ABSTRACT
Economic aircraft design demands for short development times. In frame of interior noise this requires reliable prediction methods for the design process, where the complex interaction of the excitation/fuselage as well as the radiation to the cabin is captured. Especially in the mid frequency range between 80-250Hz modern finite element based numerical models still show a lack of accuracy for a full aircraft configuration. However it is difficult to find out which part of the model has the highest impact on accuracy. Flight tests/ground tests of full aircraft configurations have an inherent high complexity and only a limited observability. Therefore in frame of the Lufo-4 funded project COCLEA an acoustic design platform is developed to serve as basis to improve numerical models by stepwise increase of the complexity. The main design requirements are: realistic excitation, fuselage structure with low complexity and clean boundary conditions.

In this paper the importance of these requirements are demonstrated by results from an existing platform (A400M Fuselage Demonstrator). Here the limits due to high complexity and boundary conditions are shown by comparison of numerical model with detailed test data. Furthermore first results of the excitation reproduction system consisting out of 128 speaker array are presented.

Keywords: Finite element method (FEM), Aircraft, Correlation
I-INCE Classification of Subjects Number(s): 75.3
1. Limitation of current vibro-acoustic models
2. Investigation of influence of boundary conditions
3. Impact of representativeness of excitation

2. A400M fuselage demonstrator

An original Airbus A400M fuselage structure w/o the cockpit section from the pre-series is installed in a test hangar at the HSU. The overall dimensions of the fuselage consisting out of 54 frames and 99 stringers are ~30m length and a diameter of ~5.64m. A portal framework structure supports the fuselage on the wing box attachment points and at the connection points for the vertical stabilizer, for more details see [1]. The fuselage is bare, this means no insolation and no systems are installed. All brackets for system installation and local stiffening elements like landing gear attachments are installed. The fuselage demonstrator is used for R&T purpose. Several test campaigns performed by German Aerospace Center (DLR) are conducted to investigate the dynamic structural behavior [2]. An overview of the demonstrator structure is given in figure 1.

![A400M fuselage mock up: DLR Testing (2), ©Airbus S.A.S.](image1)

Based on an existing dynamic FE-model, a complete simulation model including framework structure is built [3]. The FE model covers only the main structure: frames, stringers, skin fields and floor structure. The model has about ~1 million degrees of freedom. In figure 2 an overview of the created model is given.

![FE model of A400M fuselage demonstrator](image2)
3. Limitations of current vibro-acoustic models

The creation of dynamic FE models of an aircraft fuselage is a challenging task. Beside the correct choice of element type and size, connectors etc. also the number of geometric dimension to be considered is very large. Typically the design of a fuselage is optimized for static strength and weight and therefore the structure design is changing from frame to frame and from stringer to stringer. A typical frame cross section could be approximated by ~20 geometric parameters, stringer and skin add another ~10 parameters and so considering a fuselage with 54 frames and 99 stringers, this results in a design space of ~160 000 parameters (30x54x99). Floor structures and cabin components add further parameters to the model. Even considering that in some areas only a few parameters are changing, it is still a very high effort to create a FE-model, where all parameters are correctly considered.

Fortunately the resulting large models with approx. one million degrees of freedom (DOF) could be solved without difficulty on modern computers.

In the current FE-model of the A400M structure several simplification due to modeling effort are present:
- Frame & stringer parameters are smoothed
- Several local stiffening’s are included especially in landing gear and wing area
- Floor structure parameters are approximated
- All brackets for system installations are not modelled

In order to study the limitation of the A400M model under consideration, several comparisons of FE-results to test data are performed. Here different set of test data, as well as several types of correlation criteria, have been studied to get a good understanding about the accuracy of the FE-modelling and by that design criteria for the AFL.

The comparisons could be split into two groups:
- One where the focus is put on global comparison and low frequency range from 1Hz to 80Hz. Here the measurement sensor grid is distributed all over the fuselage and measurements. In figure 3 an overview of the selected 230 sensor locations is given (green area).
- The other with focus on a single section and a higher frequency range from 50Hz-300Hz. Here a much finer sensor grid and about 3200 measurement positions located in the forward part of the structure see figure 3 (red area).

