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# 1 Effect Of Temperature On The Dynamic 2 Response Of Adhesively Mounted 3 Accelerometers

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## 9 **ABSTRACT**

10 This paper focuses on the effect of temperature on the frequency response function (FRF) of three  
11 different structural adhesives; namely a two component methylmethacrylate (HBM X60), a modified  
12 silane (Terostat 939) and a cyanoacrylate (Loctite 454). The structural adhesives are commonly used in  
13 vibration analysis to mount accelerometers on structures or machines. The stiffness of the adhesive can  
14 influence the response function on large frequency band, affecting the proportional excitation between  
15 the structure and the accelerometer. In the “system structure + adhesive + accelerometer”, the adhesive  
16 may acts like a filter between the source and the sink of vibrations. A variation of the dynamic response  
17 of the filter could lead to an erroneous analysis. The authors already investigated the relation between  
18 the frequency response function and operating conditions of the test. This paper expands the research  
19 by considering the temperature effect in order to depict a complete picture of the adhesive behavior  
20 on dynamic response of an accelerometer. A design of experiments (DOE) approach was used to test  
21 two bonded aluminium bases at different levels of temperature and frequency of the external sinusoidal  
22 excitation, supplied by an electromagnetic shaker. The results clearly demonstrate that the adhesive is  
23 not able to change the system response, therefore the signal transmission is good in the entire range of  
24 temperature regardless the adhesive chosen.

25 **Keywords:** Temperature, Mechanical properties of adhesives, Accelerometers mounting, Vibration  
26 transmissivity, Experimental testing

## 27 **1 INTRODUCTION**

28 Accelerometers are widely used in reliability and maintenance services to perform analysis and condition  
29 monitoring of mechanical components and systems. Most common faults in machines are due to rotating  
30 components, such as bearings, gears and shafts. The coupling between the rotating part and the frame of  
31 the machine is subject to wear, to fatigue effects, poor lubrication or changing environmental conditions.

32 As far as the wear increases the mechanical component breaks, causing unexpected stops of the machine  
33 and subsequent economic loss due to lack of production. The accelerometer is a sensor that detects  
34 and acquires vibrations of the component it is fixed to, allowing an early detection of the wear before it  
35 causes severe damage to the machine, avoiding unexpected stops. Among the so-called Non-Destructive  
36 Testing techniques [1], the vibration analysis has a relatively low costs for the sensor and an easy set-up  
37 on the machine. All the vibration measurements are normally performed by means of a piezoelectric  
38 accelerometer or based on Micro Electro-Mechanical Systems (MEMS) technology. The development of  
39 both MEMS and piezoelectric technology leads to better products, resistant to environmental agents, with  
40 small dimensions and a great bandwidth. The application of MEMS in many technological products, such  
41 as smartphones and gaming application makes these devices extremely low price and very interesting  
42 for the vibration monitoring. The introduction of the piezoelectric accelerometer was in the '50s while  
43 MEMS technology comes lately, thus a relevant amount of papers on signal processing can be found in  
44 technical literature, setting the state of the art on vibration analysis so far [2]. Despite the thousands of  
45 papers dealing with the problem of vibration signal processing, there are only few papers which focus on  
46 a correct setup of the vibration sensors, even though it is crucial for every accelerometer applications [3].  
47 This practical aspect is mainly based on the information retrievable in university courses on vibrations  
48 analysis, either on personal experience or to information given by the accelerometer suppliers [4–6]. The  
49 supplier' guidelines usually focus on a specific aspects of the accelerometer setup, the mounting between  
50 the sensor and the surface of the component. The main solutions available are: screw mounting, stud  
51 mounting, magnetic mounting, adhesive mounting and probe mounting. Each method has a specific field  
52 of application depending on: the working temperature, the mounting surface conditions, the accessibility  
53 to the specific mounting point, etc. A detailed description of all the mounting techniques could be find in  
54 classic handbook on shock and vibration [7]. Among other techniques, the adhesive and the screw/stud  
55 mounting are the most typical. These mounting techniques result in a rigid connection with high stiffness  
56 and wide frequency range response. Compared to screw/stud mounting, structural adhesives are more  
57 reliable in the fastening of sensors and accelerometers, since they provide a simple and quick mounting  
58 without the need of permanent mechanical processing, such as threaded holes, on the chassis of the  
59 machine as stated by Harris [7] as well, while the stud/screw mounting allows a quicker setup on the  
60 sensor. In a previous work [8], the authors focuses on the adhesive mounting of accelerometers, assessing  
61 experimentally the dynamic response of three different adhesives which cover the most common type of  
62 structural adhesive used in on-field applications; namely a two component methylmethacrylate, HBM  
63 X60 [9], a cyanoacrylate, Loctite 454, [10] and a modified silane, Terostat 939 [11]. Often it is believed  
64 that "soft and rubbery" adhesives, which works above their glass transition temperature, like the modified  
65 silane could not be used in this type of application. Secondary objective of the paper is to prove if this  
66 sentence, retrievable in literature but with little evidence, is true. By means of an electrodynamic shaker,  
67 a design of experiment approach was proposed consisting of three variables in the experimental plan:  
68 adhesive type, frequency and amplitude of the vibration signal. The main results proved that the transfer

69 function of the adhesive layer does not distort the signal regardless of the type of adhesive. In this paper,  
70 a further step of that research is proposed, investigating the influence of the temperature on dynamics  
71 response of the above-mentioned adhesives. The effect of temperature on the adhesives was studied in  
72 technical literature [12] and also by other authors [13–16], but scarce information is retrievable on their  
73 viscoelastic properties at different temperature when in thin films. The global information is related to  
74 their polymeric nature, therefore softer adhesive are more affected by temperature and tend to relax more  
75 than the stiffer ones when temperature increase. The aim of the paper is to estimate which is the effect  
76 of the adhesive film used to join the parts in terms of vibration monitoring and signal transmission. The  
77 adhesives are used to join two aluminium bases, the first one connected with a threaded coupling to an  
78 accelerometer and the second one coupled with the head of electromagnetic shaker. The specimens are  
79 placed in climatic chamber together with the shaker and the sensors. The description of the experimental  
80 procedure and the detailed experimental set up are shown in Section 2.3. The Materials and Method  
81 section describes as well the design of experiment approach used. It consists of four variables in the  
82 experimental plan: adhesive type, frequency, amplitude of the control signal and temperature of the  
83 climatic chamber. The amplitude and the frequency are chosen in order to explore the entire range of the  
84 electromagnetic shaker available in the laboratory, while the temperature spans the range available on the  
85 climatic chamber (23 °C - 80 °C). A finite element modal analysis, reported in Section 2.4, was carried out  
86 in order to estimate numerically the influence of the adhesive layer on the resonant modes of the structures.  
87 The results confirm the little influence of the adhesive layer, due to its very low thickness. The Section  
88 3.2 shows the detail of the post processing procedure carried out on the experimental data. The signal is  
89 post-processed through a LabVIEW environment and four significant output parameters are extracted:  
90 the spectral amplitude of the excitation frequency (Spectral Amplitude - SA), the percentage of signal  
91 energy stored at the excitation frequency (Stored Energy - SE), and their weight percent over a reference  
92 specimen (Spectral Amplitude Ratio - SAR - and Stored Energy Ratio - SER - respectively). These  
93 data are elaborated with a statistical software to evaluate which variable affects the system responses  
94 and which is the adhesive's effect on the vibration monitoring. The Section 3.3 exploits the ANOVA  
95 (Analysis of Variance) technique to estimate which are the most significant effects on the responses  
96 by means of half normal plots and variable interactions diagrams. In the conclusions we present some  
97 interesting consideration about the adhesive bonding of the accelerometers and some practical hints useful  
98 in laboratory and industrial environment are presented.

