AN EXTENSIVE HELICOPTER GROUND VIBRATION TEST: FROM PRETEST ANALYSIS TO THE STUDY OF NON-LINEARITIES

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Abstract

The Ground Vibration Test (GVT) is one of the key milestones in the characterization of an aerospace structure, allowing to describe its structural dynamic behavior. Moreover, a helicopter GVT is associated to additional challenges deriving from the rotorcraft architecture, such as a high modal density and non-linear phenomena. In this paper, these challenges are treated by presenting the extensive H145 GVT campaign carried out in June 2017 by AHD and DLR, from its conception to the first analysis of results. Starting from a H145 FE model, the pre-test analysis began with the selection of target modes from the initial numerical modes set based on modal participation and energy considerations. An optimal sensor distribution was also achieved as results of the implementation of sensor placement metrics like the Normal Displacement Method and sensor elimination methods based on MAC analysis. An extensive description of the testing methods and procedure is as well documented, from the use of a dedicated test rig to the excitation of the structure by means of several exciter constellations using different force levels in order to assess non-linear behavior and therefore identify the structural variability. After data acquisition, the efficient post-processing performed using DLR correlation tool allowed the identification of modes family and the creation of a modal model. In the first analysis of results, modal identification has shown the validity of the pre-test analysis by identifying more than 40 modes for the first helicopter configuration and exhibiting an excellent data quality. Comparison between two H/C configurations has given also a first sample of how structural variability can influence the modal layout. Furthermore, focus has been put on the identification and analysis of non-linear phenomena, proving how non-linear behavior can affect significantly the H/C dynamic response and the modal identification. Finally, a comparison between FE and test results for one H/C configuration has been performed, allowing an objective evaluation of the predictive capability of current FE models. On this basis, the path for future works in the field of FE modal updating and structural optimization is clearly defined.

NOMENCLATURE

AHD	Airbus Helicopters Deutschland
CG	Center of Gravity
DAMVIBS	Design Analysis Methods for Vibrations
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DOF	Degree Of Freedom
DPR	Driving Point Residue
FE	Finite Element
FRF	Frequency Response Function
GFEM	Global Finite Element Model
GPKE	Grid Point Kinetic Energy
GVT	Ground Vibration Test
H/C	Helicopter
MAC	Modal Assurance Criterion
MIF	Mode Identification Function
MPA	Mode Participation Analysis
MPC	Modal Phase Collinearity
MPD	Mean Phase Deviation
MTOW	Maximum Takeoff Weight
NDM	Normal Displacement Method
PRM	Phase Resonance Method
PSM	Phase Separation Method
SEAMAC	Sensor Elimination using MAC
SQL	Structured Query Language
φ_j	Mode shape of the j_{th} mode
ω_j	Eigenfrequency of the j_{th} mode

1. INTRODUCTION

Vibrations have always been a relevant issue for helicopters (H/Cs). In general, the highest vibratory loads are generated by the main rotor at its blade passage frequencies; however, several other sources inducing significant loads at other frequencies may also be present. In the last decades vibration levels have been lowered considerably by means of improved design and a variety of other solutions. Nevertheless, they remain a topic of concerns as customers ask for H/Cs that can fly faster and perform more aggressive maneuvers, all without renouncing an improved ride comfort. Furthermore, nowadays the market requests more delicate instrumentations, accurate sensor and weapon pointing, more demanding visual tasks, all of this

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leading to requirements for low aircraft vibrations [1]. Improvement, i.e. reduction, of vibration levels can be achieved both globally and locally by means of additional systems, e.g. rotor isolation system or passive/active vibration absorbers. Nevertheless, the dynamic characteristics of the airframe remain the biggest contributor in the structural response. Knowing and understanding how the rotorcraft dynamically behaves is a key factor in order to predict and improve the vibrations in-flight.

This is exactly the goal of a Ground Vibration Test (GVT), one of the main milestones in the characterization of an aerospace structure. The GVT allows identifying experimental modal parameters such as eigenfrequencies, eigenmodes, damping ratios, generalized masses and transfer functions, which describe the structural dynamic behavior of the tested airframe. Acquiring this wide database provides not only a precious insight into the aircraft structural dynamics, but also fundamental information for the validation and update of dynamic Finite Element (FE) models.

Next to the main technical difficulties widely known in the aerospace industry [2], a helicopter GVT is associated to important peculiarities deriving from the rotorcraft architecture, such as several flexible components, wide spread of large masses (e.g. main rotor, engines, tail rotor, gearboxes, etc.), extremely high number of interfaces and wide frequency range targeted. All these features pose some additional major challenges related to modal density and non-linear phenomena. Besides the technical aspects, GVTs are also often performed in conditions of extreme time pressure due to limited availability of the aircraft. Therefore, an understanding of the rotorcraft structure and a correct preparation in view of the GVT are of crucial importance in order to increase the amount and quality of the test data while simultaneously reducing the testing time.

Concerning numerical models, the FE methods are nowadays a standard and widely used in the H/C industry, allowing an estimation of the rotorcraft dynamic characteristics way before the first prototype is built. Extensive work regarding the correlation within test and FE models was performed within the DAMVIBS program [3]. Of particular interest are the achievements regarding the role of “difficult components”, i.e. components that do not belong to the primary structure but may affect significantly the global rotorcraft response. Moreover, the comparison between test and FE data is reported for several rotorcraft models, highlighting the relevant differences and the importance of structural optimization in the design process. Updating of H/C generic FE Models was described in [4], where the GARTEUR AG14 has analyzed the feasibility to update a FE model of a Lynx Mk7 airframe on basis of modal test data. The recommendations of the paper advise to use a high spatial resolution of sensors and also to study the influence of structural variability. More recent experiences about the complexity behind FE model correlation for H/C structure are also available in [5]. The GVT described on this paper tried to follow the recommendations of these precedent studies using a high sensor number and testing multiple structural configurations, acquiring even measurements of the test rig response.

In June 2017 AHD launched, in collaboration with DLR, a large GVT campaign at the structural dynamics laboratory of the institute of aeroelasticity in Göttingen, Germany, with the ambition to create an unprecedented database for future numerical validation of a helicopter structure. The platform chosen for this campaign was the light twin H145 helicopter, shown in Figure 1 [6]. The H145, developed and built in cooperation with Kawasaki Heavy Industry, features a 4-bladed Hingeless rotor system and Fenestron® anti-torque system, and with its 3.7-ton MTOW is operated for a wide range of missions both in the civil and military market.

