Chapter 9

Thoughts on Automatic Impulse Hammer Parameters and Sensor Fixation Methods

Johannes Maierhofer, Max Gille, and Daniel J. Rixen

Abstract The majority of data acquisition in experimental structure dynamics are conducted using impulse excitation and acceleration sensors. As the shape of the impulse in time domain is the crucial basis for the frequency content calculated from the impulse, mechanical parameters of the automatic modal impulse hammer (AMimpact) are discussed that have an influence on the impulse function. Using minimal models, the individual effects of the parameters are theoretically discussed and shown in experiments. Mounting the sensors to the structure is a critical step towards achieving good measurement quality. This investigation presents an overview and compares several, feasible methods for fixing acceleration sensors to metal (aluminum) structures. The methods are discussed regarding their effort, their positional precision, and their repeatability. The various methods are discussed in terms of their positional precision and their repeatability. The experiments are conducted and analyzed on an academic aluminum test structure and the automatic modal hammer (AMimpact). One difficulty is the lack of any ground truth, for which reason two sensors are stacked together to compare frequency response functions. These FRFs are obtained in two directions to enable the sensor fixation to be loaded in normal and tangential direction. The conclusion of the paper states that the fixing methods used for acceleration sensors are not critical in the normal direction but can have a non-negligible influence on measurements in the tangential direction. This effect should therefore be considered at an early stage of a measurement campaign.

Keywords Sensor fixation · Testing equipment · Automatic modal hammer · AMimpact · High-quality FRF

9.1 Introduction

Devising the instrumentation of test rigs is an art in itself. It is necessary to discriminate between the actuation of structures on the one hand and sensing outputs on the other. In experimental structural dynamics, impact hammers and acceleration sensors are employed in the vast majority of tasks, such as experimental modal analysis (EMA), determining frequency response functions (FRFs) for substructuring techniques, as well as for measuring operational signals for operational modal analysis (OMA) or monitoring purposes. The first topic in this paper is devoted to the influences of various mechanical parameters of the automated impulse hammer AMimpact, which is used to excite the structure. The following parameters are examined:

The first topic in this paper is devoted to the influences of various mechanical parameters of the automated impulse hammer *AMimpact*, which is used to excite the structure. The following parameters are examined:

- Tip material
- Mass of the hammer
- Spring strength (stiffness and preload)

A lot of effort is put into selecting the right sensors and placing them at the best possible position for gaining the best results for the measurement task. However, mounting a sensor is a critical step. In structural dynamics, acceleration sensors must be mounted to the surface of a structure. This surface can be of various shapes and have different properties stemming from its material, surface treatment, or lacquer. Depending on the operator's abilities and the possibilities available in the workshop, a number of sensor fixation methods may be feasible for mounting the sensor on the surface.

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The second part of this chapter investigates different mounting techniques and their influence on the resulting measurements:

- Petro Wax
- Cyanoacrylate (Super Glue)
- Hot Glue
- Double-sided tape

9.2 Automated Impulse Hammer Parameters

9.2.1 System Description

To obtain a repeatable, good quality impact, the automated impulse hammer *AMimpact* (developed at the Chair of Applied Mechanics, [1]) was used. Further reflections on the subject of impulse hammering can be found in [2].

The system consists of a linear sliding bolt, which is attracted by a reluctance electromagnet. The bolt is retracted back to its rest position by a spring. A force sensor (PCB Model 086E80) is glued to the tip of the bolt to measure the impact force. The system is packed into a compact device (Fig. 9.1a) controlled via a USB interface or a WiFi connection in conjunction with a web app running on a smartphone. The device is positioned with a magnetic stand (Fig. 9.1b). The actuator is only active up to the point where the force sensor tip approaches the structure. The actuator is then deactivated, so the impact is purely ballistic (free-flight phase) without the driving force of the magnetic actuator. This ensures a single impact (for the majority of target structures; for exceptions, see [2]).

The shape of the force impulse in the time domain can be influenced by various parameters. The two most important once are the impact velocity and the material pairing between force sensor tip and target. A higher impact velocity (corresponding to a higher kinetic energy of the bolt) results in a higher peak force. The stiffer the material pairing, the shorter (and in result also higher) is the peak. In Fig. 9.2, two series of impacts are shown that differ in the material of the force tip, namely steel (red) and vinyl (gray). Within one series (the same material pairing), different levels of force amplitude are excited. The force amplitude is adjusted by varying the time for which the acceleration force F_{actuator} is applied to the bolt. With increasing time, the force amplitude increases. The difference between two curves is a constant 1 ms increase of actuation time.