## 99 **2 METHODS AND MATERIALS**

### 100 **2.1 Design of Experimental plan**

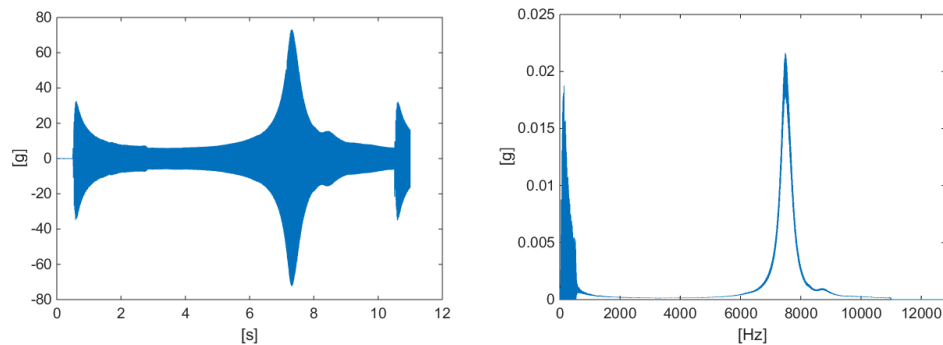
101 The Design of Experiments (DoE) method was developed to optimize the experimental tests especially  
102 for multiple variables involved in a problem [17]. The same principles can be also stretched to numerical  
103 studies [18], treating each numerical analysis with a different set of levels and variables as a *virtual*  
104 *experiment* . In the present work the DoE technique was used to assess the effect of the temperature and of

105 the input excitation on the dynamic mechanical response of adhesive mounting accelerometers at different  
106 working conditions. Four factors were considered in the analysis, namely:

- 107 1. Adhesive type,  $G$
- 108 2. Excitation amplitude,  $A$
- 109 3. Temperature,  $T$
- 110 4. Excitation frequency,  $f$

111 A previous paper of the authors [8], analyzed the effect of the frequency and the amplitude on different  
112 adhesive bonding, although the chosen levels were different. A cross-check of the results with the ones  
113 obtained in the previous work, will be still possible.

114 The levels of the excitation frequency have been chosen based on a resonance test on a reference  
115 specimen at room temperature. The shaker was excited by a linear sine sweep signal in all the shaker  
116 frequency range, i.e. from 0 to 12kHz, with a rate of 1kHz/s. The acquired vibration in time domain is  
117 shown in the left part of Fig. 1, revealing the presence of a resonance peak at 7 seconds. The right part of  
118 Fig. 1 shows the corresponding frequency spectrum, fixing the resonance at 7485Hz. It is worth noting  
119 that the high amplitude at low frequency is not a resonance of the system, but a limit in the performances  
120 of the shaker, optimized to work at mid-high frequencies.



**Figure 1.** Frequency sweep and resonant peak of the acquisition test rig

121 Based on the sweep test, the three levels of excitation frequency  $f$  are chosen viz. 15 Hz, 3500  
122 Hz, 10000 Hz in order to span the entire range of the accelerometer [19], taking into account also the  
123 non-linear behavior at low frequency. It was decided to consider the low frequency range even though the  
124 input signal is not clean for two main reasons. The first reason is that at low frequency we have an higher  
125 amount of energy and therefore is interesting to monitor these bandwidth. The second reason is that the  
126 desired behaviour of the adhesive should not be dependent on the input signal, no matter how bad or  
127 distorted is. The values chosen for the excitation amplitude are expressed as a percentage of the maximum  
128 amplitude provided by the shaker, i.e. 50% and 100%. The temperature is the core factor of this analysis,  
129 so four levels are chosen to better highlight its influence in the tests: 23°C (room temperature), 40°C,

130 60°C, 80°C. We decided not to exceed 80°C since it is practical limit for many rotating machineries  
131 driven by electrical motors. Each specimen was stored in the climatic chamber for a proper time before  
132 the test, in order to heating up the aluminum specimen checking the surface temperature by means of a  
133 infrared thermometer. The adhesive type are the same four used in [8]: G1 is the commercial superglue  
134 (Loctite 454), the G2 is an elastic adhesive modified silane (Terostat 939), both produced by Henkel  
135 Adhesive, Cerano (NO), Italy. The G3 is a very stiff two components methylnmethacrialte adhesive (HBM  
136 X60), produced by HBM, Milan, Italy and G4 is a reference configuration in which there is no adhesive  
137 but continuum material. A Dynamic Mechanical Analysis (DMA) on the selected adhesives would have  
138 been useful, but in literature we could not trace precise information about the viscoelastic behaviour of  
139 the adhesives chosen. Moreover the adhesive behaviour in bulk form and in thin film is pretty different  
140 [20–23] so the eventual information given by a DMA in bulk are not immediately applicable to thin  
141 adhesive layers. Qualitatively the adhesives have very different viscoelastic behaviour, as retrievable  
142 on the basis of the chemistry and on the datasheets of the polymers involved [12, 16, 24]. The stiffer  
143 adhesives, which works below the glass transition temperature which is 137°C for G1 see [10] and about  
144 150°C for G3, see [9] have limited viscous effect, while the softer one (G2) is quite viscoelastic, since it  
145 works in its rubbery state at room temperature [11]. A summary of the variable levels is reported in Table  
146 1. Each specimen is made by two cylindrical aluminium blocks, connected with a thin layer of adhesive,  
147 the lower one is screwed to the shaker, the upper one has a threaded connection for the accelerometer. In  
148 the reference configuration (level 4 of "adhesive type" variable in Tab. 1), there is no adhesive between  
149 the two blocks but a unique aluminum cylinder with double mass of a single block, in order to keep the  
150 same nominal natural frequency. The authors decided to set the adhesive layer thickness at a constant  
151 value of 0.05mm and then to exclude it from the experimental plan even though it is important in the  
152 adhesive stiffness and strength [12–17]. The adhesive thickness is typically an uncontrolled parameter in  
153 a practical application of a bonded accelerometer and, the thickness is controlled by the surface roughness  
154 only. The description of the deposition of the adhesive layer and the curing process is reported in Section  
155 2.3.

