SUBCOMPONENT MODAL TESTS IN THE H135-PRODUCTION LINE TO FURTHER IMPROVE FINITE-ELEMENT MODEL UPDATING

BACKGROUND, EXPERIMENTAL SETUP AND RESULTS OF EXTENSIVE VIBRATION TESTS

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Abstract

Helicopters are designed to be as light as possible, in order to increase flight performance, to decrease the environmental footprint and to minimize operating costs. However, lightweight structures are generally susceptible to vibrations. As a byproduct of the lift and thrust created by the main rotor, oscillatory loads are inevitably introduced into the airframe via the main rotor hub and the main gear box. This combination of lightweight design and dynamic loads makes structural dynamics of the airframe a relevant topic in helicopter design. In recent years, the simulation techniques to calculate the aeromechanic forces of the rotors system have become reasonably accurate. In spite of these advances, simulation models of helicopter airframes are not yet fully capable to predict the propagation of vibrations due to the introduced forces. The finite element (FE) models used for these simulations are created during the design phase and continuously adapted during design iterations. At the end of the design phase, a prototype of the optimized design is built. Its structural dynamic characteristics are determined in a so-called shake test. The result of the shake test are experimentally determined modal parameters like eigenfrequencies, damping ratios and mode shapes which can be compared with simulation results obtained from the FE models. If the deviations between test and simulation are too large, the FE models must be adapted to reality. However, a complete helicopter is an intricate system and the possible sources of modelling errors in the FE models can be numerous. Therefore, this goal is difficult to achieve. Due to this known limitation, Airbus Helicopters and DLR jointly developed a new approach for the improvement of dynamic models of helicopter fuselage. The key idea is to perform subcomponent modal tests on a successively built serial production helicopter in the assembly line. These tests took place during normal manufacturing operations in the production line and are used to validate the respective subcomponents in the FE model. As an outcome of this validation process, poor modeling assumptions can be identified and an accurate simulation model of the entire helicopter can be synthesized. In order to proof the feasibility of this approach, an extensive measurement campaign was conducted on an H135 in the assembly line at Airbus Helicopters Germany in 2022. In the process, modal tests were performed on the successively assembled helicopter at 10 production stations. This publication is intended to show the experimental setup, as well as results of this extensive modal test campaign. Even though the approach was demonstrated to be feasible and effective on a well-established helicopter model (i.e. H135), it was developed for application on future helicopter developments.

1. INTRODUCTION

Helicopters, like all aircraft, require lightweight design in order to minimize the environmental impact while maximizing performance, range and cost efficiency. The interaction between the air and the main rotor which is crucial to create lift and thrust also leads to oscillatory loads which are introduced into the lightweight airframe via the main rotor hub and the main gear box. While the accuracy of the simulation of these aeromechanical loads has improved significantly over the past 10 years, predicting vibration propagation in the airframe remains challenging. The conventional approach to validate finite element models of helicopters is to perform a shake test (Refs. 1, 2, 3, 4) on the prototype and to update stiffness and mass parameters of the finite element model based on those experimental results. Since both the numerical and the experimental side of investigations on such an intricate structure are challenging, DLR-AE and Airbus Helicopters jointly adapted, refined and extended the approach shown in Ref. 5. In the present study, a helicopter is tested step-by-step as it gets assembled. This allows to divide the experimental and numerical challenge into smaller “sub-challenges” that are then easier to solve. The

Figure 1: Airbus Helicopters H135 and H145 Assembly Line

required modal tests took place directly in the production line (shown in Figure 1) as opposed to a laboratory or a hangar.

Finite element models corresponding to the structural states in which the helicopter was tested were provided by Airbus Helicopters. The models at each of the respective assembly stations are shown in Figure 2. These finite element models are also used in a numerical study (Ref. 6) which is supposed to complement the present study and thus summarized in the following paragraph.