The problem is that there are situations in which an appropriate choice of parameters cannot be made that will achieve the desired frequency range. In particular, the material pairing is often fixed, as the target material cannot be changed without affecting the system dynamics. This is an important issue, for example, in systems made from plastics or even wood. That low stiffness of these target materials means that the force peak softens considerably and the frequency range drops rapidly (cf. Fig. 9.3).

For the AMimpact, there are two parameters left, which can be tuned to modulate the impulse shape within a certain range and which can therefore overcome certain difficult excitation situations. First, the influence of the bolt mass can be

(a) (b)

Fig. 9.1 Tools for automated impulse excitation. (**a**) The Automated Impulse Hammer, *AMimpact*. (**b**) Magnetic stand to orientate and fix the *AMimpact* [3]

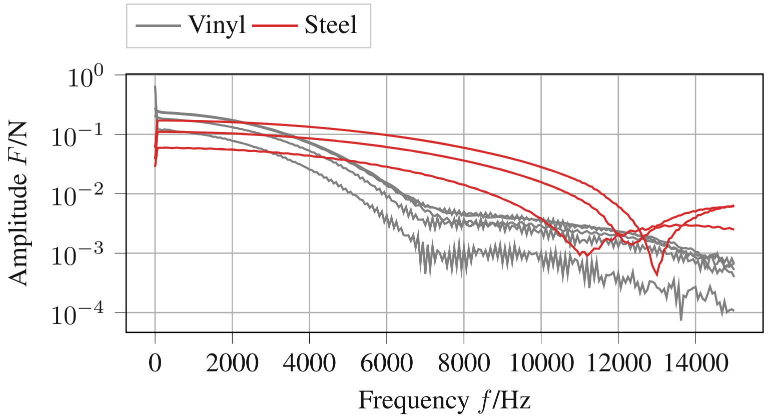


Fig. 9.2 Influence of different material pairs

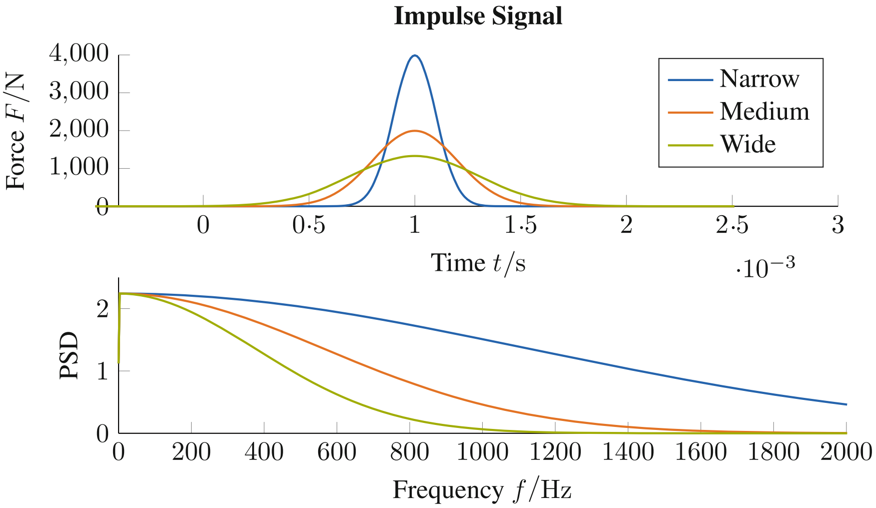
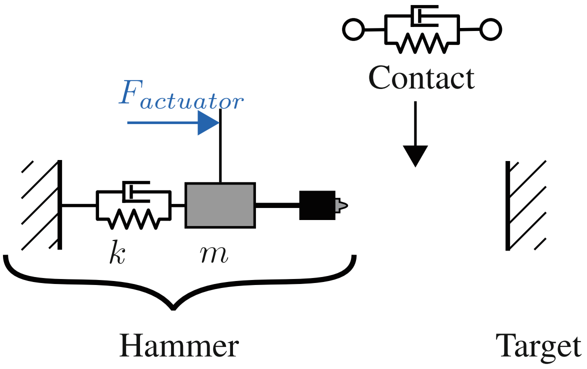


Fig. 9.3 Different impulse shapes show the frequency content of the excitation

Fig. 9.4 Minimal model of the *AMimpact* system against a rigid target



varied, followed by the spring strength. A simple explanatory model is shown in Fig. 9.4. The actuator force F_{actuator} is not influenced by the variation of the mass m or the stiffness k. The losses due to friction of the mechanism are embedded in the unknown (and not further investigated) damping. The sequence of the hammer being in contact is modeled with an additional spring/damper element due to the Hertzian contact theory, see [1].

