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Simulator Study on Ride Comfort of Flexible Aircraft

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Increasing structural flexibility of modern aircraft, driven by advances in lightweight materials and high-aspect-ratio wing designs, has introduced new challenges for passenger and ride comfort. High-frequency oscillations of flexible modes can degrade the passenger comfort and well-being. The joint Project RiCoFlex (Ride Comfort of Flexible Aircraft) of DLR and Embraer has the goal to identify the impact of aeroelastic flexibility on passenger comfort and to develop assessment criteria, which also provide a basis for the design of control laws to improve passenger comfort of flexible aircraft. A large simulator study in the passenger cabin of the DLR full-motion simulator AVES was conducted to address this topic. The present paper describes the setup up of the simulator campaign including the development of relevant test cases and the applied questionnaires. The passenger ratings showed different dependencies for frequency variations in the lateral and vertical axis and a parallel shift of the frequency-dependent trends with increasing amplitude of the oscillations.

I. Introduction

Recent aircraft developments aim at an increase in efficiency to make aircraft ecologically and economically more attractive. Modern aircraft designs are therefore usually characterized by light structures of new composite materials as well as high aspect ratio wings. This results in reduced weight and fuel burn but at the same time also leads to increased aeroelastic flexibility. Previous studies [1]-[4] showed that aeroelastic flexibility can influence the handling qualities of the aircraft and can trigger pilot-induced oscillations as well as involuntary pilot inputs, so-called biodynamic coupling. Schwithal et al. conducted a simulator study in [5] to investigate the impact of structural flexibility on handling qualities. Even though the main focus of this study was on handling qualities, the pilot ratings also revealed that increased structural flexibility leads to impaired ride comfort, as structural vibration resulting from the flexible modes provoke uncomfortable oscillations for the pilots as well as for the passengers.

Different studies have already addressed passenger comfort during flight. Mansfield and Aggarwal [6] provide a literature review of whole-body vibration in fixed-wing aircraft and present different studies on measurements of vibrations covering various aircraft types. However, these approaches do not particularly address aeroelastic flexibility and Mansfield and Aggarwal in general recommend further studies on whole-body vibration in aircraft. Many studies on passenger comfort in aircraft use ISO 2631-1 [7] or BS 6841 [8] as evaluation criteria. Both regulations represent general metrices to evaluate human exposure to whole-body vibration. Ciloglu et al. [9] for instance apply ISO 2631-1

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and BS 6841 to evaluate the comfort in different aircraft seats in different flight conditions. Kubica and Madelaine [10] also apply ISO 2631-1 in their control law design for passenger comfort improvement. Even though these requirements are often used for ride comfort assessment in aircraft, they represent very general references for any kind of vibration found in vehicles, in machinery, in buildings, or close to working machinery. These metrics are not specifically designed for aircraft, nor do they cover any specific aspects relevant for flexible aircraft. NASA conducted a very large simulator study to develop an empirical model for the prediction of passenger ride discomfort in the presence of complex noise and vibration inputs [11]. This model is a good reference but has a very general focus and does not specifically concentrate on aeroelastic flexibility either. Other studies e.g. by Petit [12] applied an extension of a motion sickness prediction model developed by Kamiji [13], which directly models the human motion sickness mechanism. Due to its focus on motion sickness, which usually occurs at lower frequencies, however, this approach is not assumed to cover all aspects of discomfort of flexible aircraft either.

In the framework of the project RiCoFlex (Ride Comfort of Flexible Aircraft), DLR and Embraer address the topic of passenger comfort with a specific focus on aeroelastic flexibility. The project has the goal to develop an assessment metric for ride quality and passenger comfort of flexible aircraft. The project partners conducted a simulator campaign in the DLR full-motion simulator AVES (AirVehicle Simulator) [14] to identify the specific impact of aeroelastic aircraft flexibility on passenger comfort. The developed criteria should also provide a basis to design control laws to improve the passenger and ride comfort of flexible aircraft by mitigating uncomfortable oscillations. The present paper describes the setup of the conducted simulator campaign, including the development of an adequate test matrix on the basis of preliminary offline simulations and motion pretests, the questionnaires used to gather the passengers' perception, as well as first results of the passenger ratings and possible ride comfort criteria for flexible aircraft.

II. Test Matrix Development

In preparation of the simulator campaign, an important aspect is the specification of the test cases. In order to receive meaningful and generally applicable results, the tests should be realistic and representative for flexible aircraft. Detailed offline simulations and simulator pretests are therefore performed to derive an adequate test setup.

A. Offline Simulations

The test matrix for the simulator tests shall consist of generic motion sequences that allow the derivation of general, aircraft-independent ride comfort criteria. The criteria shall, however, be developed for motion patterns that cover a realistic range of present and future flexible aircraft. Extensive offline simulations have thus been performed in preparation of the actual simulator campaign, in order to determine relevant amplitudes and frequencies to cover the characteristics of flexible aircraft. The simulations include different maneuvers with a generic flexible aircraft model of a modern midrange aircraft (developed in the project DinAFlex [3][4]). Table 1 gives an overview of the simulated maneuvers, the positions, at which the accelerations are considered, and the flexibility levels. The variation of the flexibility level has the goal to cover future aircraft, which are assumed to show even higher degrees of flexibility than present aircraft configurations. Therefore, a so-called extended flexible model is included in the simulation, whose stiffness is artificially reduced by factor two. The maneuvers are simulated at different flight points and with different mass conditions in order to cover a large range of envelope.

Table 1: Overview of maneuvers, positions, and flexibility level of offline simulations.