In every experiment of this study, the structural state of the helicopter was gradually changed. In the first experiments, different components were tested alone. Later on, additional components were mounted and another experiment has been conducted on the next structural state. The installation of a complete component might change the dynamic behavior significantly and it can be difficult to track changes in the dynamic behavior from one state to the next. The simulation study shown in Ref. 6 circumvents this inherent limitation of installing complete components in an experiment. Instead, the finite element models of the structural states have been used where mass- and stiffness properties of entire components have been gradually blended in. This was done from 5 % to 150 % of the nominal stiffness and mass value of the elements associated with a component in steps of 1 %. After every alteration by 1 % a numerical modal analysis is performed. The results and thus the effects of subcomponents on the overall dynamic behavior are tracked over the smooth

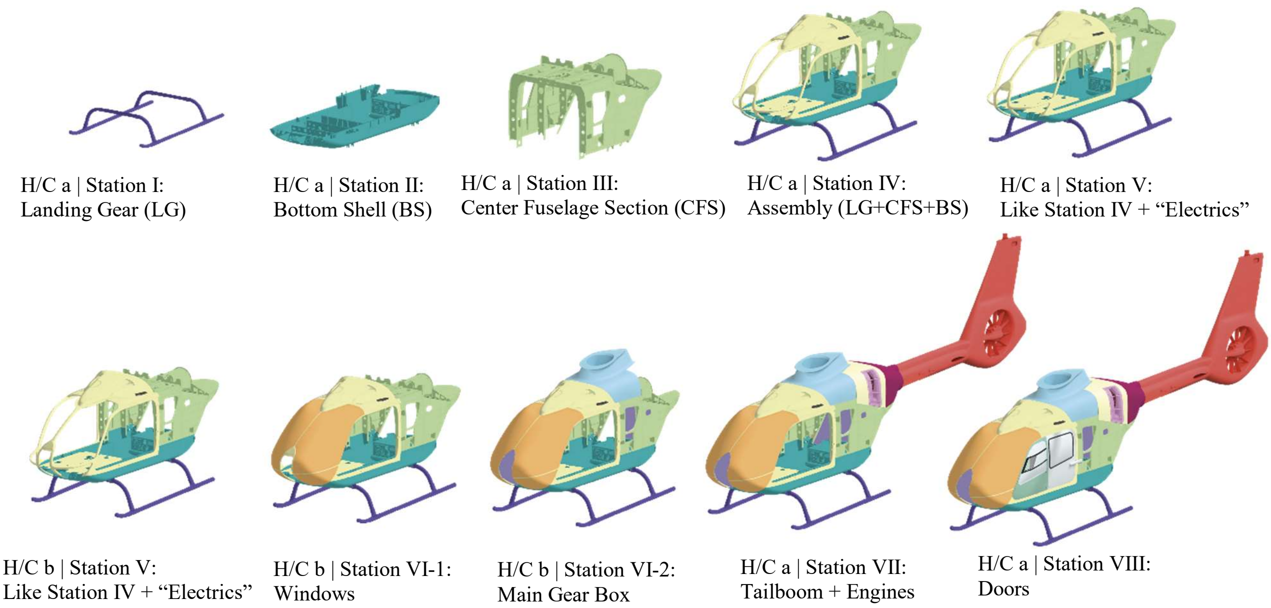

Figure 2: Assembly stations at which experimental modal tests were conducted (schematically)