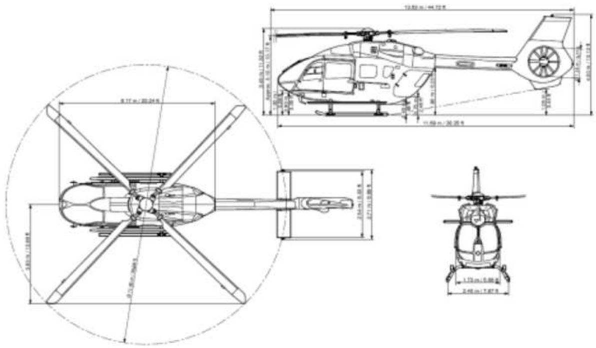

Figure 1: Three-view of Airbus Helicopters H145

The current paper describes the procedures and methods that have been used to plan and perform this GVT. After the test description, a special focus is put on how to address non-linearities and how to handle with the big amount of data acquired.

2. PRE-TEST ANALYSIS

Pre-test analysis is typically performed as first step in the planning of a modal survey test, and is of fundamental importance in a GVT. Starting point is a MSC® NASTRAN numerical model that describes the H/C architecture, called Global Finite Element Model (GFEM). Through modal analysis, the GFEM aims to describe the modal

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characteristics of the structure, such as modeshapes and eigenfrequencies. As this baseline model is used to simulate the GVT itself, the boundary conditions have also to be modelled already with sufficient accuracy

Pre-test analysis studies for the H145 GVT were performed using the commercial software FEMtools™ from Dynamic Design Solutions. The first step is the selection of the target modes, based on energy considerations, e.g. modal effective mass or kinetic energy. A set of candidate sensor locations is then defined by the engineer, who has to consider with experienced eyes factors like accessibility, geometry and costs. Fundamental is then the selection of the optimal locations and directions to position the acceleration sensors and to excite the structure. For this purpose, several methods are used: some metrics base their selection on the observability of target modes, using information about modal displacement or energy (normalized modal displacement, nodal kinetic energy); other methods proceed to iteratively eliminate sensors from the set of candidates in a way to optimally maintain linear independence or orthogonality between mode shapes. This is the case of effective independence method, elimination by MAC or iterative Guyan reduction.

After all these information are acquired and merged together yielding the final sensors setup, the FE model is truncated and converted to the test model using the retained sensor locations. Reduced mass and stiffness matrices are also calculated.

2.1. The Global Finite Element Model (GFEM)

The H145 GFEM is a MSC® NASTRAN numerical model built at AHD to delineate the H145 dynamic behavior by means of parameters like eigenfrequencies, mode shapes and frequency response functions (FRFs). These are obtained running a normal modes analysis (SOL103) or a direct/modal frequency response analysis (SOL 108/111).

During the past years, several different H145 GFEMs have been built at AHD in order to investigate different modelling strategies, featuring for example a finer discretization of the airframe, detailed modelling of secondary components like gearboxes, engines, doors, etc. It is evident that most of these models, which approach multiple million elements, are extremely accurate but result also in prohibitive calculation times for GVT applications.

The GFEM chosen for the pre-test analysis of this GVT refers to a model of medium complexity, which turned out to be the best compromise between calculation efficiency and results accuracy. The model includes the H/C main architecture and several components that are considered relevant for dynamic analysis (see Figure 2). Moreover, different mass distributions are designated to represent different H/C configurations and missions.

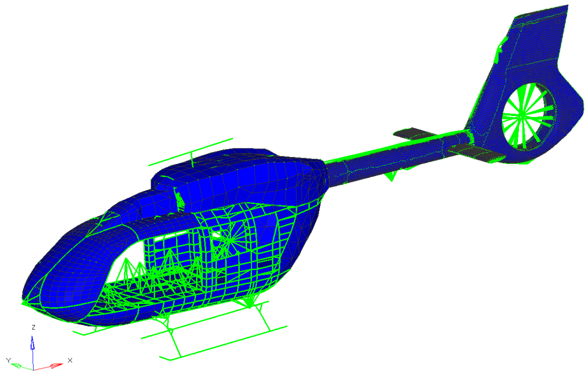

Figure 2: H145 baseline GFEM available at AHD

It is evident that an accurate GFEM has a solid base in the proper description of H/C geometry and elastic properties, like wall thickness, material density, elastic modulus, etc. Next to these parameters, the right modelling of the boundary conditions is likewise important in order to have a realistic test model. During the H145 GVT a dedicated test bench from DLR was used, featuring a metallic test rig and a pneumatic suspension. In order to include a correct boundary condition description in the pre-test analysis, a MSC® NASTRAN FE Model of the test bench was made available by DLR. A detail description of the test rig and the extensive work carried out to validate the FE model is documented in [7]. Therefore, modes with participation of both H/C and test rig can be properly described (see Figure 3).

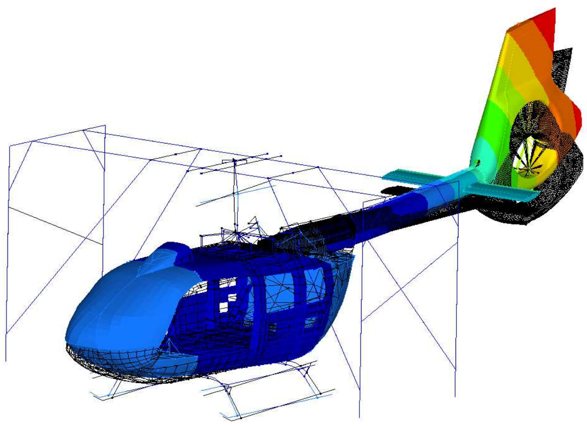

Figure 3: Example of elastic mode shape with H/C and test rig participation (eigenvectors contour)

Due to the interest in the transfer function for flight test applications, two main load paths were used

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during the H145 GVT, corresponding to main rotor and Fenestron® excitation. Additionally, further locations were defined in order to excite extensively the structure and any component of interest and achieve a comprehensive FRFs set.

2.2. Selection of the target modes

Aim of this GVT was to explore the dynamics of the H145 H/C in a frequency range up to 50 Hz. One of the major challenges in the modeling of an H/C structure is the description of the inertial properties. In such complex GFEM, depending on the level of detail in the modeling of components and subsystems, it is common to deal with some spurious local modes. In this paper, local modes are defined as modeshapes that do not describe the dynamic behavior of the global system, but are generated locally, for example due to lack of details in the meshing or a too much simplistic modeling and connection of lumped masses. These modes are the natural outcome of a compromise between model accuracy and computational efficiency. An identification of these spurious modes at the beginning of the pre-test analysis is fundamental, in order to avoid an inadequate sensor placement. Fortunately, many local modes are easily recognized by an experienced eye and can be therefore removed from the set of target modes with minimum effort. Furthermore, several methods are available in order to facilitate the task. Among these, two methodologies suitable for freely suspended structures were used for the H145 GVT.