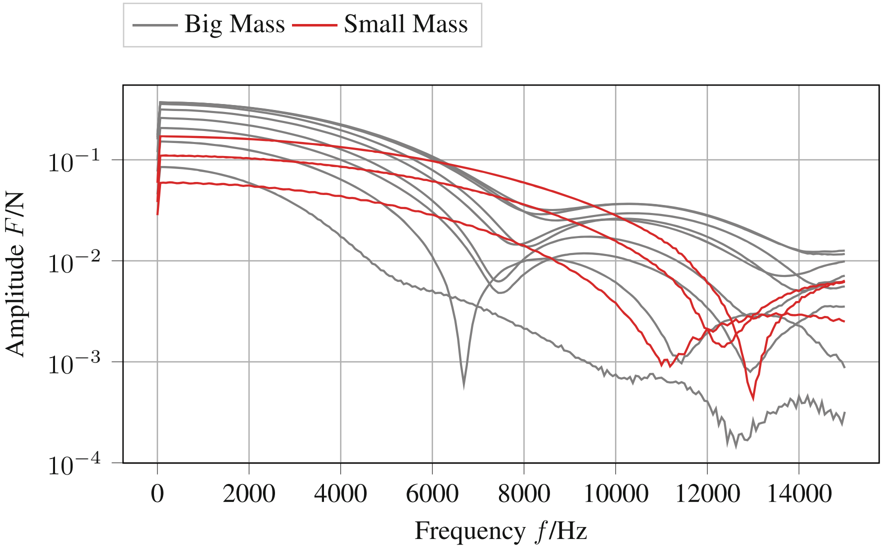


Fig. 9.5 Influence of a mass increase of factor 2.5

9.2.2 Influence of the Bolt Mass

Increasing the movable mass m in turn causes the inertia to increase. This leads to a longer contact phase which means a wider force peak that results in a lower cutoff frequency. On the other hand, a greater mass allows much better control of the impact energy. As the actuator is regulated with a bang-bang limit controller, a small timing error is less significant. Additionally, the distance of the free flight phase is less critical, as the effects of friction play a smaller role.

Figure 9.5 shows two series of impacts with different energy levels. The two series differ in the mass m of the movable hammer. The red series has no additional mass, so the conclusion is as previously discussed in theory that the lighter the hammer, the wider the excitable frequency spectrum. But it can also be seen that the steps of the force levels in the series are bigger (the actuation time still increases by 1 ms per graph) than in the heavier system (depicted in gray). The two mass configurations differ by a factor of about 2.5.

Intermediate conclusion: For the lab worker, a higher mass is always preferable. After checking material parings with different force sensor tip materials, the mass of the bolt can be lowered to achieve a higher excitation frequency range, if required.

9.2.3 Influence of the Spring Stiffness

In this section, a medium mass is attached to the bolt to fix this parameter. Changing the spring strength is effected in one of two subparameters: Either by changing the prestress of the spring and maintaining the spring stiffness, or changing the spring stiffness itself. Theoretically, a stronger pull-back force will result in a shorter contact phase, leading to a wider frequency spectrum. Both of these subparameters can only be varied within rather narrow limits to maintain the device in an operable state. The effect is shown in Fig. 9.6, in which the spring has been completely detached for the second series (red). The plunger is pulled back manually before each new impact, but the experiment shows only minimal changes in the frequency behavior. The effect of the spring is therefore more important for the handling and robustness of the device's operation.

Intermediate conclusion: The effect of spring stiffness on the excitation frequency range is negligible. The spring should be adjusted such that a secure retraction of the bolt is ensured and the magnet has sufficient force to enable controlled acceleration of the plunger.

