Combined Acoustic and Modal Structural Health Monitoring and Structural Assessment

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ABSTRACT

The paper presents the first results of a recently completed R+D project KamoS - the acronym stands for Combined Acoustic and Modal Structural Health Monitoring and Structural Assessment. The scope of the project was to understand how combined approaches based on guided ultrasonic waves, acoustic emission and vibration measurement can be used for the monitoring of aircraft structures under changing operational conditions. The main idea is to combine the advantages of local and global Structural Health Monitoring (SHM) approaches.

For the experimental validation of the first developed algorithms an extended measurement campaign was carried out on a realistic aircraft door environment. The laboratory tests combined active and passive measurement principles based on ultrasound and vibration to ensure robust and reliable damage detection and localization.

In this paper only the experimental setup of the aircraft structure and some results based on vibration monitoring are presented. The obtained measurement data sets serve for the development of further damage identification algorithms.

THREE DIFFERENT SHM-METHODS FOR MONITORING THE TEST SPECIMEN

In order to increase the safety of aircrafts and to make maintenance and servicing processes more efficient, a multivariate Structural Health Monitorig system was investigated.

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The monitoring object is a real door surrounding structure of an aircraft fuselage under changing mechanical loads. This test structure was designed and manufactured as part of a European project MAAXIMUS. KamoS continues to reuse the structure. The door surrounding structure, based on the design of the Airbus A350, is made of carbon fiber reinforced plastic, and has the dimensions of 5.8m x 4.3m, see Figure 1.

The sensors on the structure are related to the applied SHM methods. Three different physical principles were used:

1) Acousto-ultrasonics, lamb waves (active). The excitation and reception of guided ultrasonic waves is carried out with the help of piezoceramic transducers. Damage is detected based on signal changes using different algorithms (evaluation of amplitudes, energy, frequency, wavelengths, etc.).
2) Structural vibrations (active and passive). The vibrations are excited by external excitation (passive) or by applied coil actuators / microphones on the structure (active). The structural vibrations are recorded by applied accelerometers. Damage is detected by means of an operational modal analysis approach (OMA) in time domain and by means of covariance-driven stochastic subspace identificationthen (SSI-COV) and null space-based fault detection (NSFD) method.
3) Sound/acoustic emission (passive). Damage events emit sound in the form of elastic waves in the structure. These waves are recorded with the help of applied piezoceramics. By evaluating the sensor signals, the location of the sound emission and the intensity of the detected event can be determined.

One of the project aims is to create a unified actuator-sensor module that combines all measurement methods in a single device (see Figure 2). Based on all fused measurement signals, an assessment of the state of the monitored object is then to be carried out in a final step. The novelty of the approach lies in the combination of active and passive measurement principles based on ultrasound and vibration, which ensures redundant and robust information about the damage state. The vibration monitoring, as a global approach, is based only on a few sensors and serves mainly for

