Chapter 7
Parameter Investigation of Sensor Fixation Methods Compared with High-Quality Laser Measurement Using a Scalable Automatic Modal Hammer

Robin Pianowski, Robert Kamenzky, Stefan Wolter, Zeyun Song, and Peter Blaschke

Abstract The need to measure complex mechanical structures has grown in importance for efficiency in the design process and for structural monitoring. Despite the convenience of using a 3D scanning laser Doppler vibrometer (LDV), fixed acceleration sensors are still widely used for industrial applications. However, the effects of sensor attachments cannot be disregarded for lightweight structures. This paper provides a thorough description of how various sensor attachment techniques affect vibration measurements over a wide frequency range (up to 16 kHz). Frequency response function (FRF) measurements were conducted on an aluminum plate using both the LDV and an accelerometer simultaneously, excited by a scalable automatic modal hammer (SAM). For particular frequency ranges of interest, recommendations for fixation methods are proposed. Recommendations for fixation techniques are proposed for certain frequency ranges. The study's findings offer practical advice for industrial structure measurement evaluations.

An important outcome of this study is how the fixation method influences the experimental results of the modal properties. The research reveals that the fixation, the contact area, the sensor, and the test specimen built a dynamic system that influences the results especially at higher frequencies and should be considered for precise measurements.

Keywords Sensor fixation · Scalable automatic modal hammer · Modal damping · High-quality FRF

7.1 Introduction

Accelerometers are still widely used for vibration measurements and experimental modal analysis, although LDV enables contactless and fast measurements. It is common knowledge that the transducer and attached sensor will add mass to the system. This mass loading effect is even more significant for lightweight structures. Numerous attempts have been made to study and eliminate the mass loading effect [1–2]. In addition, the sensor mounting can contribute to additional relative motion and alter the stiffness and damping, affecting the structural dynamics and the accuracy of acceleration measurements. Marscher et al. [3] studied the FRF measurement fidelity for several fixation methods and found that all fixation methods exhibit good agreement up to 5 kHz, while the fidelity is related to the adhesive layer thickness at higher frequencies. Shokrollahi et al. [4] examined the response amplification and transmissibility for modal wax, magnetic, and screw fixation, which revealed that rigid bonding reproduces the input acceleration more accurately, especially at higher frequencies. Maierhofer et al. [5] compared the FRFs of an aluminum beam under various fixation conditions, finding that in the frequency range of interest (up to 2 kHz), there is no significant difference in FRFs between fixation methods in normal direction, whereas tangential vibrations are more sensitive. Colombo et al. [6] investigated the performance of different adhesive materials based on a set of weighted assessment criteria, delivering a helpful guideline for adhesive selection. This paper deals with the influence of sensor fixation methods on two-dimensional structures, whereas most of the previous research has focused on beam structures. Despite this, few studies have been conducted on sensor performance at even higher frequencies (above 5 kHz), where the vibration characteristic becomes increasingly relevant to sensor dynamic properties. In this work, frequencies up to 16 kHz are considered, providing precise insights into different frequency ranges.

R. Pianowski · R. Kamenzky · S. Wolter · Z. Song · P. Blaschke (✉)
Laboratory for Machine Dynamics and Acoustics, Technical University of Applied Science Wildau, Wildau, Germany
e-mail: pblaschke@th-wildau.de

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7.2 Materials and Methods

The experimental setup is shown in Fig. 7.1a. The specimen is a 210 × 150 × 5 mm aluminum plate weighting 418 g, which was suspended on acoustic foam to approximate free-free boundary condition. For repeatable measurements and constant contact points between the plate and foam, the specimen position was marked on the foam. A Polytec PSV-500-3D-H 3D scanning laser Doppler vibrometer (LDV) was utilized to take contactless vibration measurements. For an optimal incidence angle of 90°, the laser beams were redirected over a mirror onto the plate surface. A precise measurement is a crucial basis for further analysis. Therefore, a scalable automatic modal hammer (SAM) (NV-TECH-Design, Steinheim a.d. Murr, Germany), shown in Fig. 7.1b separately, was used to exert accurate, repeatable, and precisely adjustable force impacts on the specimen [7]. The SAM was instrumented with a light impact hammer (model 086E80 from PCB Piezotronics), enabling a non-mass loaded broadband excitation with constant force and location, eliminating the transducer's mass effect when using a shaker as well.

