White Paper

Latest design trends in modal accelerometers for aircraft ground vibration testing

Abstract

Accelerometers are widely encountered in structural analysis applications such as modal analysis with vibrational or impact input excitation and operational modal analysis. This paper aims to outline design trends and requirements for acceleration sensors in order to insure optimal structural analysis measurement results. Key parameters for a performing modal sensor are: sensitivity, mass, noise level, amplitude and phase frequency response, as well as thermal transient response, thermal sensitivity response, transverse sensitivity (cross axis), base strain and survivability which will be taken into detailed consideration in this paper.

Nowadays three IEPE (Integrated Electronic Piezo Electric) sensor designs can be considered: piezo-ceramic shear, piezo-bending beam and piezo-crystal shear mode sensing elements.

Unfortunately, none of the sensor technologies available on the market today will allow for the best of all parameters mentioned earlier. Advantages and disadvantages have to be considered in order to make the optimal choice. Even though Variable Capacitive (VC) MEMS sensors can be used in cases of operational modal analysis at ultra-low frequencies, such as Bridge Structural Testing or Monitoring, only IEPE technology will be in this study.

Besides the technical properties of an accelerometer, the handling qualities during installation and removal are extremely important for high channel count systems. Installation time, error rate and reliability for more than 10 years during several tests a year are of special interest for the user. Among the considerations made here, easy monitoring and sensitive axis alignment compared to the overall coordinate system will be examined.

The German Aerospace Center (DLR) will illustrate the applicability of accelerometers in context of industrial testing such as Ground Vibration Testing (GVT) of aircraft structures or structural and modal testing of wind turbine blades where innovative methods such as allowing one free adjustable degree of freedom around one rotational axis in order to freely orient the sensitive axis.

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Content

1. Introduction

To measure mechanical properties like force, pressure or acceleration, piezoelectric sensors have a long tradition in the industry. Since the beginning, Kistler Instruments is one of the leading companies in this technology and helped drive the development forwards. Piezoelectric sensors are based on the principle that a mechanical deformation to a non-centrosymmetric crystal lattice system, like quartz or some ceramic materials results in a proportional electric charge on the electrodes. This charge signal can be converted with a charge converter into an analog voltage signal. If the sensor is used for a fixed measurement range, low impedance IEPE sensors with integrated charge to voltage converters are commonly used.

Acceleration sensors have a diverse application use for noise and vibrations measurements and also in experimental modal analysis. For best results, the sensor should strive to be invisible to the structural unit under test having high sensitivity, low mass, high signal to noise ratio and very little cross talk effects to other influences. Other aspects that should be minimized are cross axis sensitivity, base strain sensitivity, sensitivity against case deformations, thermal transient response for sudden temperature changes, low thermal sensitivity shifts and others. For a guideline of common practices of these test procedures where the above sensor properties are in most cases standardized refer to international standards like the older series of ISO 5743 [1], which is transferred to the new standard series part by part ISO16063 [2] or national standards like the RP37.2 of the Instrumentations Society of America [3]. These standards provide in most cases a guideline for traceable and uniform specifications of vibration and shock sensors. In some cases, specifications are not standardized, such as resolution, threshold and signal to noise related data.

This paper describes the requirements of accelerometers for modal investigations of large mechanical structures like Ground Vibrations Tests (GVT) on complete airframe structures or wind mill blades as they are used more and more frequently for renewable power generation. This kind of modal testing is mainly a MIMO test configuration (multiple input – multiple output) where several electrodynamic modal shakers excite a structure in swept sine or white noise modes to its natural frequencies or Eigen modes. A network of up to several hundred accelerometers measure the signals at the test structure is necessary to resolve the mode shapes from such complex structures. A general scheme of test setup and data acquisition during ground vibration testing is given in Fig. 1.

