Ground Vibration Testing of Large Aircraft – State-of-the-Art and Future Perspectives

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Abstract

A ground vibration test (GVT) on the prototype of a new aircraft is often regarded as necessary to update the mathematical model of the aircraft in order to make reliable flutter predictions for flight tests. Due to very high development costs for such aircraft, the goal is to strive for a significantly shorter testing time by simultaneously increasing the amount and quality of the test data. In the past, the duration of such GVTs was reduced significantly due to the combined application of the phase resonance method (sine-dwell) and phase separation techniques instead of using only the time consuming phase resonance method for modal identification (extraction of mode shapes, frequencies and damping parameters). This switch in test philosophy, including the application of a sufficient amount of equipment, caused a reduction in testing time of large aircraft by 1/3.

Nowadays, the application of the common GVT strategy is more or less a standard process, depending on the size of the investigated structure. Nevertheless, the scope of requirements of the aircraft manufacturers regarding the test program has increased in the last years in order to cover new issues like passenger comfort, fan-blade-off (wind-milling) or aero-servo-elasticity within the same time-window as for the modal identification topic during past GVTs. Mid-term improvements are continuously achieved due to test strategy improvements or enhanced soft- and hardware developments. However, a great leap with respect to test time reduction, quality enhancement and cost efficiency can only be made if the complete aeroelastics process is taken into account. Thus, it must be scrutinized if the classical GVT will play the same role in the future within the aeroelastics process as nowadays or if equivalent data required for aircraft certification can also be gained from other tests which are performed anyway during aircraft development.

In this paper the advanced GVT strategy of the transnational ONERA and DLR team is presented. After that, mid-term improvements are shown which are related directly to the test strategy issue. A vision with respect to ground vibration testing in the future, which will have a significant effect on the complete aeroelastics process, is discussed and will complete this publication.

Introduction

The experimental modal analysis of large aircraft prototypes is, for several reasons, different to vibration tests on smaller technical objects. When such test concerns a brand new prototype, several hundred sensors are required to achieve a sufficient resolution of the spatial motions of all structural parts of the aircraft. It is no longer possible to work with a small number of sensors or to use them in a ‘roving’ manner. Furthermore, the excitation can not be realized with e.g. simple impact hammers. Several large electrodynamic exciters have to be operated simultaneously in order to excite all modes of vibration with sufficient amount of energy. Naturally, the results have to be of high quality and accuracy since they are used for the verification and validation of analytical FE models. In addition, for new aircraft prototypes the regulations of the Airworthiness Authorities require such vibration tests, the results being used in the certification process. Therefore, it has to be assured that all modes in the requested frequency range are identified and that the accuracy of the modal parameters is as high as possible. Finally, the test programmes for aircraft usually require the investigation of several configurations, like full and empty fuel tanks, failure cases of control surfaces and tests on the landing gears. All these demands lead to the fact that:
• the performance of such GVTs may take up to some weeks,
• a test team with a sufficient number of specialists has to be organized,
• the work is performed in two or three shifts,
• the experiments have to be carefully planned and prepared.

Also, a highly sophisticated test strategy for the modal identification is required for the GVT to be efficient. Such a test strategy was developed and established in Europe during the last years [1], and has been applied and further improved for the ground vibration tests on all new Airbus prototypes.

As mentioned before, the GVT on an aircraft prototype is a complex and time consuming but well-established task within the certification process. In the past, much effort was spent on test strategy optimisation, new hardware developments and ‘fine tuning’ of tools for test time reduction and, thus, to reduce the standstill period of the aircraft and the cost for the aircraft manufacturer. Nevertheless, it seems that another great leap with respect to a further reduction in testing time is only possible, if the verification and validation process of aeroelastic models from a structural dynamics point of view will be adapted. Figure 1 shows the actual verification and validation process of aeroelastic aircraft models. During the development of the prototype of a new aircraft, a FE-model is developed based on state-of-the-art FEM modelling, expert knowledge, and experiences gained from former development processes on predecessor aircraft. If all parts of the prototype are manufactured and finally assembled, a GVT is performed on different configurations in order to determine the structural dynamic characteristics of the aircraft. The measured modal data provide the basis for the verification and validation process of the analytical model. This verification and validation process of the FE-model starts in parallel to the performance of the GVT in terms of model updating. The model updating process takes up to several weeks because the validated FE-model must be as accurate as possible in order to predict the flutter critical speeds of the aircraft. The usage of the updated FE-model for the flutter calculations enables to cover future modifications on the aircraft without any specific GVT. Smaller modifications can be introduced directly in the FE-model which will be used afterwards for the flutter calculations of the modified aircraft structure.

