Experimental modal analysis of structures with conventional vs. contact-free suspension

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Nomenclature:

EMA	Experimental Modal Analysis
FRF	Frequency Response Function
MAC	Modal Assurance Criterion
NVH	Noise, Vibration, Harshness
RTM	Resin Transfer Moulding
SAM	Scalable Automatic Modal Hammer
SLDV	Scanning Laser Doppler Vibrometer

Abstract

The existence of free boundary conditions is frequently assumed for Experimental Modal Analysis (EMA) of a structure. However, free-free conditions can only be approximated because the structure must be supported in some manner. Therefore, comparing simulated data with experimental data can be deceiving, because these suspensions falsify modal parameters especially structural damping and stiffness. The current scenario of structural analysis is more towards focusing on modal updating or correlation, rather than the simulation results (FE) or the experimental results. So it is imperative to bridge the gap between FE and EMA, by carefully studying various parameters.

To overcome these drawbacks, levitation is suggested as a truly free-free suspension method. The levitation method was developed to allow a non-destructive, adaptable, and completely contactless approach for material testing: the structure under test is suspended on a thin film of pressurized air providing an aerodynamic bearing, levitating the specimen. Two suspension devices were constructed. Pressurized air is circulated into a casing with a single outlet ("air cushion") or a fine grid of outlets ("air bed").

A study was performed to investigate the influence of the support conditions on the modal parameters eigenfrequency and damping. Tested specimens were a brass plate, a stainless steel plate and two composite material probes. The tested suspension methods were (a) foam mat, (b) air cushion and (c) air bed. Modal tests were performed using a Scanning Laser Doppler Vibrometer (SLDV) and an automatic modal hammer for excitation. Evaluations of the measurements were performed manually.

The results showed that the detected eigenfrequencies of the metallic specimen have a variation below ±0.3% for the tested suspension methods. This variation is 10 times higher for the composite plates and lies between ±3%. The damping ratios of the levitation suspensions show the different material behavior of metallic and composite specimen: damping ratios of metallic specimen lie between 0.05 – 0.5 % whereas damping ratios of composite plates are ten times higher and lie between 0.3 – 3 %. The damping ratios measured with the air cushion are smaller than the damping ratios for the air bed supporting the hypothesis that a laminar air film under the specimen leads to less additional damping.

The study shows that EMA can be performed on metallic and composite specimens using contact-less suspension methods. Especially for light-weight material specimens where EMA cannot be performed or where the results are not reliable, the contact-less suspension (levitation method) can be used.

Keywords

Modal Analysis, levitation, free-free suspension, composite materials, automatic modal hammer

Introduction

The existence of free boundary conditions is frequently assumed for the Experimental Modal Analysis (EMA) of a structure. However, free-free conditions can only be approximated because the structure must be supported in some manner. Usually, soft supports like foam mats are used to suspend the specimen, but the stiffness and damping of these supports will affect the modal parameters of the combined structural system, [1].

The current scenario of structural analysis is more towards focusing on modal updating or correlation, rather than solely the finite element simulation results (FE) or the experimental results. So it is imperative to bridge the gap between FE and EMA, by carefully studying various parameters. Free boundary conditions are the desired support conditions for comparing the experimental results to the computational results. The free-free test environment is easily achieved in theoretical calculations but is usually compromised when measured experimentally due to the requirement to support the structure against gravity forces, [2]. Therefore, comparing simulated data with experimental data can be deceiving, because these suspensions falsify modal parameters especially damping and stiffness.

To overcome these drawbacks, levitation is suggested as a truly free-free suspension method. The levitation method was developed to allow a non-destructive, adaptable, and completely contactless approach for material testing: the structure under test is suspended on a thin film of pressurized air providing an aerodynamic bearing by levitating the specimen. Two suspension devices were constructed. Pressurized air is circulated into a casing with a single outlet ("air cushion") or a fine grid of outlets ("air bed").

