems is restricted more than necessary because otherwise the space envelope would not be sufficient for more aggressive maneuvers.

The standard way of dealing with this problem is to introduce a gain that reduces the incoming accelerations such that all flight phases can be reproduced within the platform's space envelope. An additional direct input for the longitudinal, lateral, and vertical accelerations, referred to as "buffet channel" here, ensures that high-frequency accelerations with small amplitudes can be fed to the motion system without passing though the wash-out filter. This is possible because high-frequency accelerations with small amplitudes only have a small space consumption and therefore do not endanger the aim to stay within the boundaries of the motion system. The main principle of this concept in described in [16] and illustrated in Fig. 5.

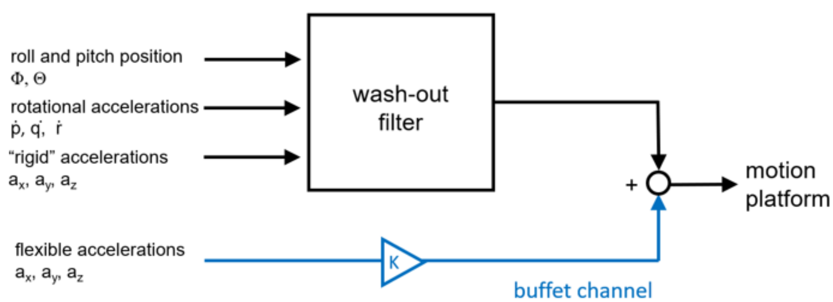


Fig. 5 Concept of wash-out filter and buffet channel.

In the DinAFlex project, two alternative ways to simulate the accelerations resulting from the flexible aircraft model were evaluated. In a first approach all accelerations are fed through the standard wash-out filter. In this approach the blue buffet channel in Fig. 5 is not used. In the alternative second approach the translational accelerations are split into the rigid and flexible part, as also suggested by [14]. The rigid components of the translational accelerations are fed though the standard wash-out filter, as usual. The flexible components of the translational acceleration (i.e. those translational accelerations that result from the flexible deformation of the aircraft), are not fed through the wash-out filter but added to the generated commands of the wash-out filter via the buffet channel as shown in blue in Fig. 5.

V. Motion Tuning

The AVES is theoretically designed to perform motions up to 10 Hz. However, up to now it had only been used to simulate rigid-body aircraft and the present campaign has been the first time a flexible aircraft has been simulated on the motion platform. Before performing the actual campaign, it had thus to be assured that the simulator is able to adequately represent the dynamics of the flexible aircraft. The questions to be answered are on the one hand how to integrate the flexible dynamics in the overall MDA and on the other hand how to evaluate whether the motion is adequately represented.

Concerning the way of integrating the flexible dynamics into the MDA the two general approaches with and without the buffet channel described in Section D had to be investigated and tuned for a good representation of the flexible dynamics.

The evaluation of a motion simulation is in general not trivial. The Objective Motion Cueing Test (OMCT) [17][18], which is sometimes applied as an objective evaluation criterion and implemented in current specifications such as FAA Part 60 [19] or ICAO 9625 [20], is designed for the standard rigid-body dynamics and the boundaries derived in ten different flight simulators [21] are only defined for frequencies up to 2.5 Hz. The flexible dynamics, whose influence on the handling qualities should be evaluated in the present project, occur, however, in the frequency range between 2 and 10 Hz. The OMCT can thus not be used as an evaluation criterion here. Nevertheless, the test of the OMCT have been applied as a preceding step to the actual motion tuning with an extended range up to 10 Hz in order to see if the AVES is physically able to principally simulate dynamics up to 10 Hz. The OMCT was performed with different motion cueing setups of the AVES motion system and demonstrated that the combination of platform and motion drive algorithm is able to reproduce frequencies up to 10 Hz.