A detailed depiction of the test specimen is shown in Fig. 7.2a with the marked excitation point, which remains the same for all measurements. 20 × 20 mm from the bottom left corner is a 3.5 mm through hole to bolt a piezoelectric acceleration sensor. For a comprehensive evaluation of the specimen's deflection shapes, a modal test was conducted using the LDV in a roving sensor setup before the sensor was put in place. The specimen was scanned with a 15 × 15 mm grid of degree of freedom (DOF) points. A total number of 116 DOFs were measured with a measurement time of 4 s and a sampling rate 125 kHz. Impact force was 40 N, and for each frequency response function (FRF) of every DOF, the average of three measurements was calculated.

To make an investigation into the influence of sensor mounting method on vibration measurements, subsequent measurements were conducted with a different test range. A triaxial piezoelectric acceleration sensor (356B21 from PCB Piezotronics) with a mass of 4 g was fixed at the hole's center on the opposite side of the excitation. Figure 7.2b gives an illustrative schematic of the sensor alignment. To obtain single-point FRFs between the excitation point and sensor point,

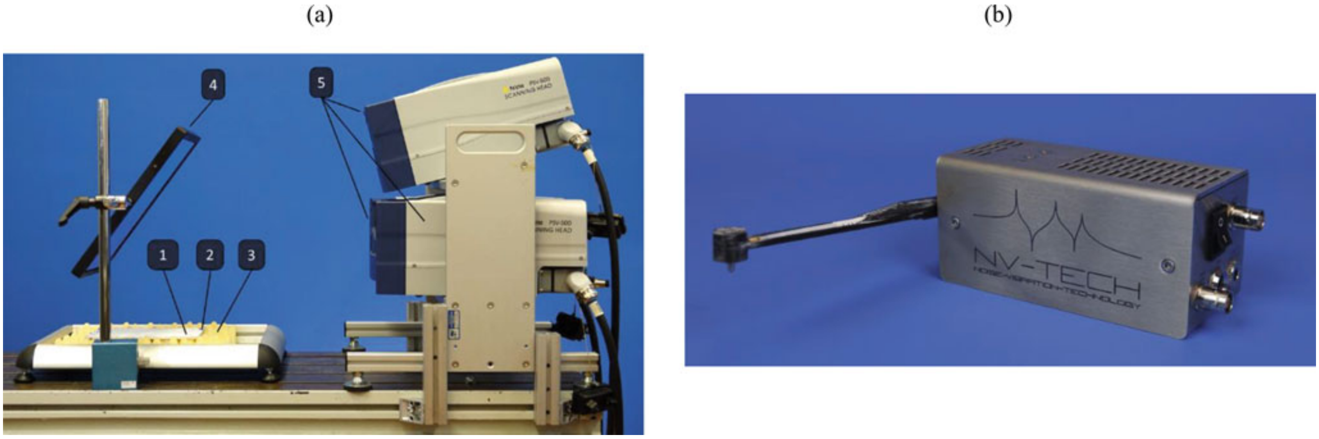

Fig. 7.1 Photographs of (**a**) the experimental setup: 1—aluminum plate, 2—accelerometer, 3—acoustic foam, 4—mirror, 5—LDV and (**b**) the scalable automatic modal hammer (SAM)