A study was performed to investigate the influence of three support conditions on the modal parameters eigenfrequency and damping ratio. Tested specimens were a brass plate, a stainless steel plate and two composite materials. The tested suspension methods were (a) foam mat, (b) air cushion and (c) air bed. Modal tests were performed using a Scanning Laser Doppler Vibrometer (SLDV) and an automatic modal hammer for excitation. Evaluations of the measurements were performed manually.

Materials and Methods

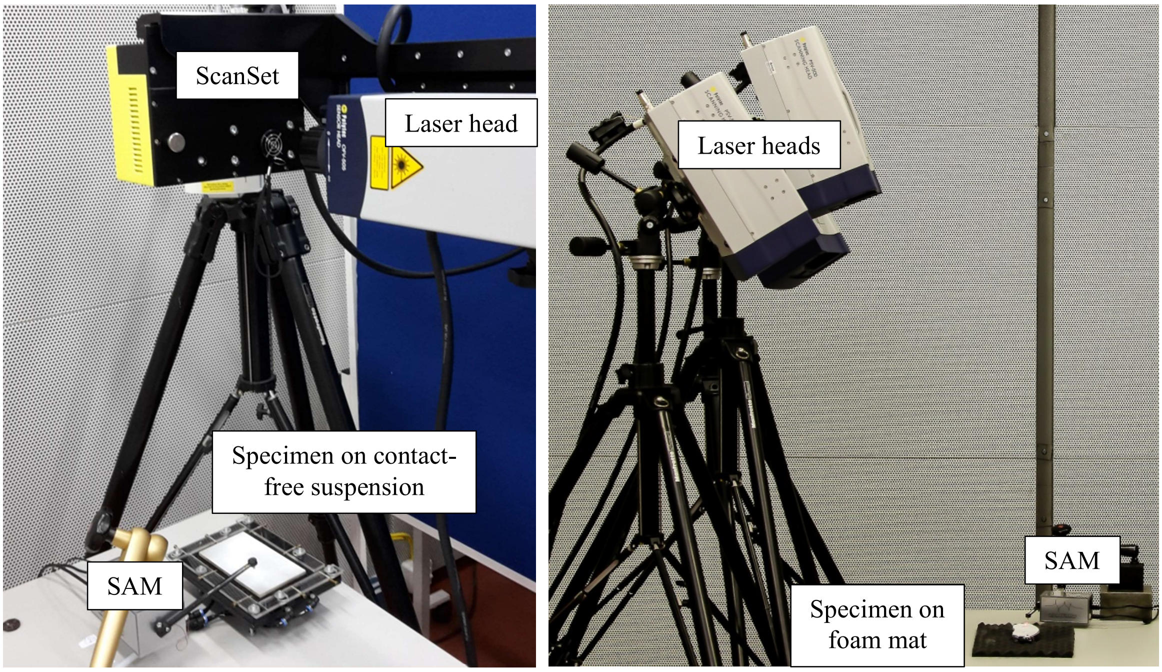


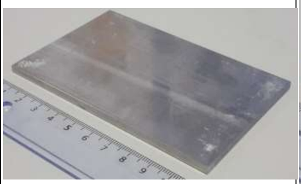
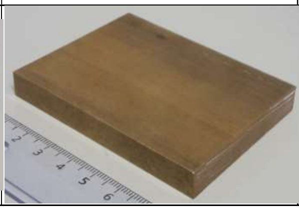
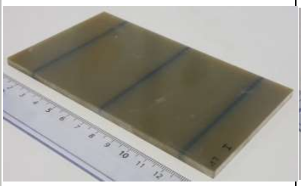
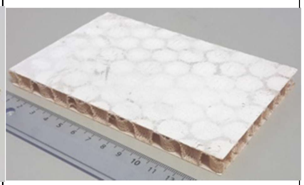
Fig. 1 Setup of the EMA measurements. A scalable automatic modal hammer (SAM) was used to excite the specimen. System response was measured with 1D SLDV (Left) or 3D SLDV (right)

The EMA measurements of the steel plate and composite plates were performed with a Scanning Laser Doppler Vibrometer (SLDV) ScanSet (Maul Theet GmbH, Berlin, Germany) with laser head OFV-5000 (Polytec GmbH, Waldbronn, Germany) as a roving response sensor, Fig. 1 left. The EMA measurement of the brass plate was performed using a PSV-500-3D SLDV system (Polytec GmbH, Waldbronn, Germany), Fig. 1 right.