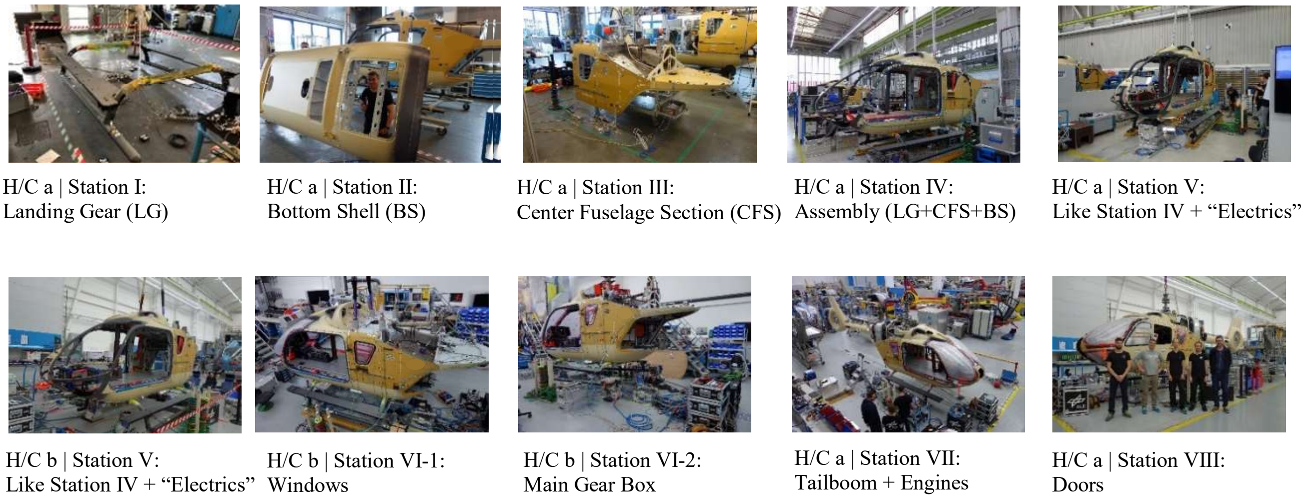

Figure 3: Assembly stations at which experimental modal tests were conducted (reality)

parameter variations. The simulation study (Ref. 6) is therefore considered a preconditioning step for the planned finite element model updating of the H135 finite element model, while the present work shows the required experimental side.

2. MODAL TESTS IN THE H135-ASSEMBLY LINE

2.1 Test intention

One of the main intentions of the herein described test campaign is to provide the experimental results which enable the updating of the finite element models in the different structural states. This allows to assess the validity of modelling assumptions especially for the interfaces between the subcomponents. Based on validated subassemblies an improved finite element model of the entire helicopter can then be assembled.

Besides this goal of creating validated finite element models, the experimental modal results from different assembly stages are related to each other using mode tracking. This method, which originates from flight vibration testing (see e.g. Ref. 7) herein allows to quantify the influences of subcomponents on the overall dynamic behavior.

2.2 Test planning

A helicopter is assembled from thousands of parts and many components. It is thus not feasible to perform a modal test after each component is mounted.

Against this background, it is essential to identify assembly stages in which the changes to the structural dynamic behavior are especially large, or for which the corresponding stiffness and mass parameters of the joint are uncertain. Heavy and/or stiff components are expected to influence the dynamic behavior more than others. One significant example showing changes in the modal properties (e.g. eigenfrequencies) is when the front windows are mounted. A less significant modification occurs when wind-shield wipers are mounted.

The sensor-setup was chosen with the intention of capturing all relevant global modes. As the assembly of subcomponents becomes larger, the dynamic behavior becomes more complicated. In order to capture the intricate behavior, the number of accelerometers also has to become larger. While the number of sensors is increased, as the helicopter gets assembled, the initial sensor positions are retained. By only adding sensor positions as subcomponents are added, the results from different stations can be related and compared to each other. To allow for this, the sensor positions have to be accessible over the entire production process.

While there are established methods to automatically choose sensor positions (see e.g. Ref. 8) based on finite element results, they have two main drawbacks for the purpose of this study. Firstly, they cannot ensure that the positions are accessible over the entire production process, if that information is not defined as a constraint. While such a definition is feasible it is very tedious since it requires that everything is modelled not only mechanically but also geometrically. Furthermore, these methods typically do not suggest a regular sensor layout. An irregular distribution of sensors (which could for instance be lacking symmetry) makes mode shapes more difficult to interpret for the analyst. The sensor positions were therefore chosen manually based on the finite element results at the respective assembly stages as well as inspections during on-site visits in the Assembly Line. For all modal tests, the helicopter was softly suspended from bungee cords using a hall crane in the production line as shown in Figure 4. This boundary condition can easily be incorporated in the simulation

Figure 4: Helicopter softly suspended using bungee cords from the hall crane (highlighted in red)

model and ensures a sufficient decoupling of rigid body modes from elastic airframe modes. The measurement equipment has to be removed from the helicopter, after the modal test on the respective structural state is completed. Only stickers marking the sensor positions and 3D-printed excitation adapters (Figure 5) remain on the aircraft. As a lesson learned

Figure 5: Sticker to mark positions for accelerometers on helicopter (left), 3D-printed adapter to introduce forces (right)

from testing in the production line, leaving stickers on the airframe is a challenge in terms of foreign object debris and must be planned well in advance with involvement of quality control.