Maneuvers	Position of accelerations	Flexibility level
Level flight in light/moderate/heavy turbulence	Cockpit Center of gravity Rear of cabin	Quasi-static Flexible Extended flexible
Approach with light/moderate turbulence		
Landing with moderate/without turbulence		
Offset landing		
Lateral/vertical gusts with 18m, 50 m, 100m, 160m, 214 m gust length (according to CS 25.341)		
30° bank angle capture with 5°/10°/20° bank angle		
Go-around		
Takeoff with 2°/s, 4°/s, 6°/s pitch rate		

Figure 1 displays the power spectrum density (PSD) plot of the translational accelerations during level flight in moderate turbulence. Red lines represent the accelerations at the pilot seat. Blue lines display the accelerations at the passenger seat in the very back of the aircraft. Different line styles display different flexibility levels of the aircraft. The dotted line shows the accelerations of a quasi-static version of the generic aircraft model, the dashed line displays the accelerations of the generic aircraft model with its regular flexibility level, and the solid line presents the accelerations of the extended flexible aircraft model with artificially increased flexibility. Only frequencies up to 10 Hz are included in Fig. 1 as the AVES simulator cannot reproduce frequencies above 10 Hz. The generic flexible aircraft model also contains modes with higher frequencies. Their influence is, however, low in comparation to modes below 10 Hz. Even though ISO 2361 predicts impacts on human comfort for vibrations up 80 Hz, these frequencies are out of scope of the present study. This study only focusses on frequencies at which an improvement of passenger comfort could be achieved by active control. The bandwidth limitation of the simulator to 10 Hz is thus sufficient for the scope of the present study.

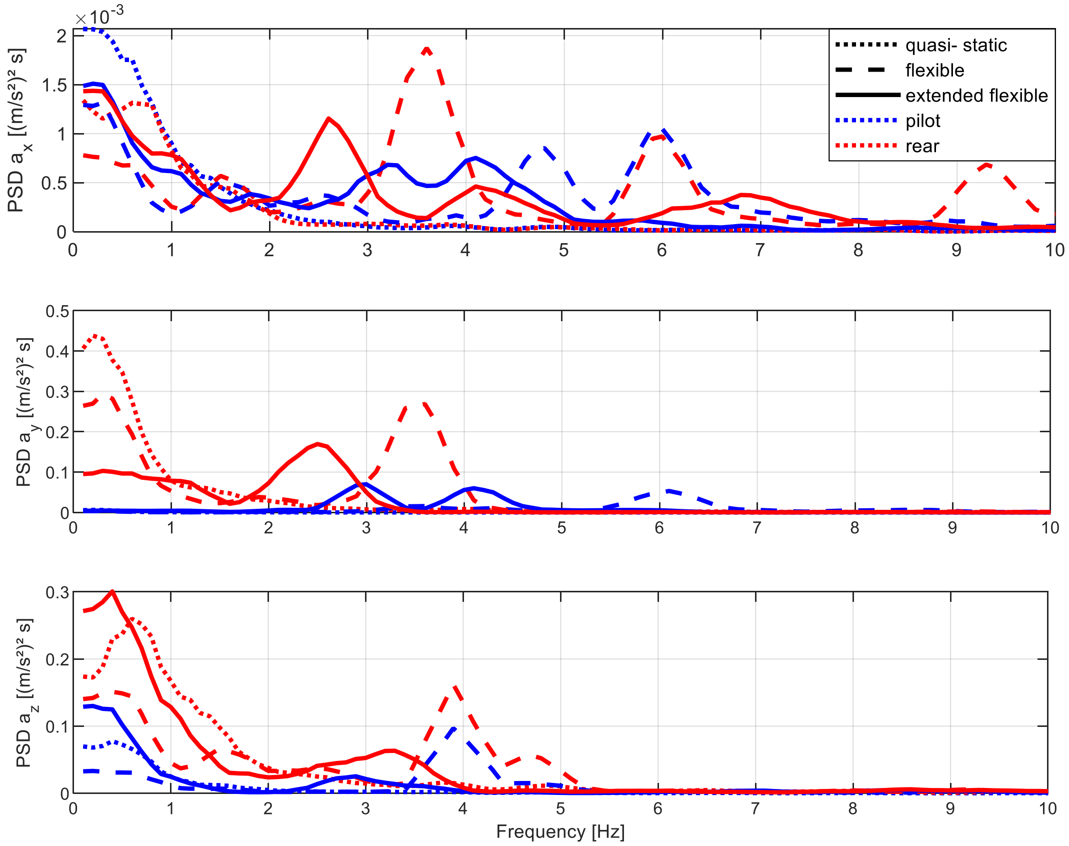


Fig. 1 PSD of translational accelerations.

In order to derive generic test cases from the simulated maneuvers, the most relevant frequencies and amplitudes from the PSD plots of the offline simulations are extracted and replaced by generic sine functions. The generic sine functions should thereby not be limited to the exact amplitudes and frequencies found in the simulated maneuvers, but should include some variations, in order to allow the development of ride comfort criteria, which are independent of a specific aircraft type.

For the determination of the relevant ranges of the frequencies and amplitudes, the amplitudes of the peaks in the PSD plots and corresponding frequencies at which they occur are collected for all different maneuvers, trim points and flexibility levels. Fig. 2 exemplarily shows this for level flight in moderate turbulence. Red markers again show the amplitudes that occurred at the pilot seat during a simulation of flight in moderate turbulence. Blue markers display the amplitudes at the rear of the aircraft. Crosses are simulations with a quasi-steady aircraft model, circles with a flexible aircraft models and diamonds with the model with extended flexibility.

