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FLIGHT TESTING USING FAST ONLINE AEROELASTIC IDENTIFICATION TECHNIQUES WITH DLR RESEARCH AIRCRAFT HALO

J. Sinske [1], Y.Govers[1], G. Jelicic[1], R. Buchbach[1], J. Schwochow[1], V. Handojo[1], M. Böswald[1]and W.R. Krüger[1]

[1] German Aerospace Center (DLR), Institute of Aeroelasticity
Göttingen, Germany
Julian.Sinske@DLR.de

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Abstract: The research aircraft HALO (High Altitude and Long Range Research Aircraft) of the German Aerospace Center (DLR) can be equipped with under-wing stores at different wing positions to transport scientific instruments for atmospheric research. The PMS (Particle Measurement System) carrier is one example of such an external store which can carry three instruments at the same time per wing to detect and count particles of different size (ice, carbon, dust, etc.) in different layers of the atmosphere.

Any modification on an aircraft must be investigated numerically and experimentally to ensure the structural integrity and safe operation of the aircraft for all flight conditions. For loads and flutter analyses, flight test data is the essential means for validation. In preparation of the flight test, the airframe and the under-wing stores must be instrumented with acceleration sensors and strain gauges. In order to reduce flight test time and to maintain safety it is important to have tools available that indicate relevant safety margins to support the flight test engineers in making decisions for continuation of cancellation of a flight test.

The DLR Institute of Aeroelasticity in Göttingen (Germany) has developed a real-time analysis procedure for online identification of modal parameters like eigenfrequencies, damping ratios and mode shapes. These parameters vary with flight conditions, payload and fuel configuration and must be monitored to assess the aeroelastic stability margin of the system. In a joined flight test campaign, the department of Loads Analysis and Aeroelastic Design and the department of Structural Dynamics and System Identification of the DLR-Institute of Aeroelasticity have tested the newly developed flight test procedure in 14 flight hours using the HALO research aircraft. A network of three distributed data acquisition modules enabled the recording of the flight test instrumentation with 51 accelerometers and 16 strain gauges integrated in Wheatstone bridges. The measured data were distributed online to several computers on which the newly developed software was implemented, allowing an instantaneous analysis of the structural dynamics and dynamic loads in flight.

This paper provides an overview of the flight vibration tests (FVT) conducted with HALO. It also shows the capability of the newly developed online monitoring system for aeroelastic identification.

1 INTRODUCTION

Aircraft prototypes and major modifications on an aircraft must be tested at first a in ground vibration test and later on in a flight vibration test. For the latter, the modal parameters of the aircraft need to be identified from various flight states (altitude and speed) in the form of eigenfrequencies, modal damping ratios and mode shapes. The procedures applied in vibration tests in flight are similar to those applied in ground vibration tests [1-4]. Excitation forces are introduced into the structure e.g. via actuation of the control surfaces using pulses or controlled swept sine excitation. The pre-defined movement of control surfaces is only possible in case of an Electronic Flight Control System (EFCS) or a Fly-by-Wire (FBW) control. Even external exciters with mass unbalances or aerodynamic exciters with oscillating vanes are being used for excitation in flight. However, they require additional certification, can affect the aircraft behaviour are quite expensive and not easy to install.

In the context of the iLOADS [5] flight test campaign, modal identification methods, e.g. Operational Modal Analysis (OMA), as well as methods for experimental load determination were tested by DLR the first time in a flight vibration test. OMA methods, that seek to identify modal parameters from measured responses only without knowing the input forces. It is based on the assumption that broad band excitation forces are present that sufficiently excite the structure in the frequency range of interest. During the ALLEGRA project (2012-2016) the DLR Institute of Aeroelasticity optimised the computational highly demanding methods to such an extent that they reached nearly real-time capability [6-8]. The developed system has already shown real-time aeroelastic identification capability within several wind tunnel testing campaigns in the transonic wind tunnel Göttingen (TWG) and the cryogenic wind tunnel in Cologne (KKK) operated by German Dutch Wind Tunnels (DNW) [6, 9, 10].

HALO (Figure 1) is already equipped with a basic aircraft parameters measurement system called BAHAMAS which was designed for supporting atmospheric research. Appropriate flight test instrumentation (FTI) suitable for vibration tests and loads identification was not available and had to be developed and prepared for the iLOADS campaign. The developed FTI consists of the sensors with the necessary cabling, a suitable data acquisition system, a data acquisition PC and four data analysis PCs. In order to be able to analyse the measured time signals efficiently in flight, the PCs were arranged in a network for live data distribution.

The online monitoring software, which was developed at the DLR Institute of Aeroelasticity, is used for the first time in a flight test to online analyse the measurement data. OMA methods are examined for their flight test capabilities on large aircraft structures, as will be presented in the following. During the first part of a longer flight test campaign, different types of vibration excitation were tested (i.e. natural turbulence, pilot induced continuous stick-raps, turbulent wake of a chase aircraft) to provide sufficient excitation levels for the identification of the modal parameters. In order to avoid the risky combination of a newly developed analysis method with a newly developed aircraft configuration, a configuration already tested in flight some years ago has been re-used here to demonstrate that the new approach based on OMA methods has the ability to monitor the aeroelastic stability margin during flight.

The second part of the flight test campaign focuses on the loads between the under wing stores and the wing attachment points. Dedicated flight manoeuvres (i.e. accelerated rolls and pull-up manoeuvres) have been performed to validate the measured data with simulation data of the numerical model.

Figure 1: HALO during flight test with under wing stores.

The flight test campaign consisted of five flights in total, which had flight durations between 90 and 180 minutes. This results in an overall flight duration of approximately 14 hours. Test flights number one, three, four and five mainly focused on in flight vibration analysis. On the second flight the focus was put on dynamic loads measurement with dedicated manoeuvres at seven different altitudes and three flight speeds. For the flight vibration tests several altitudes with different flight speeds have been covered in order to observe the changes in the structural dynamical behaviour of the aircraft. At each measurement point, the flight speed and the altitudes have been kept constant for about five minutes each. Within this timeframe the automated OMA implementation provides quasi real-time results of the changes in the vibration behaviour.
A typical flight profile is shown in Figure 2. The blue curve shows the flown altitude profile, whereas the red curve shows the true airspeed. Some acceleration signals of a typical flight are plotted in the background of the two parameter variations. They represent the response due to different excitation levels, e.g. by extending the spoilers at approximately 3600 sec and around 7000 sec of flight test, impulse inputs via the control surfaces or the take-off at the beginning of the time data plot can also be observed in the response data.

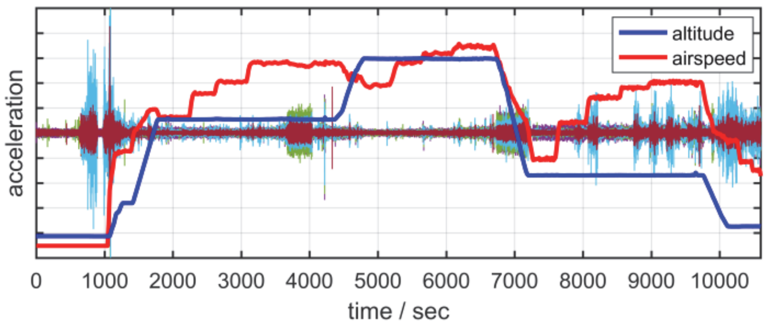

Figure 2: Flight profile with flight altitude (blue), flight speed (red) and acceleration signals.