After this physical feasibly had been demonstrated, the actual evaluation of the motion cueing was based on the subjective evaluation of a test pilot. The test pilot was an experienced Embraer test pilot with a flight experience of 9150 hours in total and 4000 hours as a test pilot. He was involved in the flight test programs of several Embraer aircraft. During the subjective motion tuning the test pilot performed the synthetic task as described in Section A with a range of predefined motion cueing configurations. These predefined motion configurations included on the one hand the variation of the motion setup (i.e. whether wash-out filter is used with or without the buffet channel) and on the other hand different parameter sets for the wash-out filter parameters and different gains of the buffet channel. These configurations represented the starting point for the pilot assessment. The pilot evaluated which configuration felt most similar to a real aircraft, considering flexible dynamics, of the given size and characteristics. Afterwards, the most promising configuration has been adjusted in cooperation with the pilot to further improve the motion perception for the given maneuvers and to avoid reaching boundaries of the motion platform.

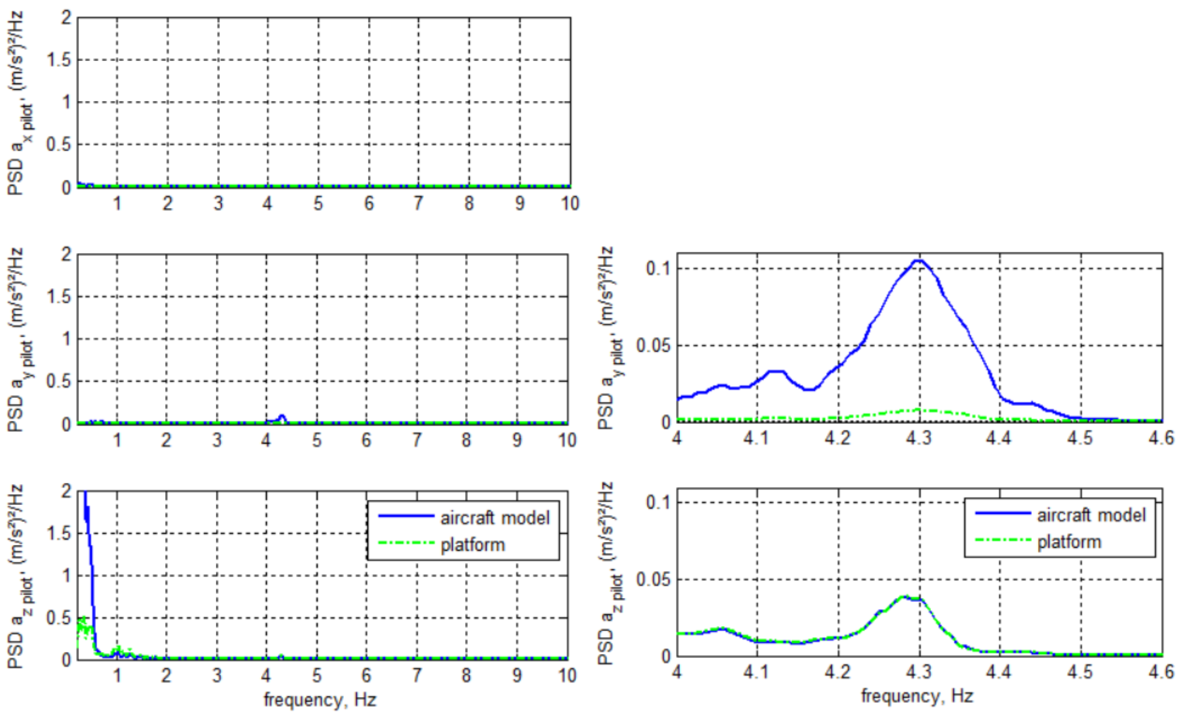
In addition to the pilot evaluation, the selected motion cueing settings have been analyzed in the time and in the frequency domain. The commanded model accelerations are compared to the actual motion of the motion platform in the time and in form of power spectral density plots in the frequency domain in order to evaluate if the motion adequately represents the commanded aircraft dynamics. Whereupon it is evident that the motion platform cannot follow large amplitudes at low frequencies due to its limited actuator length, the relevant higher frequencies with smaller amplitudes of the flexible dynamics should be matched appropriately by the motion platform.