Another important step within the verification and validation process of aeroelastic aircraft models are the flight tests for the verification of the updated FE-model. Based on these flights a decision is made whether the updated FE-model has to be adjusted to the measured in-flight modes or not. Furthermore, also the aerodynamic model is adapted, if necessary.

Since many years all prototypes of different aircraft passed through the previously explained verification and validation process successfully. Nevertheless, some stages within this process should be reviewed with respect to efficiency and quality aspects. Some general comments concerning the verification and validation process of aeroelastic models from a structural dynamics point of view might be helpful to initiate a discussion on the strategy itself:

• The verification and validation of the FE-model starts as soon as the GVT has been performed. Thus, the model verification and validation aspect is considered in a very late phase of the certification process, even though the FE-model and nearly all parts of the aircraft are available several months before the scheduled time for the GVT.
There is only little information available about experimental modal data prior to the performance of the GVT. Verification and validation of the analytical model from experimental data is not considered during the aircraft development phase.

A long-term schedule for the performance of the GVT is necessary in order to gather enough data for FE-model validation (different configurations, hundreds of sensors, etc.). Thus, the prototype is blocked for several weeks and the final production steps before the flight flutter tests are shifted backwards in the timescale of the certification process.

FE-model updating is typically performed using a huge modal data base which needs not necessarily to be that large. Thus, a significant amount of work is spent on model validation, even when the flutter calculations require much less information from a structural dynamics point of view since not all modes of the aircraft will be involved in possible flutter mechanisms.

All the comments listed above outline the possible potential for a further reduction of the timescale for the verification and validation process of aeroelastic aircraft models. In the next sections, these potentials are discussed in detail. First, the state-of-the-art ground vibration testing on Airbus aircraft is presented, in order to point out the effort that must be spent during GVT on large scale structures. Afterwards, some ideas on improvements with respect to future GVTs are presented. These so-called mid-term improvements focus on the ‘fine-tuning’ of hardware, tools, methods and test setup in order to improve the modal data quality by a simultaneous reduction of the GVT time. Then, as a future vision, a modification of the actual verification and validation process of aeroelastic aircraft models is proposed based on [2] and adopted by the authors to this specific application, which are directly referred to the comments listed above.

**State-of-the-Art Ground Vibration Testing (GVT)**

In this section, the optimised GVT strategy promoted by the French ONERA and the German DLR since 1999 is discussed in detail, see [1] and [22]. Figure 2 shows a flow-chart of this strategy. The core of the optimised test strategy is to consistently combine Phase Separation Methods (PSM) and the Phase Resonance Method (PRM) with their particular advantages. After setting up the test (complete GVT is performed in shifts with plenty of trained personnel), where special aircraft boundary conditions are realised, several hundreds of accelerometers, a lot of exciters and scaffoldings are installed, the ground vibration test starts with the measurement of the frequency response functions (FRFs) in optimized exciter configurations. Figure 3 shows a typical test setup, the GVT on Airbus A380. In order to guarantee high quality results, special accelerometers (measurement range 0.5 Hz to 1000 Hz), carbon push-pull rods and long stroke modal exciters are used. In addition, the exciters are mounted on special slip tables and tripods (in-house developments) in order to dynamically decouple the exciters from the scaffolding. In order to generate high quality FRFs, special care is taken with respect to the signal processing issue. During the test, different spectral analysis methods are applied to the measured time domain data (e.g. FFT and peak reference hold (PRH) technique). Some previous GVTs and studies showed that the swept-sine excitation signal with exponential sweep rates performs best for large aircraft applications. In order to account for modes which behave non-linear during multiple correlated excitations, a special approach was developed and implemented in the GVT facility to characterise the respective non-linear behaviour, see [4]. The procedure is based on the concept of equal complex power which simulates a single input multiple outputs (SIMO) measurement with a virtual driving point instead of a conventional multiple inputs multiple outputs (MIMO, but correlated inputs) measurement which requires multiple measurements with independent excitation force patterns for FRF estimation. After the generation of the FRFs in parallel to the ongoing measurements, this data is analysed using commercial Phase Separation Techniques, see [5] and [6]. In order to generate a final modal model from the different swept-sine excitation runs for each configuration, special in-house developed correlation tools are used. These tools utilize a database which stores all modal information (eigenfrequency, damping ratio, mode shape vector, modal mass), but also other relevant information from the FRF- and force spectra generation (excitation point, generalized force) and quality indicators from the experimental modal analysis (e.g. modal indicator function, mode participation, etc.). The collection of all relevant data of a mode in the database system [15] provides the basis for reliable and easy correlation of modes from different test runs and the accessibility of the modal database from different computers and by different operators. This selection process (comparison of mode from actual swept-sine run and mode already existing in the database) is performed in a semi-automatic way. The operator is supported in the correlation task by a so-called decision window which graphically presents the quality criteria of the modes compared for a fast selection of the
most reliable modal data. Additional exciter configurations have to be used, or respectively, certain frequency ranges need to be investigated, only if not all expected modes are experimentally identified or if the quality of the results is not sufficient.