2 FLIGHT TEST INSTRUMENTATION

The flight test instrumentation, which was developed and configured for this flight test, consists of acceleration sensors, strain gauges and the necessary cabling. All sensors are measured with a compact and robust National Instruments cDAQ data acquisition system. The time data is continuously measured by the data acquisition system and streamed to the hard disk drive of the data acquisition PC. At the same time, the data stream is distributed via local area network (LAN) to the (multiple) analysis PCs.
A specific requirement of this flight test campaign was distributed data acquisition hardware. Thus, cDAQ acquisition systems were placed in the PMS-Carrier under the wing, which provided a cylindrical space of 15cm diameter and approximately 1m length. An advantage of the PMS-Carrier is the already existing network connections, which transfer the data into the cabin, as well as the available power supply for the individual components of measuring system.

Figure 3: Measurement and analysis chain.

The complete HALO flight test measurement chain is shown in Figure 3 comprising the acceleration sensor (green boxes), the NI data acquisition systems (orange boxes), the data acquisition PC (yellow boxes) in the cabin and finally the analysis PCs for the online modal analysis (red box).

Sensor positions for the flight test included 51 piezoelectric accelerometers (see Figure 4) for the flight vibration tests and 16 strain gauges for the determination of dynamic loads in flight. As can be seen from the sensor plan, sensors are installed to observe the global airframe mode shapes and the local PMS Carrier modes.

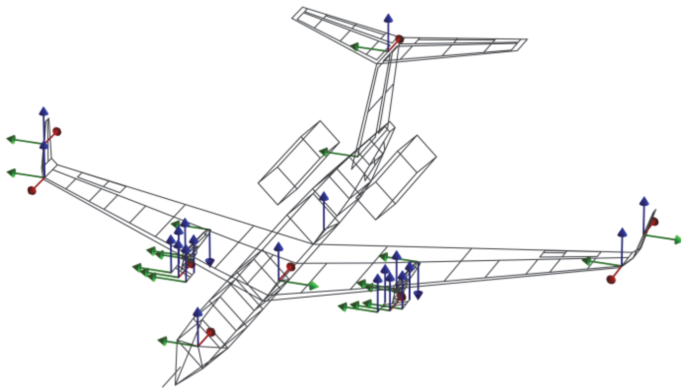

Figure 4: Sensor plan of the accelerometers.

2.1 Sensor positions

The acceleration sensor positions are concentrated on the PMS Carrier in order to resolve the local vibration behaviour of the PMS Carrier as well as on the fuselage and the tail plane to analyse the global vibration behaviour of the aircraft.
16 strain gauge bridges are placed on the Hanger Beam (i.e. a beam spanned from the front spar and the rear spar of the wing) which connects the PMS carrier to the aircraft. From these

strain measurements the dynamic loads between the wing and the PMS-Carrier shall be determined in case of manoeuvres, gust encounter or turbulence.

2.2 Rugged and open DAQ for flight testing with real time capabilities

A new measurement unit had to be selected and procured for the flight test. An important criterion for this is the possibility of being able to access the measured time data online and transfer it to the DLR in-house analysis software for real time processing. Furthermore, the data acquisition system must be compact in order to be able to build it up in a distributed manner and to be able to fit it in the limited space of the PMS-Carriers.

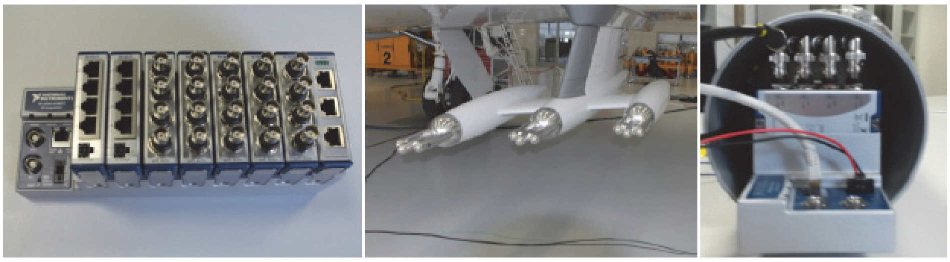

Figure 5: Small and robust measurement unit for flight testing.

The distributed architecture of the data acquisition systems with modules inside and outside the pressurized cabin requires robustness. It has to operate reliably at low temperatures and low ambient pressure in high altitudes. The selected NI cDAQ data acquisition system (see Figure 5), which is very compact and allows online access to the time data, is specified by the manufacturer only up to an altitude of 5000m and a temperature down to -40 ° C. This limited specification required a climatic chamber test in which the requirements of a flight profile were simulated, as would occur in the later flight test.

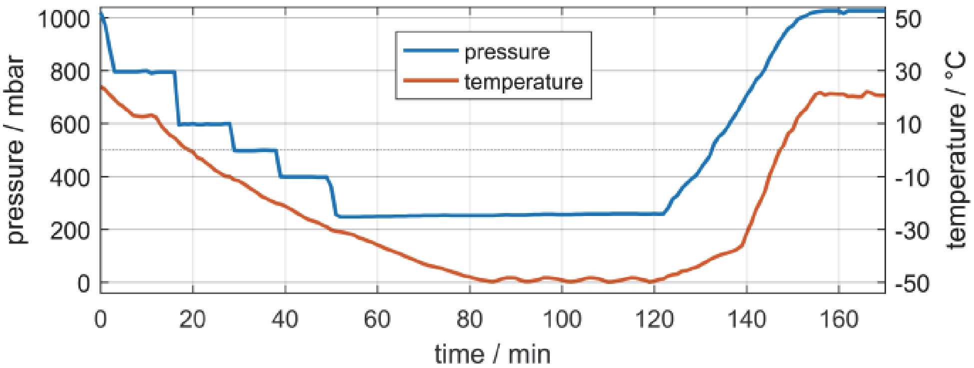

Figure 6: Qualification test of DAQ in climate chamber.

During this climatic chamber test (see Figure 6), the data acquisition system and the sensors were subjected to a pressure of less than 250 mbar, which is equivalent to an altitude of approx. 11500 m and a temperature of below -50 ° C. The measurement system worked perfectly during this 3-hour test and showed no drifts in the measured signals, errors or even failures.

A further request for the flight test certification on the data acquisition system is a test of electromagnetic compatibility in an EMC chamber and later in the installed state on the entire aircraft. These tests are intended to exclude the measurement electronics from influencing important components of the aircraft such as on-board electronics or radio communication.

The suitability of the relatively inexpensive Ni-cDAQ data acquisition system for airborne test conditions has also been successfully demonstrated in the EMC test. The findings of these tests were confirmed during the flight test campaign under real conditions, where the data acquisition system worked without any problems over the entire duration and no interference with the aircraft systems.