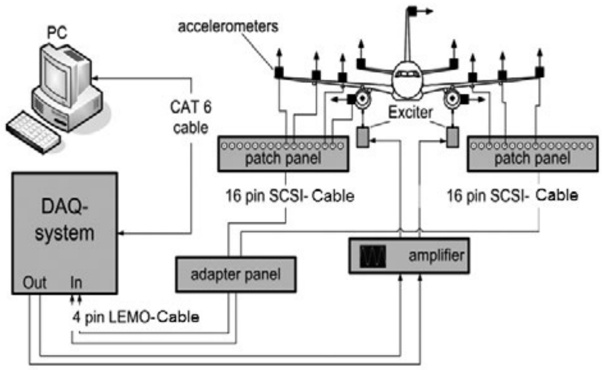

Fig. 1: Scheme of data acquisition for ground vibration testing at DLR

In most of structural analysis applications, easy monitoring and sensitive axis alignment compared to the overall coordinate system are required. Sensor mounting methods such as stud, clip, wax or magnet mounting will be considered. In addition, innovative methods such as allowing one free adjustable degree of freedom around one rotational axis in order to freely orient the sensitive axis can be used. Such a solution using a cylindrical sensor shape that can freely rotate in a specifically designed housing will be presented here.

For selected optimal designs, two examples of modal testing applications of large structure using MIMO methods will be in focus: Fig. 2 Ground Vibration Testing of Aircraft and Fig. 3 Structural and Modal Testing of Wind turbine blades.

Fig. 2: Beluga XL ground vibration test performed by the German Aerospace Center from Göttingen Germany in June 2018 (Source: Airbus)

Fig. 3: Wind turbine blade modal testing performed by the German Aerospace Center from Göttingen Germany in February 2018

2. Requirements of accelerometers for large structure modal testing

Large test structures described here are mainly characterized by low frequencies of their structural modes (Eigen frequencies) and a wider scale of amplitudes. This is a result of the measurement points being different distances away from the driving points. Special requirements are related to the numerous numbers of input channels and the possibilities to arrange mounting and demounting of the sensors to the test structure for easy, quick and reliable test arrangements.

For the assembly of the numerous sensors to the test structure, it should be easily possible to adjust the measurement direction in one degree of freedom (DOF) as shown in Fig. 4. For this purpose, the sensing element has to be designed in a compact, small cylindrical housing which allows one rotational degree of freedom within a cubic polymer adapter by a small special adjustment wrench, where the sensitive direction of the accelerometer can be fixed by a clamping mechanism. This one axis sensor can now be arranged in a planar way in three axes (Fig. 5) to measure concurrent acceleration components in an orthogonal coordinate belonging to a unified coordinate system of the test structure. The acceleration vectors measured are positioned to the sensitive axis intersecting with the center of gravity (COG) of sensor seismic mass.

In addition to the housing and adapter, certain specifications have been required which are summarized in Table 1.
In order to answer the application requirements, the full-scale range has been set to ±50 g_n. The frequency response should cover 0,5 Hz to 1 kHz with the sensor mounted in the adapter for a sensitivity deviation of ≤ ±5 % referenced at 10 Hz. Phase shift response should not deviate more than 15° at 0,5 Hz and phase shift congruence between sensors should be within 3°. Last but not least, noise should be at the lowest feasible range. This will allow the threshold to resolve a measurement signal as low as possible. Details are listed in Table 2.

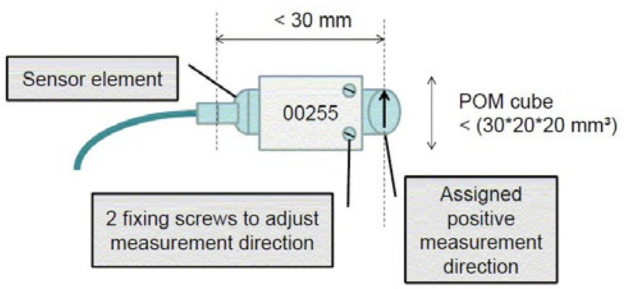

Fig. 4: Sensor and adapter requirements for adjusting sensitive direction

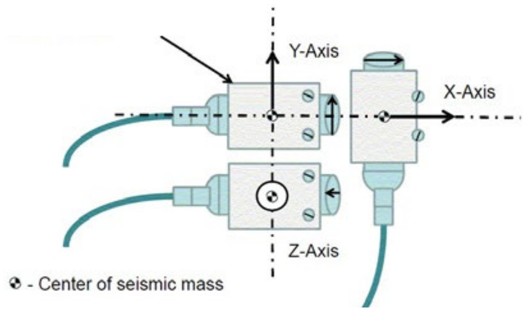

Fig. 5: Instance for triaxial planar arrangement of the accelerometer with COG marked

3. Accelerometer technologies for modal applications

For the realization of the most common technologies available today in sensor design, consider these following principles:

- the piezoelectric ceramic shear technology
- the piezoelectric crystal shear technology, based on present advanced crystal technologies like Kistler PiezoStar® KI-85
- the piezoelectric bimorph bending beam technology, called PiezoBeam® within Kistler and a
- K-Beam® MEMS sensor design in silicon based on a variable capacitive (VC) sensing element.