Variables	Level 1	Level 2	Level 3	Level 4
Temperature, $T$	23 °C	40 °C	60 °C	80 °C
Frequency, $f$	15 Hz	3500 Hz	10000 Hz	
Amplitude, $A$	50%	100%		
Adhesive type, $G$	Loctite 454	Terostat 939	HBM X-60	None (solid)

**Table 1.** Levels of the variables considered in the DOE

156 A full factorial plan is adopted, with two replicates for each experimental plan. This approach is  
157 combined with a blocking procedure to take into account the different bonding of the adherends. The  
158 blocking procedure is a useful tool, used in the DoE approach, in order to avoid any influence of the  
159 experimental set up or the operator, as described in [17, 18, 25]. Four different temperatures, three  
160 frequencies, two amplitudes, four adhesives and two replicates lead to a total amount of 144 experiments

161 on the bonded configuration, which can be used to estimate the influence of the primary variables and the  
 162 interactions. Further 48 additional experiments on the reference configuration were carried out, leading  
 163 to a total of 192 experiments. We exploited the software Design Expert in order to build the set of  
 164 experimental test to be carried out and to randomize the order of the experiments. The software was also  
 165 used to post process some of the results using mainly an analysis of variance technique (ANOVA).

## 166 2.2 System response

167 The statistical influence of the variables is evaluated in terms of four system responses. The shaker  
 168 excitation is a sinusoidal wave at a given frequency, therefore the amplitude of the corresponding spectral  
 169 component is the main output choice. The two main of the outputs of the experiments are:

- 170 • Spectral amplitude at excitation frequency (SA)
- 171 • Percentage of signal energy stored at excitation frequency (SE)

172 The SA is obtained by applying the Fast Fourier Transform to the vibratory signal, considering the  
 173 amplitude of the measured signal at the excitation frequency, the SE is the energy of the vibratory signal  
 174 at the excitation frequency divided by the total energy of the system.

175 Other two outputs are computed dividing the values of the experimental points by the value of the  
 176 reference configuration (on average). The block with double mass and no adhesive is taken as reference  
 177 configuration. These outputs are not dependent on the system configuration and allow the adhesive effect  
 178 to be compared more efficiently. The two additional parameters are:

- 179 •  $SAR = SA/SA_{no\_adhesive}$  Spectral amplitude ratio (SAR)
- 180 •  $SER = SE/SE_{no\_adhesive}$  Stored energy ratio (SER)

181 The four parameters (SA, SE, SAR, SER) were firstly proposed in [8].

## 182 2.3 Experimental set-up

183 The experimental set-up consists in the test specimens, a climatic chamber, a small electrodynamic shaker,  
 184 a monoaxial accelerometer, a data acquisition board and a function generator. Table 2 summarizes the  
 185 model and the characteristics of the components.

Component	Model	Specifications
Climatic chamber	homebuilt	2x600W fan heater - PT100 temperature sensor, Ascon hysteresis controller, precision 23 °C
Shaker	ModalShop K2004E01	20 N peak sine force, frequency up to 11 kHz
Accelerometer	PCB 353B18	Monoaxial, freq. range 1-10 kHz ( $\pm 5\%$ ), 10 mV/g
DAQ	NI USB-9162 + NI-9233	50 kS/s per channel, 24-Bit IEPE
Function generator	Rigol DG1022	2 channels, 20 MHz waveform generator

**Table 2.** Specifications of the components used in the experiment.

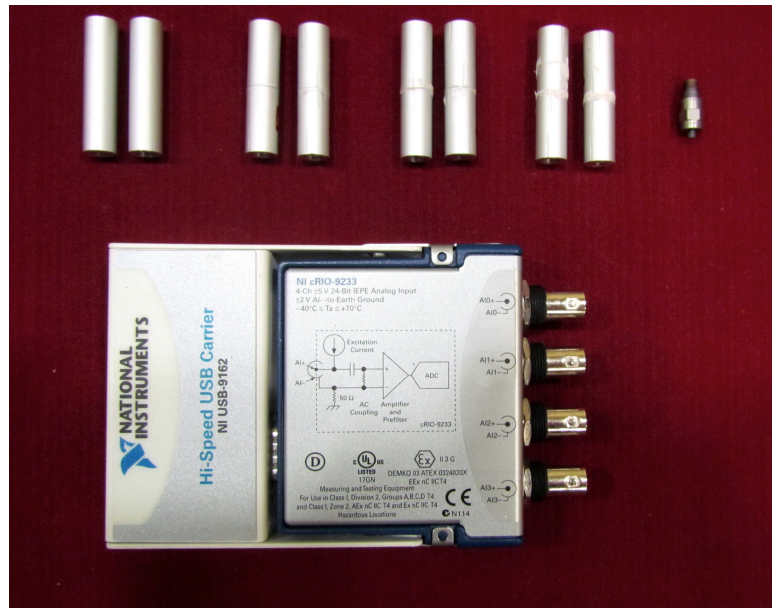
186 All the specimen blocks are built from a single aluminum bar, with a circular cross section of 10 mm  
 187 of diameter. Each block is 20mm high, except the reference block that has a double height 40mm, being

188 negligible the adhesive weight. The size of the blocks is chosen to ensure space for the threaded hole,  
189 but still keeping enough mass in order to have a stiff specimen. All the blocks have been threaded to be  
190 coupled with the shaker head and the accelerometer by means of an adaptor. The blocks were bonded  
191 using a jig to maintain alignment between the upper and lower one and a small dead weight (0.1 kg)  
192 was used to apply a sufficient pressure to the entire adhesive layer. The adhesive fillet is removed with  
193 a cutter immediately after the applications, in order to avoid any extra mass and due to the very fast  
194 curing (few seconds) of the Loctite 454 and XBM X60. In order to achieve complete polymerization we  
195 kept all the joints at room temperature for 48h, to ensure a proper curing of all the three adhesives. The  
196 estimated nominal thickness is 0.05mm. The eight specimens (4 adhesive levels and 2 replications), the  
197 accelerometer and the acquisition board are shown in Fig. 2. The shaker is provided with an embedded  
198 amplifier, open-chain controlled with 0-1 VRMS signal supplied by a Rigol function generator. The  
199 shaker is equipped with an amplitude gain which can be selected by the user, but in this experiment  
200 we decided to keep it constant for all the tests. The accelerometer is acquired by means of a NI-9233  
201 board which is specifically designed for IEPE devices. The shaker is fixed to the ground of the climatic  
202 chamber, while the shaker body is connected to its fixed frame by vises. In each test the head of shaker  
203 moves harmonically with characteristics listed in Table 2. The amplitude is not measured in absolute  
204 “g” value, but it is expressed by a percentage of the maximum control voltage, i.e. with a  $V_{peak}$  value  
205 of 1V for the 100% of amplitude and 0.5V for the 50% amplitude. The sampling frequency is 50 kHz  
206 and the acquisition time is 3 seconds. The acquisition system waits two seconds before starting to avoid  
207 acquisition of undesirable transient effects of the shaker. The climatic chamber is home built, made in  
208 PVC insulating panels (12mm thick) with two fan heater (600W each) controlled by an Ascon controller.  
209 The controller ensures the desired temperature by means of a PT100 thermocouple and implements  
210 a threshold control with a mean error of 0.5 °C. The fans, integrated in the heater ensure an uniform  
211 temperature distribution in the climatic chamber. Figure 3 shows the final setup of the shaker in the  
212 climatic chamber.