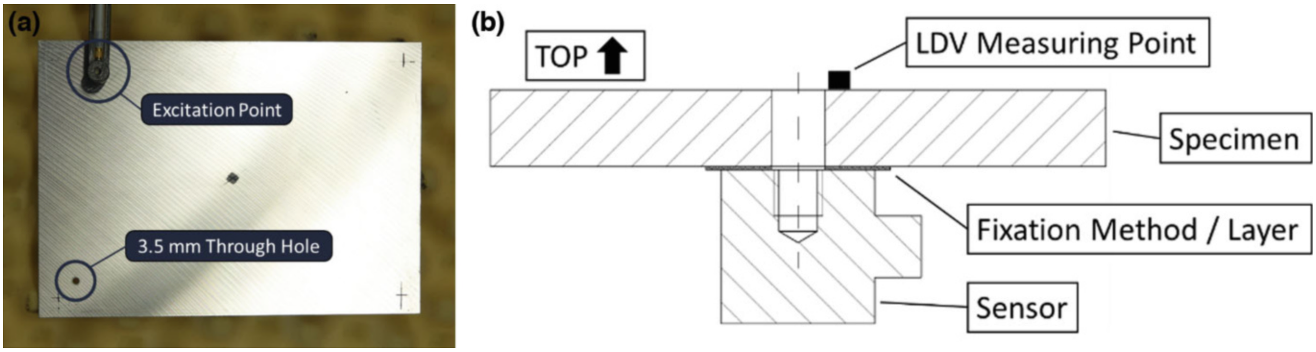

Fig. 7.2 A detailed view of (**a**) the tested specimen and (**b**) the sensor alignment

measurements were performed with the accelerometer with a measurement time of 4 s and 125 kHz sampling rate, averaged from ten measurements. Simultaneously, LDV measurements were conducted for comparison. Hence, it is desirable that the laser beam of the LDV is focused on the nearest possible location from the sensor on the upper side of the plate.

For the following measurements, different mounting methods for the sensor were tested:

1. Super glue: This investigation used cyanoacrylate-based Loctite 454, which enables rapid bonding and strong adhesive force [5] with only a thin layer of glue, leading to the assumption that it is highly rigid and only slightly dampens materials. However, removing the sensor and cleaning the surface can be challenging, as no damage should be done to the sensor or the specimen.
2. Modal wax: Modal wax is often used for sensor attachment because installing and removing the sensor are easy, and there is no hardening effect. Furthermore, the stiffness of the bonding contact is sensitive to the thickness of the wax and shows relatively high energy loss in viscous damping. At the same time, high damping is anticipated; a study by Colombo et al. [6] compared the use of superglue and modal wax, implying that FRFs measured with the waxed sensor showed notably reduced amplitude and accuracy. Therefore, a high damping is expected.
3. Ceramic glue: This study uses X60 adhesive, which uses a methacrylate mixture as the base material. The lowest possible usable temperature is −200 °C. Compared to cyanoacrylate-based glue, X60 adhesive provides stiffer bonding [6] better operational capabilities for rough surfaces [8]. It is assumed to have the lowest internal friction in the glue layer.
4. Hot glue: A hot glue gun was used to apply Bosch Glue Stick Set Ultra Power to the surface. Care has to be taken to achieve a thin adhesive layer between specimen and sensor. Due to its low bonding stiffness, it is assumed to have similar modal material properties to modal wax.
5. Screw fixation: A N 5–40 UNC B screw with a length of 11 mm was used to assemble the sensor. Consequently, a slightly higher additional mass and a shifted center of gravity of the attached sensor occur and a significant stiffening effect in the contact zone is assumed. In contrast to all other mounting methods, energy losses caused by relative motion between sensor and specimen occur because of contact friction instead of material damping. However, the requirements to drill a hole in the structure make this application less practical.