Designs such as traditional piezoresistive accelerometer technology were not consider as it is believed that the highly sensitive sensor elements made in the past in the bonded strain gage technology are costly and less robust against environmental influences, like shock or misuse. Piezoresistive accelerometers have also been replaced more and more by variable capacitive MEMS sensor technologies in ranges below 200 g.

The MEMS VC technology, like Kistler K-Beam® sensors [4], would open the frequency response down to static accelerations and is mainly very shock resistant against misuse, such as dropping the sensor to the floor. On the opposite side with this latest technology, sufficient low noise characteristics are not available in comparison to the IEPE technology. A main problem here would become the shape of the sensor and the damping characteristics of the seismic element. The damping coefficient of approx. 0,7 offers a steady changing phase shift between electrical output and mechanical input signal from DC to the upper frequency limit, which makes them unsuitable for this kind of application. In addition, it has not been possible to accommodate a MEMS sensing element in a compact, small cylindrical housing to allow one rotational degree of freedom to adjust the sensitive direction of the accelerometer. Consequently, this principle has not been considered for use.

All the piezoelectric sensor technologies for applications here are capable of 120°C operation and in some cases up to 165°C, with today's IEPE technology and its integrated charge converter already in the sensor housing. This low impedance output signal opens the door for long cables with sufficiently low EMI problems and is today's most technical standard. In addition, the lower frequency response can be accommodated down to 0,5 Hz with reasonable phase response as required by the application. The IEPE combination with TEDS (Transducer Electronic Data Sheets) belonging to IEEE 1451.4 allow sensor identification and read out of sensor data by the data acquisition system. This arrangement enables channel range scaling as Class I type sensors with digital and analog signal path in the same coaxial wiring.

Since its introduction over 30 years ago, the PiezoBEAM® [5] has become a successful line of small and low mass accelerometers specifically designed for modal and seismic applications.
The PiezoBEAM combines the requirements of a lightweight and precise sensor for measurement of linear accelerations, with sufficient wide frequency range. It is the first choice of sensors for modal and seismic applications where a high signal to noise ratio for high resolution data and lowest mass loading are required. These accelerometers are basically the lowest weight sensor with the highest resolution on the market and therefore ideal for the application of interest. For example, since the mid-1990's and until the end of the program in 2011, the NASA Space Shuttle program (GVT) has been performed at various locations using these types of sensors for monitoring the conditions of the shuttle and its payloads. Manufacturing these sensors with very low rates of cross axis sensitivity can be easily achieved in the order of 1,5 %. It should also be noted that a disadvantage of such technology can be the limited use under transient thermal conditions. The thermal transient response of the bending bimorph has been greatly lowered by design changes but is still in a magnitude where sudden temperature changes can sometimes saturate the output signal.

Using a shear design is the preferred method to keep thermal transient response as low as possible during quick thermal cycling. Two technologies are considered; ceramic shear or crystalline shear based on Kistler PiezoStar® crystal KI-85 [7]. In addition, especially in applications with steady thermal cycling PiezoStar® sensors have advantages, as their thermal sensitivity shift between -55 °C and 165 °C is very low (in the range of 3 % deviation overall). The very stiff KI-85 piezoelectric crystal material provides a very flat sensitivity response with almost no frequency dependency, in comparison to ceramic shear which always exhibits a slope in the frequency response of the sensitivity. On the other end, their dynamic range is, unfortunately limited compared to a ceramic shear design; the noise level is higher, consequently leading to a higher threshold.

Table 1 is offering an exhaustive comparison of all four different principles based on specific existing sensors.