![Figure 2: Actual Aircraft Ground Vibration Testing Strategy](image)

The time consuming but accurate Phase Resonance Method is nowadays only applied for selected modes, e.g. modes that have significant deviations from linearity, modes which are important for flutter calculations, and for modes which significantly differ from the analytical prediction. Optimal exciter force amplitudes can be determined as a by-product from the multivariate mode indicator function derived from measured FRFs. These optimal exciter force patterns speed up the force appropriation task, as long as the modes of vibration are linear. The calculated force vector is applied and the corresponding eigenvector is tuned by adjusting the excitation frequency. Once a mode is identified, the classical methods for identification of modal damping and generalised mass are applied, see [7]. A linearity check can be performed simply by increasing the overall excitation force level. During this linearity check, possible changes of the modal parameters with the force level are monitored and are displayed in so-called modal characterisation functions (MoCFs), see [3] and [8]. Nevertheless, these MoCFs can also be generated by using the identified modes from swept-sine excitation, because nearly all modes are excited several times from different excitation points and at different force levels. In contrast to Phase Resonance Testing, the necessary quantities like modal amplitudes, effective input forces, and eigenfrequencies, are not measured directly in the Phase Separation Method, but are identified from the measured response data. Additional information about the swept-sine run like excitation force amplitude and sweep rate are stored together with the response data for correlation purposes. The time domain data of several swept-sine runs are processed and, from the resulting FRFs, modes are identified via experimental modal analysis. With the identified modal parameters, the force amplitude and the sweep rate, the generalised force and generalized modal displacement can be computed for each mode identified. From this information, MoCFs can be generated for the respective modes to indicate possible non-linearities, see [9].
It is quite obvious, that the implementation of the phase separation techniques into the test strategy as a complement to the phase resonance method has been one of the most important issues for the improvement of the test productivity and the data quality. This switch in test philosophy, including the application of a sufficient amount of special developed in-house equipment and software and the development of specific long stroke exciters, caused a reduction in testing time of large aircraft by 1/3. Nevertheless, it took more than a decade to convince the aircraft manufacturers to reconsider their conservative, safe but time consuming, strategy and to integrate the advanced test concept in the verification and validation process of aeroelastic aircraft models. Figure 4 gives a good overview about the impact of the integration of PSM methods on the verification and validation process of aeroelastic aircraft models in the past decades. The figure depicts the number of identified modes for the main structural configuration delivered to the customer. During the nineties, only the PRM method was applied within GVTs on large aircraft. Thus, the FE-model was updated only on a database generated by the classical approach. In 2001, the FE-model of the Airbus A340-600 was adopted to modal data stemming from both, PRM and PSM. During the certification processes of Airbus A340-500 and Airbus A318, the use of PSM became more and more important. Nowadays, the classical PRM method is applied only for very few flutter critical modes. The FE-model of the Airbus A380 was updated mainly on modes stemming from the identification using PSM methods.

Figure 4 shows that the actual test strategy has approached its limit with respect to the potential for GVT time reduction. A great leap with respect to test productivity enhancement can only be achieved by resizing the objectives of the GVT. This, however, involves a truncation of the test database, since less experimental data would be available to check the prediction capability of the updated FE-model with respect to different structural configurations (operating conditions). A further reduction of the timescale for the verification and validation process of aeroelastic aircraft models, while maintaining predictive FE-models with respect to different structural configurations, can only be achieved, if the certification process itself is modified or reorganized (not only the GVT which is one part of this process). This will be discussed in the next sections.
Future Perspectives

The goal of this section is to present some ideas for mid-term improvements which are directly related to the GVT (e.g. test strategy). Afterwards, a modification of the actual verification and validation process of aeroelastic aircraft models is proposed based on [2] and adopted by the authors to this specific application.