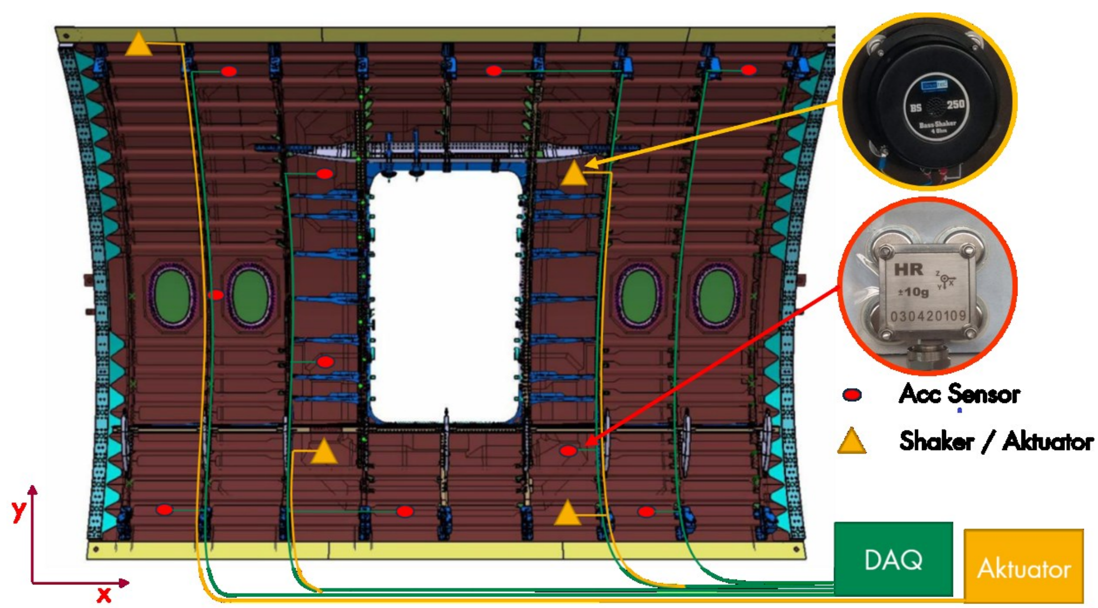

Figure 1. Drawing of the door surrounding structure, incl. the position of accelerometers and shakers (the position of piezoelectric sensors/actuators is not shown in this figure)

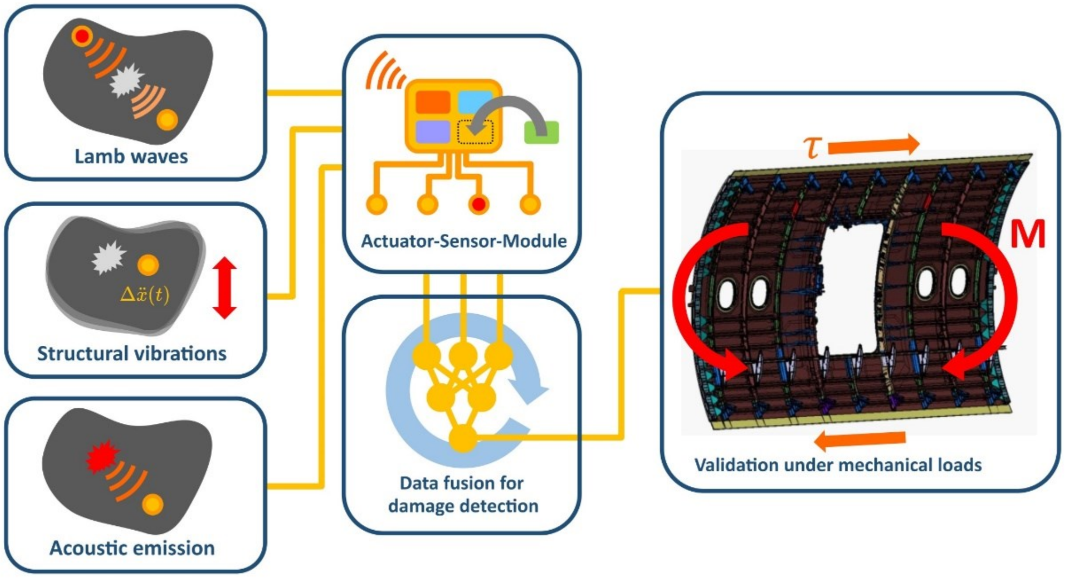

Figure 2. Combined acoustic and modal SHM-system, data fusion and structural assessment

pure damage detection in presence of changing operational conditions. The acousto-ultrasonics and acoustic emission need more sensors and higher sample rates, but these are more reliable if the localization of damages is necessary.

This paper discusses mainly the function of the vibration monitoring subsystem. The comparison with the results based on the other measurement methods is well possible and allows a relatively safe damage detection. This will be shown in future papers.

SHORT DESCRIPTION OF TESTS RIG AND MEASUREMENT SET UP

The door surrounding structure and the SHM overall system were tested and validated under mechanical operating loads typical for flight conditions. For this purpose, the structure was installed/clamped in a test rig at IMA in Dresden (Germany) and subjected to various static loads as well as different dynamic excitations (see Figure 3).