For EMA excitation the automatic modal hammer SAM (NV Tech Design, Steinheim, Germany) was used. The SAM was instrumented with a light impact hammer 086E80 (PCB Piezotronics, Inc., NY, US). The metallic specimens were tested with a measurement time of 1.28s and a sample rate of 20 kHz (25600 FFT-Lines), for the composite specimens a measurement time of 2.56s and sample rate of 5 kHz (12800 FFT lines) was used.

Measurements of eigenfrequencies and modal damping ratios were performed on four different materials and with three suspension methods. Table 1 shows the geometrical parameters of the used specimen. The composite specimens were provided from *Fraunhofer Institute for Applied Polymer Research / PYCO*, Teltow, Germany. The "Composite RTM" was manufactured using a Resin Transfer Moulding (RTM) process with 17 layers of glass fiber (269 g/m^3) and resin (Cytech 890) resulting in a fiber content of 40 %. The "Composite Sandwich" is a nap core sandwich composite consisting of aramid hybrid yarn knitted fabric impregnated with the phenolic formaldehyde resin and a facing of Isovolta Airpreg 8242.

Table 1 Material parameters and picture of the four specimen included in the study

Material	Stainless Steel	Brass	Composite RTM	Composite Sandwich
Weight in g	249.8	398	93.5	18.3
Dimensions (WxLxH) in mm	70x110x4	60x78x10	80x140x4	90x140x10
Specimen				

Three suspension methods were used in this study (Fig. 2):

(a) Foam mat,
(b) Air cushion,
(c) Air bed.

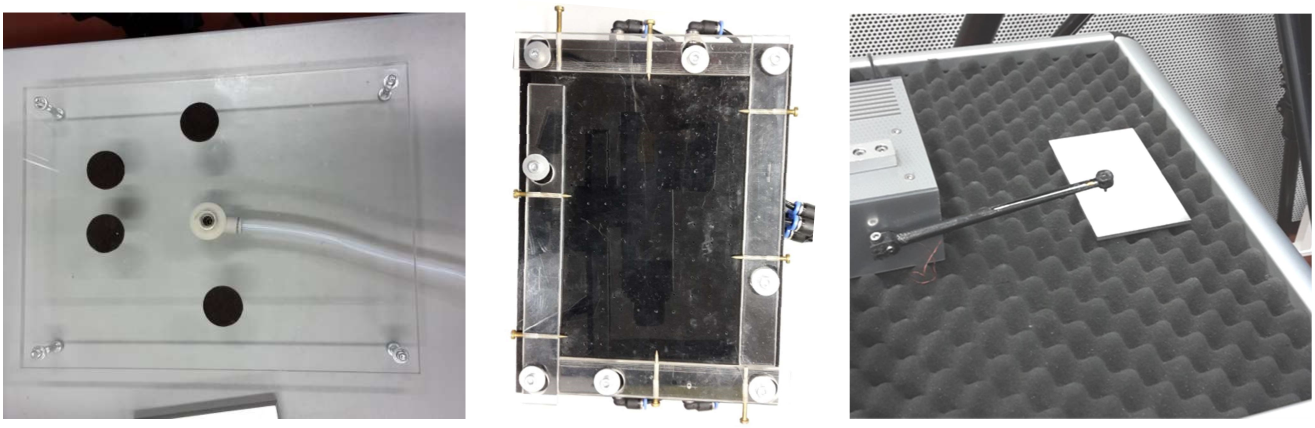


Fig. 2 Utilized suspension methods. Left: Air cushion with a single outlet for pressurized air. The adhesive felt stickers keep the specimen in the correct position. Center: Air bed with fine grid of holes for pressurized air. Pointed screws prevent the lateral movement of the specimen. Right: Foam mat with specimen and automatic modal hammer (SAM)

The EMA was performed using the hand-fit method in vModal (Maul Theet GmbH, Berlin, Germany) using a generally damped SDOF (Single Degree of Freedom) approach.