The Modal Participation Analysis (MPA) [8] computes the relative contribution of each mode to the overall response of the H/C. The MPA value for a mode *j* is calculated, assuming a unit input at each input DOFs, as:

$$MPA_j = \frac{trace(\varphi_{i,j}\,\varphi_{i,j}^T)}{trace(\sum_{j=1}^{nm}\varphi_{i,j}\,\varphi_{i,j}^T)} \quad (1)$$

where $\varphi_{i,j}$ is the mode shape of the j_{th} mode reduced to the input DOF *i*. By inverting equation (1), it can also provide the relative importance of each input DOF. This turns to be a useful parameter to identify for example the optimal excitation location for a known selected mode shape.

A second approach that helps to identify spurious local modes is based on energy considerations. In particular, the NASTRAN output Grid Point Kinetic Energy (GPKE) reveals to be very helpful by showing how much each DOF is participating in the motion of a specific mode. A comprehensive formulation is available in [9]. It is worth to remind that, like all kind of energy parameters in modal analysis, the GPKE cannot be compared across modes, but only within them. That is, given a selected mode, if the GPKE is shared across many DOFs, it hints the mode being a global mode. On the other hand, if only a small group of DOFs shows a significant GPKE, this is an indication of a possible local mode that has to be checked and treated carefully [10].

After recognizing the spurious local modes in the H145 GFEM, some of them were corrected with a more accurate remodeling, others were simply excluded. From the original set with more than 40 H/C eigenfrequencies, only 21 were considered trustworthy and therefore retained as target modes for the pre-test analysis.

2.3. Definition of sensors locations

Finding an optimal sensor placement is one of the main expectations behind the pre-test analysis. It is known that the choice of sensors locations have a strong influence on the quality and amount of modal test data, and therefore also in the correlation with FE Models. While in the past engineering experience was the main driver of the choice, nowadays several methods have been developed in order to support the test planning. An extensive amount of literature has been published over the past 20 years [11][12][13], introducing a pretty large group of criteria that can be applied, including observability, linear independence of modes, effect of sensor elimination on MAC, kinetic and/or strain energy and others. Some methods aim mainly to guide the engineer and must be complemented by engineering judgment, others try even to automate the entire selection process. Both approaches were used for the H145 GVT pre-test analysis.

2.3.1. Sensor placement metrics methods

Sensor placement metrics provide a measure of the candidate sensors locations with respect to the response observability of target modes and are also the most commonly used due to a high computational efficiency [8]. Unlike the sensor elimination methods however, they do not take into account the linear independence between modes, which is fundamental in order to distinguish mode shapes, especially for a structure like the H/C with a high modal density and where eigenfrequencies are closely spaced. Therefore, in a second step an additional refinement with checking of linear dependency is normally necessary.

In the first skimming to reduce the candidate DOFs, two metrics are used, respectively the Normalized Modal Displacement Method (NMD) and the Nodal Kinetic Energy (NKE). The NMD is

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based on the computation of the driving point residues for the DOFs *i* of the GFEM mode *j* according to equation (2):

$$DPR_j(i,i) = \varphi(i)_j^2/\omega_j \quad (2)$$

As driving point it is intended any node of the structure where excitation DOF and response DOF are the same, hence typically where the shaker is located. A comprehensive formulation is available in [14]. The Driving Point Residues (DPR) are normalized and compared for a range of target mode shapes. Comparison criteria are based on minimum, maximum, average or weighted NMD. The weighted NMD is usually the most representative in order to identify a good sensor location, where the highest values represent the better choice [8]. In Figure 4 the plots for weighted NMD over node ID for the three translational DOFs are reported.

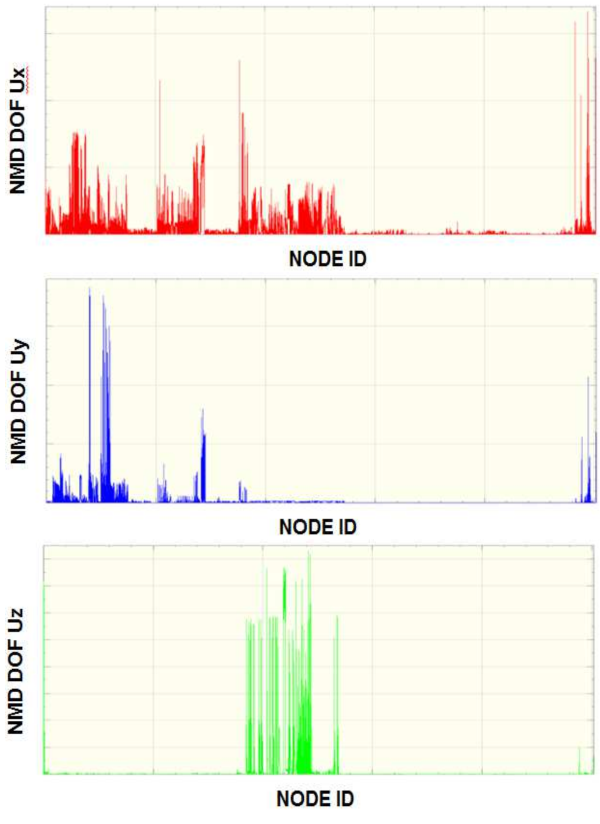

Figure 4: Weighted NMD (Y-axis) over Node ID (X-axis) for translational DOF X (upper), Y (middle), Z (lower)

2.3.2. Sensor elimination methods

Sensor elimination methods are iterative methods which help reducing the sensors from the initial set of candidate DOFs by studying the effect on some elimination criterion at each iteration step. Several variations of this method exist, depending on the criterion chosen for sensor elimination, number of sensors remove per iterations, etc. Some methods involve many intensive computations and might be computational expensive. It is then common practice, as in this case, to use these methods as second step, when the set of candidate DOFs is already significantly reduced. For this purpose FEMtools™ provides several options by using the Effective Independence, Modal Assurance Criterion (SEAMAC) or the Iterative Guyan Reduction.

One of the most commonly used criterion to check and calculate linear dependency between modes is the Modal Assurance Criterion (MAC). A complete description, including mathematical formulation and its uses, can be found in [15]. On MAC lays the foundations of the SEAMAC algorithm, which tests the removal of each candidate sensor DOF and carries out the one resulting in the minimum largest off-diagonal term of the MAC Matrix. The process is then repeated for the remaining candidate sensor DOFs. Clearly, although these procedures represent a big step forward towards an automatic process, a review from an experienced engineer is necessary and of importance in order to ensure a valid sensor setup.

After final review, the Auto-MAC matrix of the reduced test model is reported in Figure 5. It is shown that the off-diagonal terms assume quite small values, granting the observability of the modes and their linear independence.