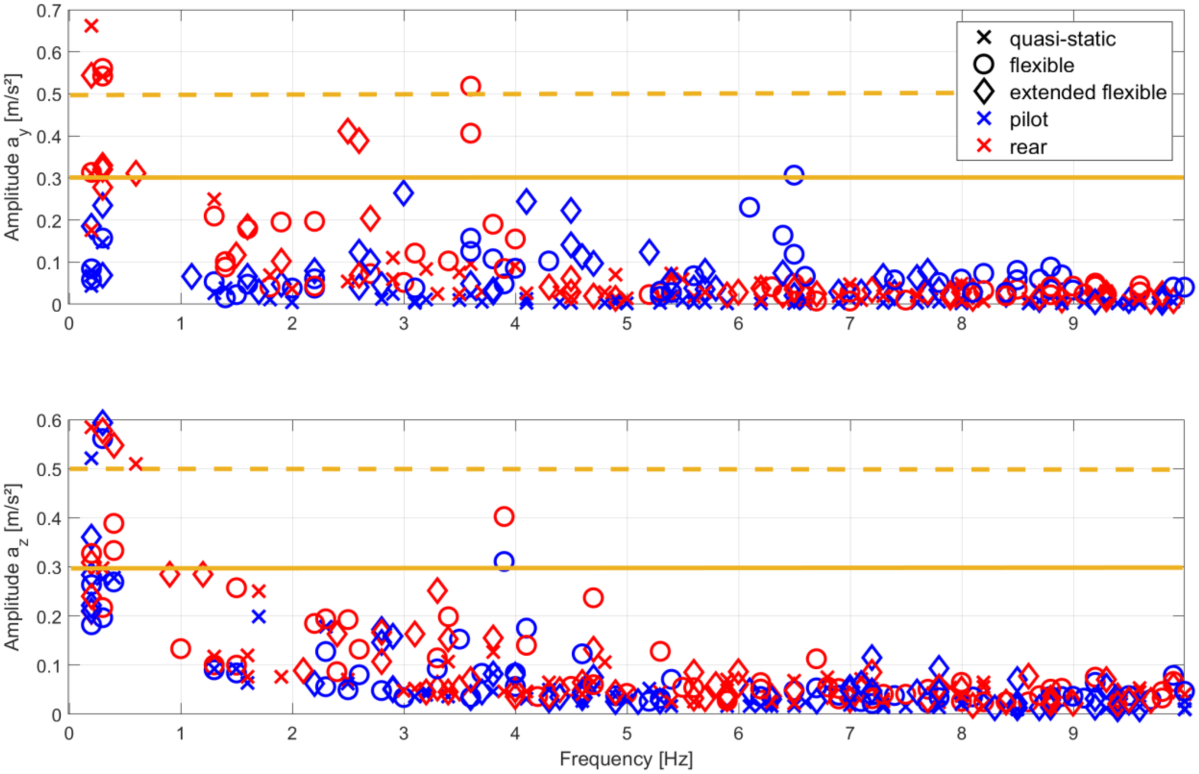


Fig. 2 Amplitudes-frequency-combinations derived from PSD peaks.

Frequencies below 1.5 Hz are not considered in the further analysis as they result from the rigid body motion of the aircraft. Obviously, rigid body dynamics strongly influence the ride comfort as well and it has to be assured that uncomfortable motions such as e.g. strong Dutch roll motions are prevented. However, this is out of the scope of the current study, which specifically focusses on the impact of high-frequency vibrations arising if aircraft structures become increasingly flexible. Considering frequencies above 1.5 Hz, it can be noticed that the majority of the amplitudes is below 0.3 m/s² (solid yellow line in Fig. 2) and all amplitudes stay roughly below 0.5 m/s² (dashed yellow line in Fig. 2). Amplitudes of 0.3 m/s² and 0.5 m/s² will thus be used as a basis for the simulator campaign.

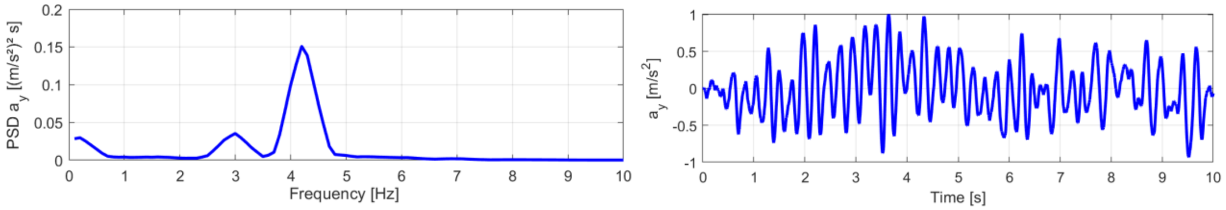
B. Preliminary Motion Tests

After the general range of frequencies and amplitudes has been derived by offline simulations, the next step is to get a haptic perception of the maneuvers and motion sequences in the simulator. This step is essential, as the subjective impression reveals more complex insights than pure theoretical analysis. The pretest covers replays of the flexible aircraft model in turbulence as well as various generic sine functions with different amplitudes and frequencies with several overlying sine functions or only single sines, in multiple axes or only single axis, rotational and translational.

For the replay of flight in turbulence, the dynamics in different translational and rotational axes were successively artificially set to zero. This test revealed that the oscillations of the flexible aircraft in the rotational accelerations, in the Euler angles as well as in the longitudinal accelerations have no noticeable effect on the overall perception during flight in turbulence. Obviously, rotational and longitudinal accelerations can generally have significant effects on passenger comfort. Considering the effect of structural flexibility, however, the dynamics in the rotational and longitudinal resulting from flexible modes are negligible. The further tests were thus limited to translational motions in lateral and vertical axis.