The “air cushion” consists of an acryl glass plate with a single outlet for pressurized air, Fig. 2 left. Lateral movement of the specimen was inhibited by circular felt adhesives. The “air bed” consists of a casing with a fine grid of opening holes, Fig. 2, center. Pointed screws prevent the specimen from moving. Air bed and air cushion were connected to a compressed air supply with 5 bar. An additional pressure valve at the suspension structure was used to regulate the required air pressure. A more detailed description of the levitation casings can be found in [3].

Results and Discussion

A grid of at least 5x8 measurement points was used on the rectangular specimens. Depending on the suspension, the output signals were of different quality resulting in the frequency response functions (FRF) given in Fig. 3. Especially the air cushion leads to much noisier FRFs.

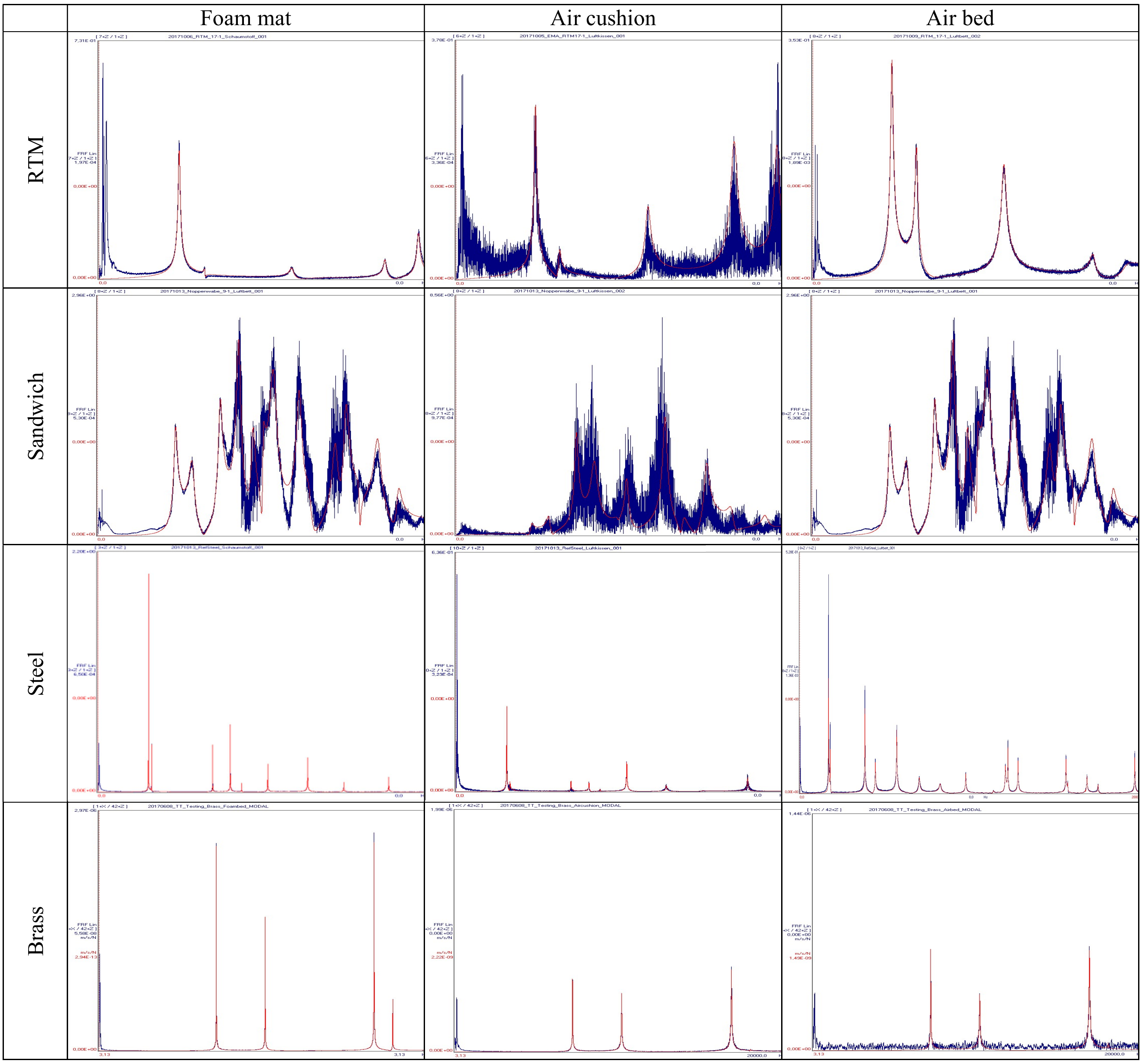


Fig. 3 FRF and hand fitted generally damped SDOF model of composite and metallic specimen on all tested suspension. The scaling of these FRF plots is different depending on the structure.

Nonetheless it was possible to perform a manual fitting procedure for all data sets to analyze the eigenfrequencies and modal damping ratios. The Modal Assurance Criterion (MAC) proved the linear independency of the detected modes for all data sets.

The modal damping and eigenfrequencies were analyzed with a generally damped single degree of freedom (SDOF) method using a manual peak-picking method in the analyzing software. Fig. 4 shows the results of the modal damping ratios of the first 6-12 modes for all specimens on all suspension methods.