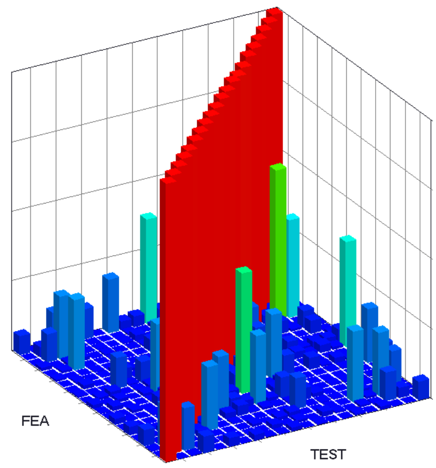

Figure 5: Auto-MAC matrix for the test model (all DOFs vs test DOFs)

The final H145 test model included 80 nodes for a total of approximately 230 DOFs. Furthermore, other 25 sensors were assigned to the study of additional subsystems transfer function, while about 50 others DOFs were added on the test rig in order to proper measure the influence of the boundary conditions.

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3. TESTING

In this chapter the complete testing phase is described, in particular the initial setup, the test procedure and the post-processing of the data.

3.1. Test setup

3.1.1. Test rig and suspension

An H/C GVT is normally carried out with boundary conditions which are close to in-flight conditions. This means to support the structure at the main rotor hub by hanging it into a test rig, resulting in a freely suspended rotorcraft. This test rig is available at DLR.

Core of such a test rig is the pneumatic suspension for the H/C which is located in the middle of the upper deck. The suspension uses four pneumatic springs between the lower and the upper bearing plate (see Figure 6). The required quasi-static pressure necessary to carry the weight of the helicopter is regulated by a controller. Furthermore, the pneumatic springs are connected with pressure vessels of 0.2m³ of pressurized air volume to achieve suspension frequencies low enough to avoid undesired interaction between enforced elastic vibrations and undesired rigid body suspension modes.

Figure 6: Pneumatic suspension system on the test rig with upper (golden) and lower (orange) bearing plate and hanger rod

As previously mentioned, a validated MSC® NASTRAN finite element model of the test rig is available at DLR (see Figure 7). The model was used to apply the GVT boundary conditions to the whole H/C model.

In order to install the H/C in the test rig the removal of the rotor head was necessary. A mechanical adapter and dummy masses representing the weight of the rotor blades were installed instead. In addition, a yellow-colored rotor cross was mounted on top of the mechanical adapter. This rotor cross is essentially a means for introducing four vertical excitation forces into the rotor head to simulate dynamic force and moment excitations at the hub.

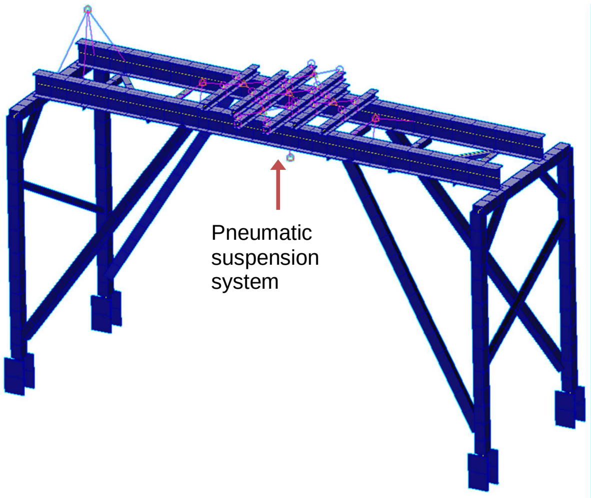

Figure 7: MSC.NASTRAN finite element model of DLR helicopter test rig

Finally, in order to avoid rigid body rotation around the vertical axis, a bungee cord was installed between two pillars of the testing hall. The H/C tail boom was then connected to this soft bungee.

3.1.2. Data acquisition system

The measurement system was a LMS SCADAS III system with 3 frontends which comprises 96 acquisition channels in a single mainframe. The system is capable to measure all channels simultaneously with an input level up to ±10 V. The A/D conversion is 24bit accuracy with a maximum sampling frequency of 51.2 kHz. The mainframe is equipped with 8 V12L modules (12 channels each). The master frontend is additionally equipped with one signal generator card (QDAC modules) for in total 8 channels of independent signal generation.

The DLR institute of aeroelasticity uses special patch panels to support the test setup with well-organized cable branches. The patch-panels are connected to the V12L modules of the SCADAS III system by custom made cables with LEMO connectors. From the patch panels, cable branches can be set up starting with a few SCSII cables towards connection boxes with 16 analogue inputs provided on LEMO plugs. There, the piezo-resistive acceleration sensors or ICP force sensors can be connected with shielded low-noise cables.

Each channel, each cable and each sensor is labelled by an internal numbering scheme, providing a unique assignment of sensor, cable

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and acquisition channel. This numbering and labelling scheme helps to minimize errors during installation and to reduce troubleshooting efforts in the verification of the test setup.

3.1.3. Sensor and exciter setup

As outcome of the previous pre-test analysis, the helicopter was equipped with about 250 acceleration sensors. In many locations measurements were acquired in all three directions. Additionally, the test rig was equipped with other 50 sensors to observe its influence on the test.

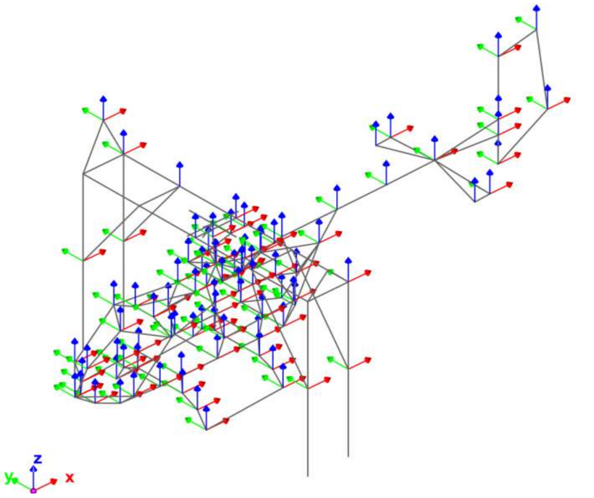

Figure 8: Sensor locations on helicopter and test rig

The excitation of the structure was performed with long coil shakers ranging from 220 to 2200 N. The main rotor location was excited with 4 shakers from the test rig, where two were always operated simultaneously either in phase to introduce pure vertical loads or 180° phase shifted to introduce moments (see Figure 9 and Figure 10). Additionally lateral excitation of the main rotor was performed in both directions. The Fenestron® location was also excited in vertical and lateral direction, as well as the landing gear.