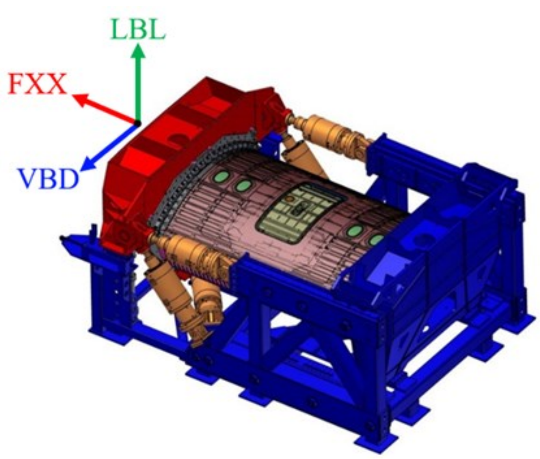

Figure 3. Door surrounding structure installed in test rig

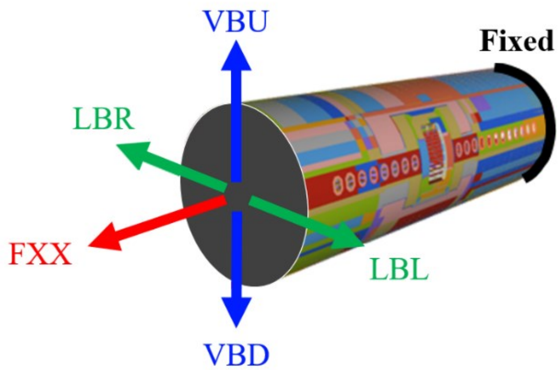

Figure 4. Static loads applied on the door surrounding structure

The applied static loads cause stresses and strains in the structure. These were measured and controlled with the help of strain gauges. To reduce the test time, the following three load cases were selected (see Figure 4):

- Pure tensile stress (abbr.: FXX).
- Lateral bending left (abbr.: LBL)
- Vertical bending down (abbr.: VBD)

During the measurements, the already described load cases were applied until 75% of the limit load value (abbr.: LL) determined in advance was reached. The measurements were made step by step with the load factors based on the definition of the limit load (e.g. 0.75 means 75 % of the limit load). The following load levels were used for the reference measurement for each of the three load cases FXX, LBL and VBD: 0.0 / 0.2 / 0.4 / 0.5 / 0.6 / 0.65 / 0.70 / 0.75 / 0.60 / 0.4 / 0.2 / 0.0.

During the measurement campaign, a total of 12 damages were introduced into the structure: eleven impact damages and a stringer detachment (broken cleat), see Figure 5. The test sequence after each introduced damage also consists of the three above mentioned static load cases FXX, LBL and VBD but only of the following 4 load levels: 0.0 / 0.4 / 0.6 / 0.75. After each damage the structure was examined with the SHM system.

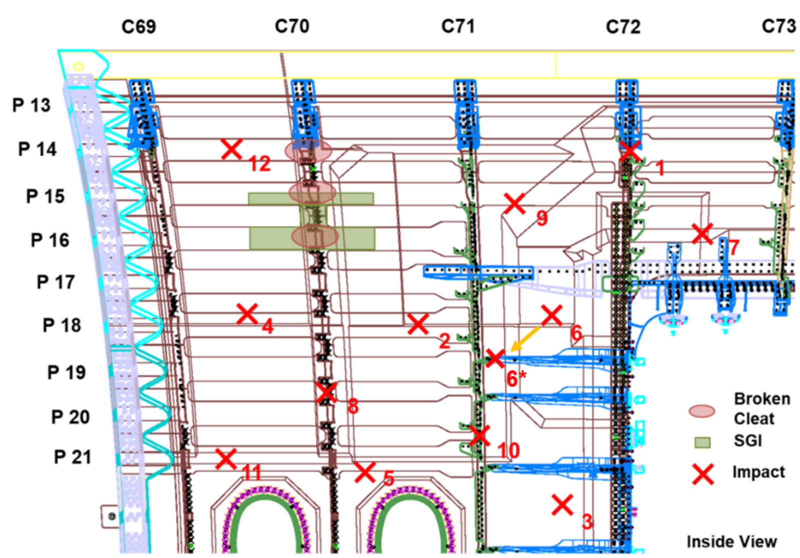

Figure 5. Impact positions, sketch

FIRST RESULTS BASED ON VIBRATION MONITORING

Damage detection by means of OMA and SSI-COV

Operational Modal Analysis, OMA, is used to detect structural damages during the stochastic excitation by the coil actuators. The method used here based on changes in the natural frequencies [1]. The OMA-based damage indicator (cannot be described here due to lack of space) uses the sensor signals of all acceleration sensors in Figure 1. The results for the load case "LL-FXXs" at load step 0 are shown in Figure 6. Different damage phases (D01-D12) are highlighted in different colors, the reference measurement is marked with "Ref". Figure 6 and Figure 7 show - as expected - that different frequencies are differently sensitive to the damages. But generally, a decay tendency of the eigenfrequencies with the stiffness reduction can be clearly observed.