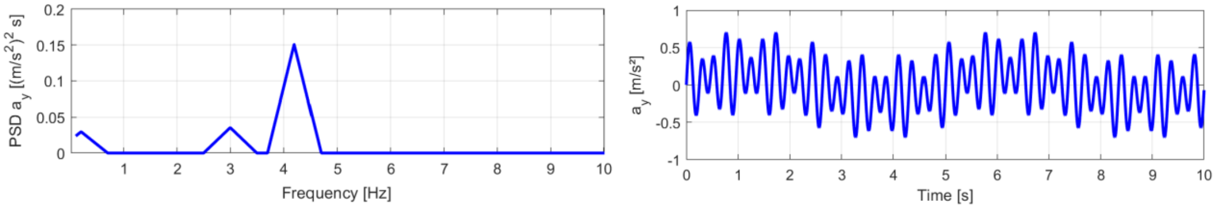
In the process of breaking the actual aircraft dynamics down to generic sine functions, the most dominant frequencies are extracted from the PSD of a flight (with the generic model with extended flexibility) in moderate turbulence and reconstructed as an overlay of three sine functions. The selected maneuver and trim case are just an arbitrary example to study the suitability to reduce the actual aircraft dynamics to a few (here three) generic sine functions and to test the perception of the generic sines in the simulator. Figure 3 shows the PSD and time history of the lateral acceleration a_y during level flight in moderate turbulence. The peaks in the PSD occur at 0.2 Hz, 3 Hz, and

4.2 Hz. Figure 4 shows the PSD and time history of three overlaying sine functions at these three frequencies with the corresponding amplitudes that reproduce the PSD of the flight in turbulence. Both cases, the lateral oscillations displayed in Fig. 3 as well as the three sines shown in Fig. 4, were tested in the simulator.



(a) PSD of lateral acceleration **(b) time history of lateral acceleration**

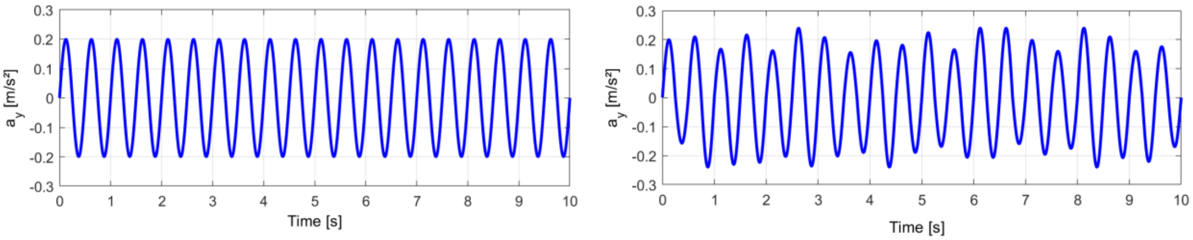
Fig. 3 lateral acceleration of a flexible aircraft during level flight in moderate turbulence.



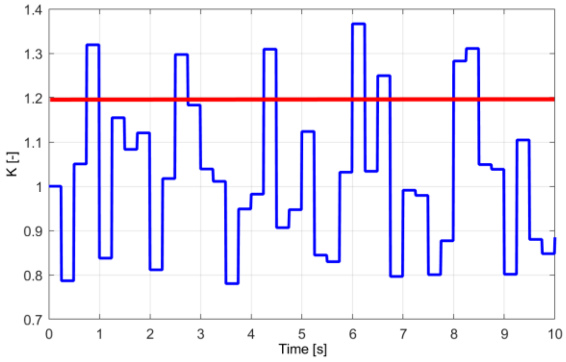
(a) PSD of lateral acceleration **(b) time history of lateral acceleration**

Fig. 4 three generic sines reproducing PSD of Fig. 3.

Even though the PSD plots look similar and three overlaying sine functions seem to reproduce the lateral accelerations of the flexible aircraft in flight quite well, the subjective impression in the simulator is noticeably different. The generic sine oscillations feel similar to a replay of the flight in turbulence but more regular and thus more synthetic. This effect can also be observed in the time history plots of the two motions patterns. The frequencies are comparable but the amplitude varies more in the case of the simulated flight in turbulence (Fig. 3 (b)).



(a) Sine with fixed amplitude of 0.2 m/s² **(b) Sine with random amplitude variation**



(c) Random factor K varying the amplitude of the sine

Fig. 5 Sine with random amplitude variation.

To provide a less synthetic oscillation feel, the amplitude of the generic sines is adjusted by a random gain variation as shown in Fig. 5. The amplitude is modified by randomly varying the gain (with a normally distributed random signal with a standard deviation of 0.5, which is updated with 6 Hz) as displayed in subplot (c) of Fig. 5. This addition of noise results in a more realistic perception, but still allows to focus on the selected isolated frequency, which remains unchanged. Amplitudes above 120% are cut off in order to avoid too large amplitude increases above the nominal amplitude. The impression in the simulator was deemed to be more realistic.

C. Final Test Matrix

The final test matrix is designed on the basis of the findings of the offline simulations as well as the preliminary motion tests. The first test case of all experiments is always the same replay of flight in moderate turbulence with the generic aircraft model with regular flexibility. In this test case, the full dynamics in all axes (translational and rotational) are reproduced in the simulator, i.e. even though the lateral and vertical axes are the most relevant axes, the remaining axes are also included in the replay case and not artificially set to zero. This first case thus serves as a reference, indicating how sensitive the participants generally react to the motion.

Table 2: Parameter variations of excitations in test cases.