The most important aspect in the planning of this test-campaign is to ensure that the production process is not disturbed. This requires a combination of suitable planning as well as a high degree of flexibility from everybody involved. Based on these considerations ten modal tests were performed in the assembly

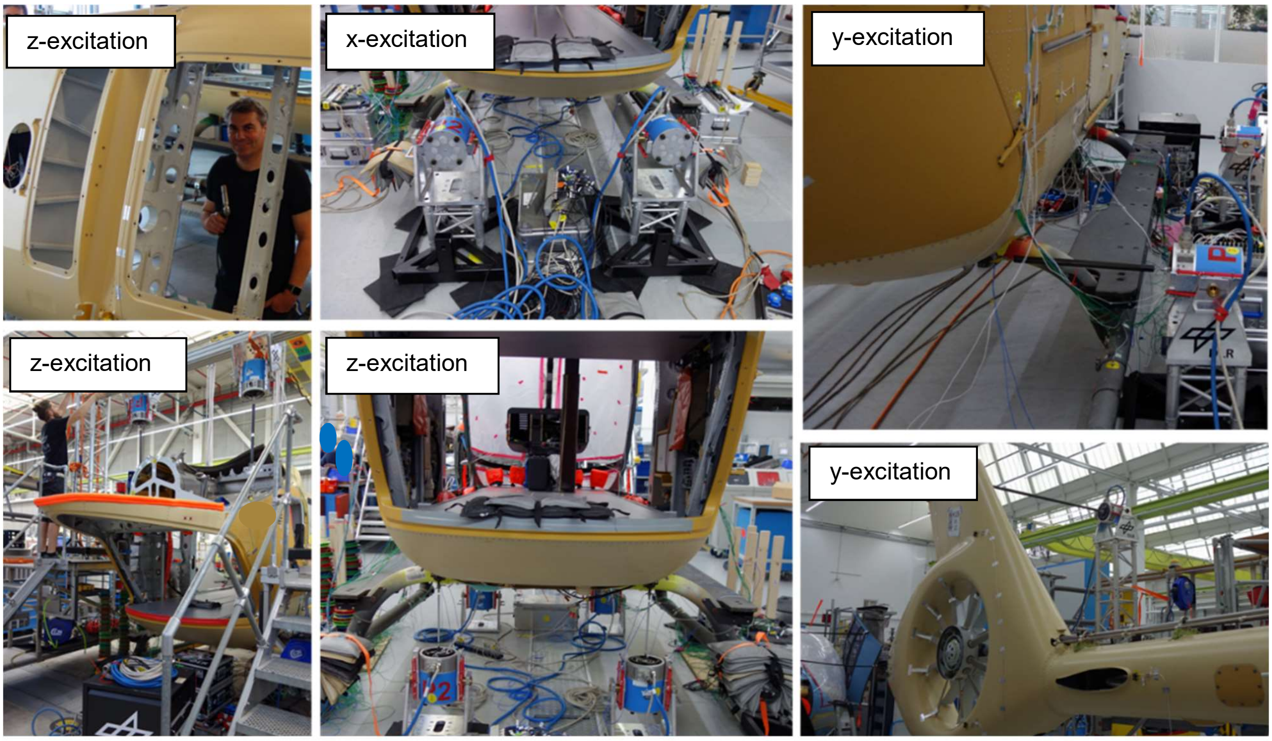

Figure 6: Excitation at multiple locations in all three directions using impact hammer and multiple PRODERA EX 220 C40 shakers.

stages shown schematically in Figure 2 and in reality, in Figure 3. At the first three assembly stations an impact hammer was used (Figure 6). As the structure becomes larger and heavier at later assembly stations, multiple electrodynamic shakers were used and the number of accelerometers was increased (i.e. from 30 at the early stations to 185 at the later stations). The sensor grid shown in Figure 7 was chosen. As the sensor setup grows from assembly station to assembly station, the sensor positions belonging to already mounted subcomponents are retained. In cases where multiple electrodynamic shakers (see Figure 6) are used, the frequency response functions are calculated using the single virtual driving point (SVDP) approach (Ref. 9). In addition to modal parameters the overall mass of the helicopter in the respective assembly state is determined using a crane scale. Apart from the experimentally determined modal models this information is considered a crucial