Improvements with Respect to Future Ground Vibration Tests

As discussed previously, a lot of effort has been spent in the past on all GVT related topics, e.g. hardware development, test strategy improvement, etc. A great leap with respect to GVT time reduction will not be possible unless the information content of the test data will be significantly reduced or the model verification process will be changed. Nevertheless, in some areas mid-term improvements might be achieved with respect to test productivity and data quality enhancement due to some sort of ‘fine tuning’ of the tools currently used in a GVT. Such improvements could be realized in investing the following topics (which are more or less related together):

- **Measurement hardware developments**: Of course, new hardware developments enhanced the test productivity and data quality enormously in the past. For example, the application of special developed sensors with an electronic adjustment system or the continuously increasing computer power of PC’s reduced the timescale of the installation phase and of the data processing and data evaluation processes respectively.

  The application of distributed converters and/or wireless sensors could save time during the installation phase. During the GVT on Airbus A380, nearly 900 sensors and more than 25 km of cabling were installed. If wireless sensors will be used, only a fractional amount of these 25 km of cabling would have to be installed. Nevertheless, actual telemetry systems are limited with respect to the number of channels which is due to the fact that the data for each channel is transmitted on a separate frequency.

  Another topic of interest could be the application of optical measurement systems/procedures during future GVTs. In the automotive industry, vibration measurements are nowadays to the most part performed using laser scanning vibrometers, see e.g. [10]. Actually, such laser scanning vibrometers could be used for vibration measurements on smaller parts of the aircraft which are of high interest so that a high spatial resolution would generally be desired. Nevertheless, the application of laser scanning vibrometers instead of classical accelerometers during GVT on a complete aircraft will not be possible in the next years because of the size and the complexity of today’s aircraft (not practicable and too time intensive). Nonetheless, other optical measurement techniques are considered more suitable for a possible application during GVT on large aircraft. One of these techniques is based on the principle of photogrammetry and has potential for application in classical phase resonance tests in the future, see [16].

  If only a few hundred sensors and swept-sine or random excitation is considered, data acquisition hardware’s of today like e.g. LMS SCADAS III, see [11], are sufficient and more or less standard. A great leap with respect to data quality improvement and test productivity enhancement could be achieved, if the analogue to digital conversion is done directly on the accelerometers (digital sensors). Thus, a compressed data transfer and a simultaneous reduction of the sensor cabling can be achieved. A prototype of such a system was used during a research GVT, see [12].

- **Tool and method developments**: As discussed previously, the integration of methods and tools like the PSM or the DLR and ONERA correlation-tool enhanced the test productivity enormously. A further development of new methods and tools could cause also an enhancement of the test productivity, especially if non-linear modes are considered. Actually, non-linearities are only characterised in terms of generating the MoCFs using PRM or the analytical approach based on PSM. Unfortunately, it is neither possible to determine a suitable mathematical model for the type of the non-linearity from these functions, nor the parameters associated with such a model. Basically, the actual test strategy lacks the application of procedures for the detection of non-linearities from swept-sine measurements. Thus, structural non-linear behaviour increases the test duration of the complete GVT since adequate tools are not at hand. Consequently, equivalent linear models are identified in experimental modal analysis, instead of identifying information about the non-linearity, which can be used for improving the prediction capabilities of the analytical model.

  In [13], a **toolbox including different methods for the detection of non-linearities** based on swept-sine measurements is proposed, which could be integrated in the existing test strategy. As an add-on, DLR and
ONERA aspire also the implementation of another toolbox to efficiently characterise and identify non-linearities in the framework of industrial GVTs on large aircraft, see [8] and [14]. Both toolboxes have the potential, to enhance the data quality as well as the test productivity.