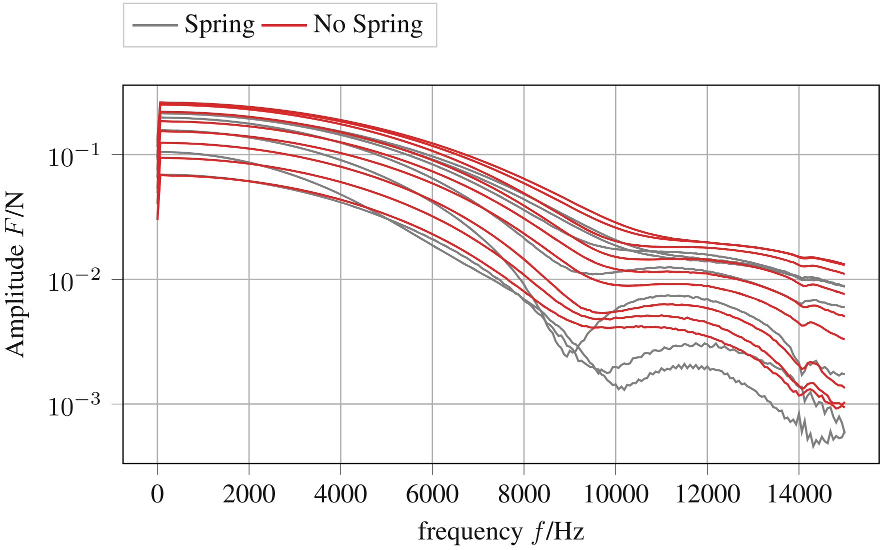


Fig. 9.6 Difference in the force spectrum with the both extrema: spring and no spring

9.3 Sensor Fixation Parameters

The counterpart of structure actuation is motion sensing. The use of familiar acceleration sensors raises the question of how to mount these sensors to the structure.

9.3.1 Technical Properties of Fixation Methods

This section discusses the mechanical and application properties of the various fixation methods. A little chemical background is provided for the different adhesives to enable the reader to gain a feeling for their correct use. The order is already in a way that represents the feasibility of the fixation method.

Wax The most traditional way of mounting acceleration sensors to a structure is to use wax. Originally beeswax was used and indeed it sometimes still is today. One drawback is that the cohesive forces are very small, so that the sensor can be moved out of position with very little force from the outside. On the other hand, removing the sensor is not a problem, as the wax retains its kneadable consistency. The sensor and structure can be cleaned with turpentine. In most cases, no damage to any surface is to be expected. PCB Petro Wax is used throughout this investigation.

Cyanoacrylate Once the polymerization process has started by way of hydroxide ions present in the moisture of the air, initial solidity is attained in a few seconds and full strength within a range of few hours. Cyanoacrylate glues are also available in high viscous gel formulations. This makes them easy to apply in non-horizontal positions. Also, small gaps up to 0.1 mm can be evened out. The high adhesive forces for surfaces with high surface energy (such as metals and duroplasts) produce a stable sensor attachment but are problematic when it comes to dismantling. This has to be done carefully so as not to damage the sensor or the object being measured. To clean the sensor, acetone can be used as it dissolves the glue. The product used in this investigation is LOCTITE 408.

Hot Glue Classic hot glue is an ethylene-vinyl acetate copolymer. A problem occurs when trying to use it to glue metal parts: Due to the high thermal conductivity of, in particular, aluminum, the heat is extracted from the glue so quickly, that the glue hardens before it can bind to the surface. The result is that there is little or no adhesion. Moreover, it is not suitable for plastics like PE, PP, and PTFE. The application itself is very simple and the joint can be subjected to use after a maximum of 2 min. Here, Pattex Hotmelt Sticks are used.

Double-Sided Tape Two acrylic bonding sheets envelop a thin foil of 10–100 μm. A drawback of this fixation method becomes apparent when the surface is not flat. Due to the thin foil carrier, the tape is not able to even out any geometric curvatures. The sensor would have near-line contact, which is of course not acceptable. After pulling off the tape, the residues can be cleaned with acetone. The product used in this case is *Tesa*.

Magnetic Bond A neat way of mounting sensors which enables them to be easily repositioned and without effort to structures is to use magnetic adapters. However, there are two major issues. As only ferromagnetic structures are attracted by a magnet, neither aluminum nor plastic of any type can be instrumented. Also, the dimensions and weight of the magnets are not negligible. For these reasons, this method is not considered further during this work.

Direct Screw Mount Some sensors have a thread in the housing which enables the sensor to be screwed directly to the surface. The major drawback here is the fact that the surface has to be bored and an opposing thread must be created. This is not possible in most applications. It is therefore not considered here.

9.3.2 Experimental Setup

The test structure used in this work is a monolithic L-shaped aluminum beam welded to an aluminum base plate which is screwed to the ground. This structure was already used in [4] to perform various procedures to obtain FRFs to be used in the field of experimental substructuring. Two sensors are mounted to the structure in a vertical stack. The lower sensor is fixed to the structure with a thin layer of wax as this seems to be the common practice. The fixing layer between the two sensors is varied. The lower sensor 1 therefore always has the same position and orientation, while the fixing of the top sensor 2 may vary between a very thin wax layer (<0.1 mm), a thick wax layer (1 mm), double-sided tape, or an adhesive bond of hot glue and cyanoacrylate glue (Loctite 408).