Amplitudes [m/s²]	0.1, 0.3, 0.5
Frequencies [Hz]	1.5, 2, 2.5, 3, 4, 5, 6, 7
Axes	a_y, a_z

After this reference test case, the sinusoidal test functions with different amplitudes and frequencies are applied in different axes. Table 2 gives an overview of all parameters included in the study. The amplitude is set to 0.1 m/s², 0.3 m/s², or 0.5 m/s². Thereby 0.3 m/s² and 0.5 m/s² match the results of Fig. 2. The 0.1 m/s² amplitude is added as an additional case with low excitation. The frequency range is defined in such a way that it covers the relevant range for the aeroelastic flexibility of present aircraft as well as aircraft in the near future. Frequencies below 1.5 Hz are not considered as they are below the usual frequency of the first flexible mode. Frequencies above 7 Hz are also not included anymore since active mitigation at such high frequencies is not expected to be viable due to actuator restrictions. Aiming at the development of a ride comfort criteria that can be used as a design criterion for ride comfort control and with the constraint to keep the number of parameter combinations at a feasible number for the simulator study, the upper frequency limit is set to 7 Hz. Table 3 shows the assignment of the parameters of Table 2 to the different test cases. In order to allow a clear analysis of the influences and the derivation of a criterion, most test cases use a sinusoidal oscillation in only one translational axis and with only one frequency at a time. Frequency, nominal amplitude[7], and axis remain constant during each test case. A test case lasts 10 minutes, followed by a break of 5 minutes for the participants to recover from the preceding motion. The different colors indicate different testing groups, which will be described in detail in Section IV.

In addition to the tests of Table 3, which are considered most relevant for the analysis of the impact of aeroelastic flexibility on ride comfort, test cases of lower priority were addressed in a side study, as shown in

Table 4. These tests were executed with a lower number of participants in total, only testing groups (Group C and D displayed in grey and yellow in

Table 4) and a shorter duration per test case, as described in detail in Section IV. The test pattern of Fig. 8 was changed to six five-minute test cases with five-minute breaks in between. These experiments had the purpose to get first insights of test cases with lower priority such as the 0.1 m/s² amplitude, 7 Hz frequency, simultaneous combinations of different amplitudes or frequencies or test cases without random amplitude variation[8]. The simultaneous excitation of either two frequencies or two axes, for instance, is beyond the focus of the present study. Corresponding tests are only considered to get first insights of possible interdependencies and potential aspects that might have to be addressed in follow-up studies.

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[7] The nominal amplitude is the selected amplitude of Table 3. This amplitude is randomly varied according to the approach described in Section B.

[8] There is not random variation of the amplitude according to the approach of Section B in these test cases, but the amplitude is constantly 0.3 m/s².

Table 3: Test cases of main simulator campaign.

Case	Frequency [Hz]	Amplitude [m/s²]	Axis
0	Replay of flight in turbulence with generic aircraft model (regular flexibility level) including full dynamics in all axes		
1	🟦 1.5	0.3	z
2	🟩 2		
3	🟧 2.5		
4	🟦 3		
5	🟩 4		
6	🟧 5		
7	🟦 6		
8	🟩 1.5		y
9	🟧 2		
10	🟦 2.5		
11	🟩 3		
12	🟧 4		
13	🟦 5		
14	🟧 6		
15	🟩 3		y+z
16	🟦 2	0.5	y
17	🟩 4		
18	🟧 6		
19	🟧 2		z
20	🟦 4		
21	🟩 6		

🟦 Group A
🟩 Group B
🟧 Group C

Table 4: Additional test cases of side study.

Case	Frequency [Hz]	Amplitude [m/s²]	Axis
0	Replay of flight in turbulence with generic aircraft model (regular flexibility level) including full dynamics in all axes		
1	▨ 2	0.1	y
2	🟨 3		
3	▨ 4		
4	🟨 5		
5	▨ 6		
6	🟨 3	0.5	
7	🟨 5		
8	▨ 2	0.1	z
9	🟨 3		
10	▨ 4		
11	🟨 5		
12	▨ 6		
13	🟨 3	0.5	
14	▨ 5		
15	▨ 3+6	0.3	y
16	🟨 7		z
17	🟨 7		y
18	▨ 2	0.3 without random amplitude	y
19	🟨 6		y
20	▨ 6		z
21	🟨 2 (a_y), 6 (a_z)	0.3	y+z
22	▨ 6	0.3	y+z

▨ Group C
🟨 Group D

All test cases are performed with the same type of seat inside the passenger cabin. Even though the characteristics of the seat itself are known to have an influence on the passenger comfort [9], this parameter is out of scope of the present study, which only considers the dynamics of the aircraft frame. The seat characteristics are thus kept constant for all test cases. The passenger cabin of the AVES is equipped with displays that could simulate an outside view. The vision outside of the cabin windows is, however, kept black, corresponding to a flight at night, in order to avoid additional influences as, for instance, latencies in the displays. The influence of visual inputs is thus deliberately excluded from the study.

III. Questionnaires

The simulator campaign had the goal to evaluate how the passengers react to different motion patterns. Questionnaires are used to record the passengers' perception during the experiment. Each passenger had to answer three different types of questionnaires before, during, and after the simulator test.

The questionnaire before the experiment gathered background information of the participants such as age, gender, size, weight, general and current frame of mind, general motion sickness susceptibility, anxiety, and current physical state. The questions are based on the State-Trait-Anxiety Inventory [15], the Motion Sickness Susceptibility (MSSQ) [16] and the Simulator Sickness Questionnaire of Kennedy et al. [17][18].