The results are presented in following subsections. After some baseline motion configurations have been prepared beforehand, the motion tuning process with the pilot was thereby performed in the following sequence:

- pilot evaluation and time and frequency analysis of the regular wash-out filter, i.e. with original parameters of wash-out filter and without using the buffet channel (results presented in Subsection E)
- pilot evaluation and time and frequency analysis of the wash-out filter (with original wash-out filter parameters) but with usage of the buffet channel with varying gains (results with gain of 0.4 in buffet channel presented in Subsection F)
- assessment of violation of actuator limits for selected motion cueing configuration (original wash-out filter gains and buffet channel gain of 0.4)
- fine tuning of wash-out filter gains (while using buffet channel with gain of 0.4) to avoid actuator limits (final results after this tuning presented in Subsection G)

E. Results Using Regular Wash-Out Filter

In the first motion setup, which was tested in the subjective motion tuning, the overall translation accelerations, including the additive flexible values, were sent through the standard wash-out filter without the buffet channel (displayed in blue in Fig. 5) being used. This represents the standard setup for aircraft simulations in the AVES. Figure 6 shows the power spectral density (PSD) plot of the translational accelerations at the pilot seat. The left subplot (a) of Fig. 6 includes all three translational accelerations, a_x in longitudinal direction, a_y in lateral direction and a_z in vertical direction in the whole relevant frequency range up to 10 Hz. The right subplot (b) of Fig. 6 represents a zoom of a_y and a_z at the pilot seat in the frequency range of the first significant peak of the flexible modes. This peak corresponds to the asymmetric fuselage bending mode. This mode leads to a deformation of the fuselage and displacement of the cockpit, especially in lateral direction, and has consequently the biggest influence on the cockpit accelerations and thus on the pilot perception.



a) up to 10 Hz for a_x, a_y and a_z b) zoom of a_y and a_z

Fig. 6 PSD of translational accelerations at pilot seat for standard wash-out filter.

Subplot (a) of Fig. 6 shows that the rigid-body accelerations below 2 Hz occur mainly in the vertical axis. Flexible accelerations occur in lateral and vertical direction. The longitudinal axis does not exhibit significant accelerations in any frequency domain. Even the flexible accelerations are about one order of magnitude smaller than in the other axes. The analysis in this paper will thus focus on the y and z axes, which are much more relevant for the pilot's perception. Furthermore, the analysis will focus on the frequency ranges of the flexible aircraft dynamics. The rigid-body dynamics, which are dominant at low frequencies up to about 2 Hz, are evaluated as satisfactory by the pilot and are not the main focus here. Rigid-body aircraft have also been simulated in various versions in the AVES before and do not pose particular challenges. Higher frequencies of flexible aircraft have, however, not been simulated in the AVES before and require special focus concerning the motion tuning.

The zoom of a_y and a_z in subplot (b) of Fig. 6 illustrates that the power spectrum of the measured motion platform acceleration meets the spectrum of the acceleration commanded by the model very well in the vertical direction, whereupon it is much lower in the lateral direction. The reason for this behavior can be found in the gains of the wash-out filter. The gain in the vertical direction of the standard AVES wash-out filter is one. This matches the observation that the platform curve perfectly matches the aircraft model curve in Fig. 6, because the high-frequency content of the acceleration signal passes through the wash-out filter without any significant reduction in magnitude. In the lateral axis the gain of the standard wash-out filter is set to 0.2, which causes the much lower platform response compared to the lateral model outputs. The selection of the gains results from restrictions for the motion tuning of the rigid aircraft dynamics in the low-frequency range. Such gain reductions are necessary to avoid physical limits of the motion platform that lead to unnatural bumps in the motion perception. This reduction of the lateral motion in favor of smooth dynamics without reaching any limit is, however, only relevant at low frequencies. For higher frequencies with low amplitudes as in the case of the flexible mode around 4 Hz here, the physical motion limits are not critical and a gain reduction is not necessary. At these higher frequencies the reduced gain just unnecessarily impairs the motion response. The representation of the flexible modes in lateral and vertical direction do not fit together. The flexible dynamics are significantly underrepresented compared to the flexible dynamics of the vertical axis. The lateral flexible accelerations are five times smaller than the vertical flexible accelerations, which leads to a distorted perception of the flexible modes.

The frequency response also matches the pilot opinion who was not satisfied with the representation of the flexible modes in this motion setup and stated that it felt to low and unnatural. Even though the pilot did not explain the unnatural feeling of the flexible dynamics in more details, it is likely that the unequal amplitude of the flexible dynamics in lateral and vertical direction led to his abnormal perception of the flexible vibrations.