There are several criteria available to compare simulation results to test data. Here the question is which criteria is best suited in which frequency to proof the validity of the simulations, see [5].

In the lower frequency range for the global configuration the well-established modal assurance criterion (MAC) is used, as defined in equation (1):

\[
\text{MAC} = \frac{\sum_{i=1}^{N} \phi_{i}^{T} \phi_{i} \psi_{i}^{T} \psi_{i}}{\sum_{i=1}^{N} \phi_{i}^{T} \phi_{i} \psi_{i}^{T} \psi_{i}}
\]

(1)

Figure 3 – global measurement (green) and local measurement grid (red) of DLR test
with:

\( \psi_{num} \) = Modal vector for mode from numerical model projected to measuring points

\( \psi_{meas} \) = Modal vector for mode from measurement at measuring points

In figure 4 the comparison of the modes of the FE-model vs. the measurement for the global configuration is shown. Here the results from the much finer mesh of the FE model are projected onto the measurement mesh.

In the frequency range between 0.5Hz and 40Hz a MAC level of up to 0.7 is reached. At higher frequencies no correlation is seen by the MAC criteria for the global comparison.

In figure 5 some examples at different frequencies for the mode shapes are given. Please note that only the radial component is shown.

![Comparison FE Model vs. Measurement: MAC](image)

**Figure 4 – comparison of measured vs. simulated modes: MAC**

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Figure 5 – Comparison of measured and simulated mode shapes for frequencies ~3Hz ~15Hz and ~32Hz.

From figure 4 and 5 it is obvious, that the simulation model for the low frequency region matches quite well to the measurement, whereas for the higher frequency region >40Hz the correlation is poor. Of course the mismatch could be related to the above mentioned simplifications and modelling assumption in the FE-Model, but also the question should be raised how good the MAC is suited for complex mode shapes. The MAC is quite sensitive to local mismatch of a mode shape. This is enforced for the global comparison by the limited number of points. Here the resolution of the measurement mesh is not fine enough to resolve shapes of the modes.

Therefore at the higher frequency range a very dense sensor mesh at the forward part of the fuselage (~3200 sensor locations) close the propeller plane is measured (see figure 3). Because in the higher frequency range the number of modes strongly increases, it is very difficult to identify all modes. Therefore instead of the MAC, the Frequency Domain Assurance Criterion (FDAC) as defined in equation (2) is used.

\[
FDAC = \frac{\|x_{\text{num}}\|^2}{\|x_{\text{meas}}\|^2} \cdot \frac{\|y_{\text{num}}\|^2}{\|y_{\text{meas}}\|^2}
\]

with \(x_{\text{num}}\)=response vector for FE-model projected onto measuring points
\(x_{\text{meas}}\)=response vector for measurement at measuring points

It is quite similar to the MAC, but instead of mode shapes, response shapes due to a force excitation are used. In figure 6 the results are plotted, where the excitation by a shaker is located in the area of the propeller plane on the left hand side of the fuselage.

Figure 6 – FDAC for dense sensor grid

In figure 6 the FDAC is plotted in a frequency range from 50Hz to 175Hz. The graph shows a good correlation of the FE-model and measurements. To visualize what a FDAC value ~0.6 represents, the response shapes from simulation and measurement are plotted in figure 7 for three different
The comparison in figure 7 shows that even for a relatively complex response shape of the fuselage, the simulation results agree globally to the measurements. But especially from ~60Hz onwards shapes are locally different.

Another way comparing simulation to measurements is the averaged Frequency Response Function (FRF). Here for each excitation frequency the mean response is computed as given in equation (3). In contrast to the FDAC here also the magnitude of the response shapes is considered.

\[
FRF_{\text{mean}}(\omega) = \frac{1}{n} \sum_{\omega=1}^{n} |v_{\omega}(\omega)|
\]  

(3)

The results of the averaged FRF are plotted in figure 8. Here again for the A400M model for the frequencies up to 120Hz a fairly good match to the measurement results is found.