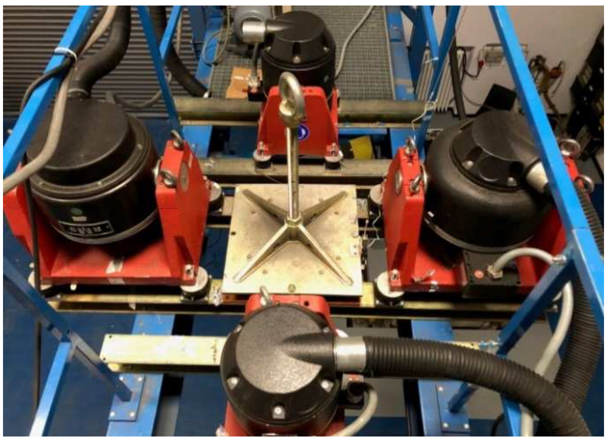

Figure 9: Shaker setup at main rotor (1)

Figure 10: Shaker setup at main rotor (2)

3.2. Test procedure

The H145 GVT had several main objectives:

- Investigate the industrial applicability of a high spatial sensor resolution for H/C GVT.
- Increase the understanding of H/C structural dynamic variation due to configuration changes.
- Obtain frequency response functions for the excitation from the main rotor and the Fenestron®.
- Identify modal parameters in terms of eigenfrequencies, mode shapes, damping ratios and modal masses.
- Assess non-linear behavior.
- Increase the understanding of the role of boundary conditions in H/C testing.
- Acquire a wide database for FE models update.

Formerly, the identification of modal parameters was performed using the Phase Resonance Method (PRM). Though this method is known to be the most accurate, it is very time consuming. Therefore the modal parameters from the current GVT were gathered from FRFs using only the Phase Separation Method (PSM).

For each new excitation configuration, random excitation runs were performed first and swept-sine excitation runs afterwards. The random runs were necessary to gather a quick overview over the dynamic characteristics of the structure without any risk of over-testing by means of excessive response amplitudes at resonances. Swept-sine excitation was performed after the random runs on different excitation force levels to detect non-linear behavior of the H/C. Different exciter locations and directions were necessary to guarantee a good excitation of all modes which is a prerequisite for the completeness and accuracy of the resulting equivalent modal model obtained from the GVT.

During the H145 GVT, multi-shaker excitations were applied at the rotor cross installed at the

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main rotor head to simulate the excitation at this point by a single force or respectively a single force moment. The determination of frequency response functions for the equivalent single-point force or moment excitation reveals to be of particular interest for comparison with flight test data. Especially in case of correlated input forces this topic required special attention [16].

3.3. Post-processing and modal identification

3.3.1. Time data processing

The data processing was particularly challenging at the main rotor hub, where the vertical excitation was induced using two shakers in parallel. Therefore both pure vertical or moment excitations were possible. Using sine sweep signals the time data needs to be treated in a special way to obtain frequency response functions.

To determine the equivalent single-point excitation, all excitation runs from main rotor in Z, i.e. vertical force and moments, were processed using a DLR internal toolbox, according to the following steps:

1. All excitation forces and driving point acceleration responses of the excitation points involved in the current run need to be considered for transformation.
2. The equivalent force and the equivalent moment for the single excitation at the reference point located on the centerline of the main rotor at the rotor head are then calculated.
3. The resultant angular acceleration and the resultant translational acceleration are calculated for the single reference excitation on the centerline of the main rotor at the rotor head from the driving point accelerations assuming a rigid rotor cross.
4. Generate frequency domain data object holding the frequency domain transfer function of all response signals with respect to the main desired equivalent single-point excitation force or excitation moment. This is achieved by using the DLR-internal toolbox which utilizes the periodigram approach according to the Welch's method [17].

3.3.2. Determination of a modal model

The excitation of the structure was performed for different exciter configurations at different locations and directions of the structure. The exciter signal can be varied in type, which means to modify the type of signal itself, typically random or swept-sine excitation, and in force level, which means to raise the amplification factor. Generally the random signals are used to get a quick overview about the structural dynamic characteristics of the structure. The energy level at each frequency line is very low and therefore the displacement amplitude levels of the responding structure are not realistic for operating conditions. Based on the information from the quick overview, optimized excitation signals for swept-sine runs are determined, achieving much higher displacement levels depending on the force amplitude. To identify non-linear behavior the input force level is increased to analyze the modal parameters over force and displacement level. Particular attention was paid since the beginning in the definition of limitations in terms of response and force levels to be considered during the GVT. These limitations were defined at key positions to ensure values below normal qualification and in general below flight test levels. These conditions were verified thanks to the sequential approach with increasing test levels and the real time monitoring of the output for chosen locations.

After modal analysis is performed on a specific dataset obtained from an excitation run, the corresponding modal data and the corresponding FRFs are transferred into a dedicated SQL database. During the analysis, specific modes can be identified multiple times from different excitation runs with slightly different properties. Therefore a need of systematic correlation among individual test datasets arises, together with the necessity of an assessment of the accuracy of modal analysis results, e.g. based on evaluation of specific quality criteria. Currently there is no commercial software on the market to collect, filter, classify and post process modal parameters. The DLR correlation tool [18] has been specifically developed to cope with this type of problem (see Figure 11 and Figure 12).

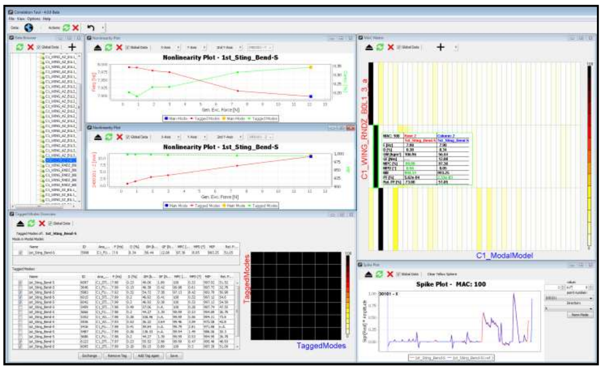

Figure 11: GUI of DLR Correlation Tool: Non-Linearity plot, Auto-MAC of mode family, MAC between new mode set and modal model and spike plot for mode comparison

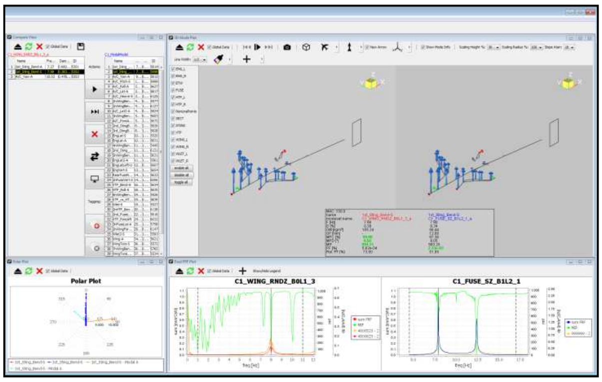

Figure 12: GUI of DLR Correlation Tool: list of modes from new mode set and modal model, polar plot for mode shape complexity, mode shape comparison in dual view window and according frequency response functions

The tool has a user based access to the SQL database described before. As aforementioned, by analyzing the FRFs for different excitation locations and levels it is evident that the same mode might appear several times with slightly different characteristics. Therefore, during modal identification families of modes are created, where a family is defined as a group of identified modes that show a high correlation with each other, meaning that they are representation of the same structural mode. The level of correlation is evaluated by the engineer with the support of several means, e.g. MAC, eigenvector spike plots and 3D mode visualization. Within each family only one mode is picked as the best candidate for the creation of the modal model according to quality criteria like modal phase collinearity (MPC), mean phase deviation (MPD), mode indicator function (MIF) or generalized force.