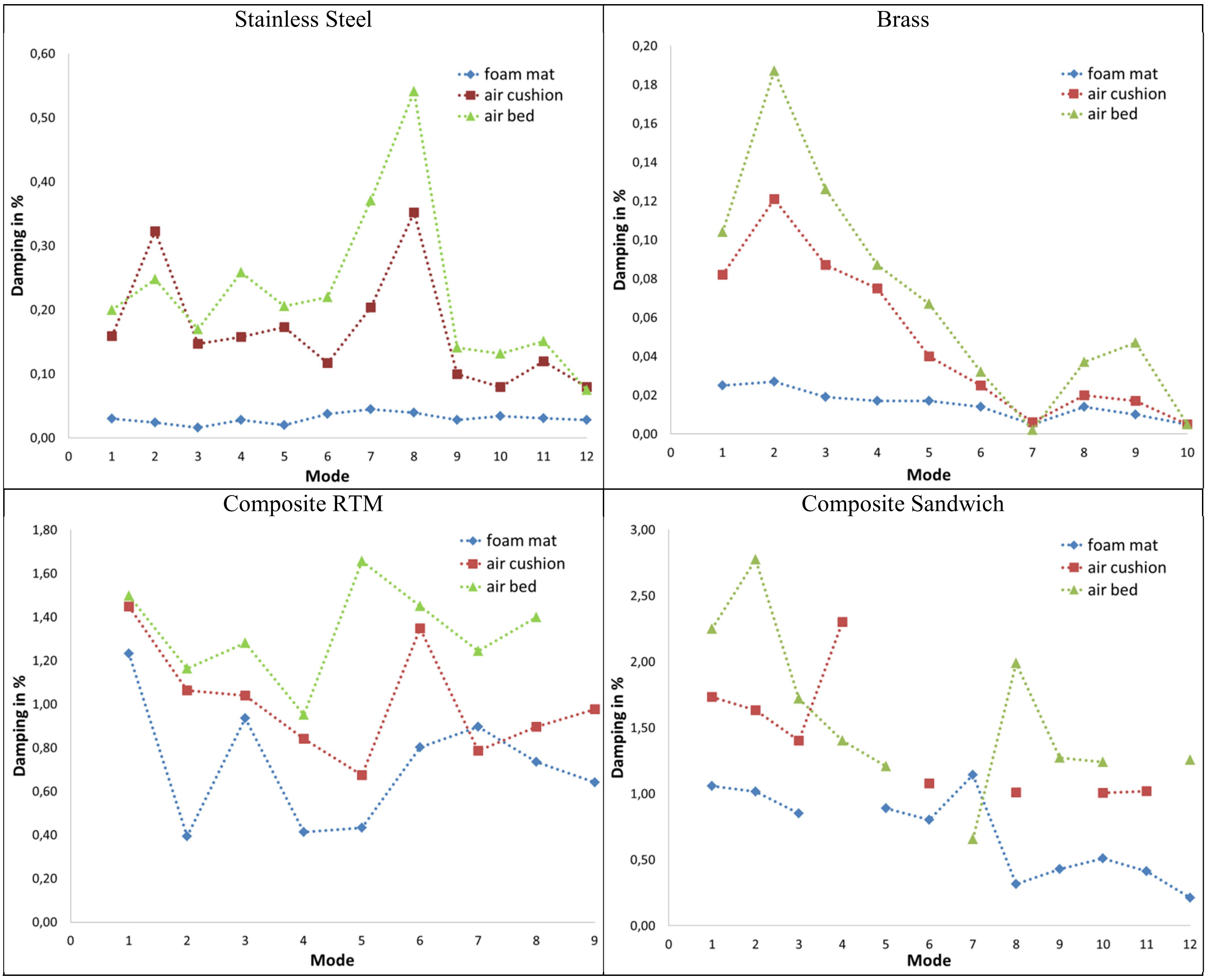


Fig. 4 Damping of metallic and composite specimens on three different suspensions

It can be generally observed from Fig. 4, that the damping ratios for the contact-less suspensions (air cushion and air bed) are higher than the damping on the foam mat. Usually, the damping obtained from the air bed is the highest followed by the air cushion and foam mat. The damping ratios show the different material behavior of metallic and composite specimen: damping ratios of metallic specimen lie between 0.05 – 0.5 % whereas damping ratios of composite plates are ten times higher and lie between 0.3 – 3 %.

Another observation is related to the general distribution of damping ratio over mode number: the differences of damping ratios between conventional and contact-free suspension methods are higher in metallic structures than in composite materials. Calculating the damping value differences between contact-free and conventional suspensions leads to the results shown in Table 2.

Table 2 Mean growth factor of damping ratio between contact-free and conventional suspensions

Specimen	Air cushion/foam mat	Air bed/foam mat
Steel	4.94	6.60
Brass	1.62	2.78
Composite RTM	0.54	1.10
Composite Sandwich	0.99	1.94

To evaluate the detectability of eigenfrequencies, the eigenfrequencies were related to the mean eigenfrequencies of the three suspension values per structure. Fig. 5 shows the percental variation of eigenfrequencies from the mean value.