F. Results Using Buffet Channel

As the project focusses on the evaluation of the flexible aircraft dynamics, the unnatural representation of the flexible modes in the lateral axis resulting from the wash-out filter gain was not satisfactory. As discussed above, an approach to improve the motion simulation particularly at higher frequencies can be the usage of the buffet channel, displayed in blue in Fig. 5. This has the benefit that the parameter settings of the wash-out filter, which have previously been tuned for rigid-body aircraft dynamics with the restriction of avoiding platform limits, do not have to be modified. The buffet channel can then freely be adapted to represent the accelerations resulting from the flexible modes. The limitations of the platform, which led to the low gain of 0.2 in the wash-out filter, are much less critical at higher frequencies with small amplitudes.

Different gains (see gain K in Fig. 5) have been tested in the buffet channel. This gain allows a reduction of the flexible accelerations, which are then added to the output of the wash-out filter and fed directly to the motion platform. It turned out that a gain of one, i.e. the unmodified flexible accelerations generated by the model, feels significantly too strong. Although this might seem surprising at first, it becomes plausible when recalling the gains of the wash-out filter. Especially in the lateral axis, the motion representing the rigid-body dynamics coming through the wash-out filter is strongly reduced due to the gain of 0.2. If 20% of the rigid-body dynamics are combined with 100% of the flexible dynamics the flexible vibrations occur significantly too strong. Test of different gains revealed that a gain of 0.4 in all three axes represents a good compromise and leads to a realistic impression of the flexible modes according to the test pilot's opinion.

Figure 7 shows the PSD plot of the lateral and vertical acceleration at the pilot seat for the wash-out filter combined with the buffet channel. The blue solid line and the green dash-dotted line are equivalent to these lines in Fig. 6 and represent the accelerations, which are the output of the aircraft model, and the actual platform response respectively. In addition, the red dashed line shows the input to the MDA. This is composed of the rigid accelerations, also shown separately in the figure as a magenta dashed line, and the flexible accelerations fed through the buffet channel, also displayed separately as the black dotted line. The buffet channel already includes the gain of 0.4. This is the reason for the deviation between the aircraft model output in blue and the motion input in red. The model output in blue comprises the true rigid-body and flexible accelerations of the aircraft model. The motion input is composed of these two components as well but the flexible acceleration contains the gain of 0.4 in this case.

The motion input thus represents the command value for the motion platform. It can be seen in Fig. 7 that the platform perfectly fulfills the commanded acceleration w.r.t. the power spectrum. The red dashed line and the green dash-dotted line match very well. The motion platform is thus able to achieve the intended dynamics. It can also be noticed in Fig. 7 that, in the displayed frequency range, the influence of the rigid-body aircraft dynamics is negligible and the overall aircraft response in this frequency range is dominated by the flexible accelerations.

Comparing Fig. 6 and Fig. 7 reveals, that even though the commanded accelerations in red are matched very well, the match with the actual aircraft dynamics in the vertical direction is, of course, worse than without the usage of the buffet channel with a gain of 0.4 as shown Fig. 6. In Fig. 6 the motion platform matches the acceleration because the regular wash-out filter has a gain of 1 in vertical direction, whereupon the gain in the buffet channel in only 0.4 for all axes such that the motion reaction is lower than the actual aircraft dynamics. The more important aspect for the pilot is, however, that the flexible dynamics are consistent between the different axes and that an adequate ratio between the rigid-body and flexible dynamics is perceived. In case of the regular wash-out filter, the perception of the flexible modes is distorted because the lateral flexible accelerations are five times smaller than the vertical flexible accelerations.

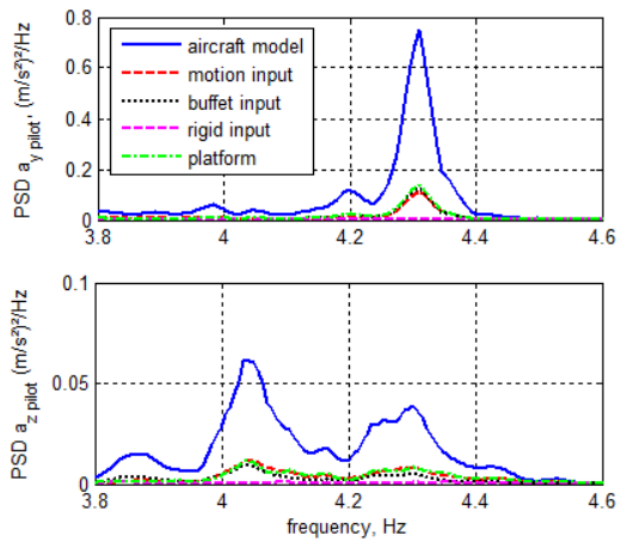


Fig. 7 PSD of translational accelerations at pilot seat for wash-out filter combined with buffet channel.