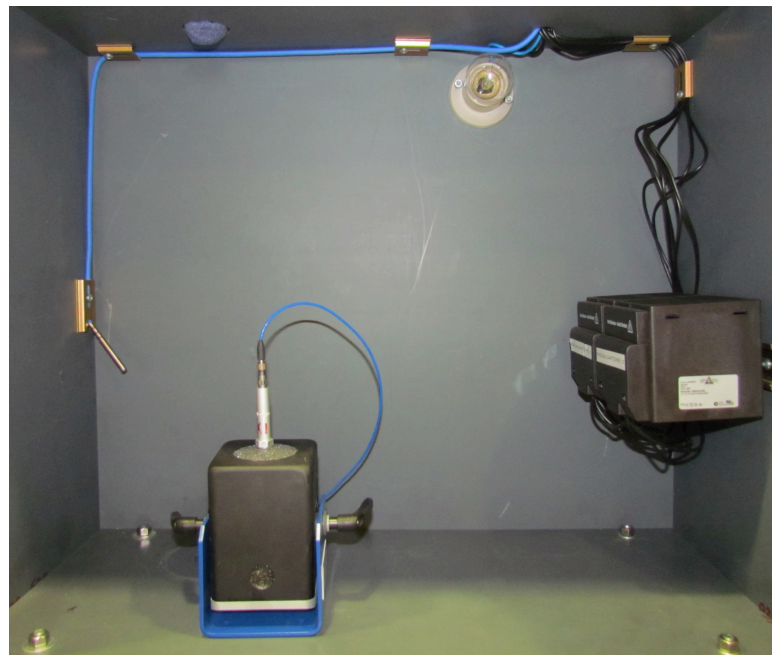
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## 214 **2.4 Finite Element Model**

215 This section describes a preliminary analysis of the system carried out by means of a finite element modal  
216 analysis. The aim of the parametric analyses is to assess the theoretical influence of the adhesive layer on  
217 the natural frequencies of the system considered. Four different analyses were carried out: three different  
218 adhesives and the reference configuration are modelled. The finite element modal analyses are carried  
219 out by using Abaqus 6.141 FEA solver. The model is composed by two aluminum blocks with the exact  
220 dimensions of the specimen described in the previous sections, bonded by a 0.05mm thick adhesive layer.  
221 The mesh continuity guarantees that no contact elements disturb the transition between different materials.  
222 The model used for the reference configuration shares the same mesh with the other three bonded models.  
223 The accelerometer weight is considered and the threaded connection of the accelerometer is modelled as a



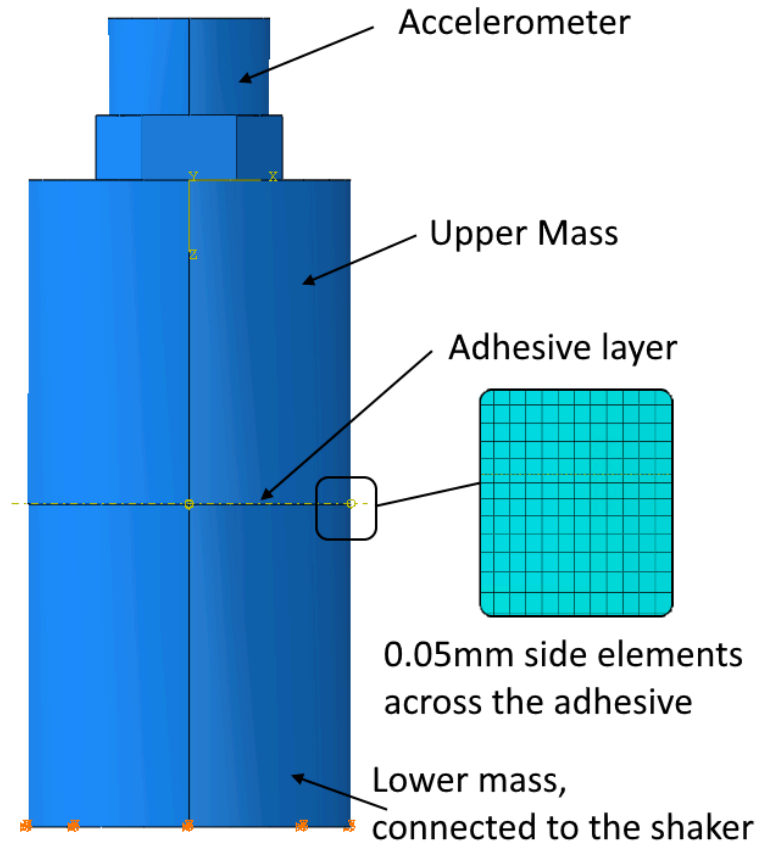
**Figure 2.** Experimental specimens, accelerometer and acquisition board



**Figure 3.** Experimental test rig with climatic chamber and mini shaker

224 perfect contact in each case. The model is implemented with linear hexahedral elements with standard  
 225 formulation, 1223470 nodes and almost 3.5 million d.o.f. The need of having so much elements is driven  
 226 by the very low thickness of the adhesive. In order to have undistorted elements in the adhesive layer,  
 227 which is crucial for the analyses, we had to force a very refined mesh size in that region. This is a very  
 228 common problem, as reported by many authors [26–28] The elastic moduli of the three adhesives are  
 229 taken by the technical data sheets in literature and span from 100 MPa for the Terostat 939 to 800 MPa

230 for the Loctite 454 and 4000 MPa for the X60 - HBM adhesive. We considered room temperature for all  
231 the adhesives, leaving the evaluation of the temperature effect to the experimental part. The boundary  
232 condition applied is to prescribe at 0mm the nodal displacement of the basis, as shown using orange  
233 triangles in Figure 4 in order to be consistent with the experimental tests. The frequency domain is limited  
234 to 20kHz, in order to save computational time and do not exceed the experimental limit given by the  
235 mini-shaker. As output we can compare the natural frequencies of the bonded models with the frequency  
236 obtained using the reference and with the experimental results.



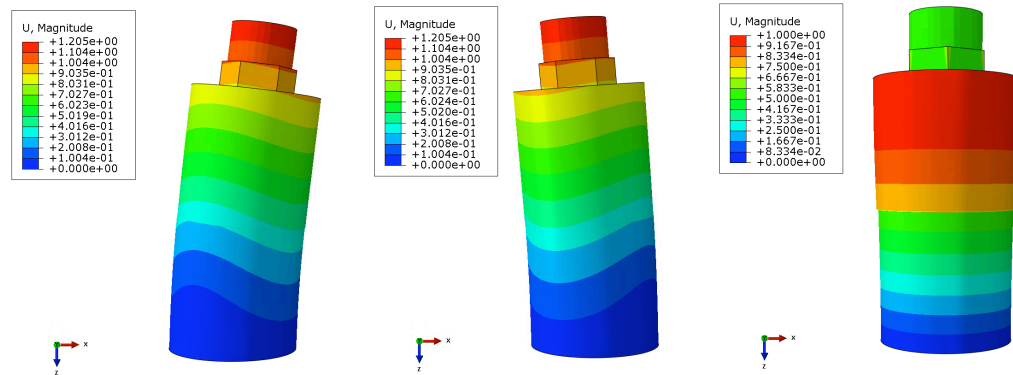
**Figure 4.** Boundary conditions applied to the FE model and magnification of the mesh of the adhesive layer