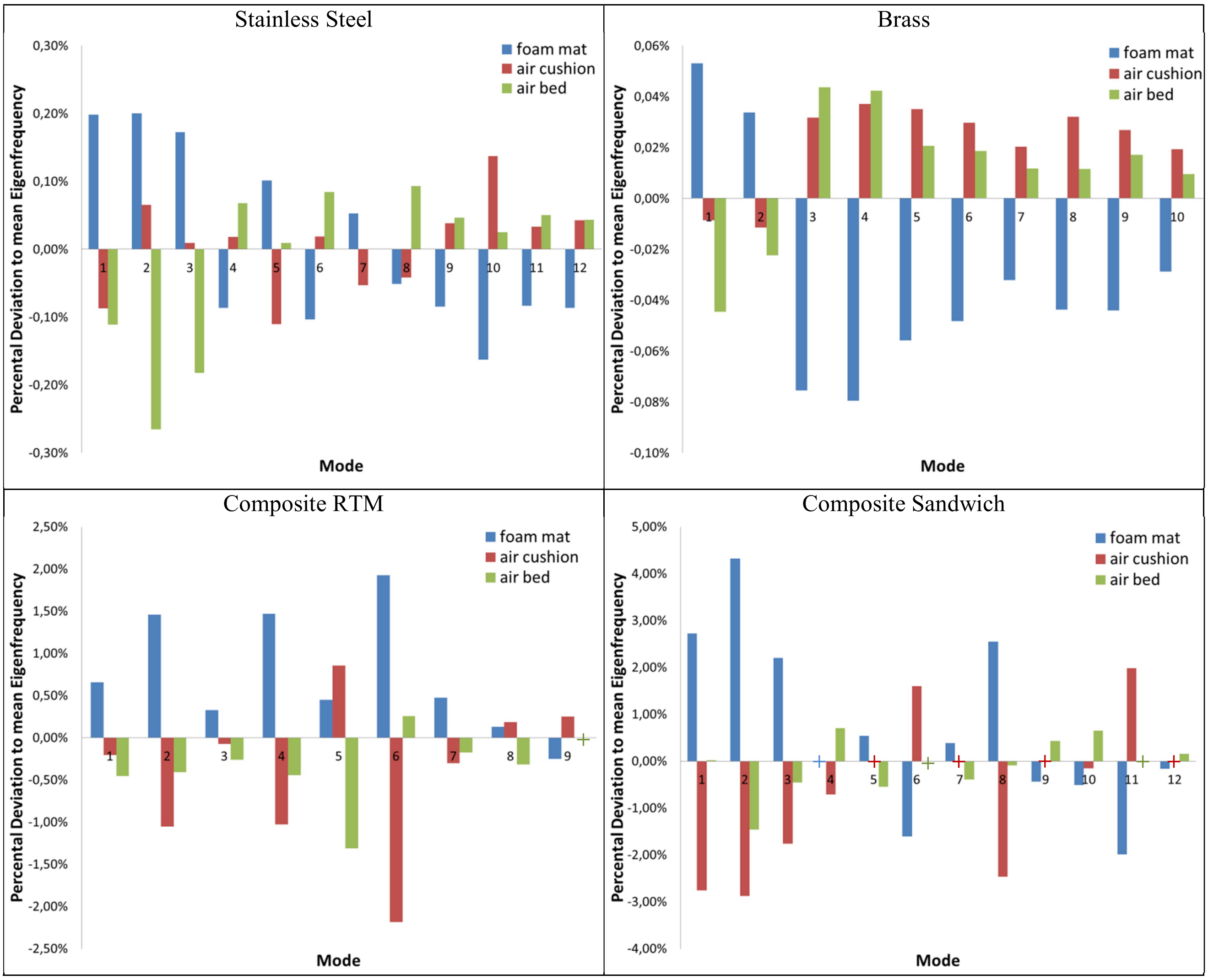


Fig. 5 Percental variation of eigenfrequencies related to the mean eigenfrequency of metallic and composite specimens on three different suspensions. Crosses mark where no mode/ no eigenfrequency could be detected

The detected eigenfrequencies of the metallic specimen have a variation below ±0,3%. This variation is up to 10 times higher for the composite plates and lies between ±3%.

Conclusion

In this study, the influence of contact-less suspension methods on the identification of eigenfrequency and modal damping using Experimental Modal Analysis was investigated.

The eigenfrequencies could be detected within a small variation range. Although the variation of detected eigenfrequencies is much higher for the composite plates than for the metallic plates (Fig. 5), the quantitative differences are low, Fig. 6.
The contact-less suspension methods leads to additional damping in the test system. The factor of damping ratio increase lies between 1.6 and 6.6 (Table 2) for the metallic specimens and between 0.54 and 1.94 (Table 2) for the composite specimens, which is substantially different.