Commercial software for modal identification like e.g. LMS Test.Lab was successfully applied to GVT datasets of large aircraft, see [6]. Especially the data management within these tools is very efficient, which is a crucial point with respect to the test productivity. For example, during the GVT on Airbus A380, 65 GB of binary data were collected and analysed. The disadvantage of these efficient tools is that they are not very flexible with respect to user demanded customization. For some applications it would makes sense to expand already existing methods to meet the specific requirements of GVT data. For example, it would be worth having a modal analysis/output-only toolbox available, including different methods for the identification of experimental data stemming from (measured) deterministic and (unmeasured) ambient excitation. Such a toolbox could be integrated in the DLR-ONERA software environment (e.g. correlation tool).

A fast method to detect non-linear behaviour and which is readily at hand was mentioned in [6] as the bandwidth sensitivity method. Basically, this method traces the stability of a pole of a certain mode when the analysis bandwidth for experimental modal analysis is continuously narrowed down. The application of such a simple method can provide fast detection of non-linear modes.

![Figure 5: Application of movable platforms during A380-800 GVT (Copyright Airbus S.A.S.)](image)

- **Test strategy enhancements (incl. installation and dismantling phase):** It is very clear, that the proposals with respect to hardware or method developments listed above also have an influence on the test strategy itself. For example, the development and integration of the correlation-tools in the test strategy enhanced the test productivity enormously. In addition to such scientific based developments, the simple reorganisation of working stages or the application of enough equipment caused an enhancement of the test strategy efficiency and, thus, lead to a reduction in testing time. Working in shifts or positioning fixed exciters (which are not active all the time) at all important points of the aircraft (e.g. engines, wings and HTP) are some examples.

There is still room for improvements with respect to test strategy enhancements, especially for the installation and dismantling phase of the GVT. One idea is to *use the flight test accelerometers for modal identification* which are anyway installed on ground. The integration of these accelerometers in the modal analysis process has two advantages. First, the installation and dismantling of externally accelerometers can be reduced, which saves time during the first and the last phase of the GVT. Second, the proper operation of the flight test sensors is checked several weeks before the maiden flight of the aircraft. Thus, damaged sensors can be replaced.

The assembling and positioning of the scaffolding at the aircraft in order to install the equipment needed for the performance of the GVT, is one of the main issues within the installation phase. One major drawback is
that the assembling and positioning is time consuming. Furthermore, the scaffolding often is too flexible to withstand the high dynamic forces which are introduced into the aircraft structure. Thus, it is sometimes not possible to put all the desired input energy into the structure when the scaffolding behaves like a vibration absorber. One solution to overcome both problems could be the application of movable platforms during GVT. Figure 5 shows such a movable platform in the test hall which has been used during the GVT on Airbus A380. This platform was used for the installation of the accelerometers at the fin and carried the shakers for the excitation at the fin tip. One possible solution for the future could be to install only a reduced amount of scaffolding in order to apply accelerometers in regions of the aircraft where a lot of sensors are required, e.g. under the wings. For the installation of sensors at e.g. the engines, two movable platforms will be used (one per side). These platforms, equipped with two exciters per platform, could then be used for the excitation of the aircraft at different positions (e.g. engines, fuselage and HTP). Thus, the amount of scaffolding and exciters that have to be installed is reduced. Furthermore, the data quality could be enhanced if the dynamic stability of the movable platforms are better compared to the scaffolding.

Another topic of interest could be the application of internal excitation for modal identification. Internal excitation means that the control surfaces are used in order to excite the aircraft. This approach has been successfully applied during previous GVTs see [17] and [20]. However, one should always consider that the generalized excitation force associated with higher modes might be too low, or that the actuators of the control surface do not permit the excitation at higher frequencies.

It is obvious, that there is still some room for improvements with respect to test productivity and data quality enhancement, if some of the above listed recommendations are considered. Nevertheless, a great leap with respect to test time reduction can only be achieved if the ground test requirements (GTR) are drastically reduced (e.g. perform modal identification for only a single structural configuration). Next, a modification of the actual verification and validation process of aeroelastic aircraft models is discussed, which could reduce the timescale for the GVT without reducing the prediction capability of the validated FE-model.

Improvements with Respect to the Aeroelastics Process

In this section, a modified process for the verification and validation of aeroelastic aircraft models from a structural dynamics point of view is discussed. This proposal is based on the actual process that was elucidated in the introduction, see Figure 1, and on [2] respectively.