### 237 **3 RESULTS AND DISCUSSION**

#### 238 **3.1 Finite element model results**

239 This section describes the finite element model results, showing the effect of the three materials and  
240 comparing the natural frequencies with the experimental results. The finite element model results can  
241 be qualitatively expressed by the modal form of the system and their natural frequencies. The modal  
242 forms of the systems are the same for all the four models and are reported, just for the Loctite 454 case, in  
243 Figure 5. It is important to note that with adopted linear perturbation analysis, the value of the magnitude

244 is not significant. The most important information is given by the frequencies of these three modal forms.  
 245 We report in Table 3 the natural frequencies obtained in the four cases. The modal analysis confirms that  
 246 the peak at nearly 7kHz is due to a natural resonance of the system, as shown in 1 and it is important to  
 247 note that this peak is almost not affected by the presence of the adhesive. The softer one and the reference  
 248 configuration differ only of less than 5%. This first result shows that the presence of the adhesive, thanks  
 249 to its very low thickness, do not modifies substantially the harmonic behaviour of the system, and therefore  
 250 confirms the previous authors' finding [8]: choosing a general adhesive rather than a specific one does not  
 251 affect the system behaviour. The experimental test will show whether or not the temperature will change  
 252 this kind of behaviour.



**Figure 5.** Modal forms of the system. From left to right, bending on first plane, bending on second plane, torsion along the axis

Adhesive type	E (MPa)	ni	rho (kg/m3)	1st (Hz)	2nd (Hz)	3rd (Hz)
Terostat 939	100	0.45	1500	6736.5	6736.6	17712
Loctite 454	800	0.3	1100	6738.3	6738.4	18262
HBM X60	4000	0.3	800	6889.7	6889.9	19046
None (reference)	-	-	-	6926.8	6926.9	19234

**Table 3.** Natural frequencies of the finite element model.

### 253 3.2 Post-processing of the experimental data

254 The post processing of the vibration data was done in National Instruments' LabVIEW 2016 environment.  
 255 In order to avoid transient effect on the acquisition, the tails of the vibration signal are removed, i.e. 0.5  
 256 seconds at the beginning and at the end of the signal are removed from the 3 second of acquired data. The  
 257 resulting 0.5 Hz of spectrum resolution allows to clearly match the excitation frequencies. The system  
 258 response if computed by means of the power spectrum of the vibration data, as reported in equation 1.

$$PS(f) = \frac{FFT^*(\bar{x}) \cdot FFT(\bar{x})}{n^2} \quad (1)$$

259 where  $FFT(\bar{x})$  is the fast Fourier transform (FFT) of vibration data, while the  $FFT^*$  denotes the  
260 complex conjugate and  $n$  is the length of samples array. In an ideal condition, the sine input of the shaker  
261 — measured by the accelerometer — returns a single peak as output in the frequency domain, at the  
262 excitation frequency  $f_{ex}$ . An interesting comparison among different adhesive type is made on two scalar  
263 output parameters (despite connected):

- 264 • The amplitude of the power spectrum at the excitation frequency (SA).
- 265 • The ratio between the amplitude of the spectrum at the input frequency and the total energy of the  
266 acquired vibration signal (SE).

267 The choice of these parameters follows a simple reasoning: SA is what is usually measured in  
268 experimental activity, i.e., it is a measure of absolute value depending of the energy at input source, while  
269 SE returns the quality of the acquired signal independently of the energy of input source. A further  
270 consideration is given by The Parseval's theorem, regarding the choice of the power spectrum instead of a  
271 simple spectrum. In fact, the theorem states that the total energy contained in a time-domain waveform is  
272 equal to the total energy of the waveform' spectrum. The equality is reported in Equation 2.

$$\int_{-\infty}^{+\infty} |x(t)|^2 dt = \int_{-\infty}^{+\infty} |X(f)|^2 df \quad (2)$$

273 It follows that the total energy of the signal can be computed as a simple sum of power spectrum  
274 components.

275 Two other outputs are computed dividing the values of the experimental points by the value of the  
276 reference configuration (on average), as mentioned in Section 2.2. The two parameters are named SAR  
277 and SER since they are derived from the SA and SE values respectively.

### 278 **3.3 Statistical analysis of the results: Analysis of Variance**

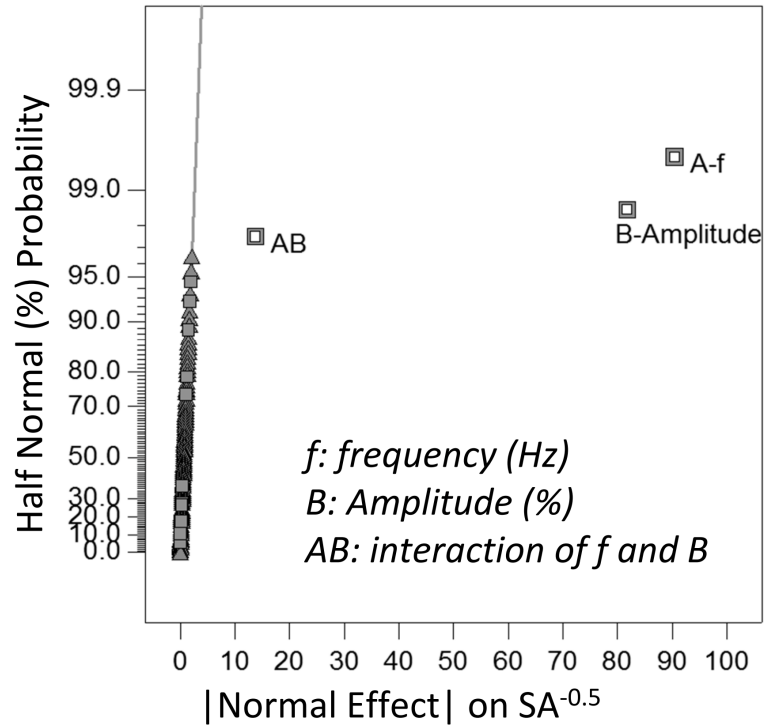
279 There are many statistical methodologies to tackle the analysis of multivariate problems [29]. Among  
280 these we adopted the Design of Experiment (DoE) procedure, a powerful statistical technique based on  
281 the analysis of variance (ANOVA) that can be conveniently applied to these classes of problems. ANOVA  
282 is based on the variance calculation (standard deviation) of a response considering the single variable and  
283 also the global variance of the responses. The ratio between these two quantities is called the F-value  
284 [29]. When we consider a random process this F-value equals one, meaning that the variable under  
285 analysis has no tangible effect on the selected response, since it behaves the same way as the experimental  
286 noise for practical test or numerical error for parametric simulation. On the contrary a larger F-value  
287 means can be associated to a variable that influences the process. Among the several approaches typically  
288 used to represent the results graphically one of the most popular is the normal plot. It is used mainly  
289 to demonstrate which are the main consequences of the variables on the system response, estimating  
290 whether a certain set of data follows a Gaussian distribution or not. When the data are approximately

291 a straight line the response is statistically "normal" i.e. follows a stochastic law. When the selected  
292 variable strongly affects the system response its effect, reported in the normal plot, will then fall outside  
293 the normal distribution line. This line, also called errors line is built up thanks to the replicates of the  
294 experimental tests which have the variability typical of the experiment considered and their effect has a  
295 normal distribution. The replicates of the experiments are therefore important because they are used to  
296 build the error line because they are ruled by a stochastic law by definition. The greater the deviation of  
297 the point from the normal line the larger the confidence interval (i.e. the probability that the variables are  
298 significant is higher). In this paper we adopted the half normal plot, which behaves in the same way as the  
299 normal plot, but considers only the absolute significance of the variables and not their sign.