2.3 Distributed setup for measurement system and data network

Inside the aircraft a distributed data acquisition system (see Figure 7) consisting of three individual NI-cDAQ chassis acquires the flight test data. The master acquisition unit of the three chassis (NI-cDAQ Master) is placed inside the pressurized cabin. The two other chassis (NI cDAQ Slave 1 and 2), are placed respectively in the left and right PMS-Carrier under the wing. The two slave chassis are connected to the master chassis inside the cabin with only two Ethernet cables for synchronization and data transfer of the digitized measured signals. This design of the data acquisition system considerably reduces the lengths of the analogue signal routing and is less prone to interference, e.g. from radio signals or from the on-board electronics. A further advantage is the significant reduction in the installation effort, because the Ethernet cables are already available and no additional cables must be routed into the pressurized cabin. The reduced installation effort was appreciated in particular, because the aircraft availability was quite limited during installation phase before the flight test.

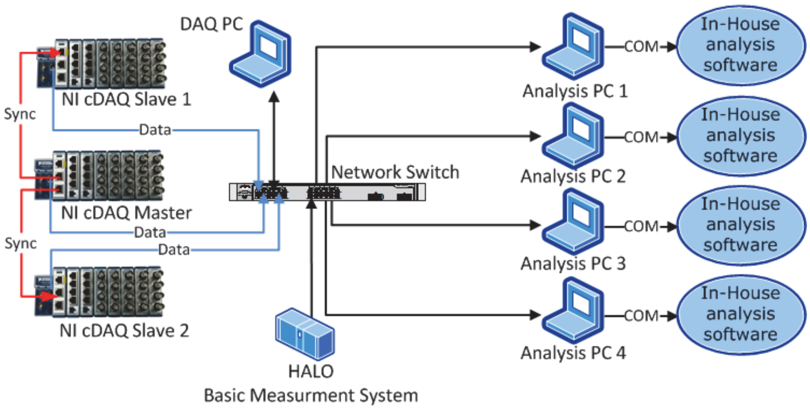

Figure 7: Data network for the online distribution of the measured data to the analysis PCs.

The time data signals are recorded with all three chassis and are stored on the data acquisition PC (DAQ PC). During acquisition the measurement signals are displayed on the screen of the DAQ-PC for verification purposes.
Time stamped flight parameters (altitudes, airspeed, pitch angle, etc.) are transmitted from the basic measurement system (BAHAMAS) via network stream to the DAQ-PC.
The DAQ-PC distributes the data directly over the network, so it is possible to perform modal analysis and loads identification simultaneously in real-time on several analysis PCs in parallel.

3 FLIGHT VIBRATION TEST

For the flight vibration tests it is mandatory to keep the flight state constant which is indicated by parameters like altitude and speed over a certain period of time. In order to measure the dynamic behaviour of the aircraft at different flight parameters first the aircraft is positioned at a defined altitude and then the flight speed is changed but kept constant for a defined period of time. This procedure is shown in the flight profile of the flight parameters in Figure 2. In this test case the aircraft is positioned at an altitude of 27000ft and the flight speed of Mach 0.55 is kept constant for about five minutes. In the flight profile this time period is between 2000s and 2300s. During this stable flight state the measured acceleration signals are automatically analysed by the DLR in-house tools for continuous real-time modal analysis and the identified modal parameters for this test point are stored into a database together with the corresponding flight conditions and operational conditions. Three additional flight speeds (up to Mach 0.82) were analysed at this altitude and the identified modal parameters were also stored in the database. Subsequently, the procedure is repeated on altitude 40.000ft and 12.000ft. Already during the flight, the modal parameters were retrieved from the database and the changes of the dynamic behaviour as a function of flight speed and altitude can be analysed and visualized (i.e. plotting aeroelastic stability diagrams during the flight). In the following three flight vibration tests, additional flight speeds and altitudes were considered. With this data available, a flight test matrix has been established, from which the aeroelastic properties of the HALO aircraft can be observed over the entire flight envelope.

3.1 FTI qualification test with the method of Taxi Vibration Test

In contrast to a conventional ground vibration test (GVT) which employs artificial excitation, natural excitation by driving on runways or taxiways as shown in Figure 8 is used in a taxi vibration test. GVT of aircraft prototypes is one of the most challenging tasks in vibration testing. For an aircraft of the size of an A320 or B737 a high channel count data acquisition system is needed that can acquire several hundred of accelerometers (~600) simultaneously. About 15-20 electro-dynamic exciters with maximum force levels in the range of 1000N and long coil stroke are required. Especially the excitation of the aircraft at flexible excitation points such as wing tips or winglets requires a lot of experience not to run into the limits of the shaker. Besides all the specific equipment an experienced team must be available to run the test efficiently in terms of time and quality of the results.

Before the first flight, a taxi vibration test (TVT) [11-15] has been performed to verify the installed sensors and data acquisition systems under operating conditions but also to fulfil the certification requirement in CS25, §629, i.e. experimental determination of natural frequencies of the aircraft on ground. The TVT method has been developed by the DLR-Institute of Aeroelasticity and has been matured by application to several aircraft types. Figure 8 shows the DLR research aircraft ATRA during the taxi vibration test at the Technical Center for Aircraft and Aeronautical Equipment (WTD 61) of the German Armed Forces in Manching in the year 2009 [14-15].

Figure 8: ATRA Taxi Vibration Test, Manching 2009.

The TVT method is conducted by simply towing an aircraft over runway or taxiway at constant speed, e.g. 5, 10 or 15 km/h. This method provides enough vibration amplitude on the installed acceleration sensors to enable output-only modal analysis. Proceeding this way,

it is possible to identify the majority of eigenfrequencies, modal damping ratios and eigenvectors of the aircraft.
With the TVT on HALO (see Figure 9) the flight test setup has been verified. Furthermore, the eigenfrequencies and mode shapes of this configuration as obtained from a GVT some years ago were confirmed so that no additional flutter analyses had to be performed to achieve the permit to fly. Finally, it should be mentioned that the modal parameters obtained on ground served as an initial reference from which changes in modal parameters have been tracked in the course of the flight test.

Figure 9: HALO Taxi Vibration Test, Oberpfaffenhofen 2016.

During TVT a continuous stream of time data was recorded for a duration of roughly one hour. It is beneficial for a high quality TVT results to maintain a constant level of excitation on the whole structure. The level of excitation is dependent on the driving speed of the tractor and also on the roughness of the ground or pavement. In general, driving at higher speed over the same surface roughness will lead to a shift of the excited frequency range towards higher frequencies at the cost of lowering the excitation levels at lower frequencies [11,15].
HALO was towed over for 60 min at the DLR flight experiments facilities at the Oberpfaffenhofen airport. Figure 10 shows time histories that are already divided into several pieces that describe where the aircraft was towed, on runway, taxiway or in between in a turn.