This selection process ensures the highest quality of the final modal mode, i.e. an equivalent mathematical model of the tested object containing a linear independent set of modes. The modes families or their subsets can be eventually used to analyze non-linearity of modes or to determine the test uncertainty in terms of the scatter among the mode family members.

4. TEST RESULTS

The H145 GVT can be described by some impressive numbers: 14 days of campaign, 26 helicopter configurations, more than 300 sensors, 10 exciter configurations and several load levels and signals used. Ending up with approx. 400 excitation runs, an extensive database was acquired at AHD. Clearly, these data open a wide spectrum of possible applications and further studies and analysis concerning rotorcraft structural dynamics. In this paper, a first review of the results is reported, starting with the analysis of the first H/C configuration, a comparison according to configuration variations, a more deep insight of non-linear phenomena for this complex structure and a first correlation with the original GFEM used in the pre-test analysis.

4.1. Modal parameters

The first configuration tested represents a possible flight case with a total gross weight of approximately 3-ton. For this configuration, the H/C was fully tanked and additional ballast weights were used to reach the target mass and CG.

The identified modes include (Figure 13):

- H/C rigid body modes, e.g. heave, pitch, roll, etc., that can be used for a further update of the suspension properties
- Test rig and suspension system resonances
- H/C elastic modes, clearly of primary importance

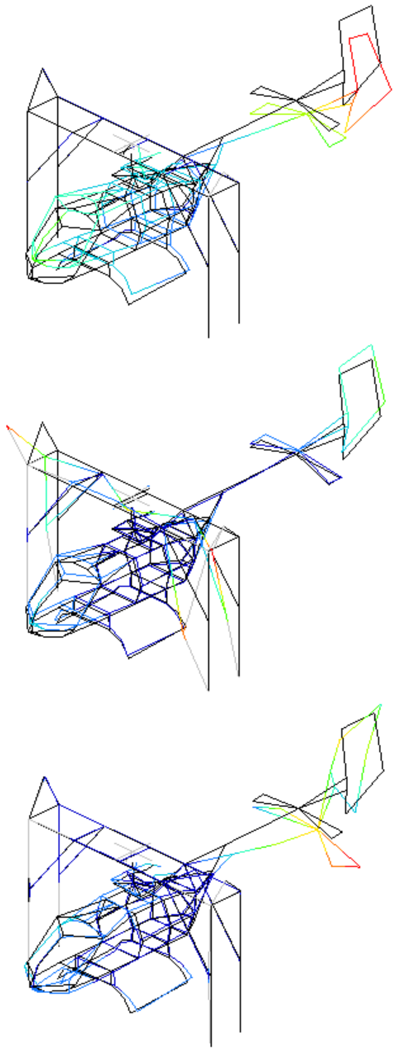

Figure 13: Example of H/C rigid body mode (upper), test rig mode (middle), H/C elastic mode (lower)

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In the frequency range of interests, more than 40 eigenmodes were found (see Figure 14).

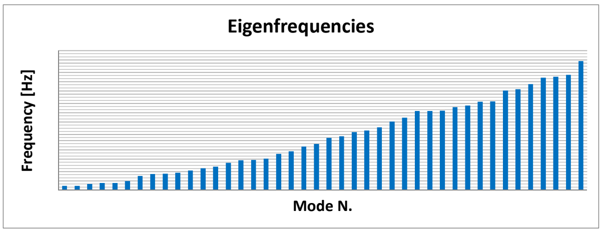


Figure 14: Identified eigenfrequencies for 3-ton

By means of AUTO-MAC calculation of the modal model, an optimal linear independence between modeshapes was observed, proving the validity of the modal identification procedure described in the previous chapter.

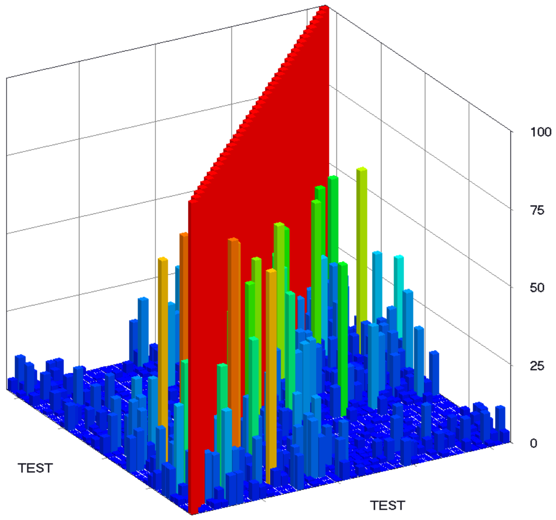
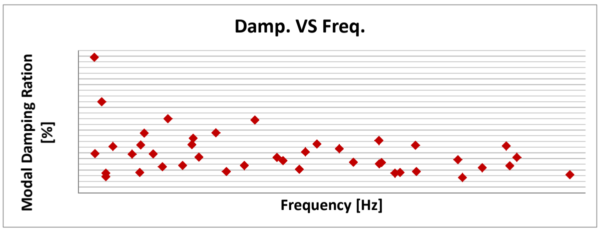


Figure 15: Auto-MAC Test Modal Model

For each mode, modal parameters like modal damping ratio and generalized mass were estimated and reported in Figure 16.



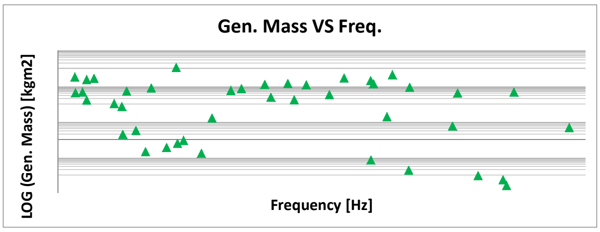


Figure 16: Estimated modal parameters for 3-ton: modal damping (above) and generalized mass (below) vs frequency

4.2. H/C configuration variations

It has been already mentioned that several H/C configurations were tested. These variations differ for gross weight, global CG position, addition of fuel, installation and/or modification of relevant equipment. For every configuration, different load paths and load levels were also applied, in order to study the influence of the modifications on the structural response as well as to gain a broader insight in non-linear phenomena.