Excitation is then performed in two directions using the AMimpact as shown in Fig. 9.7. This causes the fixation layer to be loaded in line with two different regimes: normal forces and tangential forces. The received frequency response functions (FRFs) are so called driving point FRFs, from which follows that each resonance necessarily has to be alternated by an antiresonance.

The measurements are made using a Siemens LMS device and processed to FRFs with the LMS software. Each measuring run consists of five averaged impacts by the AMimpact, using the inbuilt automatic timing function. The results are presented in two sections for the two directions (Fig. 9.8).

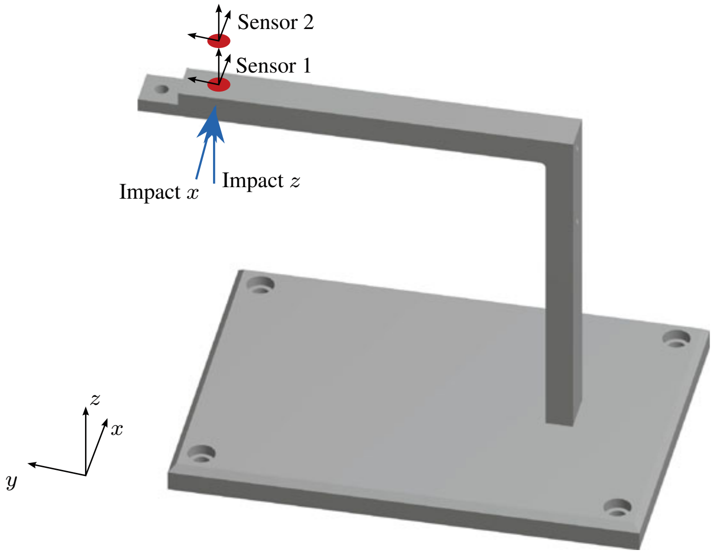


Fig. 9.7 Academic test structure with marked positions of sensors and impacts applied during the measurements

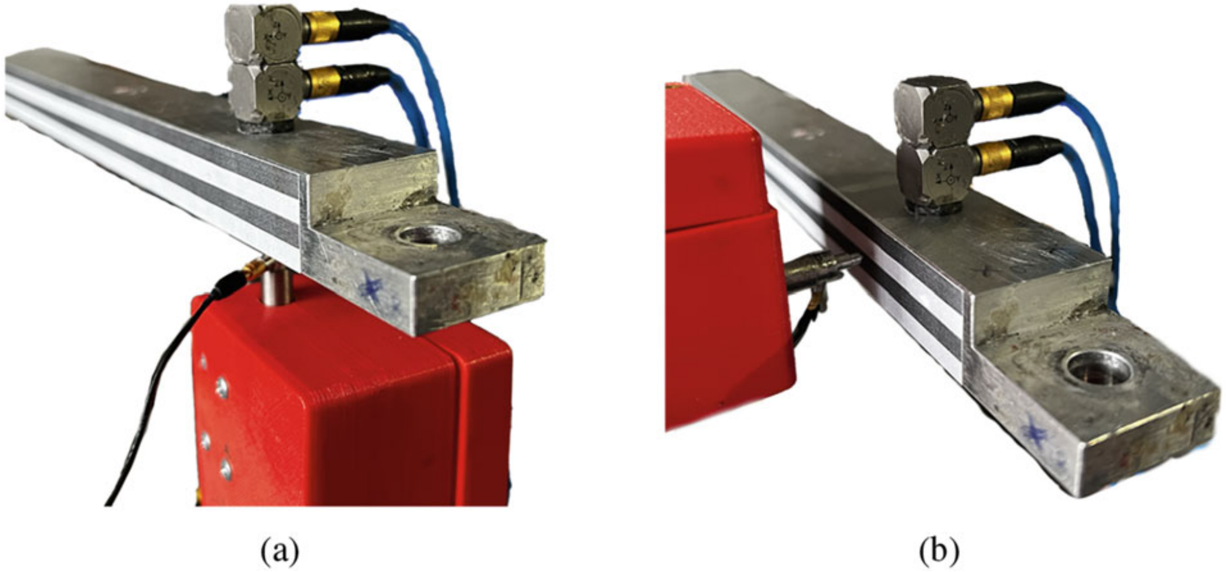


Fig. 9.8 Two sensor experimental setups. (**a**) z-direction. (**b**) x-direction