7.3 Experimental Results and Analysis

The vibrations of the sensor mounting point of the plate were measured by LDV with and without an attached accelerometer and then compared to the FRFs measured with an attached accelerometer to determine the difference between accelerometer and LDV measurements. Figure 7.3 illustrates the z-direction FRFs under three distinct fixation conditions: superglue (top), modal wax (middle), and ceramic glue (bottom). The FRFs measured by the LDV at the sensor position without the mounted sensor are plotted as blue-dashed curves. The solid red curves represent the FRFs measured by the LDV with the sensor attached to the plate. The solid blue curves show the FRFs directly measured by the installed accelerometer. The plots reveal that the mass affects all obtained eigenmodes of the plate, as a decrease at each natural frequency can be observed by the LDV and the accelerometer as well. The LDV tests and accelerometer tests produce similar FRFs in a frequency band of 300 Hz to 3.3 kHz and from 5.4 to 10 kHz. However, some deviations are evident in the mid-frequency range from 3.3 to 6 kHz. There the vibration amplitudes become smaller, and the LDV tests exhibit a smaller signal-to-noise ratio (SNR). So specific modes are no longer identifiable by the LDV. This is observable for all three fixation cases. Compared to the FRFs measured by the LDV, accelerometer tests produce signals with a better SNR, revealing more information about the eigenmodes where the sensor is located at a nodal point and specific anti-resonances. Therefore, accelerometer data are utilized for analysis in the scope of this work.

In the remainder of this section, two alternative fixation methods are considered, i.e., hot glue and screw. The FRFs at the location of the installed accelerometer are evaluated step by step in several frequency ranges marked by gray bands, as shown in Figs. 7.4, 7.5, 7.6, and 7.7. The blue-dashed curves represent data collected before sensor installation as reference signals; super glue, ceramic glue, and screw mounting are represented by red, black, and green solid curves, respectively. The modal wax and hot glue fixation are represented by red-dashed and black-dashed curves, which indicate less rigid connections.

Figure 7.4a demonstrates that measurements for all five fixation methods agree well at low frequencies, with the additional mass having the only discernible effect on the dynamic properties of the structure. From 1000 Hz, the attachment method's effect is observed, with all measurements exhibiting different damping and amplitudes.

As depicted in Fig. 7.4b, the ceramic glue fixation has the highest peak value at the resonance frequency of 1503 Hz, while the resonance peaks for super glue, hot glue, and screw fixation drop slightly to the same level. The vibration with modal waxed sensor is less dampened but exhibits the largest eigenfrequency shifting, which deviates from our expectation.