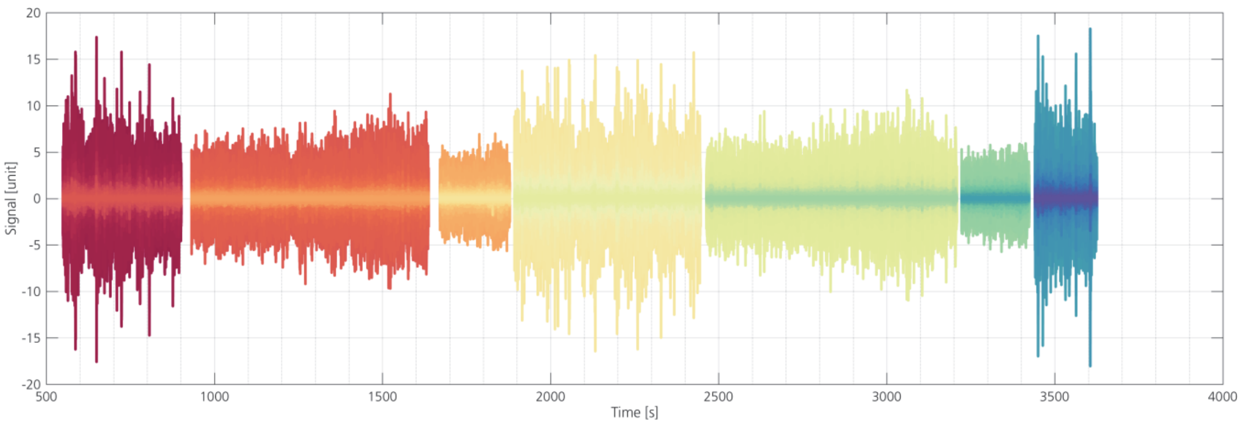

Figure 10: Acceleration time histories from taxi vibration test.

A nice representation of the different levels of excitation is given by statistical analysis of the time domain data in Figure 11, which shows the 1st to 4th sample moment of the acceleration time histories. 3rd and 4th moment of the time data signals show special features of the data. The skewness (3rd moment) shows, if nonlinear effects in the structure are activated. There is a significant difference between the normally distributed acceleration histories on the runway and acceleration histories on the bumpy taxiway.

If we consider an aircraft rolling on uneven pavement the biggest source of non-linearity originates from the influence of the landing gear shock absorbers. Figure 11 also shows that the data from the runway seems to be most consistent.

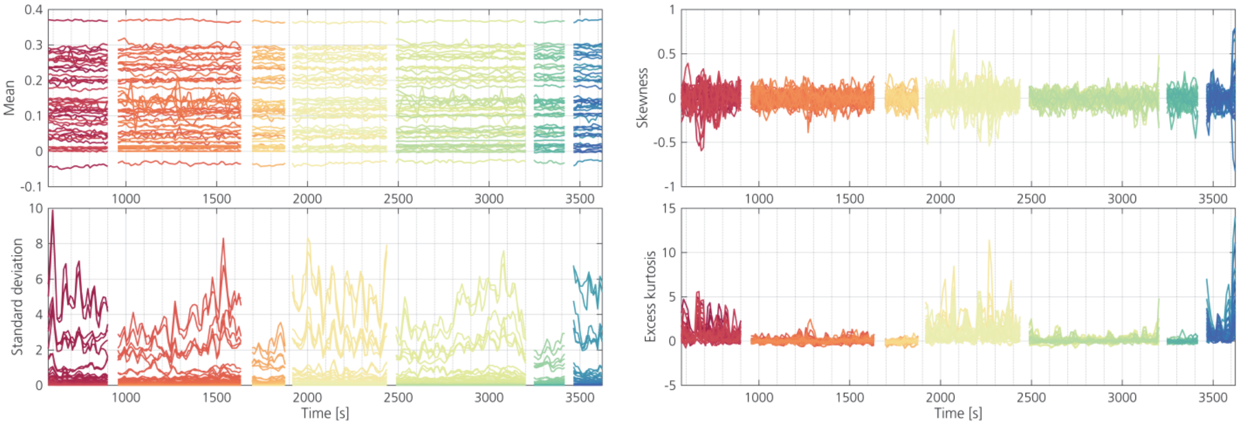

Figure 11: Sample central moments of acquired accelerometer histories during.

The analysis of the statistical moments for the random vibration time data also allows for immediate detection of faulty sensors, which is also presented by grey curves in Figure 11. The signals show significant deviation from all others for the 3rd and 4th moment. Two sensors were identified that have fallen off before we went for the first flight test.

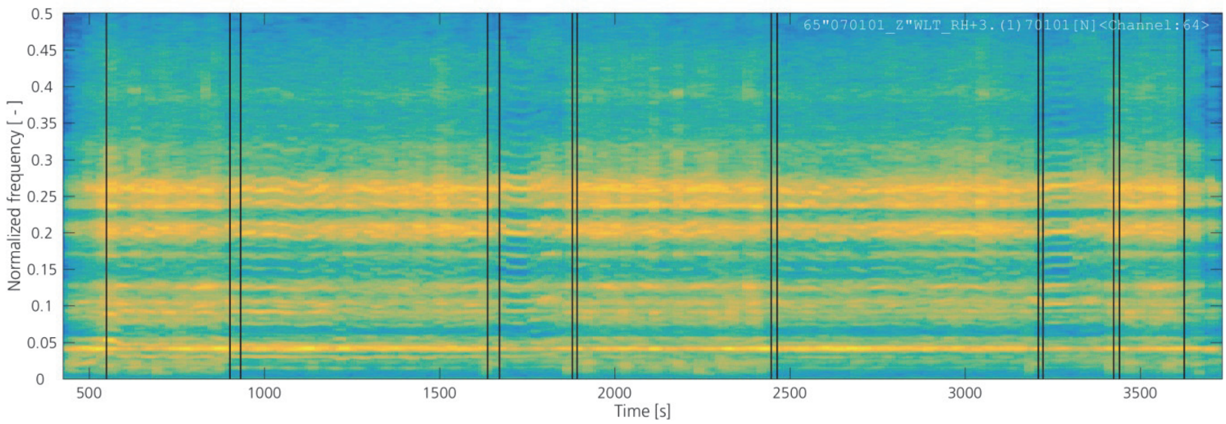

Figure 12: Spectrogram of TVT data.

A further indicator in the consistency of the acquired time data is given by the spectrogram presented in Figure 12. Especially during turns the different behaviour is visible which can also be referred to the variation of speed during turning. The most consistent excitation is again visible for the runway sections.

For further evaluation the runway dataset from seconds 1000-1600 has been chosen. The time data was used for output-only analysis. Cross-power spectral density (CPSD) functions are calculated referencing on two sensors. The sensors are symmetrically installed in y-direction and placed at the left and right wing external stores. The cross-power spectral densities are shown in Figure 13. Several peaks at distinct frequencies are visible which already indicate eigenfrequencies of the structure.

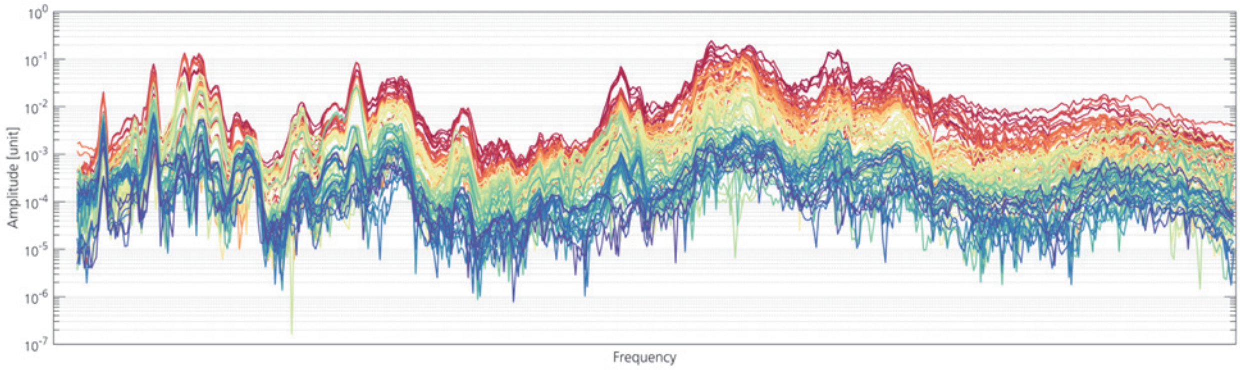

Figure 13: Auto-power spectral densities of TVT data.