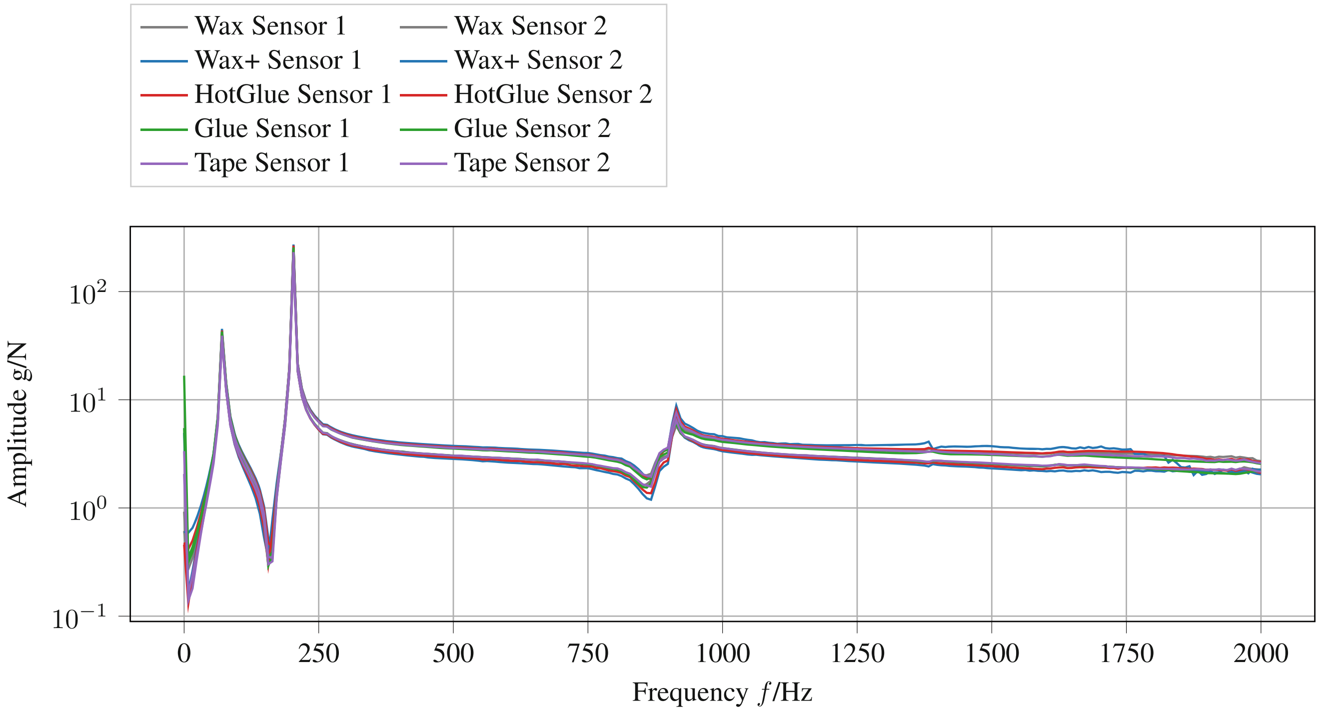


Fig. 9.9 Frequency response functions for both sensors and all fixations. No outliers are found

Normal Direction

In this setup, the fixing layers are loaded in the normal direction. Figure 9.9 shows all FRFs for both sensors and all fixation methods. No outliers are detected in the observed frequency range. The resonances are captured very well with all configurations. It can be seen that the second sensor deviates in the frequency range from 250 Hz onwards. The origin of this behavior is assumed to be in the different z-position of this sensor in relation to the reference sensor 1. Therefore, a different amplitude is expectable for modes that have a major rotational portion at the sensor's position. According to [4], the 5th mode is around 900 Hz. This mode's shape is in the plane of the L-shape and has a node very close to the point where the sensor stack is mounted. Consequently, this point undergoes a rotational motion. As sensor 1 is closer to the neutral line, the