Figures 8 and 9 show the time response of the lateral and vertical accelerations at the pilot seat. Both figures demonstrate that the motion adequately simulates the commanded aircraft dynamics. Figure 8 shows a time slice mainly dominated by flexible vibrations. The red dashed line of the command value for the motion looks very similar to the flexible accelerations, displayed as the dotted black line (already including the gain of 0.4), only with a vertical offset due to the rigid-body motion (magenta dashed line). The motion platform (green dash-dotted line) follows the red dashed command line with the same amplitude and only a small time delay. The phase lag is expected for these high frequencies. It is uncritical for the pilot's perception as the pilot does not aim to close the control loop for these flexible accelerations. At these high frequencies, the pilot is not able to distinguish the phase. He just feels these flexible modes as vibrations.

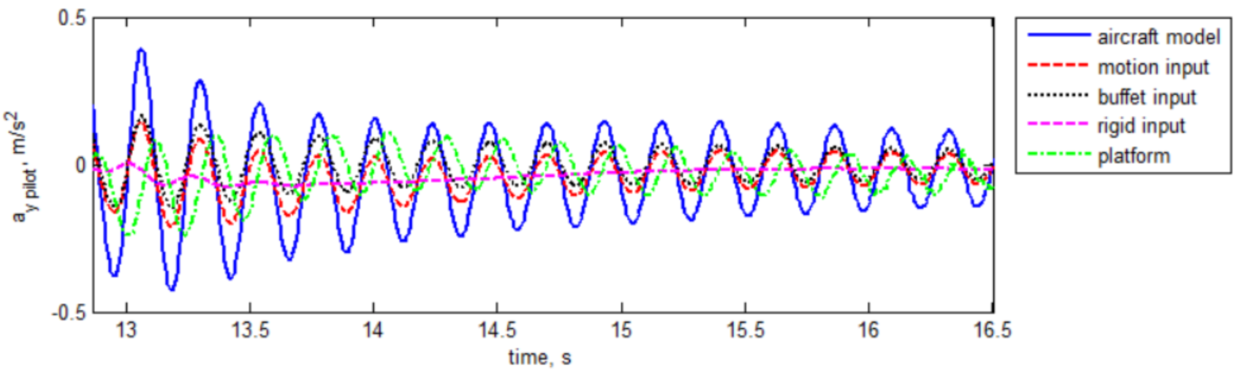


Fig. 8 Time domain plot of lateral acceleration at pilot seat for wash-out filter combined with buffet channel.

The acceleration in vertical direction is also very well reproduced by the motion platform as shown in Fig. 9. In this case, the motion is dominated by the rigid-body dynamics. The corresponding magenta dashed line lies below the blue solid line of the aircraft model output. The impact of the flexible accelerations is negligible here. In case of these low-frequency rigid-body dynamics the motion platform does not show a noticeable phase lag and can easily follow the dynamics. The comparably large amplitude acceleration in the vertical axis cannot be reproduced by a standard motion simulator with its limited actuator length. This is a classical issue addressed by the MDA deriving adequate motion movements without reaching the platform boundaries. Figure 9 shows that the simulator solves this problem appropriately as the motion adequately follows the initial model acceleration and then drives the platform back.