As mentioned before, the actual verification and validation process of aeroelastic aircraft models has some potential with respect to efficiency enhancement and timescale adjustment. The only goal of the complete process is to certify a new aircraft based on a validated, high-quality FE-model and on experiments. Thus, the main question is which tests must be performed (at least) in order to get all information that is needed for the validation of the FE-model? If the timescale of the certification process should be reduced while having in mind the question posed before, then emphasis can be given to the following suggestions for improvement:

- **The parallelisation of the aircraft development and FE-model validation process** would speed up the complete certification process and would also improve the quality of the FE-model. The parallelisation can be achieved by applying the concepts of virtual testing and component testing. Both concepts are explained below.

- **The test time reduction of the GVT** would also speed up the complete certification process. Such a test time reduction can be achieved by focusing only on the 'important' (i.e. most relevant) modes during GVT. The most relevant modes are determined based on expert knowledge, on information gained from former aeroelastic certification processes on predecessor aircraft, and/or former flutter calculations. Furthermore, the concepts of multi-objective testing should be applied; where one test is performed with an adequate sensor installation to gain enough information to achieve several objectives (e.g. perform modal identification from data obtained during wind-milling tests, collect strain gauge responses for calibrations, possibly helpful for local FEM updating, perform acoustic measurements inside the cabin during GVT, etc...).

Next, the model validation principle based on virtual testing and component testing is addressed. The principle of virtual testing was introduced in [2] and has successfully been applied to an aero-engine in [18]. This concept is now adapted to the verification and validation process of aeroelastic aircraft models. The initial FE-model of the aircraft will be validated based on experimental data obtained from experiments which are performed prior to the
First, the components of the structural assembly which are most critical (most influential) for the dynamic behaviour of the assembled structure are determined (e.g. wings). This can be achieved by using the assembled (initial) aircraft model and performing a sensitivity study for e.g. the Young’s modulus and the density of all the different structural components (substructures) of the initial aircraft model. Then, those parameters (mass, stiffness, geometry etc.) are determined within the critical components, which are most influential with respect to the dynamics of the respective component. These are the parameters which must be validated. An adequate test setup for a component test must be designed, in which those modes of the component are measured, which are most sensitive to the parameters. This enables the identification of these parameters from experimental data. **Output:** Most influential components (substructures) of the aircraft which have to be tested (can be done in parallel to the aircraft development process) and experimental setup to make critical FE-model parameters sensitive/identifiable.

Performance of modal tests on the previously defined components. **Output:** Experimental modal parameters like eigenfrequencies and mode shapes of the most influential components.

1st model verification and model validation issue: Correlation of experimental and analytical frequencies, modes and FRFs of the most influential components; (if necessary) model updating of component models. **Output:** 1st stage validated complete aircraft FE-model (after assembling of validated component models).

Reduced GVT on the prototype of the aircraft: Measurement of flutter critical modes based on 1st stage validated complete FE-model, on expert knowledge gained from certification processes on predecessor aircraft, and on the previously defined validation requirements for the complete FE-model. **Output:** Experimental modal parameters like eigenfrequencies and modes of the complete aircraft.

2nd model verification and model validation issue: Correlation of experimental and analytical frequencies, modes and FRFs of the complete aircraft; (if necessary) model updating of complete FE-model. **Output:** 2nd stage validated complete aircraft FE-model.

Figure 6 shows the flow-chart of the virtual and component testing process. The diagram shows clearly the difference to the former model verification and validation process. On the right hand side of the diagram the classical approach is still present. In the proposed new process, only a reduced GVT will be performed. On the left hand side of the diagram the new items of the proposed process are addressed. The validated 1st stage complete FE-model is the intersection of the old and the new procedure. It is clear, that such a procedure is only reasonable and valid, if the initial FE-model is sophisticated enough and the analytical predictions are close enough to the measurements of the real aircraft structure. This is usually the case in aircraft industry. As an add-on to the process, one may also include static measurements taken from the components and from the complete
aircraft structure (joint flexibilities) for the verification and validation of the FE-model. Nevertheless, such tests will cost additional time and it must be proven whether the accuracy of the model does really require such measurements. A major topic of interest within the process of component testing is the realisation of adapted boundary conditions in order to measure the modes which are sensitive to the critical FE-model parameters and the measurement of the reaction forces at the component attachments. If a specific component of the aircraft will be tested for the first time (not necessarily the very first component which will be used for the prototype), the effort for the realisation of suitable boundary conditions will be relatively high compared to follow-on aircraft family developments. In order to measure the important modes of a wing it can be necessary to perform a component test on a wing which is equipped with the engines. For this purpose, dummy engines may be used, if the real engines are not available in the run-up to the test. Another advantage of the virtual testing and component testing philosophy is that a validated FE-model is available before the GVT on the aircraft is performed. Such a model can be used for a simulation of the GVT to determine optimal excitation positions to ensure a good excitation of the reduced set of modes required for model updating of the complete aircraft structure.