	Piezoceramic shear	Piezocrystalline shear, PiezoStar	Piezoelectric bending bimorph, PiezoBeam	Variable Capacitance (MEMS)
Electronic interface	IEPE	IEPE	IEPE	Differential or single ended, bipolar
Power supply	Constant current 2…18 mA	Constant current 2…18 mA	Constant current 2…20 mA	Excitation voltage 6…50 V DC
Full Scale range	±50 g_n	±50 g_n	±50 g_n	±50 g_n
Amplitude non-linearity	±1 %	±1 %	±1 %	±0,3 %
Sensitivity	100 mV/g_n	100 mV/g_n	100 mV/g_n	80 or 160 mV/g_n
HP-Corner frequency (-5 %)	0,5 Hz	0,5 Hz	0,5 Hz	0 Hz DC
Max. Frequency for sensitivity deviation for (+5 %) to reference	10 kHz	10 kHz	5 kHz	1,5 kHz
Mounted resonance frequency	>50 kHz	>40 kHz	>25 kHz	>5,8 kHz
Damping ratio of seismic system, nom.	Very weak	Very weak	Very weak	0,7
Phase shift (max.) @ 0,5 Hz @ 10 Hz @ 100 Hz	 15° 1° 1°	 15° 1° 1°	 15° 1° 1°	 0° 2° 10°
Wideband threshold				
1 Hz to 10 kHz	400 µg_n	1 200 µg_n	360 µg_n	2 450 µg_n
Thermal sensitivity shift	-54…23 °C: 0,07 %/K			
23…100 °C: -0,01 %/K	0,004 %/K	0,16 %/K	0,01 %/K	
Thermal transient response	Low	Very low	High, constant thermal ambient conditions are required	Very low
Operating temperature range	-54…100 °C	-55…165 °C	-40…65 °C	-55…125 °C
Cross axis sensitivity shift, typ.	2 %	3 %	1,5 %	1 %
Base strain sensitivity @250µStrain	0,002	0,015	0,004	
Shock survivability 1 ms haversine	5 000 g_n	2 000 g_n	5 000 g_n	6 000 g_n
Mass, sensor	2,9 g	7,6 g	3,5 g	15 g
Ground isolation	With accessory	Yes	With accessory	Yes
Reference type	8774B050S	8703A50	8640A50	8316A050..

Table. 1: Comprehensive comparison of specifications for ceramic shear, crystal shear, bending bimorph and variable capacitance accelerometers for typical sensors

4. “The Near-Perfect Sensor Solution”

Ultimately, a ceramic shear element has been selected. A specific design has been derived from Kistler’s new sensor family Type 8774B050 and 8776B050 elements. This design provides ruggedness, low mass and low threshold for a high dynamic range of 102 dB. In addition, the thermal sensitivity shift and the thermal transient response are sufficiently low for the application (within ambient temperature ranges from 0 °C to 40 °C). The element frequency response for sensitivity and phase falls within the tight specified limits. On the other end, the cross-axis sensitivity of less than 2 % requires a selection process during production.
The technical specifications are summarized in Table 2.

Based on this technology, the sensor element Type 8000M095 has been designed in a cylindrical shape with one hexagonal end for adjustment of the sensitive direction (see Fig. 6). On the connector side is a cone-shape form in order to securely fix the sensor element in the cubic adapter Type 800M166, see Fig. 7. After adjustment, two small metric M3 Nylon headless screws are securing the sensor element within the adapter. An 8 mm hex wrench can be used to adjust the sensitive direction during installation. The sensor-in-adapter assembly is then glued to the structure under test and provides ground isolation to prevent ground loops. The sensitive direction can easily be identified by an arrow at the hex face side and is more visible by a red dot at the arrow top. Fig. 8 shows the whole sensor assembly with cable for illustration.

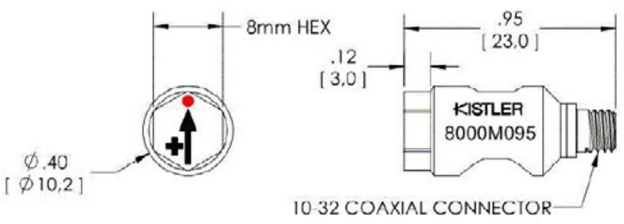

Fig. 6: Design of the sensor Type 8000M095

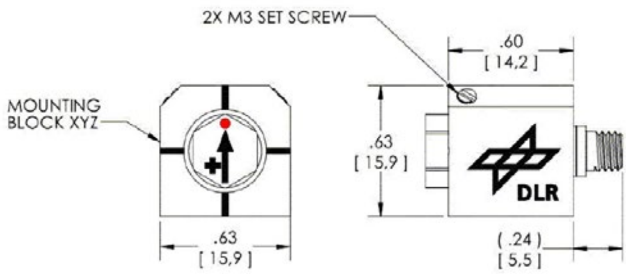

Fig. 7: Design of the insulating adapter Type 800M166 accommodating the sensor element Type 8000M095