During the experiment a questionnaire about comfort, concentration, motion sickness, and fatigue had to be answered regularly every 2 or 3 minutes. This repeated questionnaire represents the most important data base for the analysis because it rates the passengers' perception during the motion sequences. The questionnaire addresses the four subtopics as follows:

- **Ride comfort:** The passenger comfort scale is a unipolar 6-point Likert scale, rating the perception of the motion from not unpleasant to extremely unpleasant (Table 5 in the Appendix).
- **Concentration**: The passengers are asked to concenrate on something or do some calculations in their head and rate their ability to concentrate in a bipolar 6-point Likert scale, ranging from "extremely unconcentrated" to "extremely concentrated" (Table 6 in the Appendix).
- **Motion sickness**: The motion sickeness is evaluated using the misery scale (MISC) [19], ranging from 0 (no problems) to 10 (vomiting) as shown in detail in the Table 7 in the Appendix.
- **Fatigue**: The fatigue is rated by an 8-point scale oriented to the Karolinska Sleepiness Scale (KSS) [20][21], ranging from "extremly alert" (1) to "Very sleepy, great effort to keep awake" (8) and displayed in Table 8 in the Appendix.

Motion sickness is only included as a minor aspect for the sake of completeness. Due to the high frequencies no major occurrence of motion sickness problems is expected, as motion sickness is a phenomenon that usually occurs below 2 Hz. Nevertheless, it should be investigated if there are some motion sickness impacts resulting from aeroelastic flexibility.

After the experiment, the state-trait anxiety inventory questionnaire was repeated as a comparison to the state before the experiment. All questionnaires were in German, as all participants were German-speaking. The questionnaires were set up on tablets, installed on the cabin seats as shown in Fig. 6. Each time a new questionnaire had to be filled out, a new empty questionnaire occurred on the display and the passengers answered the required questions.

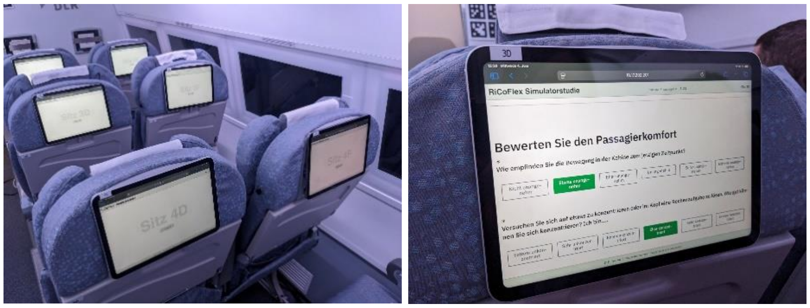

Fig. 6 Tablets in cabin, on which passengers answered questionnaires.

IV. Simulator Campaign

The simulator campaign took place from May 23 until June 11, 2025. It was conducted in the DLR full-motion simulator AVES [14]. The AVES has exchangeable modules, which can be used on the motion platform, including an Airbus A320 cockpit, an EC135 helicopter cockpit, a Dassault Falcon 2000 cockpit, and a passenger cabin module. For the present study, the passenger cabin module with 16 seats, as shown on the righthand side of Fig. 7 was used.

Fig. 7 DLR full-motion simulator AVES with cabin module: motion platform (left) and interior of cabin module[9] (right).

During the simulator campaign 19 experiments were run in 11 test days. 170 passengers participated in the simulator campaign and answered more than 9000 questionnaires in total. The participants were split into three groups with approximately 45 participants per group. Each group faced a different subset of the test cases of Table 3, as marked by different colors for the three groups. The participants of each group were distributed to five experiment runs. The blue test cases of Group A (and Group B and C respectively) in Table 3, for instance, were thus repeated in five experiment runs with different participants. During each of these experiments the order of the test cases was different, in order to assure that the test order does not influence the participants' ratings. Only the reference case (test case 0) with the flight in moderate turbulence remained the first test case in all experiments.

One experiment session of the main campaign lasted two hours with a 20-minute break in the middle, during which the passengers left the cabin to have a break. During both 60-minute sessions the passengers were exposed to four different test cases split by breaks of five minutes as shown in Fig. 8. During the test cases, the in-flight questionnaire had to be answered after 1, 3, 5, 7, and 9 minutes. During the break the motion stopped, but the passengers filled out the same in-flight questionnaire after 1 and 4 minutes to check how they have recovered from the previous motion. The test pattern of Fig. 8 was continued with different test cases after the 20-minutes break.

The additional experiments in the side study (Table 4) were run with a smaller number of 32 participants and shorter test duration of only five minutes. The test pattern of Fig. 8 was changed to six five-minute test cases with five-minute breaks in between. These experiments were used to do some supplementary tests and had the purpose to get first insights of test cases with lower priority such as 0.1 m/s^2 amplitude, 7 Hz frequency and simultaneous combinations of different amplitudes or frequencies.

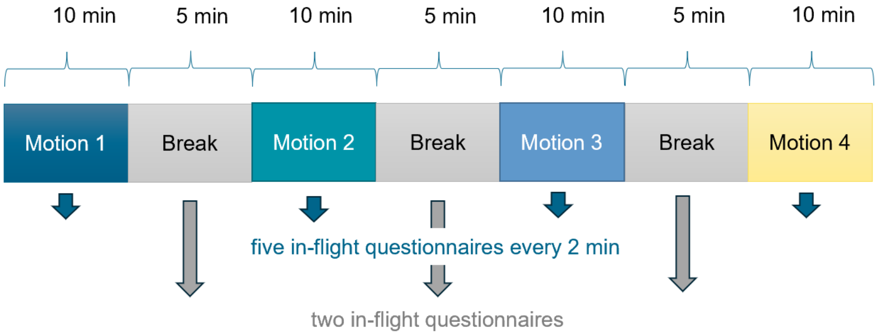

Fig. 8 Test pattern during 60-minute simulator session of main campaign.