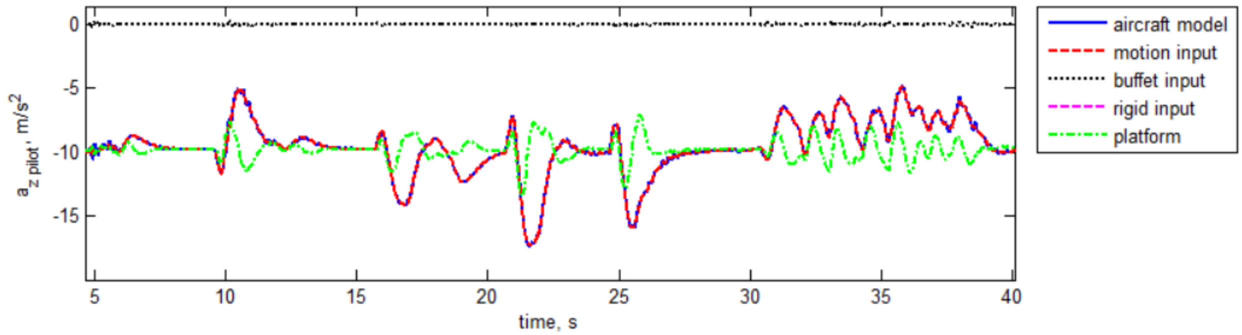


Fig. 9 Time domain plot of vertical acceleration at pilot seat for wash-out filter combined with buffet channel.

Although the motion represents the model dynamics quite well and the pilot was satisfied with the perception of the aircraft dynamics, the given setting still had the problem that it sometimes reached actuator limits of the motion platform. Even though this happened only rarely, it has to be prevented as reaching the actuator limits leads to abrupt and very unnatural movements which strongly disturb the pilot's perception. Figure 10 shows the acceleration, velocity and position during the synthetic task maneuvers exemplarily for actuator 1 and the corresponding actuator limits. The motion of the other five actuators is qualitatively the same. The acceleration and position of the actuator stays relatively far away from the limits, but the velocity limits are hit a couple of times.

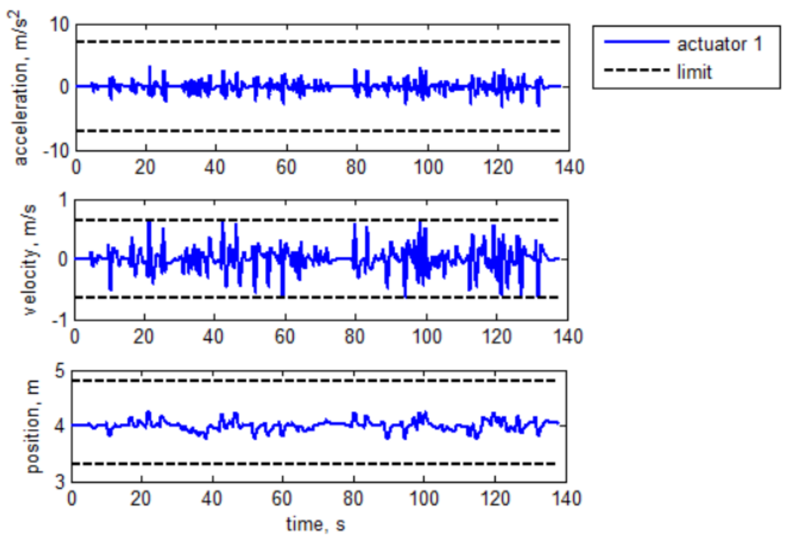


Fig. 10 Actuator dynamics for wash-out filter with buffet channel.

A fine tuning of the parameters of the wash-out filter was performed with the goal to avoid reaching the velocity limits and to further improve the overall motion perception. As the time response showed that the particularly large movements occur in the vertical axis, the fine tuning concentrated on this axis and modified the gain and cutoff frequency of the vertical wash-out filter of the MDA. The goal is to keep the gain in vertical direction as high as possible to stay as close as possible to the commanded aircraft dynamics but as low as necessary to avoid actuator limits. Testing a z-gain of 1, 0.8, 0.7 and 0.5 showed that 0.8 represents the best comprise. In addition to this, the cutoff frequency was raised from 2 rad/s to 4 rad/s. The resulting actuator movements are displayed in Fig. 11. The velocity also stays safely within the given limits. The other five actuators exhibit the same qualitive dynamics again.

As the flexible accelerations are fed through the buffet channel, the representation of the flexible dynamics remains unaffected by the adaption of the wash-out filter parameters. The overall dynamics after the fine tuning are presented in the following subsection.