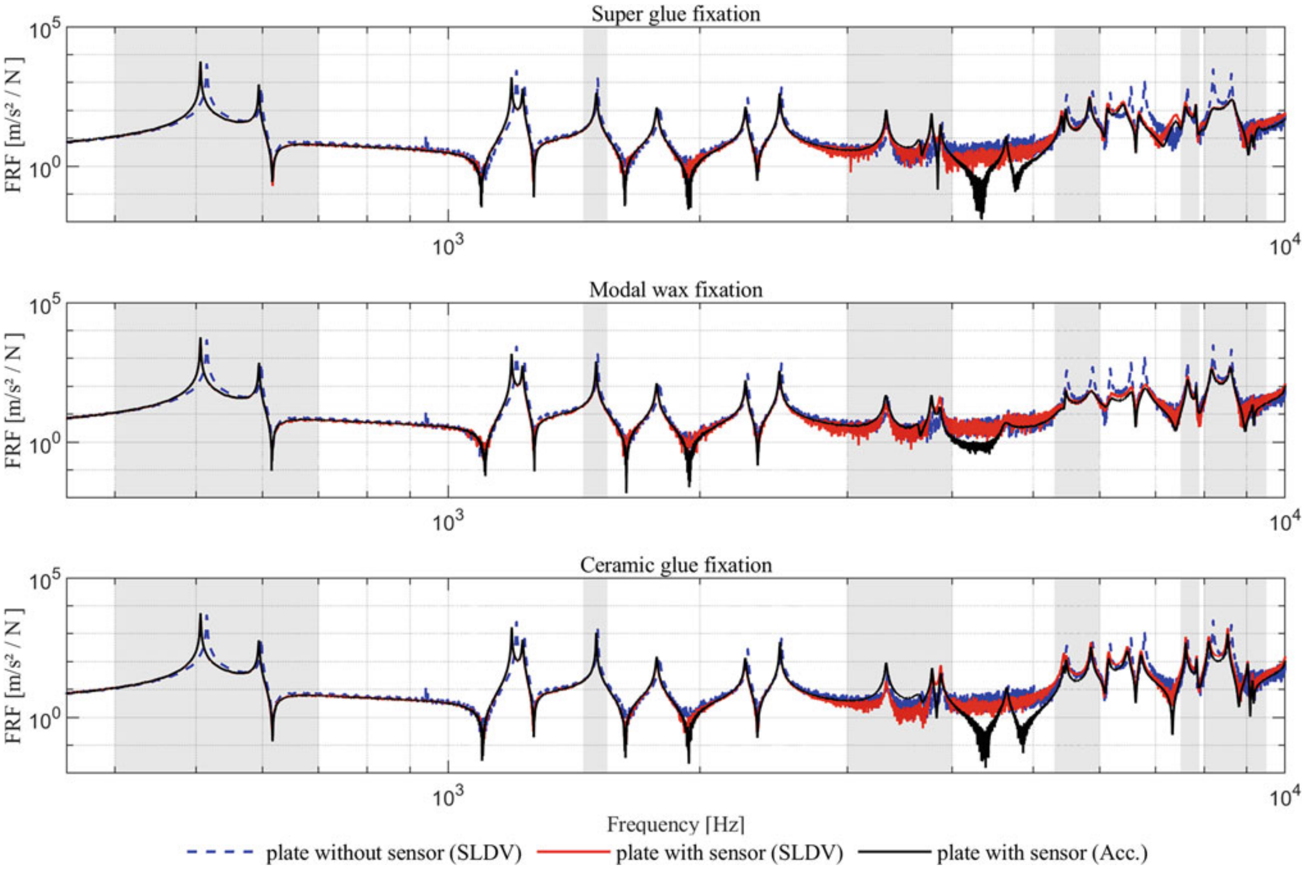

Fig. 7.3 FRFs at the sensor position using LDV and accelerometer measurements; sensor adhered with superglue (top), modal wax (middle), and ceramic glue (bottom)

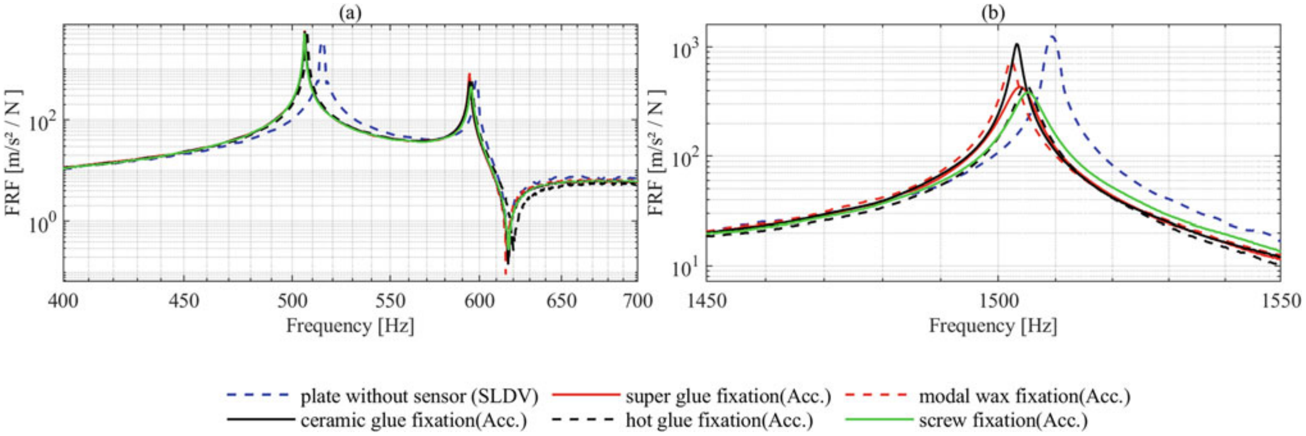

Fig. 7.4 FRFs at the sensor position; left: 400–700 Hz, right: 1450–1550 Hz

Furthermore, the similarity of the LDV and accelerometer FRFs implies a detuning of the dynamic behavior of the specimen caused by the sensor coupling in the whole examined frequency range. The sensor signal is still accurate, but the measured specimen interacts with the sensor and changes its modal parameters.