From CPSD's stabilization diagrams are calculated. The frequency-domain LSCF algorithm employed for operational modal analysis requires cross-power spectral densities.
The measured time data is not processed to frequency response functions as usually but to cross power spectra. These cross power spectra describe the dynamic response of the aircraft in dependence of a reference, which can be e.g. the signal of a predefined sensor. From these spectra it is possible to identify modal parameters.

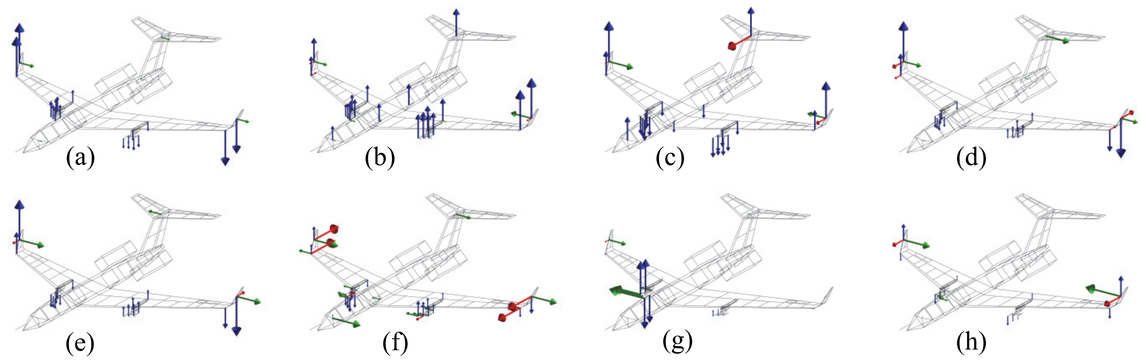

Figure 14: Identified modes from the TVT.

A selection of the mode shapes identified in the taxi vibration test is shown in Figure 14. The selection includes rigid body modes (a, b) and symmetric (c) as well as antisymmetric elastic modes (d-f) and local modes (g, h) unsymmetrical modes are e.g. from the mounted PMS carriers (g).

3.2 Automatic modal analysis in flight

An essential part of the flight test campaign is the validation of the automatic output-only modal analysis method in real-time. The graphical user interface (GUI) of the used software is shown in Figure 15. The software is able to execute the necessary steps for evaluating the TVT or FVT data within less than 3 seconds. Within this short time period, the buffered time data is processed into cross power spectral densities with pre-defined signal processing parameter settings, stabilization diagrams are generated for different model orders, poles are selected automatically from the stabilization diagrams and the corresponding modes are obtained for the selected poles by curve-fitting the CPSDs. The identified modal data sets are written into a database together with various aircraft and environmental parameters, which are provided from the BUS system of the aircraft. All this must be completed within less than 3 seconds. Then a new 3 seconds long block of data is entering into a first-in first-out buffer, old data is cancelled from the buffer and the whole analysis procedure is being repeated. This is performed in a continuous way, which enables the monitoring of changes in the

eigenfrequency and modal damping with altitude and Mach number. Eigenfrequency and modal damping ratios are properties of mode shapes and these can change with flight conditions. Therefore, the changes in the mode shapes have to be tracked to observe the changes in the eigenfrequencies and damping ratios. This mode shape tracking is performed automatically using the MACXP correlation criterion [16].
The high computing effort is handled on Core-i7 laptops. For the analysis of the data with the chosen FTI Setup three computers can operate in parallel so that different signal processing settings can be used and different modal parameter estimators at the same time.

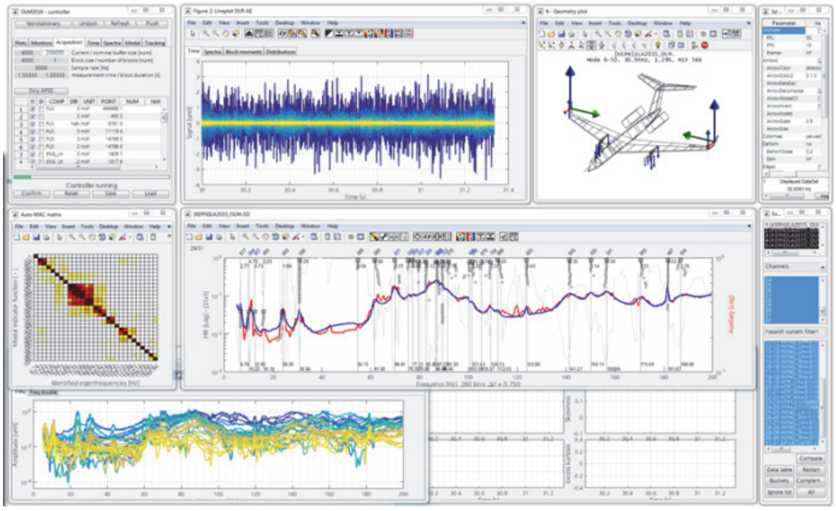

Figure 15: GUI of modal analysis software with generic data.

3.3 Comparison of various excitation techniques in flight

Various types of excitation techniques of the aircraft structure are analysed during the flight vibration tests. In this case it should be determined, which kind of excitation is particularly suitable for the output-only modal analysis procedures. The question was, for example, whether less or highly turbulent flow is better to achieve more accurate analysis results. One form of additional excitation is a pulse-shaped control input from the pilot (i.e. stick raps) on the aileron and the elevator (rudder kicks was not permitted). It is anticipated that higher-frequency modes are better excited by this type of artificial excitation. Some selected measurement points were repeated with and without spoilers. The extended spoilers generate significantly higher vibration amplitudes but due to the flow being no longer attached to the aerofoil profile, it is not clear if the true aeroelastic system is being identified, because the unsteady aerodynamic forces are no longer motion induced.

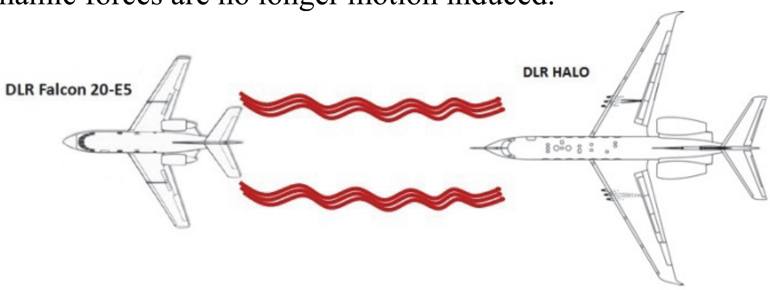

Figure 16: HALO in the turbulent flow of the ahead flying DLR Falcon.