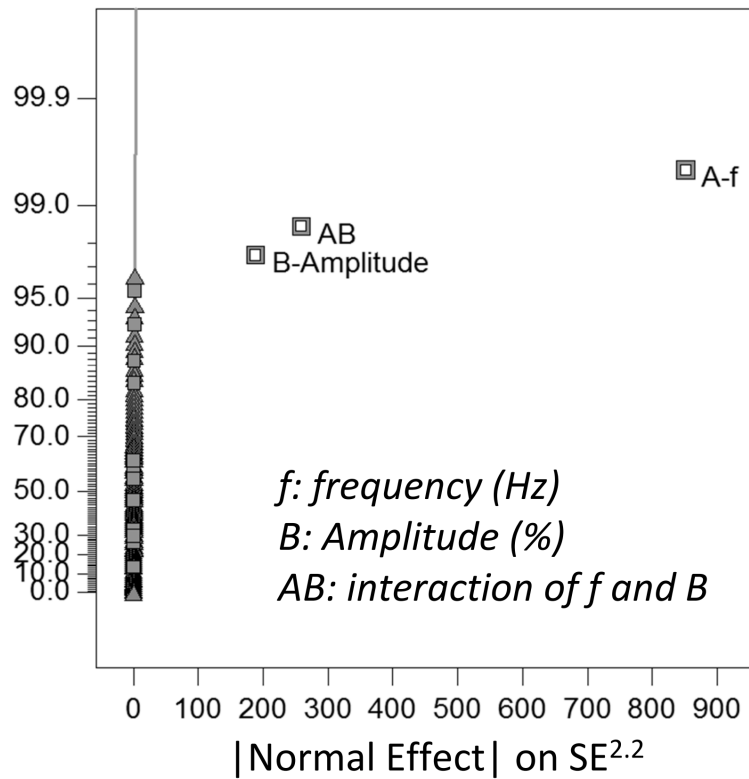
### 300 **3.3.1 Half-normal plot of the response**

301 Figure 6 shows the half-normal probability plots from an ANOVA following [17]. The analysis was  
302 performed on two outputs of the problem (system response) described in the previous subsection. Figure  
303 6 shows the SA, Figure 7 the SE. In Figure 6 and 7 on the X-axis is represented the standardized effect  
304 linked to each factor considered. The higher the standardized effect, the greater the influence of the  
305 variable on the response. The Y-axis represents the half-normal probability associated with each effect.  
306 The greater the Y value the higher the probability that the effect has an influence on the problem. The  
307 solid line is the error line, which is obtained by interpolation of the replicates of the tests, represented  
308 by triangles, and also the high order interactions of the variables, represented by the squares, which do  
309 not play any role on the system response. The points that fall off the error line represent the factors that  
310 mainly affect each response. Figure 6 and 7 show that the frequency and the amplitude have the strongest  
311 influence both on SA and SE. The effect of the frequency is the most relevant both for SA and SE. It  
312 must be noted that we applied a transformation to the selected variables, in order to normalize the data.  
313 This linearization, called Box-Cox transformation, is strongly recommended [18] when there is the need  
314 of dealing with experimental set of data by means of ANOVA technique, which gives better prediction  
315 for linear problems. In Figure 6 the effect of the variables are reported applying an inverse square root  
316 transformation and in figure 7 we have SE raised to the power of 2.2. The amplitude is relevant in both  
317 cases, while the interaction between frequency and amplitude is more important for SE than SA. The half  
318 normal plots of the SAR and SER are reported in Figure 8 and Figure 9 respectively. These Figures show  
319 that dividing SA and SE by the reference configuration causes two different behaviors.

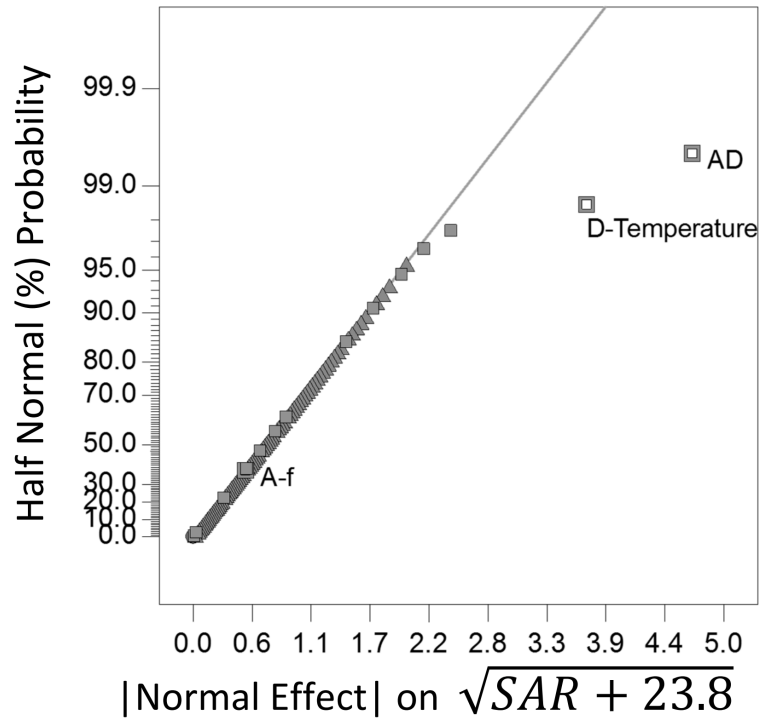
320 The SAR chart Figure 8 shows a strong dependence on the temperature (D) and on the interaction  
321 between frequency (A) and temperature (AD). The amplitude of the signal disappears when compared  
322 with Figure 6. The SER chart Figure 9 shows a more complex situation. In this case the amplitude and  
323 the frequency are important as it happens for the SE as shown in Figure 7 and in addition the temperature  
324 plays a secondary but still relevant role.