Figure 7.5a illustrates the FRFs between 3000 and 4000 Hz, where the superglue and ceramic glue exhibit many similarities. The screw fixation reduces the mass-induced natural frequency shifting compared to the other fixations. Using a screw-mounted accelerometer makes it easier to identify the eigenmode at 3600 Hz while leaving a significantly smaller peak amplitude at 3880 Hz. As shown in Fig. 7.5b, modal wax and hot glue behavior are comparable between 5300 and 5600 Hz with the lowest peak amplitude. In contrast, eigenmodes separate into two modes for super glue, ceramic glue, and

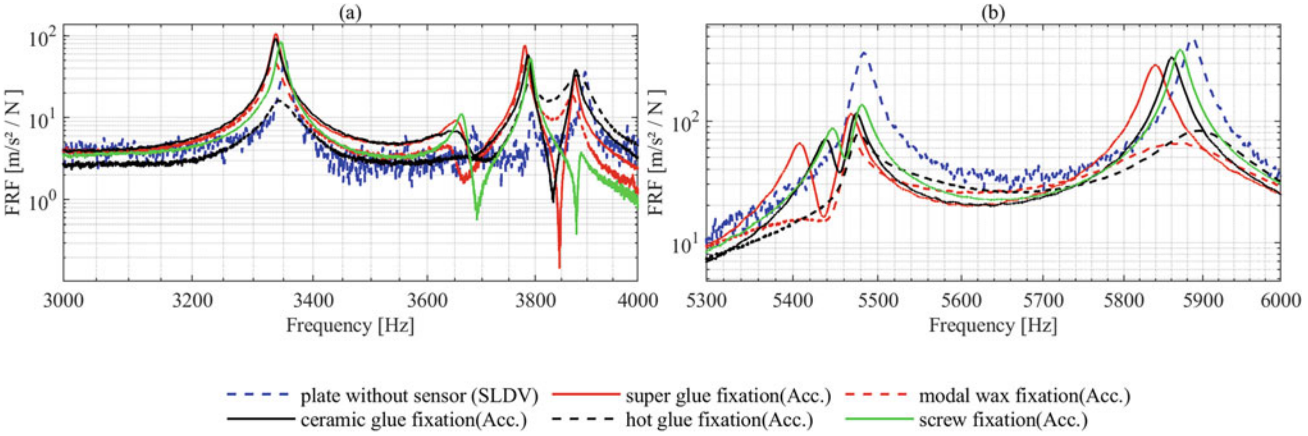

Fig. 7.5 FRFs at the sensor position; left: 3000–4000 Hz, right: 5300–6000 Hz

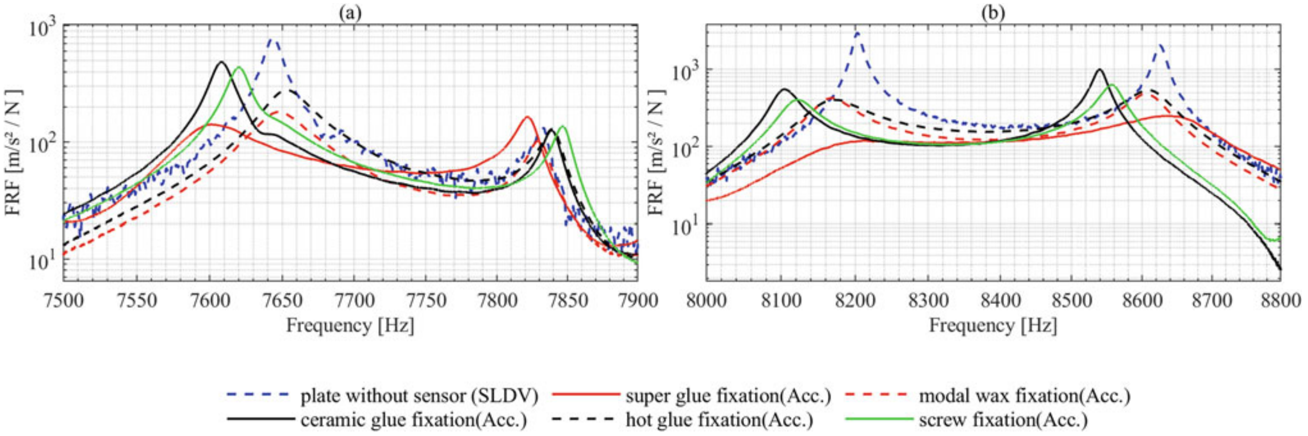

Fig. 7.6 FRFs at the sensor position; left: 7500–7900 Hz, right: 8000–8800 Hz

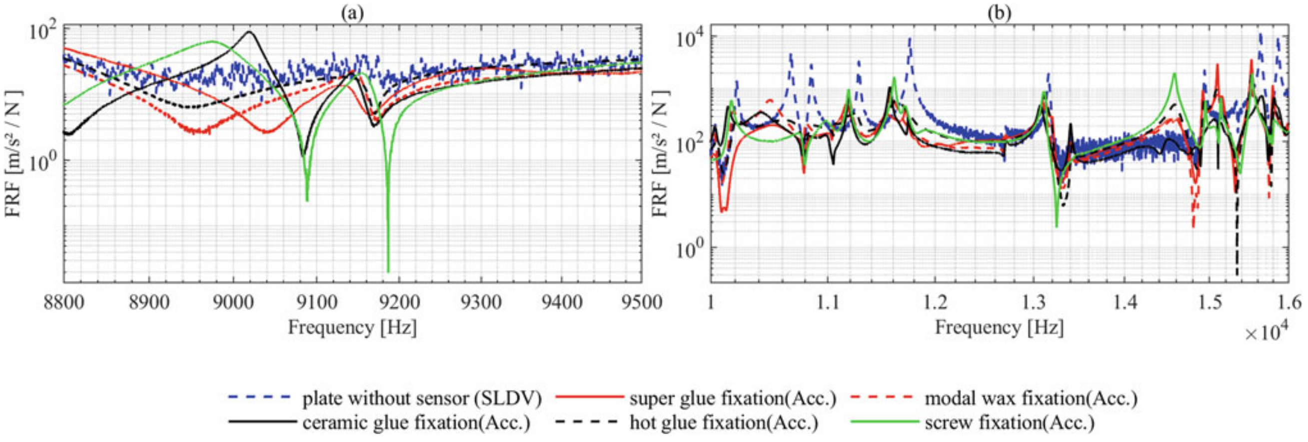

Fig. 7.7 FRFs at the sensor position; left: 8.8–9.5 kHz, right: 10–16 kHz

screw fixations. From 5800 to 6000 Hz, the less rigid adhesives (modal wax and hot glue) almost attenuated one eigenmode entirely. In addition, the eigenfrequency deviation from the reference FRF increases sequentially with the damping of screw mounting, ceramic glue, and super glue. The same performance is observed up to 6200 Hz. Moreover, if we examine the frequency range between 3000 and 6000 Hz, we can conclude that the two “less rigid” connections have greater damping than the others and that the natural frequency shifting with screw fixation is always less.

Over 7500 Hz, superglue degrades to the same level as modal wax, and the damping ratio is significantly higher, as shown in Fig. 7.6a. However, natural frequencies rise when the sensor is mounted using modal wax and hot glue. At approximately 7600 Hz, the damping of the superglue increases significantly.

As shown in Fig. 7.6b, between 8000 and 8800 Hz, superglue fixation ultimately dampens modes; peaks for ceramic glue and screw fixation are significantly lower; modal wax and hot glue provide higher damping than ceramic glue and screw, while the eigenfrequency shifting is less. In addition, the less rigid adhesives continue to exhibit similar behavior.