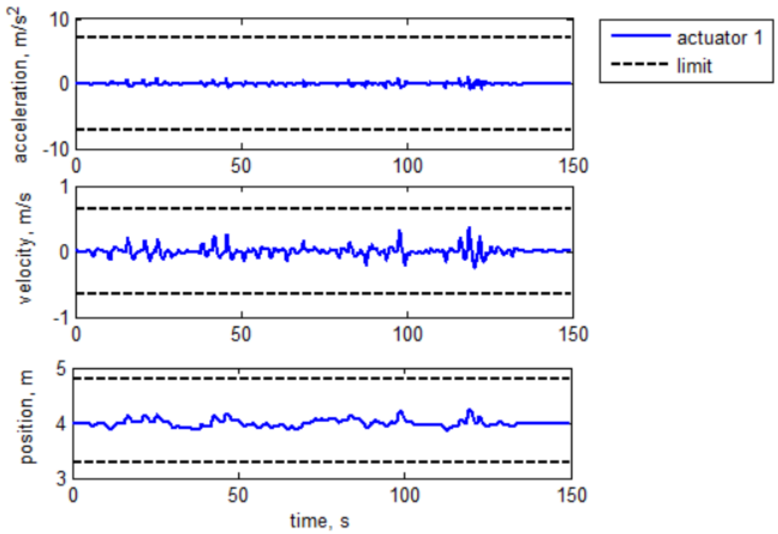


Fig. 11: Actuator dynamics for wash-out filter with buffet channel after fine tuning.

G. Final Motion Cueing Settings

After the fine tuning the final settings for the motion cueing result in usage of the buffet channel and following parameter settings for the wash-out filter and gain of the buffet channel:

- x-axis wash-out filter settings: gain of 0.6 and cutoff frequency of 3 rad/s
- y-axis wash-out filter settings: gain of 0.2 and cutoff frequency of 1 rad/s
- z-axis wash-out filter settings: gain of 0.8 and cutoff frequency of 4 rad/s
- buffet channel settings in all axes: gain of 0.4

Figure 12 shows the PSD plot of the lateral and vertical accelerations at the pilot seat with this motion cueing parameter set. The commanded acceleration spectrum (red dashed line) is matched very well by the motion platform.

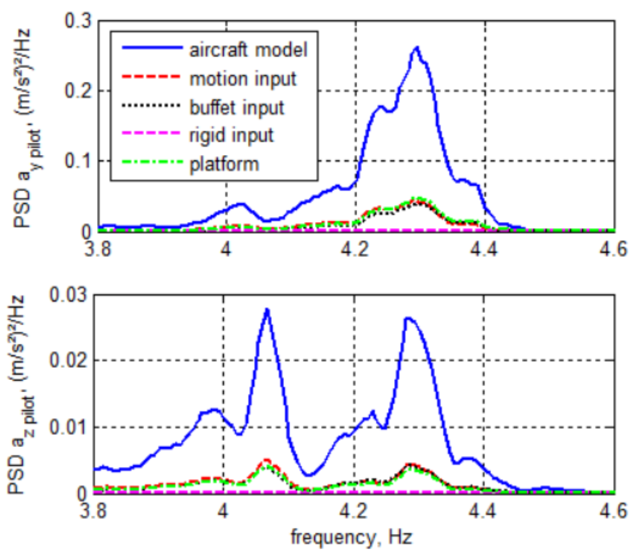


Fig. 12 PSD of translational acceleration at pilot seat for final motion cueing setting.

Figure 13 presents the time response of the longitudinal acceleration with the final motion settings. The time response of the lateral acceleration is not displayed again, as the parameter settings of the lateral filter remained unchanged compared to Fig. 8.

Although the time response of the z-acceleration is not identical to Fig. 9 because the pilot made slightly different inputs for accomplishing the same synthetic task in this case, it can be noted that the amplitude of the platform response is slightly lower compared to the dynamics of the commanded aircraft dynamics. This conforms to the reduced wash-out filter gain of 0.8 in the vertical axis. (compared to the z gain of 1.0 of the wash-out filter in Fig. 9). The pilot did however not complain about a too small perception of the vertical accelerations. The reduction of the z gain is thus evaluated as a good comprise in order to avoid actuator limits.