A comparison between two H/C configurations is here analyzed as example, respectively the already introduced 3-ton and the MTOW (3.8-ton) configurations. Figure 18 shows the eigenfrequencies comparison for paired mode shapes, where a pair is defined as a couple of mode shapes of the two modal models showing a correlation with MAC > 60.

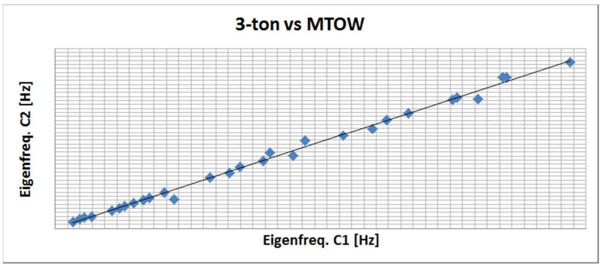


Figure 17: Paired mode shapes for 3-ton and MTOW

At a first glance it is apparent that for the low frequency the trend is almost diagonal, meaning the influence of the global mass is negligible. On the other hand the scattering increases with the frequencies, resulting in some modes being shifted in frequency up to 3 Hz. Furthermore, several “holes” in the plot are noticeable, which might indicate the appearance of new modes in the modal basis, but also a modification of the mode shape itself such that it results in a poor MAC correlation and a consequent missing pairing.

4.3. Non-linearity studies

As it has become visible in this paper, the dynamic system theory is well-established for linear systems and can rely on mature tools for the computation of normal modes both from numerical and experimental models. However, it is commonly known that non-linearity is a frequent occurrence in complex structures [19]. A helicopter structure in particular is known to show a significant number of non-linearities. Non-linear behavior can be noticed observing the variations of the transfer function when the structure is excited with different force levels. During the H145 GVT, 4 different excitation levels (L1-L4) have

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been used for each exciter configuration in order to study this phenomenon.

Figure 18 shows the frequency response functions of the driving point for a specific excitation configuration. Looking at the whole frequency range, it can be already observed that the structure behaves non-linearly.

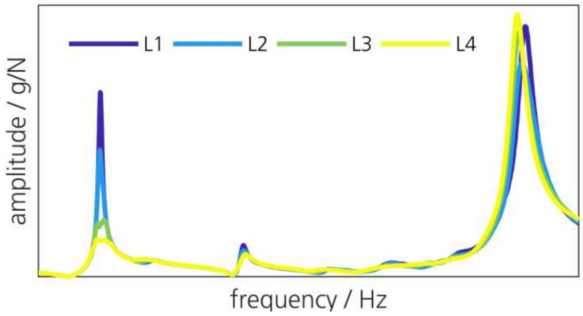

Figure 18: Frequency response functions for different force levels

Having a closer look at two peaks of the FRFs, also different non-linear behavior can be detected. While the resonance peak on the left hand side of Figure 19 shows an amplitude dependency which results in higher damping estimates for higher forces, the resonance peak on the right hand side shows a frequency dependency and shifts with higher forces to lower frequencies.

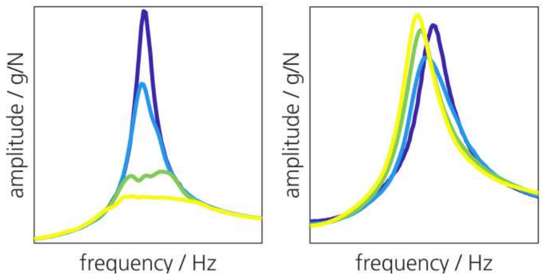

Figure 19: FRF zoom into resonance peaks for different force levels

Especially due to this last phenomenon, it may clearly happen that the same mode is recognized at two or more different frequencies according to position and amplitude of the excitation. This is considered in the creation of the mode families as describe in 3.3.2. For example in the analysis of the 3-ton configuration it can be seen that within each mode family a certain scattering is present. The non-linear behavior is recognized to be one of the main causes of this phenomenon. The absolute frequency variations are reported in Figure 20, where it is observed how clearly the scattering increase with the frequency, reaching spans up to 6 Hz for the same mode.

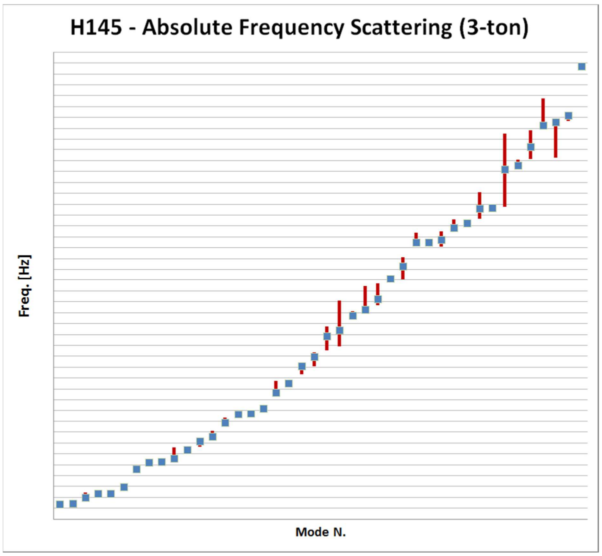

Figure 20: Eigenfrequencies and absolute eigenfreq. variation for 3-ton

Figure 21 shows instead the relative percentage frequency change, pointing out variations of up to 20%. The reference value represents the best mode of the family, included in the modal model according to the procedure described in 3.3.2.

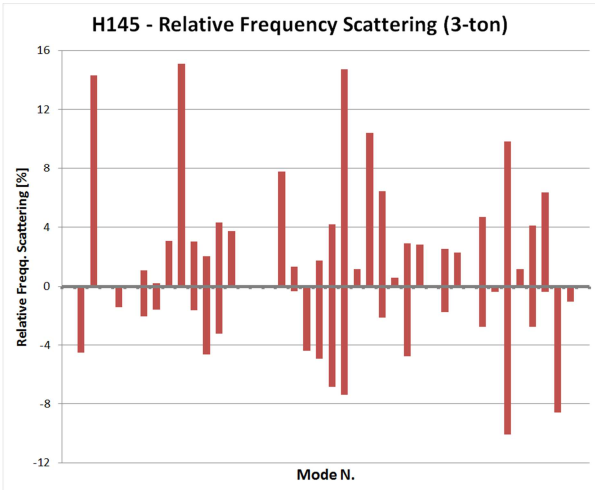

Figure 21: Relative [%] eigenfrequencies variation for 3-ton

4.4. Correlation Test - GFEM

After the GVT was concluded, one of the first questions to be answered was whether the numerical GFEM and the pre-test analysis were able to describe the GVT with sufficient accuracy. Therefore, a first and quick correlation was performed for the 3-ton model between test and FE results. Considering the complete sets of test and FE mode shapes, a first MAC calculation shows that several modes were caught with a quite high accuracy. From Figure 22 it is however clear that, due to the high modal density of both

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datasets, it is nearly impossible to draw some conclusions.