Figure 7.7a displays the frequency band from 8.8 to 9.5 kHz. The attached sensor detects an eigenmode at 9145 Hz that is absent from the reference FRF (blue curve) measured by LDV. As shown in Fig. 7.7b, from 10 kHz, ceramic glue fixation results in significantly higher damping and lower resonance peak than screw mounting. Specific peaks cannot be detected even with a screw-mounted accelerometer. It is remarkable that there is a significant amplitude increase in the resonance peaks for superglue compared to all other fixation types between 15 and 16 kHz. Above 16 kHz, the curves can no longer be aligned.

7.4 Conclusion and Outlook

This study examined how different sensor fixation techniques affected the FRF readings of a lightweight structure. Accelerometer and LDV measurements are utilized for comparison.

Because of mass addition, frequency shifting occurs for all eigenmodes. There is no outlier among the FRFs at low frequencies (up to 1 kHz). Compared to the two “less rigid” fixation methods that are assumed to exhibit similar behavior, modal wax causes lower damping at frequencies below 3800 Hz. This effect is resulted from metallic contact as the wax settles in the furrows and hot glue is hardening on the top of the asperities. The damping could result from the sensor and plate’s relative motion, and it can be assumed that fixation-induced damping increases as acceleration increases. From 5 kHz, mode separations are observed for “rigid” bonding (super glue, ceramic glue, and screw mounting), indicating that the mass is dominating at certain frequencies; due to the high damping, modal wax and hot glue become less sensitive to eigenmodes. Although superglue is effective up to 7 kHz, the error frequencies of the eigenmodes are higher compared to those of ceramic glue and screw mounting. The highest modal damping effects can be observed at frequencies between 8 and 15 kHz; above 15 kHz, the damping effect reduces. Ceramic glue and screw fixation have superior performance up to 10 kHz. Although screw fixation improves the accuracy of natural frequencies, the influence of varying pre-stress and screw mass remains problematic. Over 15 kHz, the resonance of the sensor mass becomes more dominating.

While the accelerometer is suitable for capturing local vibrations, the LDV is more suitable for obtaining mode shapes. As mentioned, vibration amplitudes decrease between 3.3 and 6 kHz. By analyzing the mode shapes, we found out that the sensor is located near a nodal point for these modes. The additional eigenmode at 8.8 kHz (see Fig. 7.7a) is identified to be an in-plane mode for the sensor-free plate, implying that the sensor attachment includes a z-component to the in-plane modes.

To summarize, the high sensitivity of acceleration sensors in measuring resonances and anti-resonances mainly benefits from the good SNR. However, the accelerometer’s installation and the adhesive’s application modify the local and global vibroacoustic behavior of the specimen. Up to 5 kHz, all of the investigated sensor fixation techniques detect eigenmodes with sufficient accuracy. At higher frequencies, the modes become more locally dominant, and due to the added mass and the fixation, the shifting of natural frequencies becomes more significant. Adhesives with high material damping like modal wax and hot glue result in significant increase in modal damping even for low frequencies. Due to ease of disassembly, modal wax can be recommended for a frequency range of interest below 1 kHz. Ceramic glue is recommended as a nondestructive alternative for screw fixation in vibration testing up to 10 kHz. In the case of exceptionally high frequencies, superglue is an alternative. For specific experimental tests aiming to identify modal damping, ceramic glue the most appropriate adhesive.

Another important outcome of the research is that besides the pure mass effect of the acceleration sensor, the fixation methods and the contact area (surface roughness) itself can detune the observed modal properties of the test specimen. This outcome is as well valid for attachment of a shaker.

In future research, influences of the mounting methods on in-plane accelerations and the effect of changing the thickness of the adhesive layer can be investigated, and the sensitivity of mass loading can be taken into account. Once the interactions of the connected sensor and the structure to be measured are fully understood, algorithms to compensate the fixation-induced effects might be developed.

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