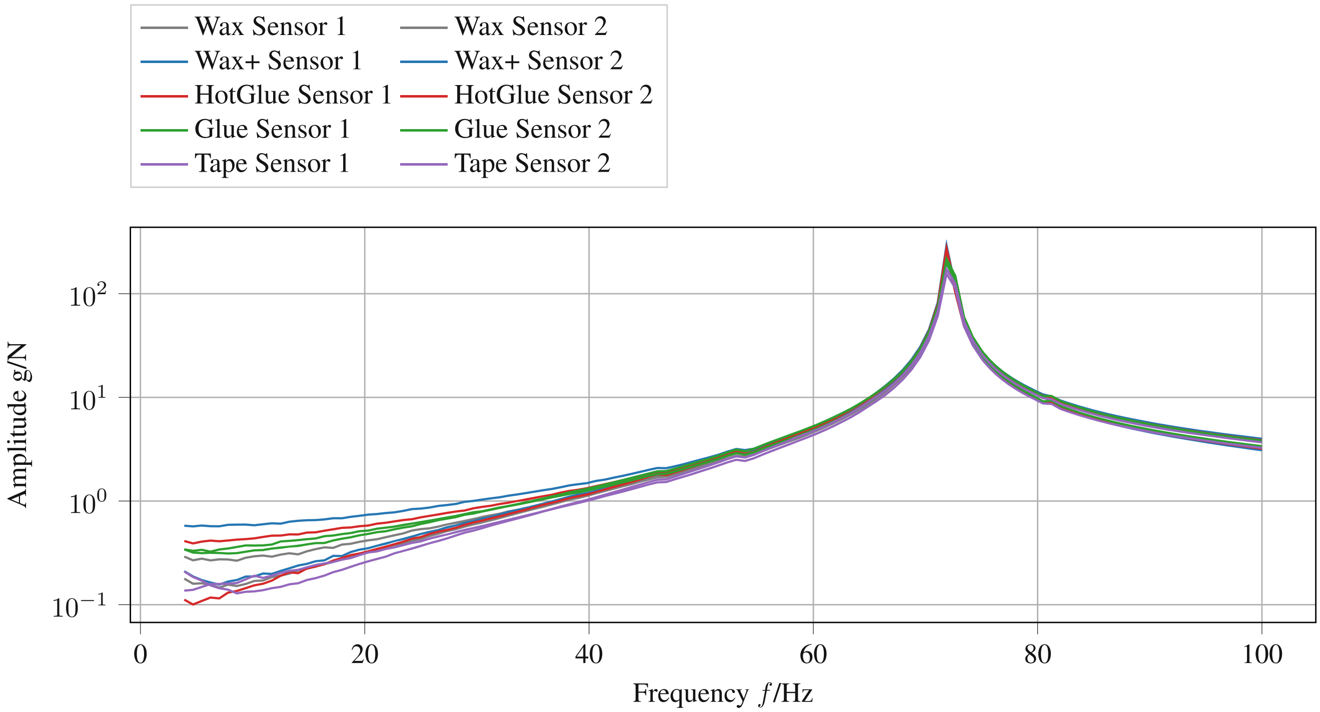


Fig. 9.10 Detail of the low frequency range. The softer the interface between the two sensor, the higher the amplitude for the low end of the frequency range

parasitic z motion is smaller than for sensor 2. Concluding, the offset of the two sensors is explained by a pure geometrical effect.

Differences can be observed in the first 50 Hz. This section has been zoomed out in Fig. 9.10, starting at 5 Hz to avoid confusion in the zone in which the sensor is not reliable. Any higher amplitudes from one fixing method always arise from sensor 2, i.e., the upper of the two sensors. It can be observed from the graph that fixation methods that have a rather thick and elastic nature seem to diverge in the very low-frequency range. This is especially the case with hot glue (red), thick wax (blue), and thin wax (gray). Thin and very stiff interface connections such as cyanoacrylate glue (green) and tape (purple) are very close together.

Intermediate conclusion: The thin wax, tape, and glue configurations show similar behavior for both sensors and are therefore to be preferred whenever possible.

Tangential Direction

The differences to the previous setup are that the fixing layer is now loaded tangentially. Figure 9.11 reveals several differences in the higher frequency range. As sensor 1 does not change its behavior, it is displayed gray, so the focus is on sensor 2, which displays a number of significant variations in frequencies above 500 Hz.

Again two fixation methods stand out: thick wax (blue) and hot glue show an amplitude magnification at various frequencies between 500 and 1250 Hz that does not seem to stem from the physical properties of the test structure. Close together are the methods: thin wax and cyanoacrylate glue. Tape is between the rigid and the soft interface connections. All in all, this tangential experiment is clearly more sensitive to the sensor-structure interface. Unfortunately, it was not possible to explain the effects for the higher frequency range above 1500 Hz. This will require deeper investigation.