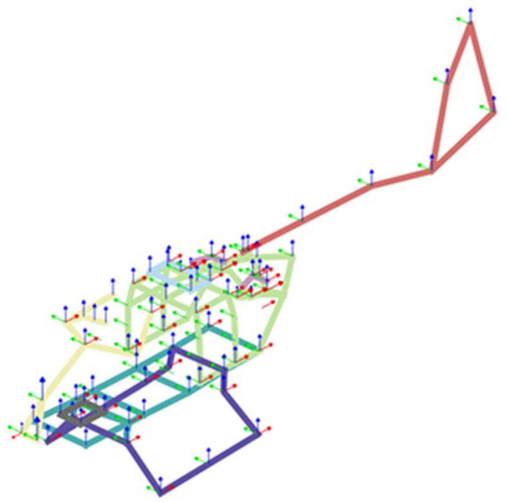

Figure 7: Sensor positions for all subcomponents. Sensors positions on each subcomponent are retained for modal tests at subsequent assembly stations. Arrows (red, green, blue) indicate measurement directions (x, y, z).

quantity, that is later used in the finite element model updating. Measuring the mass was also shown to be valuable in previous finite element model updating of helicopters (see e.g. Ref. 10).

2.3 Test execution

The tests are performed within 0.5 days at early assembly stations and 2 days in later assembly station. The test team comprises 2-4 people. More than 170 excitation runs were performed in total. In order to ensure on-time delivery of the tested helicopter (H/C a) to the customer, crucial subcomponents (Windows, Main Gear Box, Engines, Tailboom) had to be mounted without the opportunity to perform the initially planned modal tests at the respective assembly stations beforehand. In light of this, a second helicopter (H/C b) was made available by the production team of Airbus Helicopters. The second helicopter was nominally identical to the first one and it was tested at the respective assembly stations (Station V, Station VI-1, Station VI-2, see Figure 2). In order to ensure that the measured behavior was consistent, the modal test on the assembly Station V was conducted on both helicopters.

2.4 Test results

In total over 2000 modes with their modal parameters (mode shape, eigenfrequency, damping, modal mass, etc.) were identified using the Least Square Complex Frequency (LSCF) Algorithm (Ref. 11). The modal analysis results from the individual measurement runs were consolidated into representative modal models for each assembly station using the DLR Correlation Tool (Ref. 12). Due to the sufficiently high sensor density in the tests, the global modes of the modal models are well described. The linear independence of the mode shapes can be quantified using the Modal Assurance Criterion (MAC). The criterion is defined as the normalized scalar product between two modes $\boldsymbol{\psi}_{\boldsymbol{p}}$ and $\boldsymbol{\psi}_{\boldsymbol{q}}$

$$(1)\ \mathrm{MAC}(\boldsymbol{\psi}_{\boldsymbol{p}}, \boldsymbol{\psi}_{\boldsymbol{q}}) = \frac{|(\boldsymbol{\psi}_{\boldsymbol{p}}{}^{T} \cdot \boldsymbol{\psi}_{q})|^2}{(\boldsymbol{\psi}_{\boldsymbol{p}}{}^{T} \cdot \boldsymbol{\psi}_{\boldsymbol{p}}{}^{*})(\boldsymbol{\psi}_{q}{}^{T} \cdot \boldsymbol{\psi}_{q}{}^{*})}\ .$$

For two collinear modes, this value is 100 % and for two orthogonal modes, this value is 0 % (Ref. 13). Herein T refers to the transpose and * to the complex conjugate. If the MAC criterion is applied to all modes of the modal matrix, this results in a MAC matrix. If the modes $\boldsymbol{\psi}_{\boldsymbol{p}}$ and $\boldsymbol{\psi}_{\boldsymbol{q}}$ originate from the same modal matrix, this is an AUTOMAC matrix (Ref. 14). Low off-diagonal values indicate a high degree of orthogonality of the experimentally determined mode shapes. The AUTOMAC can take values between 0 % and 100 %. Figure 8 shows the AUTOMAC matrices of the modal models for all assembly stations. The number of modes within each modal model is noted in the lower left corner of Figure 8. It becomes clear that most off-diagonal values in the AUTOMAC matrices are small, which means, that the majority of the experimentally determined mode shapes are almost linearly independent. Linear independence is shown here, because it is one of multiple considerations in the synthesis of representative modal models as