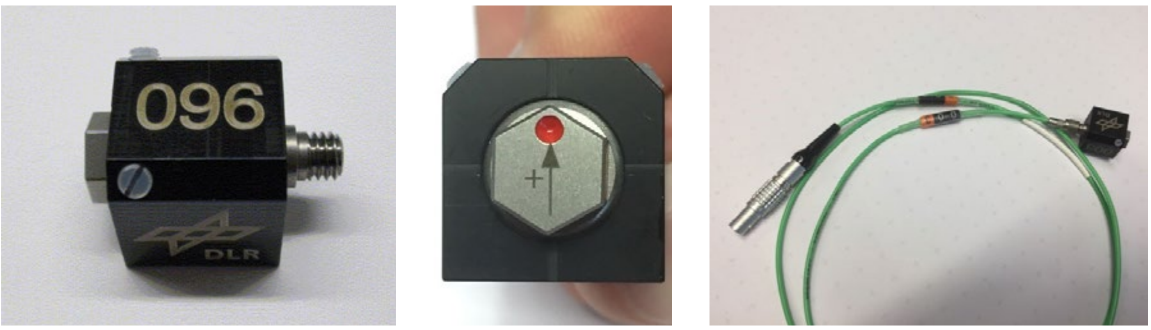

Fig. 8: Sensor Type 8000M095 with adapter 800M166 and cable assembly

	Requirements	Sensor Solution Type 8000M095 with Adapter 800M166
Sensitive axis	Uniaxial, 360° rotatable (within polymer adapter)	Uniaxial, 360° rotatable (within POM™ Adapter 800M166)
Electronic interface	IEPE	IEPE
Power supply	Constant current 2…18 mA	Constant current 2…18 mA
Full Scale range	±50 g_n	±50 g_n
Amplitude non-linearity (3 Hz…1 kHz)	±2 %	±1 %
Sensitivity, ref.	100 mV/g_n +2 %	100 mV/g_n +2 %
HP-Corner frequency (-5 %)	0,5 Hz	0,5 Hz
Max. Frequency for sensitivity deviation for (+5 %) to reference	1 kHz	1 kHz
Mounted resonance frequency (without adapter)	>10 kHz-	>62 kHz without adapter
Damping ratio of seismic system, nom.	Very weak	Very weak
Phase shift (max.) 0,5 Hz to 3 Hz 3 Hz to 1 kHz	 15° 1°	 15° 1°
Phase deviation between sensors 0,5 Hz…1 kHz	<±3°	<±3°
Wideband threshold 1 Hz to 10 kHz	---	400 µg_n
Thermal sensitivity shift	---	-54…23 °C: 0,07 %/K 23…100 °C:-0,01 %/K
Thermal transient response	Low	Low
Operating temperature range	-15…60 °C	-54…100 °C
Cross axis sensitivity shift, typ.	2 %	2 %
Base strain sensitivity @250µStrain	--	0,002 (8774B)
Shock survivability 1 ms haversine	5 000 g_n	5 000 g_n
Mass, sensor	<25 g	10 g
Ground isolation	With accessory	With accessory
Size	<20*20*30 mm³	

Table. 2: DLR Application requirements vs Type 8000M095/800M166 specifications

5. Installation procedure for the accelerometers

The sensors are affixed to the structure using double-adhesive tape. The tape is already applied to the bottom of the sensor housing before starting the test campaign. Therefore, they can be very quickly installed on the cleaned surface of the test structure, see Fig. 9. A tri-axial arrangement of three uni-axial accelerometers is presented in Fig. 10. This installation requires the rotation of two accelerometers within its housing to account for both horizontal axes of the local coordinate system.

A reliable sensor installation needs to be done within a very short time duration. Especially in the final phase of an aircraft development, added pressure forces the provider of a GVT to install up 600 sensors within three days. For DLR as GVT supplier, with several hundred accelerometers, it is therefore important to have clear documentation of the entire sensor installation. For this reason, the sensor housing is engraved with a unique DLR internal sensor number for photo documentation. This number also reflects the channel on the acquisition system which guarantees fail-safe cabling to the measurement system.