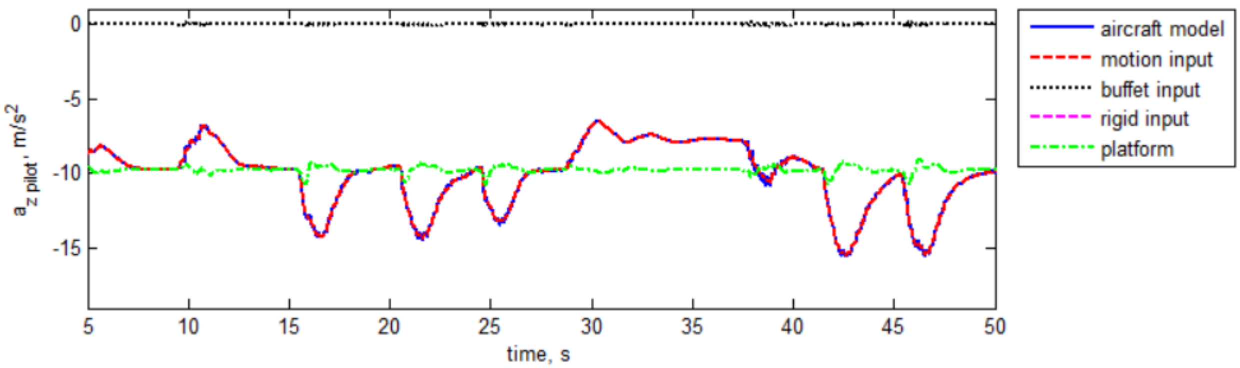


Fig. 13 Time domain plot of vertical acceleration at pilot seat for final motion cueing setting.

Overall, the behavior of the final motion cueing parameter set is very similar to the motion parameter set of Section F. The main differences are that the actuator limits are not reached, as demonstrated already in Fig. 11, and that the motion reaction in the vertical is slightly reduced. The test pilot was very satisfied with these final settings. In addition, the test pilot considered the simulation with the inclusion of the flexible modes more realistic and closer to an actual flight. The goal of finding a motion setting to adequately represent the flexible aircraft dynamics could thus be fulfilled and the simulator setup was ready for the actual simulator campaign for the handling qualities assessment.

VI. Conclusion

The present paper describes the preparation of an extensive simulator campaign for the evaluation of the effect of structural flexibility on handling qualities. It presents the preparation of the simulator setup including display modifications and the data handling process and discusses the challenges of the integration of the flexible aircraft dynamics into the motion simulation. Two different concepts are studied: the usage of the regular wash-out filter and an alternative way using a so-called buffet channel for the high-frequency accelerations to bypass the wash-out filter and feed them directly to the motion platform. These approaches were evaluated by a test pilot and analyzed in time and frequency domain. The investigations revealed that the second approach with the usage of the buffet channel was much more suitable. It allowed to keep the parameters of the wash-out filter tuned such that the rigid-body dynamics do not hit any actuator limits of the motion platform and, at the same time, the high-frequency dynamics of the flexible modes could be freely adjusted in the motion cueing. In case of the usage of the regular wash-out filter without the buffet channel the flexible accelerations were artificially reduced due to the setup of the wash-out filter. By using the buffet channel, the commanded flexible accelerations could adequately be met by the motion platform. The tuning showed that it is important to assure an adequate ratio between the rigid-body and flexible dynamics. If the rigid-body gain is reduced due to limitations of the motion platform, the gain of the flexible vibrations should be reduced as well to avoid an overestimation relative to the rigid-body motion. Furthermore, it is important to achieve a correct ratio of the flexible vibrations of the different axes. Due to the usage of the buffet channel the gain for the flexible accelerations is equal in all three axes and they are not distorted by different gains in different axes of the wash-out filter. Altogether the paper presents a successful approach to implement a flexible aircraft model on a full-motion simulator leading to a realistic impression of the flexible aircraft dynamics according to pilot opinions.

For future works it would be interesting to study the optimal ratio between the flexible and rigid accelerations, i.e. the gain of the buffet channel, in more detail. A gain of 0.4 showed good results in this first approach here. However, the general combination of low-frequency accelerations, which need to be modified by the MDA due to limitations of the motion platform, and high-frequency flexible accelerations still represents a very new aspect in the motion simulation research. A dedicated study with a larger number of pilots could bring interesting insights for appropriate ratios of rigid-body and flexible dynamics in the motion simulation.

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