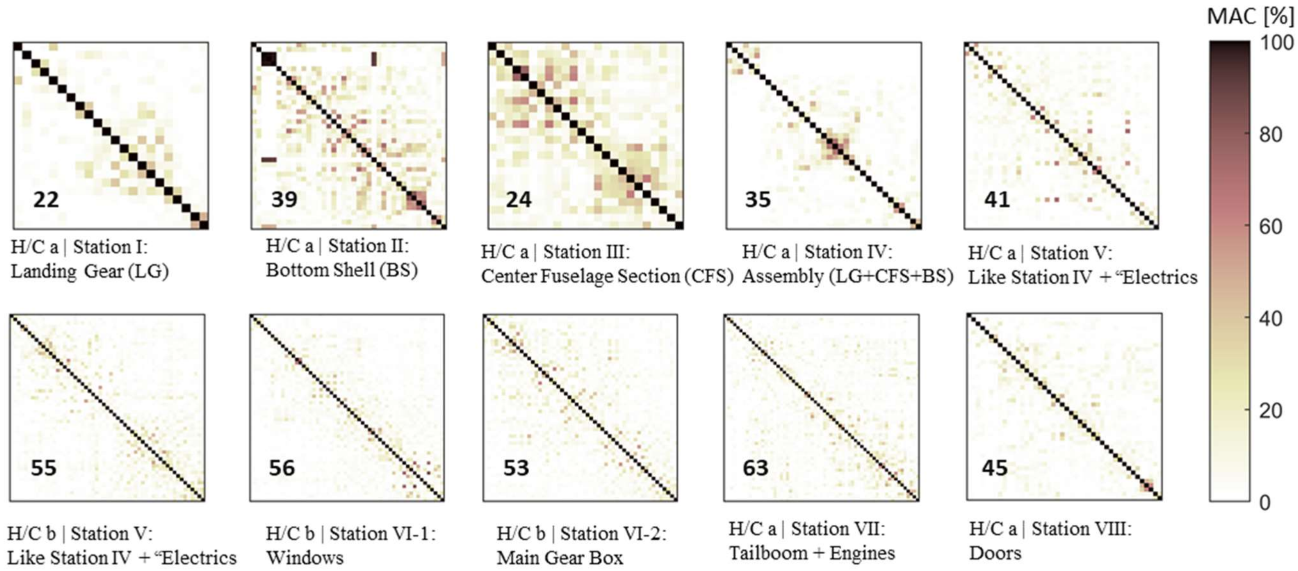

Figure 8: AUTOMAC-Matrices of modal models from all ten assembly stations, number of modes in modal model indicated in lower left corner

implemented in the DLR correlation tool. These modal models can be related to each other using mode tracking (see e.g. Ref. 7). Here the MAC criterion is also used for this purpose. By calculating the MAC value between the modes from two modal models from consecutive stations, similar modes can be identified. These mode pairs, which have a high MAC value (here: above 60 %), are relevant as they allow to quantify the effect of the additionally installed subcomponent. For example, the addition of a heavy component (e.g. Main Gear Box, Station VI-2) leads to lower eigenfrequencies, while the addition of a stiff component (e.g. doors, station VIII) leads to increased eigenfrequencies. Although this effect is qualitatively predictable, quantification of the effects is important and only possible by means of the carried out experimental modal tests. The high number of sensors ensures good linear independence among the identified mode shapes. It also offers the advantage that modes from successive stations can be compared well. The AUTOMAC matrices (Figure 8) are therefore an indication that the comparisons made are based on suitable modal models. MAC values can also be calculated among the mode shape vectors identified in different assembly stations. This allows for the tracking of changes in eigenfrequencies and mode shapes from one assembly station to the next. This mode tracking was carried out between all successive stations and is shown as an example (for the change from station IV to station V) in Figure 10.