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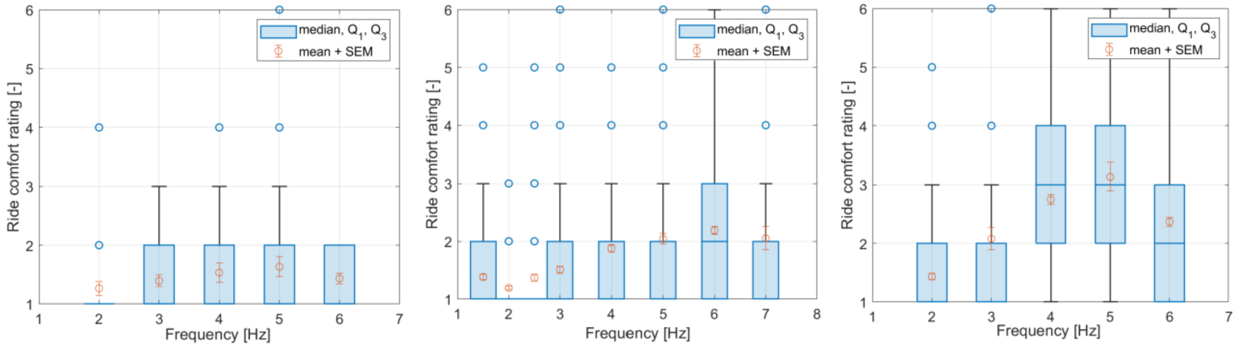
[9] representative picture of the AVES cabin module, not from the present simulator session (with black outside view)

V. Results

The analysis of the participants' ratings of the motion perception during the different test cases showed that their perception for different amplitudes and frequencies was different depending on whether these oscillations occurred in the lateral or vertical axis. Figure 9 and 10 show the passengers' ratings of their motion perception according to the six-point scale described in Section III for the vertical and lateral axis respectively. Blue boxes mark the upper quartile Q_3 (upper line of blue box), median (centerline of blue box) and lower quartile Q_1 (bottom line of blue box). The blue circles mark outliers[10]. The black lines mark the maximum and minimum values that are not outliers. The orange circles display the mean with the orange bars indicating the corresponding standard error of the mean (SEM). Ratings of one indicate that the passengers evaluated the motion as "not unpleasant", ratings of six describe an "extremely unpleasant" perception of that motion, i.e. higher ratings indicate lower passenger comfort.



(a) Amplitude of 0.1 m/s² **(b) Amplitude of 0.3 m/s²** **(c) Amplitude of 0.5 m/s²**

Fig. 9 Ratings of passenger comfort in vertical direction.

Figure 9 reveals that all ratings are relatively low, indicating that none of the test cases are very critical. Only some outliers and a few ratings at higher frequencies for amplitudes of 0.3 and 0.5 m/s² range up to "extremely unpleasant" ratings of 6, but the large majority of the ratings stays below 4 (unpleasant). The comparison of the three cases of different amplitudes shows that the same frequency-dependent trend can be found for all three amplitudes. As expected, higher amplitudes, by trend, lead to more uncomfortable ratings, but the increase in amplitude just provokes a parallel shift of the frequency-dependent trend. The mean values of each frequency, displayed in orange, clearly show this trend. The mean ratings of the ride comfort ratings increase for frequencies from 2 Hz up to 5 Hz (6 Hz in case of 0.3 m/s²) and a decrease again after that peak. So, the passenger comfort degrades increasingly with higher oscillation frequencies. For very high frequencies above 5 or 6 Hz the disturbance becomes less noticeable for the passengers such that the ride comfort is improving again. Below 2 Hz we see a light increase at 1.5 Hz in case of 0.3 m/s² amplitude. As this frequency has not been tested for the other amplitudes, no conclusions can be drawn here if this increase below 2 Hz is a general trend.

It has to be noted that the test cases with an amplitude of 0.1 m/s², as well as the 7 Hz test case with 0.3 m/s² amplitude, and 3 Hz and 5 Hz with 0.5 m/s² amplitude were part of the side experiments (Table 4) with a smaller number of participants and a shorter test duration of only 5 minutes instead of 10 minutes. The validity of these ratings can thus be considered to be lower than of the other test cases with a higher number of participants and longer exposure times. However, the trends in Fig. 9 do not give any hints that the conditions of the side experiments led to different results. First analyses of the temporal evolution of the passenger ratings also suggest that a duration of 5 minutes is sufficient for each test case. This aspect is, however, still under analysis and will be discussed in detail in future publications.

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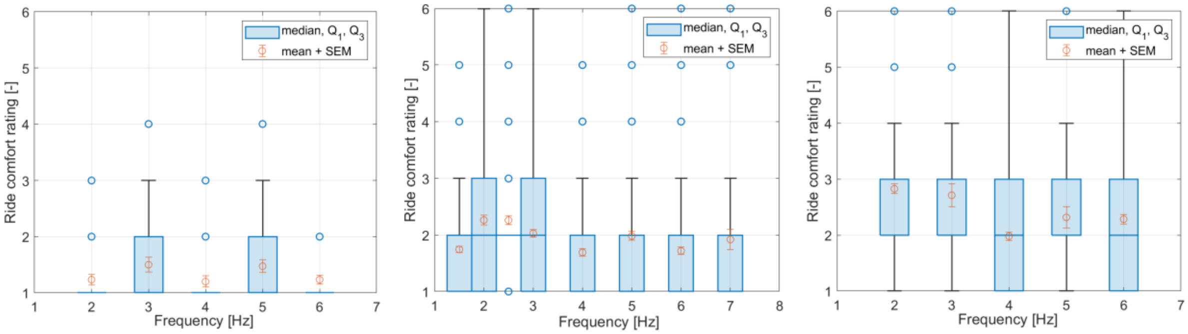
[10] Outliers are defined as ratings that are more than 1.5 times the interquartile range (IQR, i.e. the distance between bottom and top edge of the blue boxes) from the top or bottom of the blue box.