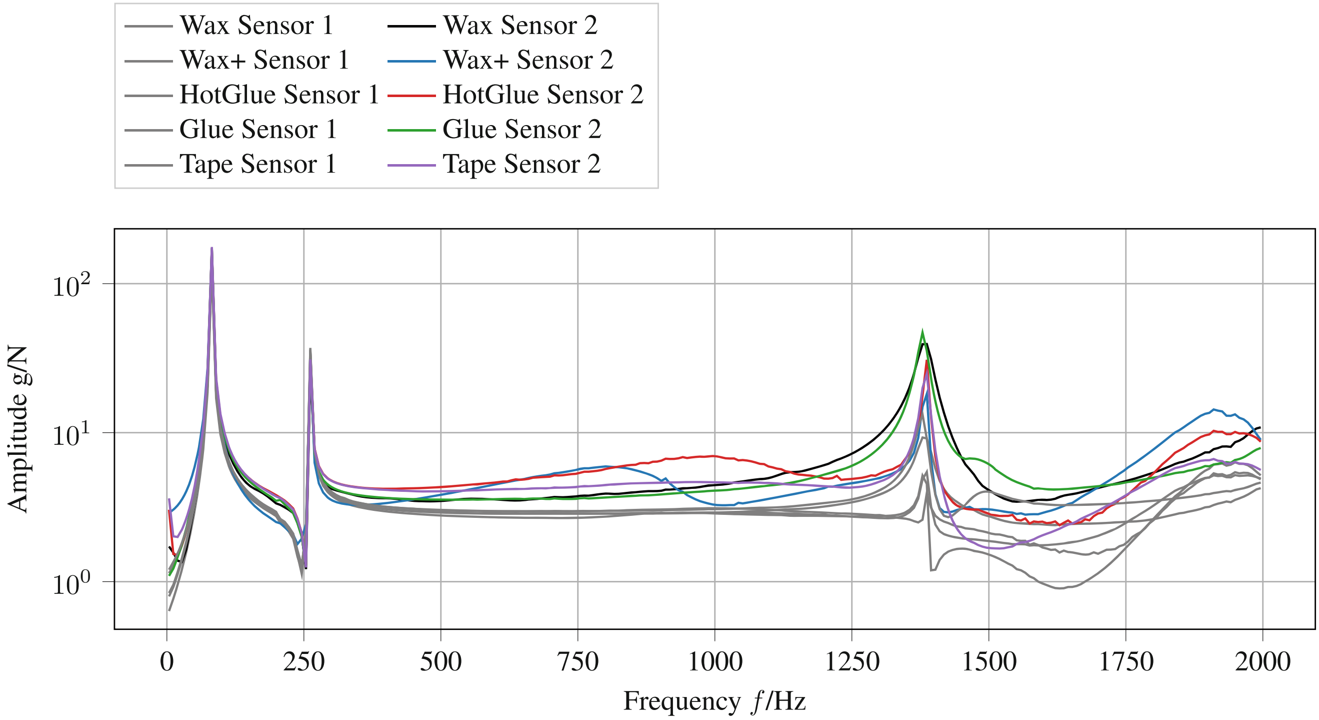


Fig. 9.11 All fixation method FRFs in x-direction

9.4 Summary

They depend very much on the experimental limits of the setup and the degrees of freedom that are available. Starting with the excitation mechanism, in this case, the automated impulse hammer AMimpact, the operator has the choice between a robust, easily controllable configuration or a less robust configuration that offers a broader excitation frequency range. Easily controllable in this context means that the energy content of the bolt and therefore the peak force is readily adjustable by the activation time of the actuator in milliseconds. The friction loss should be small in relation to the kinetic energy of the bolt. Second, the fixation of the sensors has to obey the requirements of practicability and a well-defined signal quality. Regarding the sensor fixing, we found that the practical aspects outweigh the different signal qualities, as there is as yet no clear winner or loser. As for practicability, we would suggest using petro wax if the components will not be experiencing any large movements or do not have to be assembled or disassembled during a measuring run. In such cases, cyanoacrylate glue is recommended, in order to avoid misalignment of sensors during handling. The increased effort involved in cleaning the sensor and the component must be borne in mind. For the future, a more complex experimental setup may be employed to investigate the signal quality in higher frequency ranges and to determine whether there are any differences between the fixation methods. For now, it can be said that the positioning and orientation of the sensor are far more important than the fixing method itself.

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