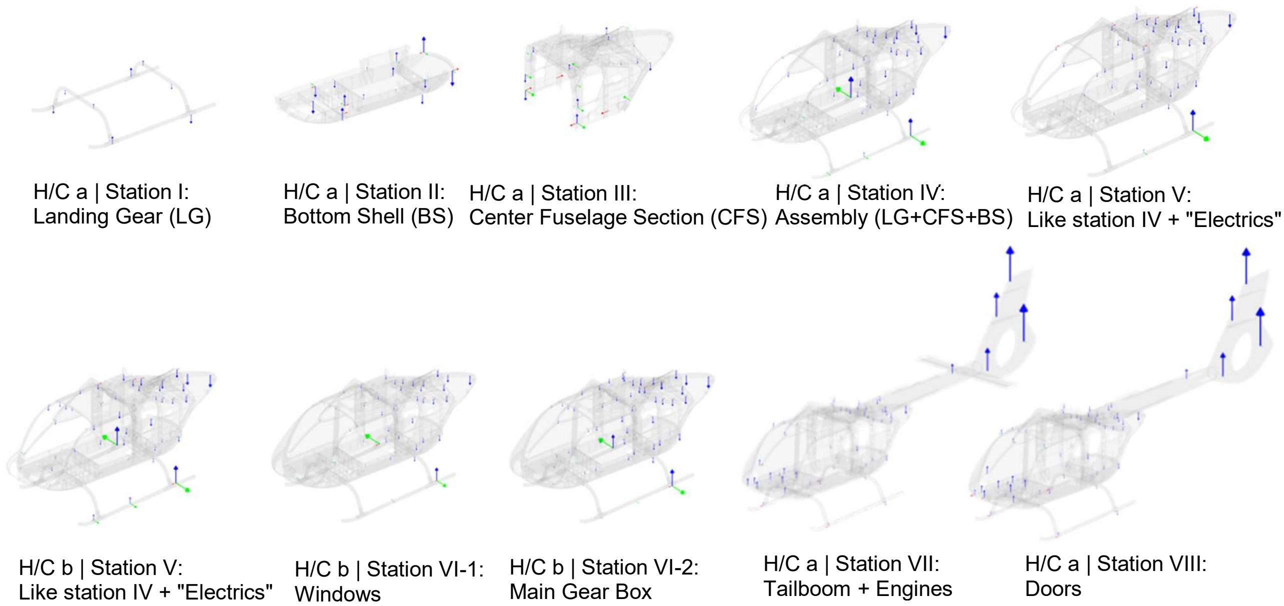

Figure 9: One exemplary mode shape of each modal model

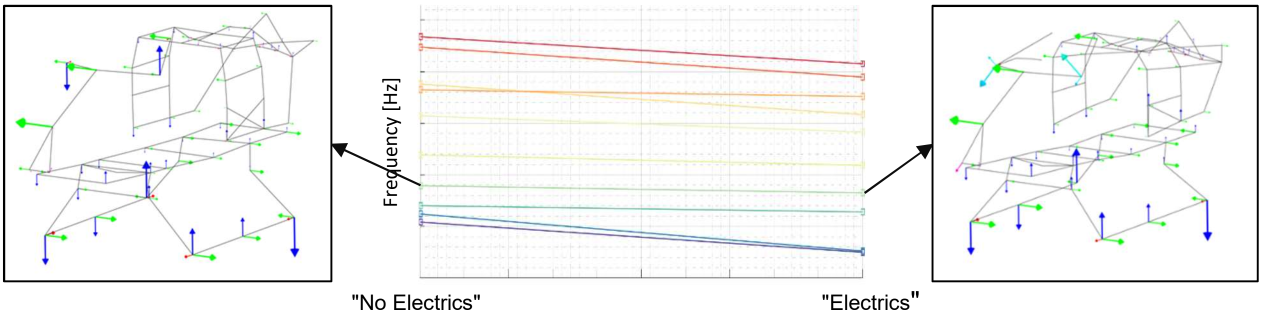

Figure 10: Tracking of mode shapes, effects of “Electrics”