![Example of 1st Fuselage Vertical Bending Modes for the Single Fuselage and for the Entire Aircraft](image)

Figure 7: Example of 1st Fuselage Vertical Bending Modes for the Single Fuselage and for the Entire Aircraft

Such focused tests were applied for a helicopter FEM updating process, the fuselage being tested and updated independently from the main gear box and the engines, whose dynamic behaviour being very non-linear, see [21] and Figure 7.

![Diagram of Enhanced Verification and Validation Process of Aeroelastic Aircraft Models](image)

Figure 8: Enhanced Verification and Validation Process of Aeroelastic Aircraft Models
The concept of multi-objective testing is the last important issue which is needed in order generate an enhanced verification and validation process of aeroelastic aircraft models. Multi-objective testing means that one test is used for several objectives by multiple uses of test data. Therefore, tests which are anyway performed on the complete aircraft (e.g. take-off and landing tests) within the complete certification process will be used for modal identification purposes. Nowadays, multi-objective testing is already performed during GVTs by gathering experimental data for wind-milling certification or acoustics and comfort purposes. Figure 8 shows the enhanced verification and validation process of aeroelastic aircraft models. In contrast to the actual strategy, a validated FE-model is generated in parallel to the aircraft development and aircraft production process. This model, which is validated using experimental data stemming from virtual testing and component testing, is verified and validated afterwards using dynamic test data stemming from multi-objective testing (tests on complete aircraft). The result will be a high-accuracy 1st stage validated FE-model. Due to the fact that this model is much more sophisticated and much more accurate than the former initial FE-model, only a reduced set of modes (important and flutter critical modes) must be measured during GVT which reduces the test duration enormously. Afterwards, the 1st stage validated FE-model is verified and updated using the experimental data from the reduced GVT. The timescale for model updating of the complete aircraft model will be also reduced if the enhanced verification and validation process is considered, because now the initial FE-model is much more accurate so that the analyst can focus on updating the joint parameters (stiffness and damping parameters of elements connecting the component models). All the following working steps are the same as during the actual certification process.

Conclusions and Outlook

In this paper, the actual verification and validation process of aeroelastic aircraft models was presented in the first step. Afterwards, the advanced GVT strategy of the transnational ONERA and DLR team was presented. It was shown that a lot of effort had been spent in the past on all GVT related topics, e.g. hardware developments or test strategy improvement and so forth. The duration of today’s GVTs on large transport aircraft was reduced significantly mainly due to the combined application of the phase resonance method and phase separation techniques instead of using only the time consuming phase resonance method for modal identification. This switch in test philosophy, including the application of a sufficient amount of equipment, caused a reduction in testing time of large aircraft by 1/3.

Afterwards, some mid-term improvements with respect to the test productivity and data quality enhancement were proposed based on the topics measurement hardware developments, tool and method developments and on test strategy enhancements. It was shown that there is still some room for improvements with respect to test productivity and data quality enhancement if e.g. toolboxes for modal identification or if flight test accelerometers are also used for modal identification on ground. Nevertheless, a great leap with respect to test time reduction can only be achieved if the ground test requirements (GTR) are revisited or if a modified verification and validation process of aeroelastic aircraft models is considered. Such a modified process was introduced in this paper based on the principle of virtual testing and component testing and on the concept of multi-objective testing. By using the principle of virtual testing and component testing and the concept of multi-objective testing the aircraft development and FE-model validation process can be parallelised. Simultaneously, the timescale of the GVT on the complete aircraft can be reduced. This presented enhanced verification and validation process of aeroelastic aircraft models is currently under discussion with the aircraft manufacturer.

More topics of interest exist which are directly related to the aeroelastic process. One of these topics is the consideration of structural damping within the calculations of flutter critical speeds. Actually, structural damping is not a design parameter in aircraft industry as it is e.g. in the aero-engine industry. Nevertheless, the consideration of structural damping will become more and more important in the future. Based on [19], where complex experimental modal data was used for the identification of a non-proportional physical damping matrix, scientific research in the field of damping identification are addressed by DLR and ONERA.

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