Another promising method was tested in the fourth flight. This flight is performed together with another aircraft (DLR Falcon) in order to excite the HALO with the turbulent wake of an aircraft flying ahead. Therefore, the Falcon is positioned at two altitudes and different speeds in front of the HALO. This procedure is sketched in Figure 16. In order to avoid unstable and unsafe flight conditions, HALO approached the chase aircraft slowly from a safe distance until the turbulences were sufficiently strong. This state was kept constant for about five minutes to perform the online modal analysis. Table 1 summarizes the measurement points acquired during flight vibration testing that are presented in this document. Modal analysis performed on these datasets is presented in [8].

#	Mach	Comment	Duration
MP11	0.55	Constant heading, pure turbulence excitation	304.7 s
MP12	0.65	Constant heading, pure turbulence excitation	306.3 s
MP13	0.70	Constant heading, pure turbulence excitation	324.4 s
MP14	0.78	Constant heading, pure turbulence excitation	310.3 s
MP15	0.77	Constant heading, air brakes active	304.7 s
MP21	0.70	Stochastic elevator/aileron excitation	434.5 s
MP41	0.70	Flying in preceding airplane's wake	375.0 s

Table 1: Presented flight vibration test measurement points; flight altitude is 27000 ft for all.

Figure 17 displays all acceleration time histories during straight level flight at 27000 ft with pure atmospheric turbulence excitation (MP11÷MP14) and with air brakes (spoilers) active (MP15) at Mach speeds approximately constant for each measurement point. It is clear that the excitation level increases significantly when air brakes are deployed. The skewness and kurtosis of multiple data blocks shown in Figure 18 display sample distributions that are mostly symmetric, but with heavier tails at lower excitation levels, which suggests a higher susceptibility to outliers caused by transients, impulsive events and course corrections. When air brakes are deployed the resulting turbulence provides highly normally-distributed acceleration histories due to higher excitation level. The auto-power spectral densities estimated in Figure 19 demonstrate how the excitation level due to turbulence (MP11÷MP14) rises monotonically in the current Mach range. Of particular interest is the fact that air brakes provide a ten-fold acceleration response increase in the higher frequency range (in RMS terms, from normalized frequency 0.15 onwards in the figure). An important characteristic of this type of excitation is producing time responses with better Gaussian distributions (less outlier, less transient effects).

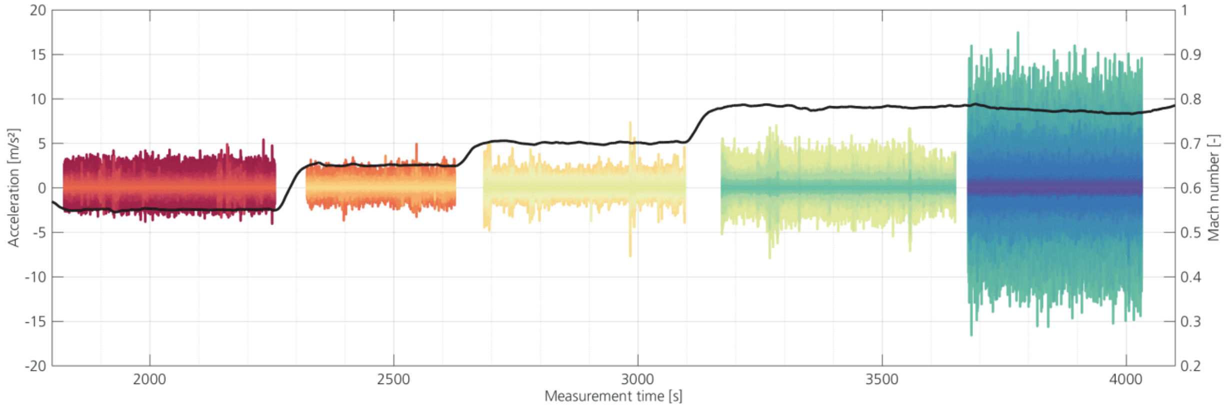

Figure 17: Time data of all accelerometers (MP11÷MP15).

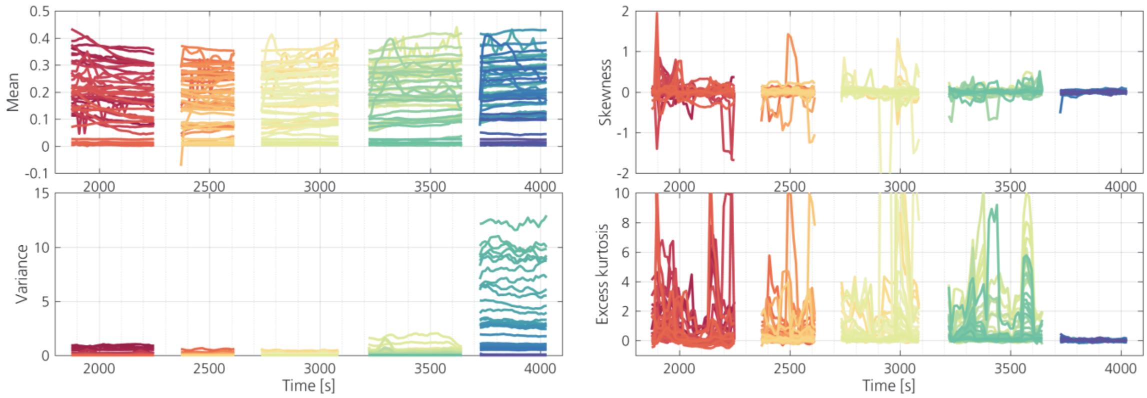

Figure 18: Sample central moments of all accelerometers over time (MP11÷MP15).

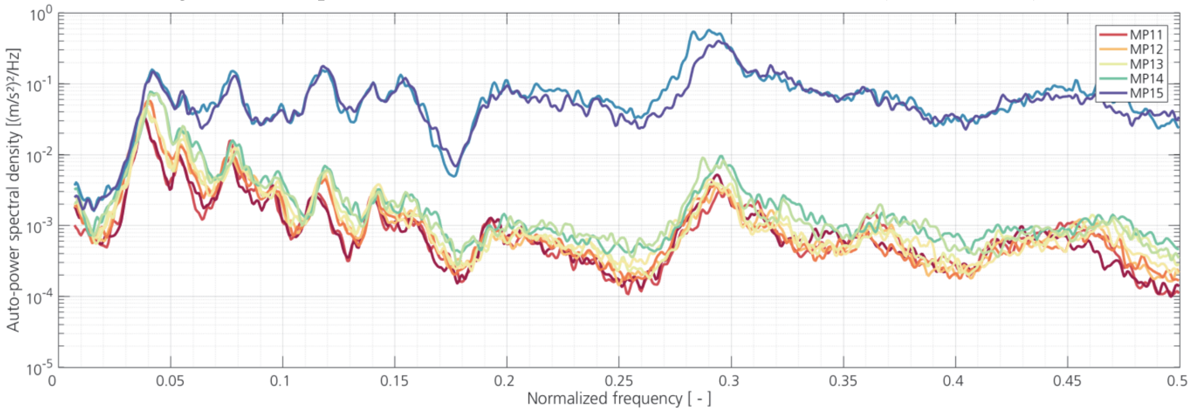

Figure 19: Auto-power spectral densities of WING+Z accelerometers (MP11÷MP15).