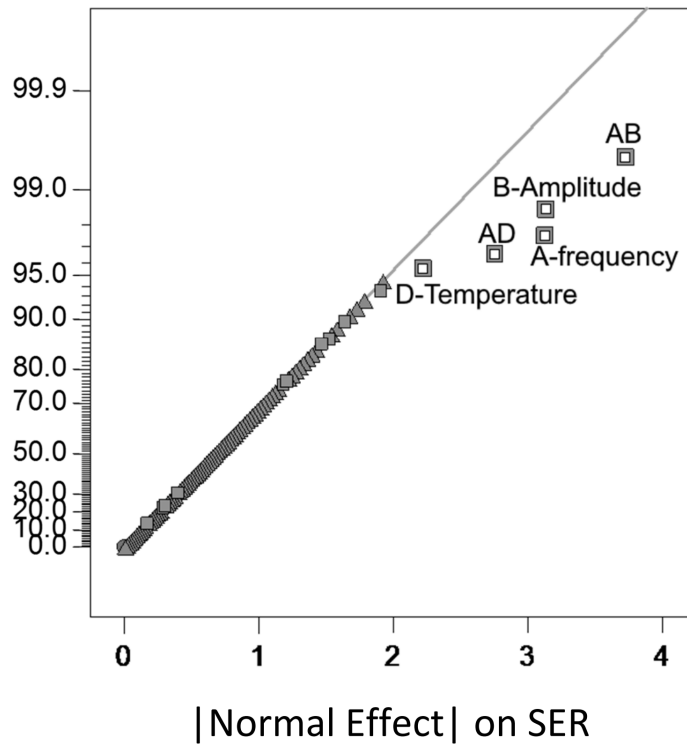
**Figure 6.** Half normal plot of the SA, with an inverse square root transformation applied



**Figure 7.** Half normal plot of the SE, with a power law transformation applied



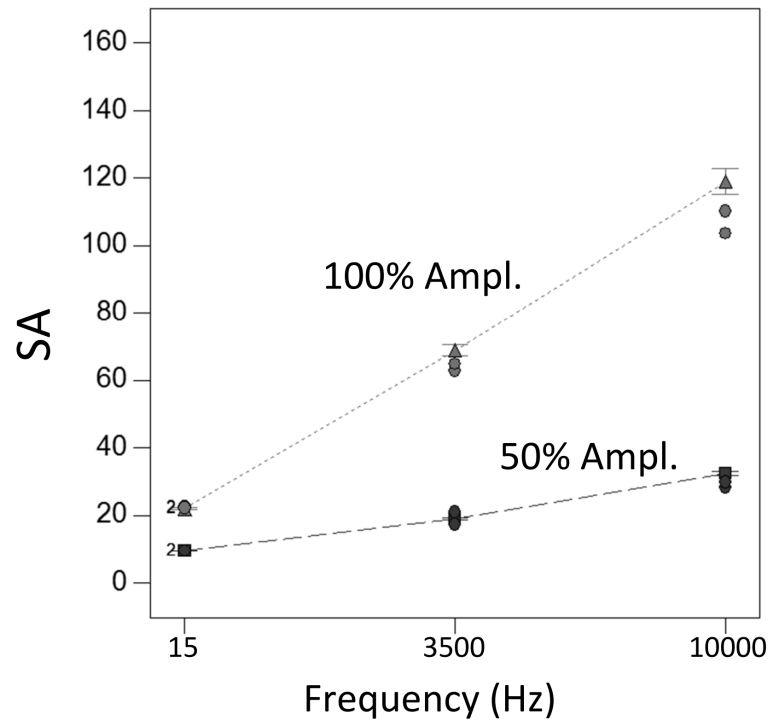
**Figure 8.** Half normal plot of the SAR



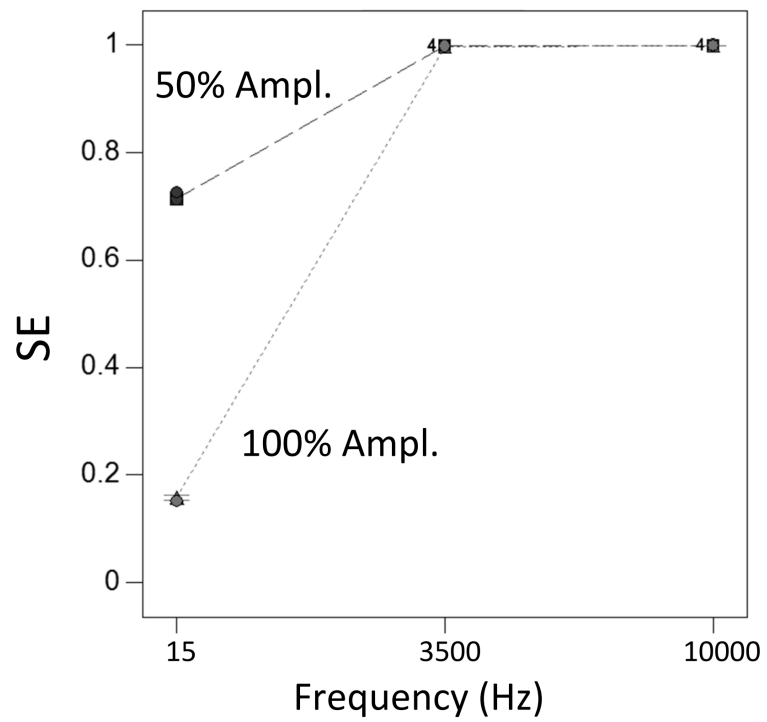
**Figure 9.** Half normal plot of the SER