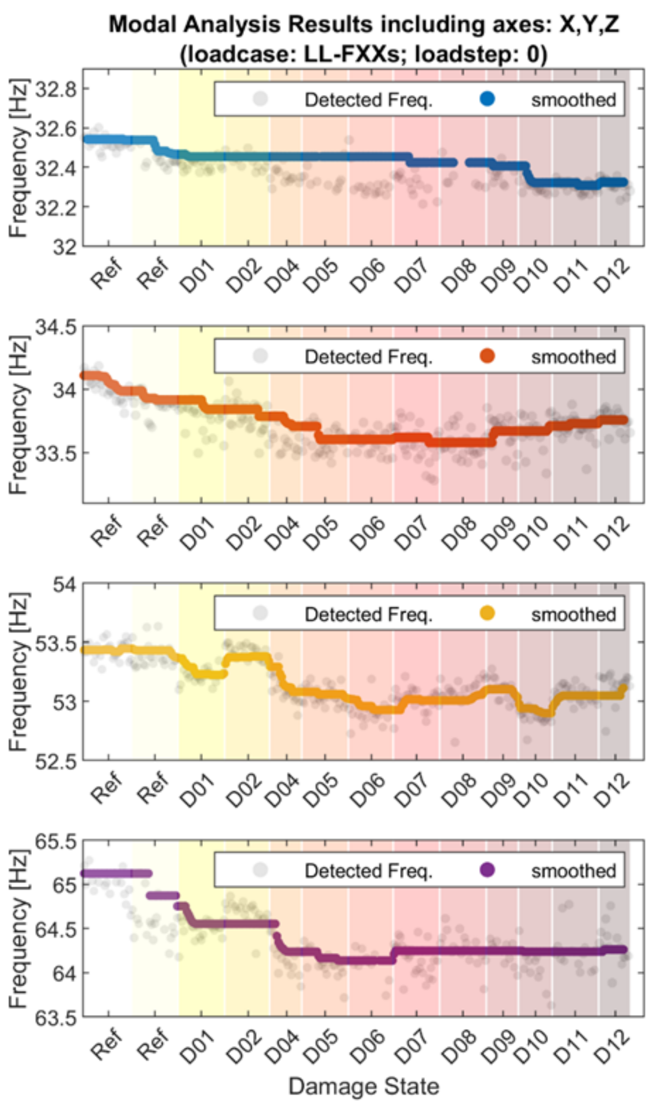

Figure 6. Decrease in frequency with increasing damage

No.	Start value	End value	Absolute decrease	Relative decrease
1	32.54 Hz	32.32 Hz	0.22 Hz	0.67 %
2	34.11 Hz	33.76 Hz	0.35 Hz	1.03 %
3	53.44 Hz	53.05 Hz	0.38 Hz	0.74 %
4	65.12 Hz	64.26 Hz	0.86 Hz	1.32 %