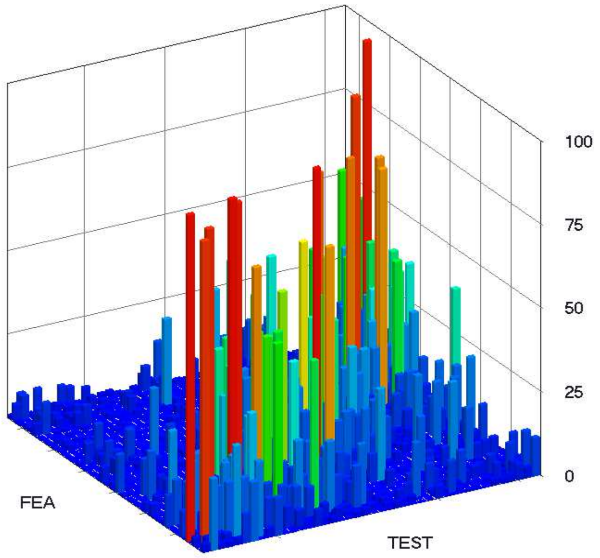

Figure 22: Complete MAC Matrix FE vs Test

Therefore in order to give a more pragmatic overview, a correlation was performed for reduced sets of modeshapes containing only the most relevant H/C modes, hence excluding modes of test rig, smaller components and of course spurious modes. In Figure 23 it can be seen how most of the modes correlates with a high accuracy, showing a MAC > 0.7. Nevertheless, some modes were not captured in the MAC correlation, although a visual comparison results in a possible correlation. Still, the GFEM proved to be a more than valid support in the successful test planning.

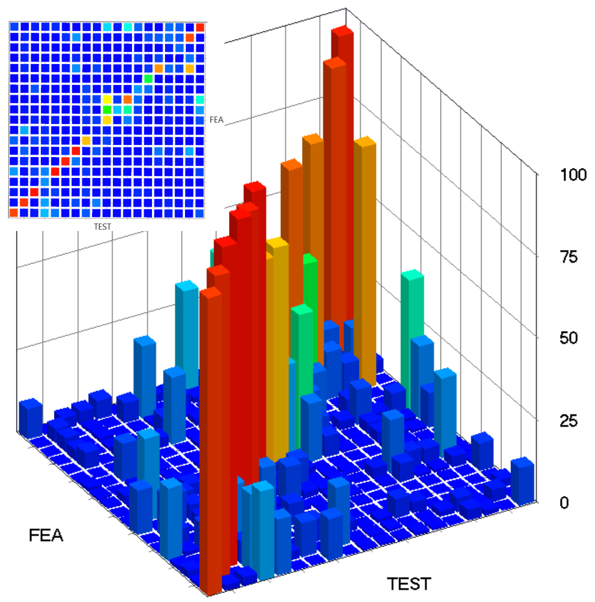

Figure 23: Reduced MAC Matrix FE vs Test for relevant modes

The eigenfrequencies for the paired modeshapes are also compared in Figure 24. It is interesting to notice how, while the majority of frequency matches with an error < 10%, several modes show a significant frequency difference between test and FE, reaching a delta up to 40%. Precisely these modes will be the main focus for future works about model updating.

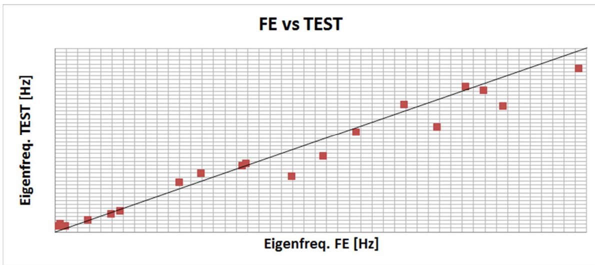

Figure 24: Frequency Comparison FE vs Test for paired modes

5. CONCLUSION AND OUTLOOK

The H145 GVT campaign presented in this paper is a milestone in the history of AHD structural testing. Extensive pre-test analyses were performed in order to increase test efficiency and data quality. Starting from AHD H145 GFEM, modal participation analysis and evaluation of grid point kinetic energy were used to select target modes from the initial FE modes set. An optimal sensor distribution was achieved as results of the implementation of sensor placement metrics method like the NMD and sensor elimination method based on MAC analysis.

During the test the H/C was suspended by means of a dedicated test rig in order to simulate free-free conditions. Vibration data were acquired with over 300 sensors, comprising variations for 26 H/C structural configurations. Each configuration was tested on different force levels with several exciter constellations in order to assess non-linear behavior of the helicopter structure. Recommendations from previous work [3][4][5] were taken into account to generate high fidelity data for finite element model updating of the H/C airframe. Post-processing was performed using DLR correlation tools, allowing the grouping the identified modes in mode families and the creation of a high quality modal model.

In the first analysis of results, several topics have been addressed. Modal identification has shown the validity of the pre-test analysis by identifying more than 40 eigenmodes for the first helicopter configuration and exhibiting an excellent data quality. Comparison between 3-ton and MTOW configurations, differing for gross weight, has been also performed, giving a first sample of how

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structural variability can influence the modal layout. In particular, frequency differences of up to 3 Hz have been observed, as well as the appearance of new modes. Furthermore, focus has been put on the identification and analysis of non-linear phenomena. It has been shown how non-linear behavior can affect significantly the H/C dynamic response and the modal identification, introducing uncertainty in the exact eigenfrequency estimation up to 20%. Finally, a comparison between FE and test results for one H/C configuration has been performed. While several modes have shown an excellent correlation, the missed correlation as well as the significant difference with regards to eigenfrequency estimation for some other modes defines the clear need of model updating.

Drawing some conclusions, the H145 GVT can be considered a significant success of the AHD-DLR collaboration, as all the target of the test have been achieved in the planned short test time. With more than 400 runs and 120000 FRFs, an unprecedented immense database was acquired, revealing a wide spectrum of possible applications and further studies and analysis concerning rotorcraft structural dynamics. In particular, questions concerning the influence of structural modifications and non-linear behavior in rotorcraft architecture can be answered on basis of reliable test data. Moreover, in the constant search for more and more predictive FE models, the variety of information available will provide concrete working material to tackle hot topics like model updating and structural optimization, as well as helping reviewing modeling guideline to set a new standard in the helicopter industry.

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