### 325 **3.3.2 Variable interactions and relevance**

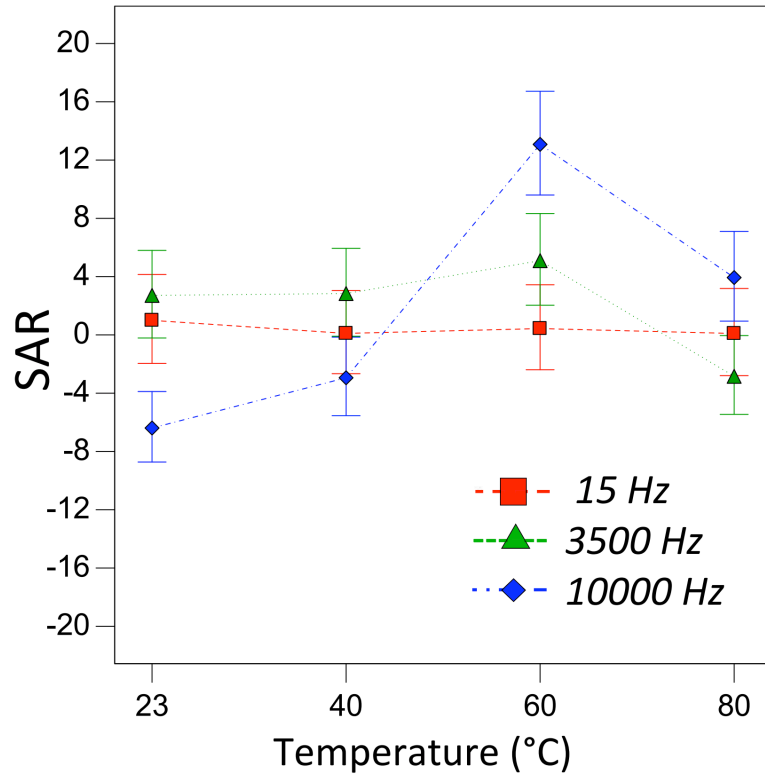
326 Two main comments can be drawn by the graphs in Figure 6, 7, 8 and 9. The first one is that the adhesive  
327 type is not relevant compared with the other variables. This is the most important finding of this research  
328 since it tells us that no matter the adhesive stiffness and the adhesive strength the bond between the  
329 excitation base and the accelerometer base is enough to transmit a correct signal. Therefore we can choose  
330 the most suitable adhesive according to other considerations such as cost, simplicity, availability and ease of  
331 application. The second important consideration is that the temperature somehow is relevant for SAR and  
332 SER. This means that it could be important to monitor the temperature as well as the vibration if we want  
333 to be sure of taking into account all the possible sources of variations. In order to show the direct influence  
334 on the four system responses of the selected variables we can take advantage of the following graphs.  
335 Figure 10 shows that the system has larger values of SA with increasing frequency and amplitude. These  
336 two variables present an interaction clearly visible due to the divergence of the two interpolating lines.  
337 The points in the graph represent the experimental results obtained and it is visible the good repeatability  
338 and the scarce significance of the other variables. Figure 11 shows a completely different situation. The  
339 main effect on SE is at the lower frequency, where we can see a difference due to the amplitude. It must  
340 be noted that the mini-shaker at 15 Hz shows some issues, as reported in Figure 1. We did not expect a  
341 behavior like that, therefore we are investigating on this problem, to see if the behavior is due to the noise  
342 at low frequency. The SE parameter describes how many portions of the system's energy is transmitted at  
343 a given frequency with respect to the total one. Probably, the non-linearities at low frequencies make the  
344 SE response sensible to the amplitude. It is worth noting that anyway no sign of a significant influence  
345 of the adhesive nor the temperature can be found as well. Disregarding the data at 15 Hz would lead to  
346 a substantial independence of SE on the other variables. Figure 12 shows the effect of the temperature  
347 and of the frequency on the SAR. In this case, in order to show the actual values we did not apply the  
348 Box-Cox transformation as we did in Figure 8. The figure 12 shows three curves, as a function of the test  
349 temperature. The red squares represent the 15 Hz tests, the green triangles depict the 3500 Hz tests and the  
350 blue dots the 7000 Hz tests. The adhesive and the amplitude have no effect, but they appear only as the  
351 error bars in the three curves. As for the SE the SER results, shown in Figure 13 is affected by the  
352 results at 15 Hz. We can easily spot a difference in the two amplitudes and frequencies as a function of  
353 the temperature, but it is much more evident at 15 Hz rather than at the other frequencies. It is useful to  
354 highlight that, even though there is some noise at 15 Hz, the experimental tests show a clear absence of the  
355 adhesive in each statistical analysis performed. This is the main outcome the authors wanted to find out  
356 and therefore the conclusion is that the bonding does not change the vibratory signal from the source to the  
357 sensor, even considering soft adhesive such as the Terostat 939 or when the test temperature increases up  
358 to 80 °C.



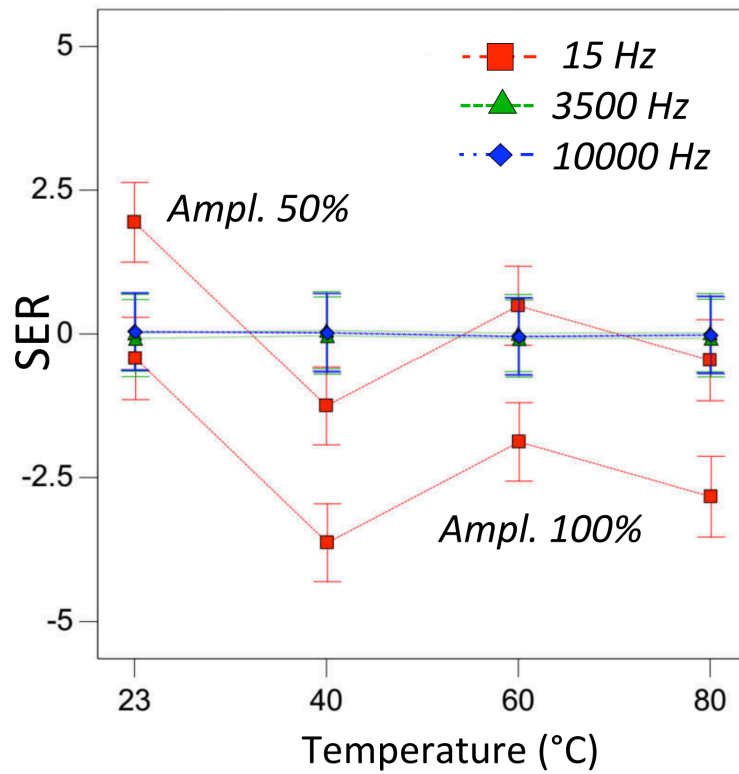
**Figure 10.** Effect of the main variables on SA



**Figure 11.** Effect of the main variables on SE



**Figure 12.** Effect of the main variables on SAR



**Figure 13.** Effect of the main variables on SER

## 4 CONCLUSION

This paper focuses on the effect of temperature on the frequency response function (FRF) of three different structural adhesives, namely a stiff two component methylmethacrylate (HBM X60), a soft modified silane (Terostat 939) and a cyanoacrylate superglue (Loctite 454). The methylmethacrylate is commonly used in strain gauge application and accelerometers setup in on-field environments due to its stiffness. The cyanoacrylate is the most used in accelerometers setup for diagnostics purposes in laboratory due to its fast polymerization time. The silane is a general purpose adhesive chosen for its different structural characteristics compared to the other two. They have been used to joint two aluminium cylinders, one connected to an accelerometer and the other to the head of an electromagnetic shaker. A reference additional experiment has been carried on a double-weight aluminium base, simply obtained using a continuum block of double length without any adhesive. The experimental setup is placed inside a climatic chamber providing a selectable temperature up to 80 °C. The shaker provides a sinusoidal vibration in terms of acceleration at different combinations of frequency and amplitude, as summarised in Table 1. A monoaxial accelerometer is used to acquire the feedback vibration signal which has been processed to compute four different parameters assessing the dynamic response of the structure. The output parameters are all computed through the power spectrum of the vibratory signal. They are: SA, i.e the amplitude of the spectrum at the shaker excitation frequency, SE, i.e the ratio between SA and the total energy of the signal, SAR and SER i.e. the values of SA and SE for a given adhesive compared to the corresponding values in the reference condition. The numerical model developed shows that the presence or absence of the adhesive layer does not modify or disturb the natural frequency of the system.

A design of experiments (DOE) approach was used to extract the main conclusions which are summarized as follows:

- Frequency and amplitude have the strongest influence on both SA and SE
- The temperature has a strong influence on SAR
- The SER is influenced by the frequency, the amplitude and the temperature
- The amplitude and temperature have an evident effect on the SA
- No sign of a significant influence of the adhesive nor the temperature can be found on SE, SAR and SER

Above them two results can be used as design guidelines: no matter the adhesive stiffness and the adhesive strength the bond between the excitation base and the accelerometer base is enough to transmit a correct signal. Therefore the most suitable adhesive can be chosen according to other considerations such as cost, simplicity, availability and ease of application. The temperature somehow is relevant for SAR and SER. This means that it could be important to monitor the temperature as well as the vibration if we want to be sure of taking into account all the possible sources of variations.

## 393 COMPLIANCE WITH ETHICAL STANDARD

394 Conflict of Interest: The authors declare that they have no conflict of interest.

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