Figure 8 – comparison of simulated and measured averaged FRF.

Because of the high complexity (many local deformations) of mode and response shapes of a fuselage structure in the higher frequency range MAC, FDAC and mean FRF have only a limited validity for correlation of simulation to measurements. Therefore a more advanced correlation criteria
has been developed and is described in [5].

In summary the simulation model is in good agreement to the measurements in a frequency range between 0-120Hz. In higher frequency range and for local details, the match between simulation and measurement should be improved.

The difficulty here is to identify the root cause for the mismatch. The discrepancies could be either linked to modelling issues but as well as to shortcomings in the measurements. Several attempts are made to improve the simulation model, but due to the complexity of the fuselage (high number of different parameters) the update of the model could be only based on global parameters like stringer stiffness, frame stiffness, global mass etc. Furthermore no alternative modelling approach for the different parts have been tried out, e.g. shell vs. beam modelling for stringer thus the impact on the results is unknown. Finally the test structure has a lot of details, like brackets, local stiffeners, etc. which are currently not covered in the simulation model and with unknown influence on the accuracy of the results.

To simplify the comparison between test and FE-result data and to allow a more accurate modelling of a demonstrator, for the Acoustic Flight Lab the variety of different parameters for frames and stringer as for skin field thickness has been set to a minimum. Finally, beside the first and last frame, whose are slightly different due to static stress reasons, the fuselage has only one design shape for frames, one shape for stringers and one skin field thickness. Also no local stiffening for doors, windows or brackets for major systems is considered at the current implementation status. This enables fast creation and update of the model. At a later stage the complexity of the fuselage will then be increased by additional installations.

4. Influence of boundary conditions

The choice of the boundary conditions has a significant impact on the comparability of the numerical model to measurements. Simple boundary conditions for the numerical model like free-free/simply supported or clamped are very difficult to realize for an aircraft structure for dynamic tests. But even small deviations of these idealized boundary conditions could lead to significant deviations in the comparison of simulation vs. measurement results.

First the influence of the structural boundary conditions is investigated, which are necessary to support the structure. As already mentioned the A400M structure is supported by a portal framework structure as seen in figure 2 and figure 3. The support is attached to stiff connection points of the fuselage structure and therefore the question arises, if the framework needs to be considered in the dynamic model or if it can be approximated with a free boundary condition.

The results of this study are given in figure 9, by the comparison of MAC simulation/measurement with and without the frameworks structure.

![MAC simulation vs. measurement with/ without considering portal framework](image)

Figure 9– MAC simulation vs. measurement with/ without considering of portal framework

From figure 9 it could observed, that the results for the model with consideration of the framework structure are representing the measured results much better than w/o the support structure. In the model without the portal structure a lot of modes are missing (shown by the off diagonal of the MAC values). More detailed analysis of the model with portal shows, that several combined modes from
portal structure and fuselage exists. This means, that not only the fuselage structure, but also the framework needs to be modelled correctly in order to get good results.

Finally it could be concluded that the boundary condition of the A400M structure is far from an ideal boundary condition represented by a free/free condition. Therefore for the Acoustic Flight Lab demonstrator a different support concept is implemented. Here the demonstrator is supported by four very soft air springs, which are decoupling the structure from the support and thus enabling a free/free boundary condition.

In order to perform vibro-acoustic tests, it is necessary to seal the structure acoustically. Therefore all openings of the fuselage needs to be closed. These openings are caused by missing parts of the A400M test structure. In the front: cockpit structure, in the rear: cargo ramp, in the wing area: wing and missing doors. For all of these missing parts acoustic barriers are implemented, which are designed to have as little contact as possible to the fuselage structure in order to minimize the impact of the structural dynamic behavior, e.g. a soft rubber sealing at front and rear of the fuselage. For more details of these barriers see [4]. A second test campaign of DLR [4], with the same measurement is conducted to identify the response shapes of the forward part of the fuselage in presence of acoustic sealing.