(a) Amplitude of 0.1 m/s² **(b) Amplitude of 0.3 m/s²** **(c) Amplitude of 0.5 m/s²**

Fig. 10 Ratings of passenger comfort in lateral direction.

The ratings for the lateral axis, displayed in Fig. 10, are in the same range as the ratings for the vertical axis, with the majority of the ratings below a value of 4 (unpleasant). The mean values show the same parallel shift for amplitude variations as in the vertical axis. However, the frequency-dependent variation of the ratings is different for both axes. In the vertical axis, the ratings show a wave-like shape over the considered frequency range with a minimum at 4 Hz and maxima between 2 and 3 Hz and at 5 Hz. Passengers thus seem to find oscillations at 4 Hz as well as very low and very high frequencies less discomfortable. Frequencies around 2-3 Hz and 5 Hz have been considered to be most disturbing in the lateral axis[11].

The test cases with an amplitude of 0.1 m/s², as well as the 7 Hz test case with 0.3 m/s² amplitude, and 3 Hz and 5 Hz with 0.5 m/s² amplitude were again tested during the additional experiments (Table 4) with a smaller number of participants and a shorter test duration of only 5 minutes instead of 10 minutes.

VI. Summary and Conclusions

The present paper describes the setup of a simulator study in a passenger cabin of the DLR full-motion simulator AVES for the assessment of the influence of aeroelastic vibrations on ride comfort. It gives an overview of the development of relevant test cases deduced from offline simulations and simulator pretests. The analyses showed that it is sufficient to consider translational accelerations in the vertical and lateral axis in order to cover the relevant effects of the aeroelastic dynamics for passenger comfort. Rotational accelerations as well as Euler angles could be neglected.

In the simulator study, 170 passengers participated in 19 simulator sessions, providing more than 9000 questionnaires during the tests. The evaluations show that the passenger comfort varies with the frequency of the oscillations and that the frequency-dependent variation differs for the lateral and vertical axis. An amplitude variation predominantly leads to a parallel shift of the frequency-dependent trend but does not change the dependence on the frequency itself. In the vertical axis, the ride comfort increases from 2 Hz up to 5-6 Hz and decreases after that peak. Ride comfort ratings in the lateral axis show a wave-like shape with a minimum at 4 Hz and maxima at 2-3 Hz and 5 Hz.

Vibrations at 5-6 Hz in the vertical axis and at 2-3 Hz and 5 Hz in the lateral axis were thus the most uncomfortable oscillations for the passengers. In order to improve the ride comfort, especially vibrations at these frequencies should be prevented, for instance by a control function that reduces the aeroelastic vibrations in these frequency ranges or by structural modifications.

VII. Outlook

The further analysis of the simulator campaign will focus on additional aspects of the passengers' ratings, such as the temporal evolution of the ratings during each test case or variations with passenger characteristics like age, gender, or anxiety. First evaluations have already provided hints that a testing time of five minutes per test case is sufficient. However, this effect will be analyzed in more detail in the future in order to prove this first impression. Whereas the present paper only provides preliminary results on the passengers' ride comfort evaluation, future analyses will also

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[11] With an exception of 2 Hz for the 0.1 m/s² amplitude case, which was rated as less uncomfortable again.

focus on the other aspects of the questionnaires covering concentration, motion sickness, and fatigue. Especially concentration and fatigue are not only interesting for passenger comfort but are even more relevant for pilots. As the present simulator campaign was focused on ride comfort and thus designed with comparably short test slots per test case, it still has to be evaluated if the testing time was long enough to allow an assessment of fatigue and concentration or if additional tests with a different test setup are required in these cases.

The next step after the detailed analysis of the ride comfort, will be to use the findings to improve passenger comfort by designing specific control functions that reduce undesired impacts of the aeroelastic flexibility on ride comfort. The frequency-dependent ratings of ride comfort, derived in Fig. 9 and Fig. 10, could, for instance, be used as H_∞/H_2 templates in the control synthesis. A follow-up simulator campaign could evaluate the improvement of the ride comfort due to the developed control functions.

Appendix

Except for the MISC scale (Table 7), the questionnaires directly contained the text (in German) as response options and the numbers were only added retrospectively for analysis purposes.

Table 5: Motion Perception Rating Scale.

Not unpleasant	1
A little unpleasant	2
Rather unpleasant	3
Unpleasant	4
Very unpleasant	5
Extremely unpleasant	6

Table 6: Concentration Rating Scale.

Extremely unconcentrated	1
Very unconcentrated	2
Rather unconcentrated	3
Rather concentrated	4
Very concentrated	5
Extremely concentrated	6

Table 7: MISC Scale [19].

No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, yawing, headache, tiredness, sweating, stomach/throat awareness, burping, blurred vision, salivation	Vague	2
	Little	3
	Rather	4
	Severe	5
Nausea	Little	6
	Rather	7
	Severe	8
Retching		9
Vomiting		10

Table 8: Fatigue Rating Scale.

Extremely alert	1
Very alert	2
Alert	3
Neither alert nor sleepy	4
A little sleepy	5
Sleepy, but no effort to keep awake	6
Sleepy, some effort to keep awake	7
Very sleepy, great effort to keep awake	8

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