Figure 20 shows a comparison of the same sensors (all at 27000ft, Ma = 0.70), with steady flight turbulence (MP13), pilot aileron/elevator stochastic (MP21) and wake turbulence excitation from the DLR-Falcon aircraft. As expected, flying in the wake turbulence of a preceding aircraft results in higher response levels, particularly in the higher frequency range (as can be seen from normalized frequency 0.15 onwards in the figure). On the other hand, random aircraft control excitation, though diligently executed by the pilot, injects little overall energy into the system.

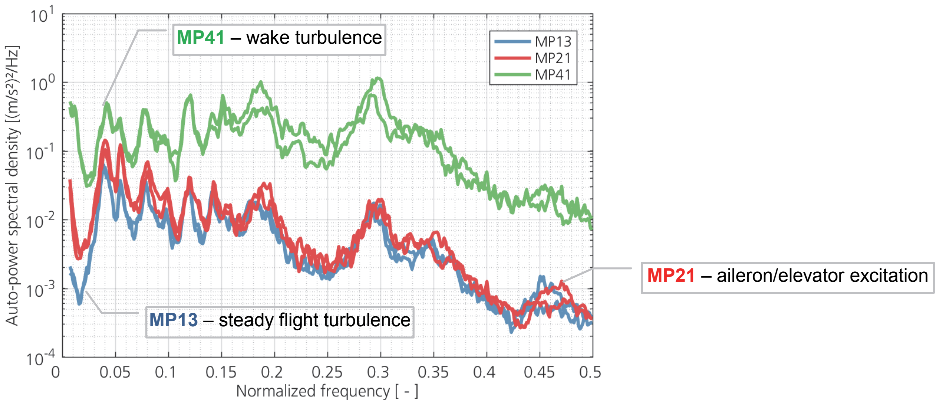

Figure 20: Auto-power spectral densities of WING+Z accelerometers with different excitation types (Ma = 0.70)

4 LOADS MEASUREMENT

The aim of the in-flight loads measurement is to acquire data for the validation of the DLR loads processes. The conducted flight tests focus on the loads at the interface between the wing and the external store. The components of the external store are depicted in Figure 21.

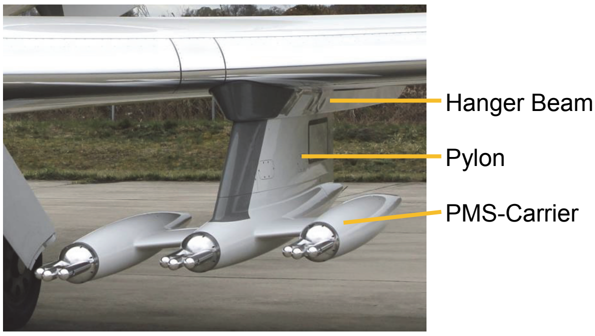

Figure 21: Components of the utilized external store.

4.1 Strain gauge positions

The loads measurements are performed with strain gauges. On each hanger beam eight strain gauge bridges are installed. Six bridges are wired to detect bending and two to detect torsional deformation. The positions of the bridges are determined with an FE-analysis to acquire measurable deformations under loading. Furthermore, two sensors of each bridge are placed on one side and the other two sensors on the opposite side of the hanger beam, as depicted in Figure 22.

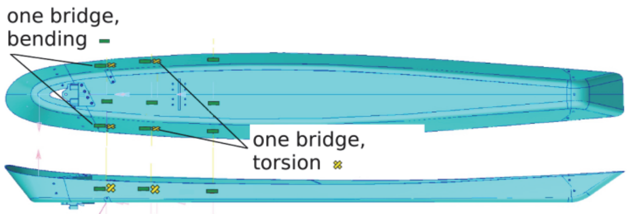

Figure 22: Strain gauge positions on the hanger beam.

4.2 Strain gauge calibration

The strain gauges were calibrated by applying linearly independent loads on the PMS carrier. With sufficient applied loads – more than the number of bridges – the relationship between load and strain signal can be identified. This enables the calculation of loads based on strain signals [17].
The first calibration of the strain gauges was performed at DLR in Göttingen with the PMS carrier alone installed on a 6-axis hydraulic vibration table (MAVIS). For the calibration the load is applied to the strain gauges with the help of sandbags. Weights up to 50 kg are attached to the force transmission points. In order to minimize the error due to hysteresis the applied loads are increased and decreased step by step and the strain signals are measured at each step. A typical strain response of a two-step load case is shown in Figure 24.

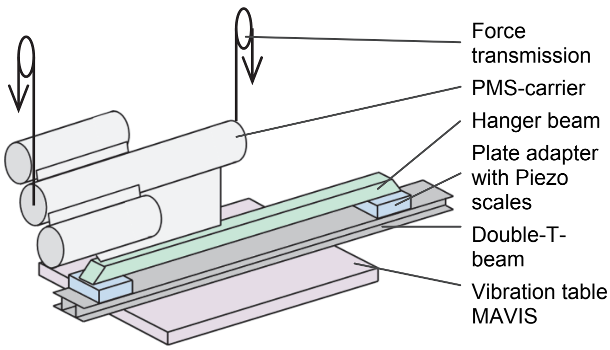

Figure 23: Setup of the calibration on the MAVIS.

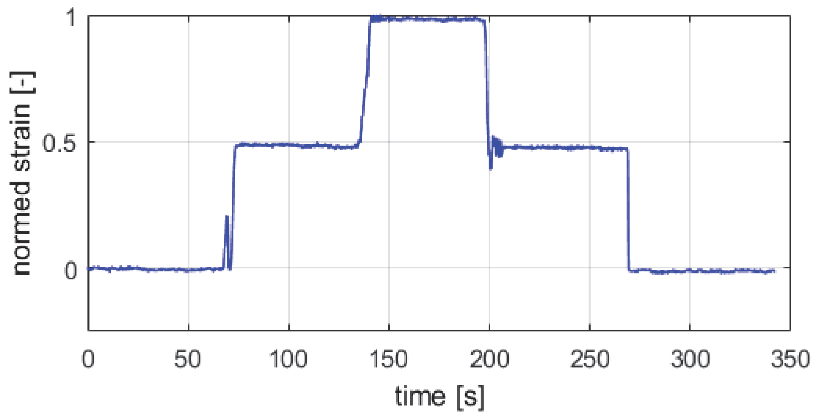

Figure 24: Typical strain response of a two-step load transmission.

The second calibration of the strain gauges was performed at DLR in Oberpfaffenhofen, where both PMS carriers are mounted on the wing station of the DLR HALO. In total nine linearly independent loads are applied on each PMS carrier. From the strain signals transfer matrices are derived in order to calculate the actual applied loads. A picture of load application during the calibration is presented in Figure 25.


Figure 25: Strain gauge calibration of a PMS-carrier.

4.3 Loads measurement in flight

Out of the five flight tests, the second is designated for manoeuvre loads. In that flight, several manoeuvres are flown in 21 flight conditions, which include seven different altitudes ranging from 12000 ft to 35000 ft (3658 m to 10668 m) and three airspeeds each. The manoeuvres consist of impulsive inputs on the steering yoke, accelerated rolls up to ±45° and pull ups up to 2 g.