The influence of the acoustic sealing is shown in figure 10. Here the measured response shapes with and w/o acoustic sealing are compared via the FDAC.

Figure 10 – comparison of measured response shapes with and (w/o) acoustic sealing: FDAC

Figure 10 shows the significant impact due to the implemented acoustic sealing on the response shapes of the fuselage structure: There is almost no correlation between first and second test campaign.

This means, that the contact between acoustic barrier and fuselage by the soft rubber sealing influences heavily the dynamic response of the fuselage structure. Further analysis of the test data shows, that the fuselage is constrained as well as damping is increased considerably by the rubber sealing. Because the forces created by this contact of the sealing are very difficult to be considered in the simulation model, no attempt to update of the simulation model was made.

It is shown, that also the acoustic boundary condition of a fuselage demonstrator has a significant impact on the ability to validate a FE-model. Therefore for the Acoustic Flight Lab demonstrator contactless acoustic boundary conditions are realized by an acoustic labyrinth: Here the fuselage structure is covered at both ends by an acoustic silencer.

5. Representativeness of excitation

Up so far the comparison of the simulation results and the measurements are based only on an artificial excitation by a force, but in flight test the main excitation is caused by a sound field. In order to take this into account a loudspeaker array to reproduce the sound field as in flight is developed. The loudspeaker array consists out of 132 loudspeakers which are arranged in an 11 by 12 matrix and mounted on a carriage, which is installed on a track supported by a truss work, see figure 11. The carriage could be moved around the fuselage, as well as the distance to the fuselage could be adjusted. Furthermore the curvature of the speaker could be changed to fit the curvature of the fuselage. The loudspeaker array covers an area by 2m x 2m. To cover the full are of the real excitation the array is...
moved to different positions (patches) and each patch is measured separately. The final excitation sound field is then derived by superposition of the individual patches. The performance of the loudspeaker array is tested at the A400M test structure, see figure 11 and 12.

Figure 11: loudspeaker array positioning

Each loudspeaker could be controlled individually, to be able to reproduce a wide range of different excitations. Several tests are performed to validate the loudspeaker array. In figure 13 the comparison of target vs. measured sound field is shown, which proofs the ability to reproduce in flight excitations.

Figure 12: speaker array ©Airbus S.A.S

Figure 13: real part of target and measured sound field at ~200Hz of loudspeaker array

Using the speaker array, additional tests are conducted, which show a high influence of up to 10dB on the structural velocity w.r.t. the spatial phase distribution of the excitation. For further details see [6].

The tests of the loudspeaker array at the A400M test structure confirm the ability to reproduce realistic sound field with the loudspeaker array and show the high influence of the excitation sound field to the fuselage structural responses.

Therefore the loudspeaker array is relocated to the Acoustic Flight Lab demonstrator to apply realistic “In-flight” excitation and further study those effects.

6. Conclusion

Based on several tests performed at A400M test structure, the difficulties to validate dynamic FE models of a complete fuselage structure for the frequency range between 80Hz and 200Hz are shown. Especially the high complexity of the structure design limits the capability to perform updates of the FE model and to improve the accuracy of these models. Furthermore the importance of the boundary conditions and the representativeness of the excitation are demonstrated in this paper.

All these lessons learnt are taken into account for the design of the Acoustic Flight Lab demonstrator located at the ZAL, the new center for applied aeronautical research.
The demonstrator, shown in figure 14, will be used to further improve the accuracy of dynamic FE models and to increase the validity towards higher frequency ranges. Currently the AFL demonstrator is a bare fuselage structure with low complexity, but it will be step by step further extended with more complex structural concepts, insulation and cabin elements. Each of these steps will be accompanied by further validation test.

Together with the loudspeaker array a unique test environment is created, which enables to study all aspects of vibro-acoustic characteristics of aircrafts in detail.

![Figure 14: Acoustic Flight Lab Demonstrator ©Airbus S.A.S.](image)

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REFERENCES