In this assembly step, electrical components are integrated into the helicopter. The lines show the changes in the eigenfrequencies. As the electrical components mostly consist of cables, which primarily increase the total mass of the structure, the eigenfrequency decreases here. The left and right side of the figure show an exemplary mode shape whose eigenfrequency drops by about 7 %. Each line represents such a relation. As described, the similarity is determined by means of the MAC value, i.e. based on mode shapes. However, this relationship can then also be used to compare all other modal parameters (eigenfrequency, damping ratio, modal mass, participation factor etc.). In addition to the mode tracking, averaged frequency responses (frequency response functions, FRFs) are used. In this, the summed absolute value of the frequency response function is divided by the number of sensors over all excitation runs. By comparing the respective averaged FRFs, it becomes clear how the averaged vibration response (divided by the applied force) is changed by the additional subcomponent. For example, frequency shifts in the resonance peaks and changes in the average vibration level can be identified. Figure 11 shows an example of the step from station V to station VI-1 on the left, i.e. the installation of the front windows. These generally have a stiffening effect and considerably reduce the vibration level, especially in the area of the cabin frame into which the windows are inserted. The influence of the doors (Figure 11, right) is recognizable, but much smaller in comparison. The average response amplitude also decreases and most of the resonance frequencies increase when the doors are installed.

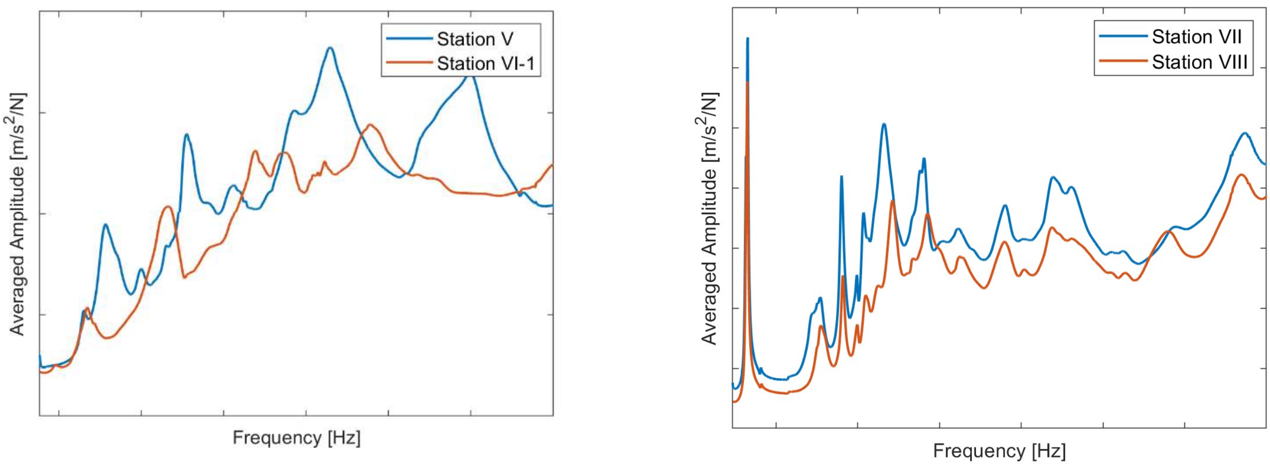

Figure 11: Comparison of averaged frequency-response-functions (FRFs) || effect of Windows (left); effect of Doors (right)

3. CONCLUSION AND OUTLOOK

Dynamic loads and a light-weight design make structural dynamics particularly relevant for Helicopters. This publication gives insight into the experimental side of a novel approach to finite element model-updating. Previous studies also used subcomponent tests. The present study is however (to the knowledge of the authors) unique in several key aspects listed in the following.

1. The subcomponents are tested on a successively assembled serial production helicopter during ongoing operations in the assembly line.
2. The scope of the study is comprehensive, in terms of the
    a. number of tested subcomponents,
    b. density of the sensor grid,
    c. number of shakers and excitation runs.
3. Meaningful modal models fulfilling quality criteria are synthesized for each assembly station using the DLR Correlation Tool
4. Regular production operations were not impaired by the experimental modal tests.

The results will be used to verify modelling assumptions, to improve the simulation models and to investigate the propagation of errors across the various assembly stations as well as to enable the development of novel methods for model updating.

The experiments have proven to be feasible and insightful and will therefore be used by Airbus Helicopters on future helicopters.

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