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Review paper

Understanding board level vibrations in automotive electronic modules

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ABSTRACT

Board level reliability can be of high interest for automotive electronic components when exposed to vibration-prone environments. However, the absence of an industry standard for board level vibration testing poses several challenges in establishing a well-characterized test setup. One of the challenges is that automotive applications can induce abnormal stresses on components that can lead to early failures in the field. Such loading conditions are not always covered in the current board level vibration test methods. This paper aims to correlate the stresses from automotive modules to board levels by measuring the printed circuit board (PCB) vibration spectrum. Firstly, the study compares and assesses several module board level vibration measurement units, such as LASER Doppler Vibrometer (LDV), strain gauges, and accelerometers. Experiments and simulations show that LDV enables good correlation with Micro-electro Mechanical Systems (MEMS) accelerometers. Secondly, the module-board interaction unveils insights into several module design features that impact the PCB vibration response and solder joint interconnect reliability. These findings underscore the necessity for the user to correctly validate the reliability of packages beyond board level testing, i.e., at the module level. This reliability test approach enables the translation of reliability test results from the lab to the field life of components once built in the final application equipment.

1. Introduction

The relentless march of technology usage in applications is propelling function densification in automotive electronics. It is leading to smaller, and densely packed electronic devices. While this trend is revolutionizing the automotive industry on one hand, it also brings forth a unique set of challenges, particularly in terms of reliability on the other hand. The reliability risks are primarily manifested in the form of board-level solder interconnect failures. The more densely packaged electronics and smaller components lead to a reduction in solder joint size. The decreased contact area and limited solder volume make solder interconnects more susceptible to mechanical loads, such as vibration.

Board level vibration testing is commonly used to assess the reliability risk of electronic components. The solder joint reliability is assessed by subjecting standardized test board assemblies to controlled vibrations. It is also referred to as second-level reliability in [1] and is depicted in Fig. 1 [1]. An electronic module in a vehicle assembles several electronic components into one functional unit or equipment, such as power modules and radar sensor modules. It involves PCB housing, thermal heatsink, thermal interface material (TIM), assembled module PCB (or application board) and boundary condition of the module board or PCB assembly clamped the same way as it would be in an actual automotive application. These are referred to as module level elements in this work. A schematic of a module and module level reliability or third-level reliability is also shown in Fig. 1. Additionally, reliability testing can also be carried out directly on the module PCB or application board without the rest of the module level elements. It is referred to as application board or module board level tests in this investigation.

While there have been several studies on board level and module level vibration test assessments of electronic packages [3–18], there is a scarcity of literature concerning the potential shortcomings in the PCB vibration measurement method itself. In [7], the study explores the comparison between accelerometers versus LASER Doppler Vibrometer (LDV) in board level vibration testing. The evaluations focus on specific standard reliability test boards only and did not include automotive-

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based module boards. Also, the investigation does not encompass other measurement methods, such as strain gauges, and Micro Electro Mechanical Systems (MEMS) accelerometers. While these sensors are used for measuring mechanical vibrations in real world environments [5,13], there is no data on whether these measurement methods influence the dynamic response of the measured boards themselves. Furthermore, there is a lack of understanding regarding the stress profiles induced by automotive modules on the electronic components residing in them.

Module housing can introduce variability in the loads experienced by electronic components at the board-level. It can either amplify or alleviate stresses at the solder joint level. It can influence both failure modes and failure rates induced at the board level. So, it is necessary to understand the implications of several module level elements on the PCB dynamic response.

This paper aims to reveal the unintended pitfalls in module board level vibration test methods. The measurement strategies investigation includes the assessment of lightweight portable accelerometers, LDV, strain gauges, and MEMS accelerometers. Using all methods, acceleration of the module PCB is measured independently and then in combined vibration measurement sensor setups. This module board contains packages such as Ball Grid Array (BGA) and Fan-out Wafer Level Packages (FO-WLP) sizing from 7.5 × 7.5mm^2 to 14x14mm^2. Finally, modal and harmonic analysis is performed using a Finite Element Model (FEM). It is developed to mimic the test measurement setup scenarios.

The study then proceeds to evaluate the influence of the aforementioned sensor module equipment level elements. It dwells on the relationship between module level design elements and the resulting stresses experienced by the solder joints. It is assessed by using PCB vibration spectrum analysis. The evaluation unravels the reliability risks by benchmarking the standard test boards employed during board level vibration testing with the PCB vibration response at the module level. Stresses at the board level and module level are correlated to assess whether the reliability risks can be covered using board level reliability testing only.

2. Experimental setup and numerical details

This investigation is limited to the automotive sensor module shown in Fig. 2. Such electronic equipment is commonly placed in the bumper of automobiles. This module and the embedded PCB in it (referred to as module board) enable replication of the real-world situations. It is commonly used for demonstrating the corner radar functionality in vehicles [2]. It also contains an inertial measurement unit (IMU) in it. Some of the details are summarized in Table 1.

The module board is fastened onto a heatsink-based enclosure by using a screw at each of the four corners. Within the module board under test, the primary attention is directed towards two components, the FO-WLP and the BGA component (shown in Fig. 2).