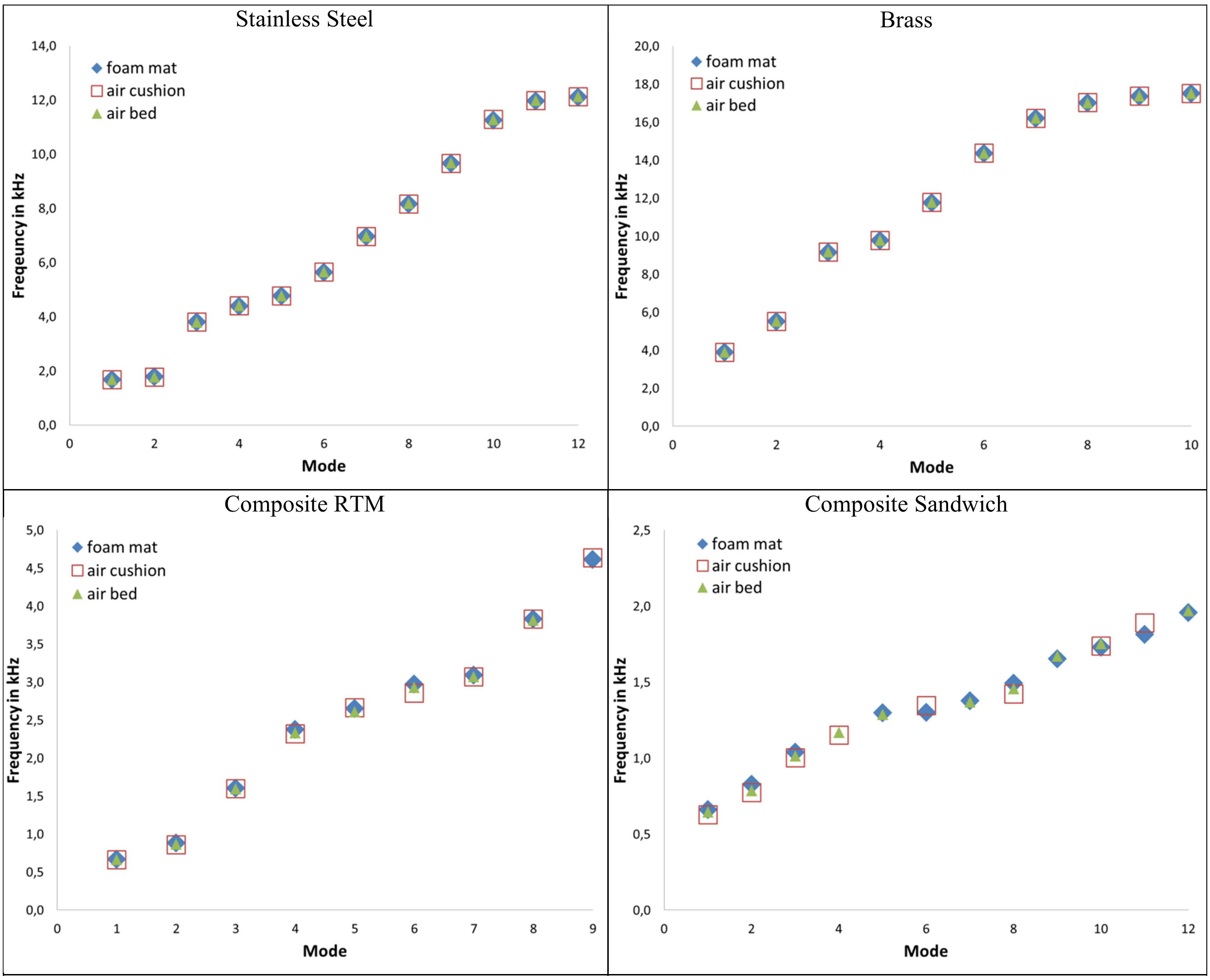


Fig. 6 Quantitative values of the detected eigenfrequencies on foam mat, air cushion and air bed.

The study results lead to the conclusion that Experimental Modal Analysis can be performed on specimens with a contact-less suspension. However, this approach seems not to be beneficial compared to the standard technique for metallic specimen with a certain weight. For light-weight material structures such as most composite materials, a standard EMA measurement often is not possible because the structure cannot be excited properly. Further research on this topic is currently being performed, [4]. For these special cases where an EMA measurement cannot be performed or where the results are not reliable, the contact-less suspension (levitation method) can be used.

Further investigations will be concentrated on the origin of the additional damping by the air flow and how to minimize this influence. In the future, a more detailed study should be performed including more/ different composite materials, the influence of specimen size and geometry and a comparison of modal parameters with numerical simulations.

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