Figure 7. Results of modal analysis

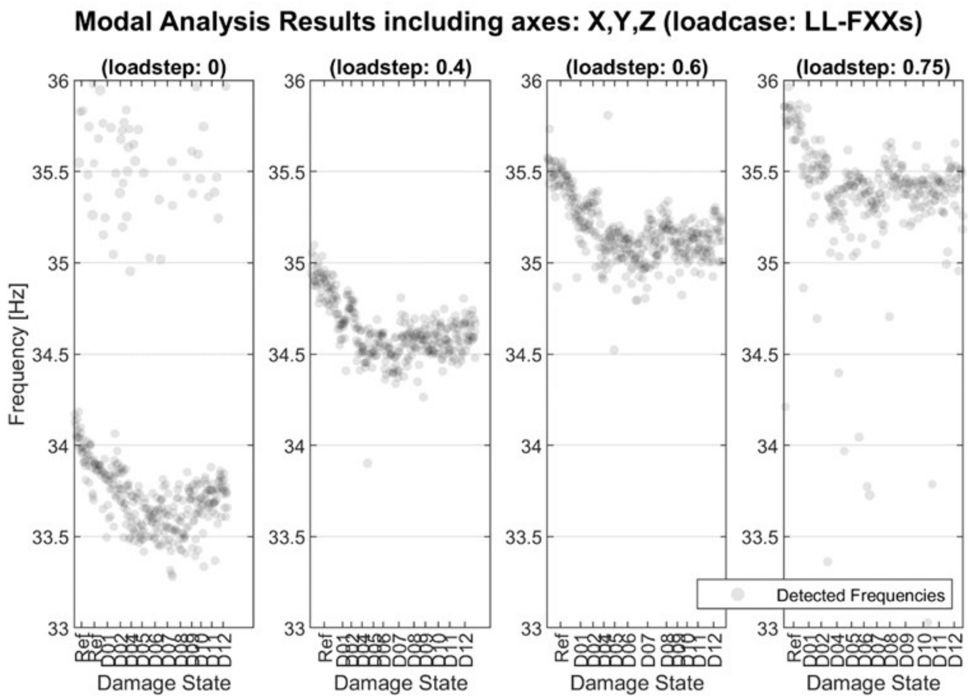

Figure 8. Comparison of load steps effects on the OMA results

The dependency on the applied static load is shown in Figure 8. The frequency gets higher values with the increasing static load. The course is very similar for all four load steps. The change due to higher loads, i.e. due to changed EOCs, is greater than those changes due to the damages. From this we conclude: the detection of structural changes in the aircraft structure is well possible if the load case i.e. the stress state of the structure is known and the acting environmental and operational conditions are known and can be separated!

Damage detection by means of NSFD

The NSFD algorithm in its basic version is well known [2]. The influence of the environmental conditions has a big influence on the NSFD-based damage indicator (DI), see [3] and [4]. Nevertheless, this influence can be minimized by a well-chosen reference space. The first approach to minimize the large influence of the three load levels FXX, LBL and VBD is to include measurements of the undamaged structure under the influence of all load cases and load levels in the reference space. The damage indicators for this approach are shown in Figure 9.

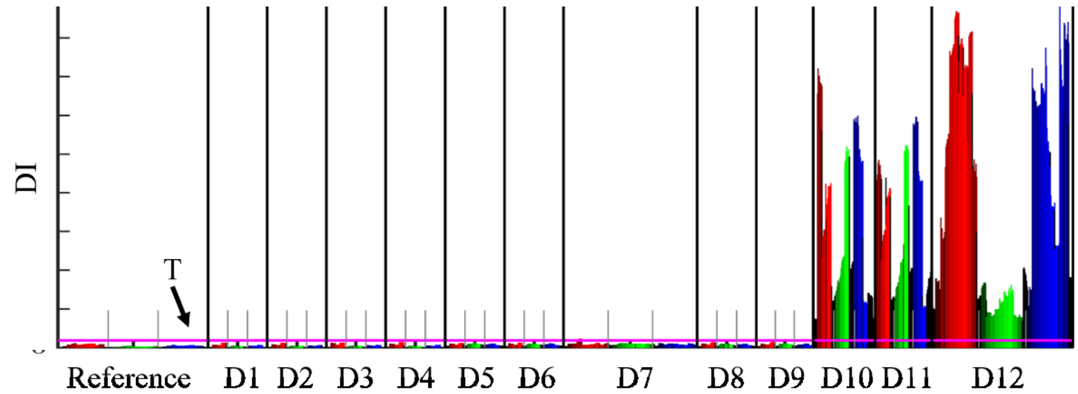

Figure 9. NSFD results for all load cases

With this approach, it is initially possible that the DI for the undamaged case does not exceed the threshold T despite the influence of the various mechanical loads. However, the sensitivity of the algorithm is also reduced by this procedure. The changes in the mechanical loads have a stronger effect on the damage indicator than a large part of the introduced damage. Up to damage D10, none of the introduced damage is detectable with this algorithm configuration. From damage D10 onwards, damages can be detected. However, the level of the damage indicator in this range is also strongly dependent on the changes in the mechanical loads. The damage indicator rises sharply with increasing mechanical load. In summary, it can be said that additional compensation of the load cases is necessary.