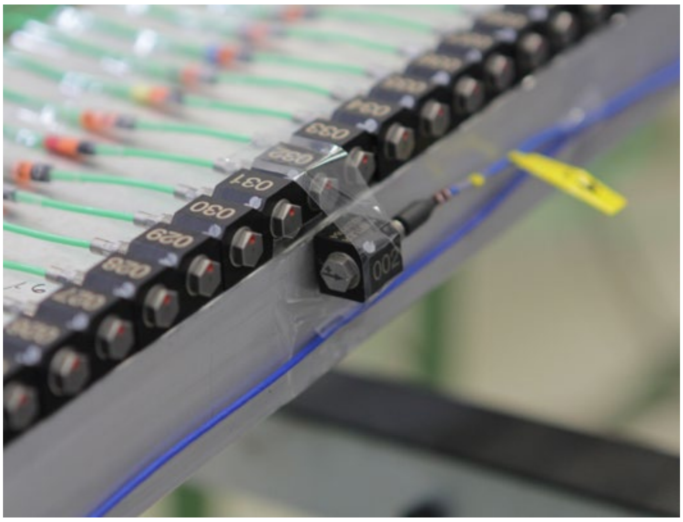

Fig. 9: Sensor installation of uni-axial application

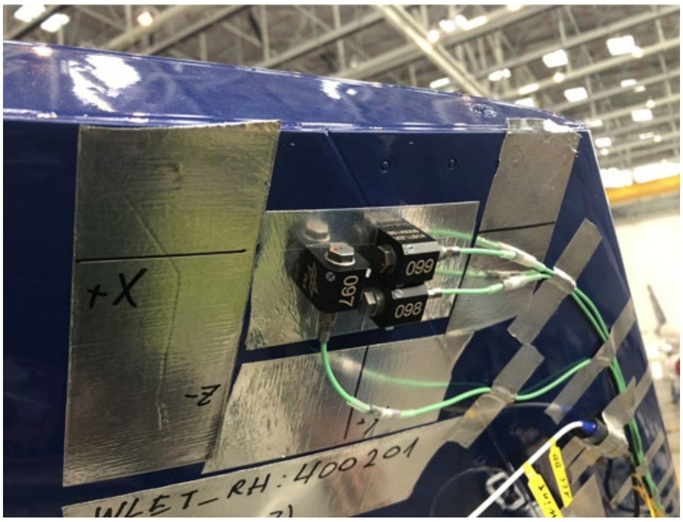

Fig. 10: Sensor installation of tri-axial application

6. Typical test setup and results

A typical application of the described acceleration sensor is shown in Fig. 11 for the modal test on a wind turbine blade [10]. The experimental modal analysis of this wind turbine blade was performed within the German research project SmartBlades2. Within the scope of this project passive load alleviation techniques are analyzed. The analyzed wind turbine blade has been designed with a passive bend-twist coupling mechanism to reduce the root bending moment for gust encounters. Therefore, a detailed analysis of the structural behavior was of high interest.

This test was conducted with a high-resolution sensor setup of ~300 acceleration sensors. The sensor setup is described in Fig. 12. Each arrow in Fig. 12 represents a uni-axial acceleration sensor.

Fig. 11: Setup of measurement campaign on wind turbine blade

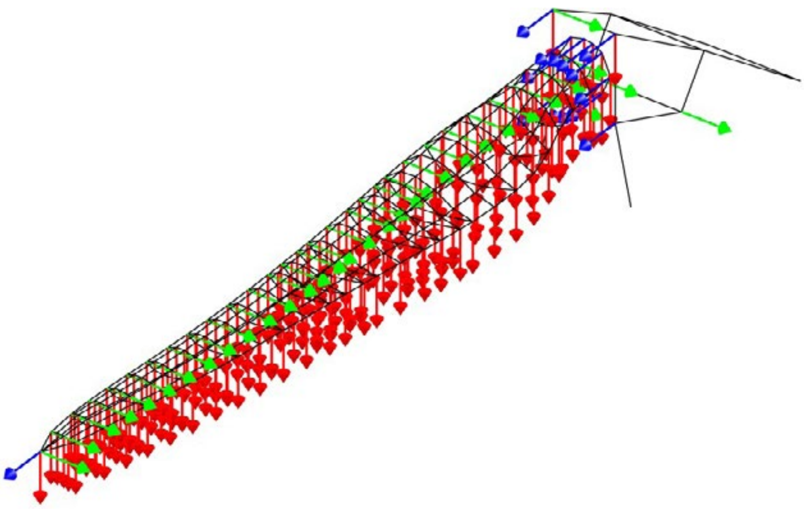

Fig. 12: Sensor setup for high resolution modal testing

Typically, time data is acquired from all acceleration and also force sensors. Time histories of all accelerometers from a swept-sine excitation ranging from 5 to 35 Hz are visualized in Fig. 13. Swept-sine excitation yields good signal to noise ratio and also provides the possibility to identify non-linearities of all kinds of structures in cases using different force levels from the same excitation location.