Initially, the idea for the flight test was to validate the numerical gust loads analysis with flight test data, since gust load cases are the relevant sizing loads for the hardpoint, where the hanger beam is mounted to the wing. Unfortunately, the level of natural atmospheric disturbance was not high enough for sufficient natural excitation during the days of the test campaign. Thus, it was discussed to substitute atmospheric gust loads by the definition of manoeuvers with a similar frequency input for that flight. However, in order to achieve these defined manoeuvres, stick raps with a frequency of up to 14 Hz would be necessary. Such a procedure is difficult to perform manually with high precision. Besides, the control surface actuation systems would dampen the high frequency input to some degree. Instead, impulsive inputs on the steering system and low frequency manoeuvres as described above are considered as safer and easier to perform. A time history of a selected roll manoeuvre is shown in Figure 26.

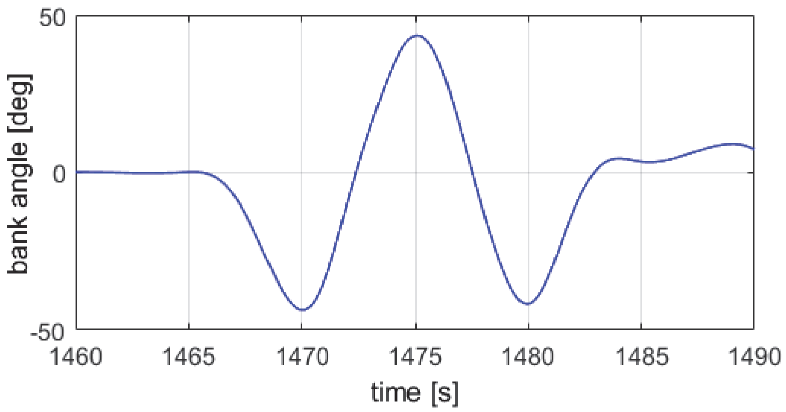

Figure 26: Bank angle during a roll manoeuvre.

The normalized moments at the right PMS carrier during a pull up manoeuvre are presented in Figure 27. In the first seconds it is apparent that the moments already fluctuate before the pitch angle changes. This indicates that the moments correlate in time with the acceleration of the aircraft. Further investigations of the loads based on the strain signals have to be performed.

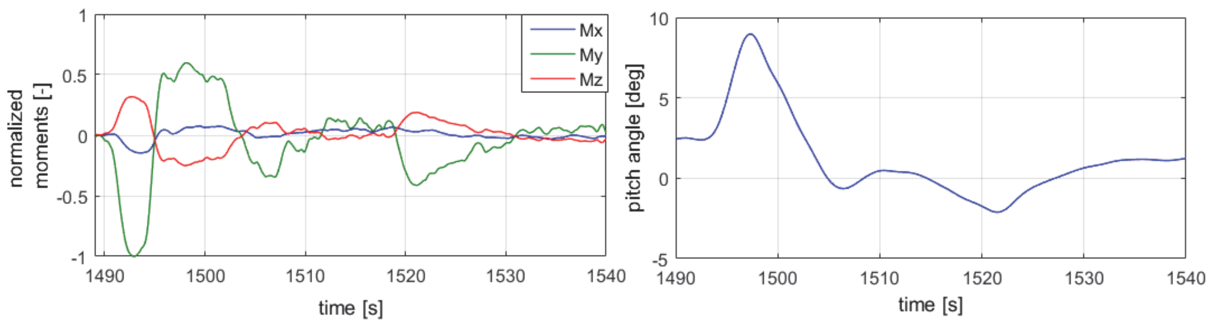

Figure 27: Normalized moments during a pull-up manoeuvre.

Beside the strain signals, data of atmospheric turbulence occurring during the flight is also collected. A first analysis shows that the power spectral density of the measured turbulence has a similar trend as a von-Kármán spectrum but with a smaller turbulence scale than 2500 ft (762 m). The latter value is defined in CS25 for loads calculations. A derived spectrum from the turbulence data and the corresponding von-Kármán spectra are shown in Figure 28. A smaller turbulence scale indicates that more energy is contained in the higher frequencies. This observation will be considered in the further development of the DLR loads process.

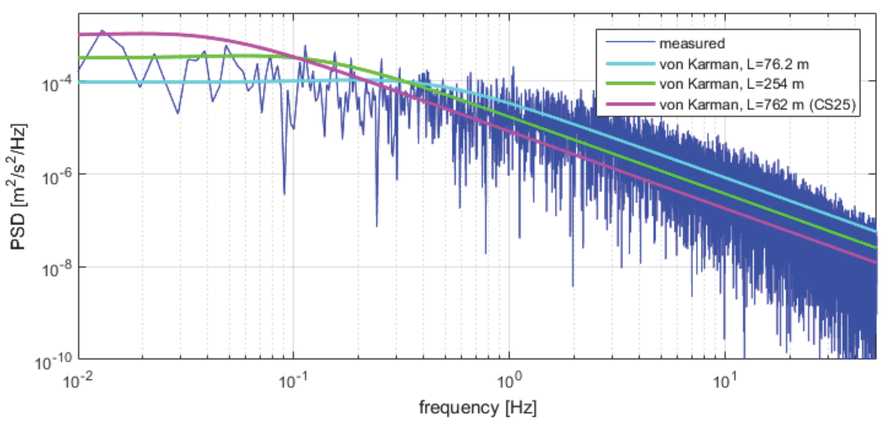

Figure 28: Power spectral density of the measured turbulence, reference von-Kármán-spectra

5 CONCLUSION AND OUTLOOK

The paper presents research scope of the iLOADS flight test campaign on DLR's research aircraft HALO, the test preparation and execution. During flight test two major research aspects have been addressed: (1) online identification of the aeroelastic behaviour with OMA methods and (2) in-flight loads analysis. For verification of the test methods, a configuration of HALO was equipped with specially instrumented PMS carriers had been re-used.
The capability of the new procedures for automated in-flight output-only modal analysis was demonstrated. Significant benefit can be achieved when this approach for flight testing is conducted in combination with a taxi vibration test on ground. Modal parameters (eigenfrequencies, mode shapes, and damping ratios) were identified continuously and almost in real-time for each new flight condition. Every three seconds the complete modal data was available and have been stored in a database. The data can be retrieved during the flight and trends of changes can be plotted over environmental parameters (altitude, speed ...). This enables the plotting of flutter stability diagrams already during the ongoing flight tests. On the basis of the raw data recorded in the time domain during the flights, it is possible to simulate the flights on a PC or to play-back all signals in real time in the laboratory. The aim is to improve the methods of the automatic output-only modal analysis, so that it is possible to quickly make decisions in the flight test about the vibration behaviour and a prediction of safety margin for the next envisaged test point in the flight envelope.
Different excitation techniques from turbulence excitation, pulse-shaped control inputs from pilot, extended air brakes and wake vortices from a preceding aircraft have been used for the excitation of the aircraft. These excitation methods do not need external devices mounted to the aircraft or the access to an electronic flight control system. The influence of the different excitation techniques on the auto-power spectral densities has clearly been demonstrated.
The loads measurements are available for further evaluation and comparison with loads simulations. For this purpose, a loads model of HALO has been built up at DLR using an in-house aeroelastic modelling process supported by data from an extensive GVT performed by the DLR-Institute of Aeroelasticity in 2009, see [5].

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