One possible solution for this problem is the separation of the different load cases, so that only measurements belonging to the same load case will be compared to each other. For this approach, additional information is needed to cluster the measurements to the different load situations. This information can be gathered by the strain gauges. With the information of the strain gauges, the load cases are easily identifiable, so that just measurements of the same load case can be compared to each other. Figure 10 shows the load-compensated damage detection based on the example of load case LBL 0.6. Here all the damages can be detected. Furthermore, the damage indicator DI rises strongly with certain damages. The impact on the structural behavior is bigger. Nevertheless, it must also be noted that there is a false positive damage detection in the reference state, caused by additional unmeasured environmental influences.

In summary, the NSFD algorithm adapted to compensate the static loads effects loads reacts very sensitive to most of the introduced damages. Since the algorithm detects damage based on the induced change in the vibration characteristics of the structure, only damages that have a measurable influence on the vibration characteristics can be detected. If there are several damages with different influence on the natural vibration of the structure, damages with a very small influence can be masked by damages with a larger influence.

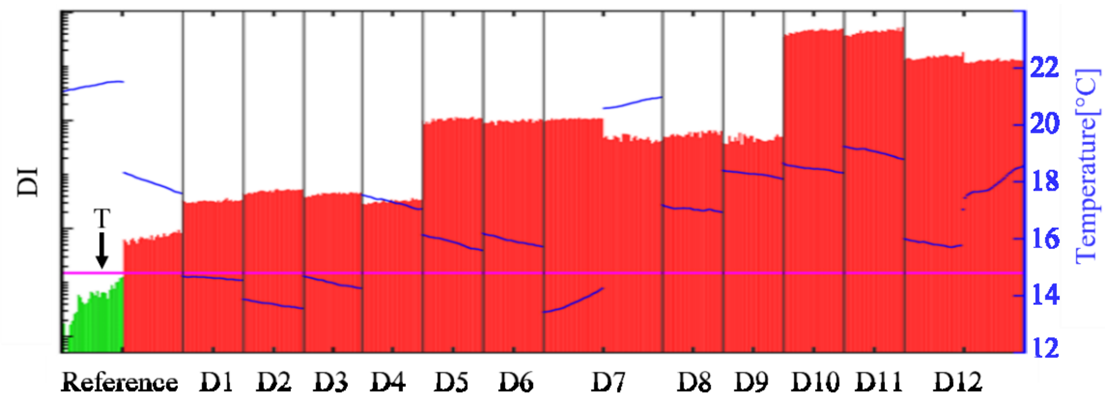

Figure 10. DI for the load case LBL 0.6

CONCLUSION

The paper is a brief presentation of the vibration measurements and the test set up within the project KamoS. In future publications, further results will be presented, particularly evaluations based on the combination of vibration-based and acousto-ultrasonic-based methods.

REFERENCES

1. KRAEMER, P. und FRIEDMANN, H., 2015: Vibration-based structural health monitoring for offshore wind turbines structures – Experimental validation of stochastic subspace algorithms, Wind and Structures, An International Journal, Vol. 21(6), S. 693-707.
2. BASSEVILLE, M.; ABDELGHANI, M. und BENVENISTE, A., 2000: Subspace-based fault detection algorithms for vibration monitoring, Automatica (Band 36), S. 101-109.
3. FRITZEN, C.-P., KRAEMER, P. und BÜTHE, I., 2013: Vibration-based Damage Detection under Changing Environmental and Operational Conditions, Advances in Science and Technology (Band 83), S. 95-104.
4. ADAM, T. and KRAEMER. P., 2022, Application of Nullspace-Based Fault Detection to an Aircraft Structural Part Under Changing Excitation, presented at European Workshop on Structural Health Monitoring, EWSHM 2022, S.784-792.

ACKNOWLEDGEMENT

The authors are grateful to the Federal Ministry of Economics and Climate Protection of the Federal Republic of Germany (Project Management Agency for Aeronautics Research, DLR) for the financial support of the project KamoS under the funding numbers 20Q1725A and 20Q1725D.