The conversion to frequency domain is accomplished using the Welch method with overlapping Hanning windows while referencing the introduced forcing signal. The frequency response functions shown in Fig. 14 are calculated from the time histories presented in Fig. 13.

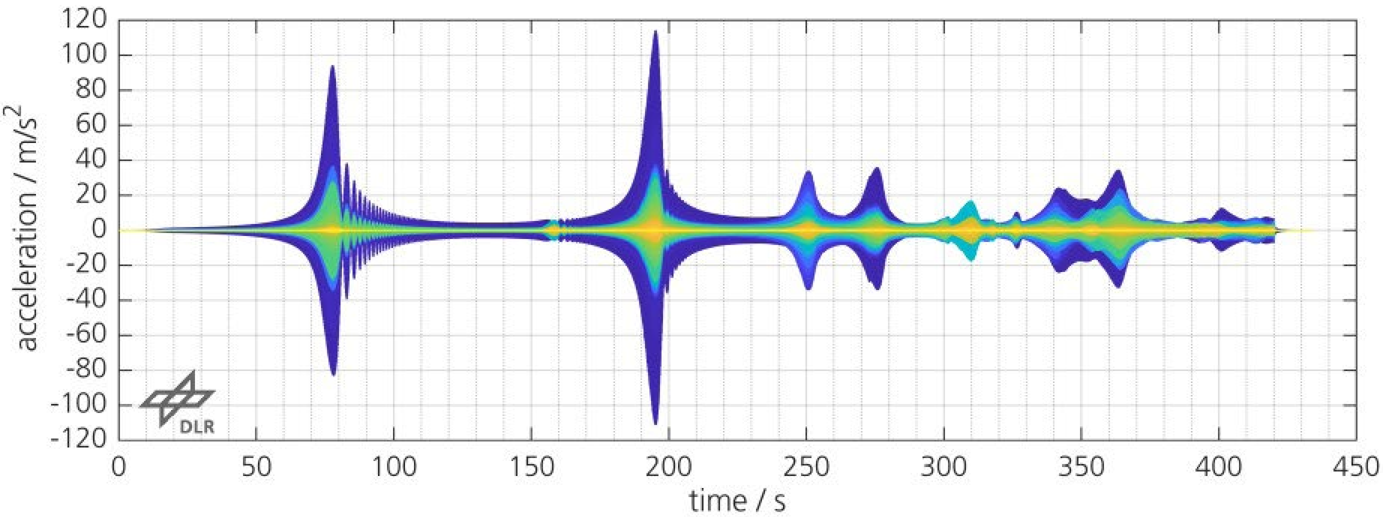

Fig. 13: Sensor setup for high resolution modal testing

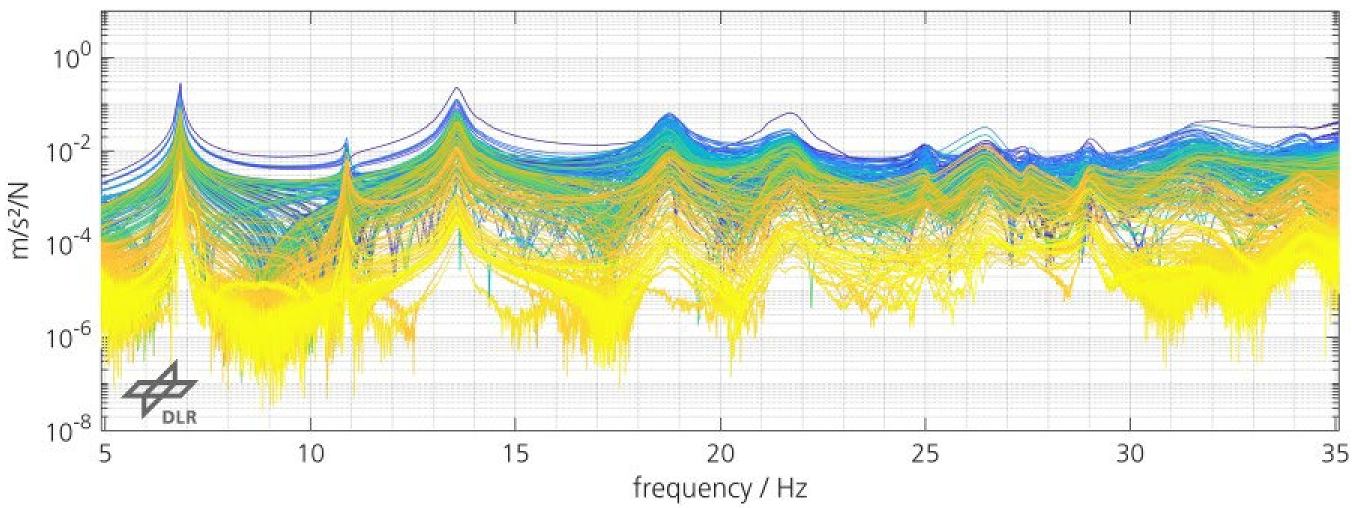

Fig. 14: Frequency response functions from time data of Fig. 13

Finally, a modal identification algorithm needs to be applied to the frequency response functions which yield the modes for the experimental modal model. Some modes from this modal test campaign are shown in Fig. 15. The identified modes are used for finite element model validation and updating.

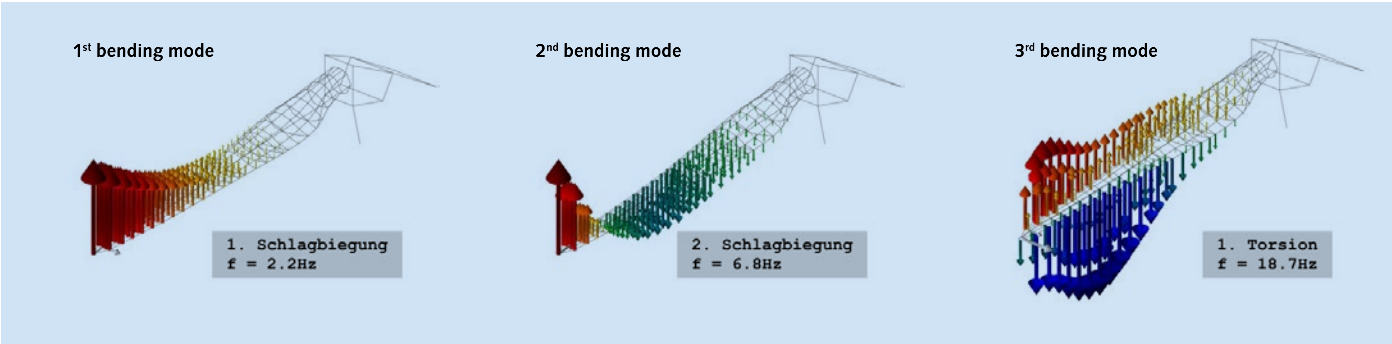

Fig. 15: Some identified mode shapes

7. Summary and conclusions

Today, the properties of an appropriate accelerometer from different technologies, mounting adapter and mounting procedure have been described and incorporated into the test procedure necessary to accomplish large scale modal tests such as the GVT of airframe structures or similar. The techniques have been developed over many years following strict precautions and guidelines and have proven to yield excellent results under very tight time constraints. Even a very sensitive test structure can be thoroughly and efficiently tested if a well-trained, disciplined group follows well defined and proven procedures. This involves a good working relationship between hardware installers, data collectors and structural analysts. Every aspect of the test is equally important, and all are interrelated.

References

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ISO 5347-17:1993, Part 17: Testing of fixed temperature sensitivity
ISO 5347-18:1993, Part 18: Testing of transient temperature sensitivity
ISO 5347-19:1993, Part 19: Testing of magnetic field sensitivity
ISO 5347-22:1997, Part 22: Accelerometer Resonance Testing-General Methods

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ISO 16063-1: 1998: Part 1: Basic concepts"
ISO 16063-21:2003 + Cor. 1:2009 + Amd. 1:2016: Vibration calibration by comparison to a reference transducer
ISO 16063-31: Part 31: Testing of transverse vibration sensitivity.
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