FO-WLP is mounted on the top side of the circuit board and BGA is soldered on the other side (bottom side) of the module board. An

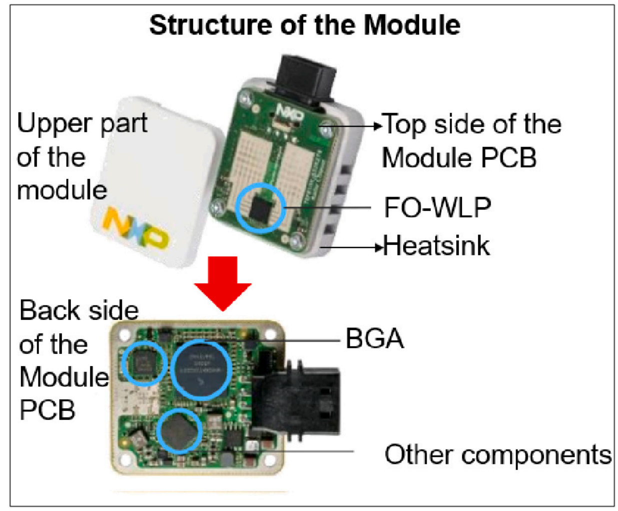

Fig. 2. Automotive sensor module under test (with Module PCB: Top side & Back side).

Table 1
Test module description.

PCB dimensions [mm x mm]	47 × 42
PCB Material / thickness [mm]	FR-4 / 1
Bare PCB Mass / Assembled PCB Mass	5 g / 8 g
Storage Modulus of PCB [GPa]	14
Number of Copper layers in PCB	8
PCB enclosure type	Heatsink based

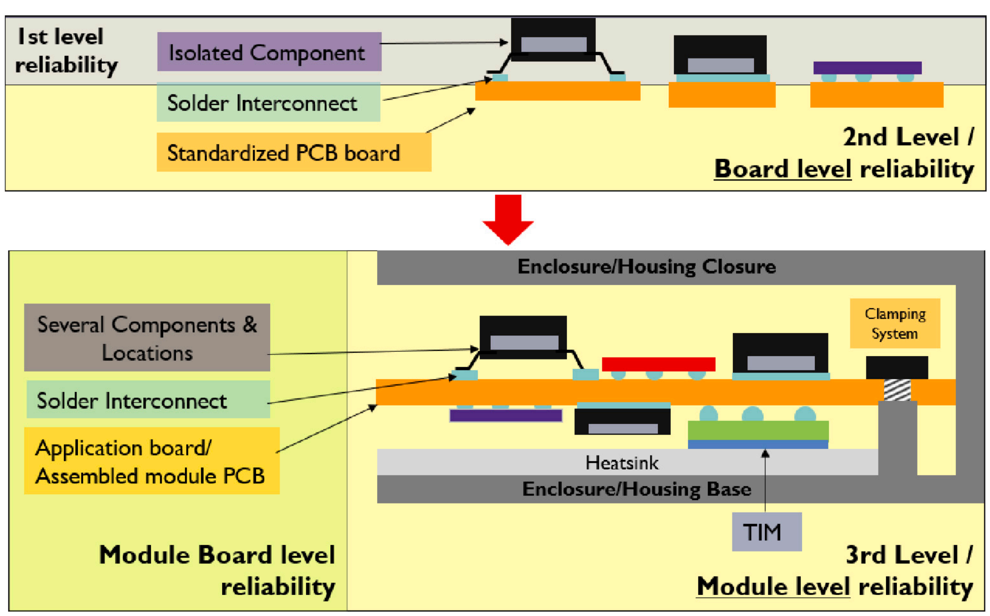

Fig. 1. Board level reliability vs Module level reliability.

experimental test setup of a board module level vibration test is shown in Fig. 3. As depicted, a PCB-module level vibration test methodology comprises of a shaker system that generates mechanical vibrations. It is mastered by a controller-amplifier closed-loop feedback system. It dictates the vibration parameters and governs the intensity and duration of vibrations. The closed-loop feedback mechanism is provided by the control accelerometer that is mounted at the vibration test fixture. By using the control accelerometer data, the vibration equipment makes real-time adjustments to maintain the desired vibrations at the vibration test fixture.

A board-module level vibration test setup contains a vibration test fixture (shown in Fig. 3). It securely holds the module board or module under test, ensuring that it remains firmly in place during the entire testing process. Counterbore holes on the back side of the fixture are used to mount the entire modules with a heatsink. It is in contrast to the usual board module level vibration test setup where the PCB is mounted onto the fixture using pillars at each corner [7]. The test fixture should allow controlled and consistent vibrations to facilitate repeatable and comparable reliability test results. It is ensured by designing a fixture that involves resonances outside the test frequency range of interest. The electronic modules are excited using the swept sine vibration test method at controlled room temperature. It is swept from 10 to 2000 Hz frequency range at an acceleration level of 5 g, with the lab environment maintained at 20 °C. These test conditions are in line with [6,7,19–27]. The corresponding stress transferred to the component is given by the dynamic response of the PCB. In this study, the PCB vibration response is measured at the center of the PCB.

PCB's dynamic response to vibrations contains a resonance frequency (f_0) associated with the PCB material properties, as defined by Steinberg [1]. The equation is expressed as follows:

$$f_0 = \lambda \left(\frac{1}{l^2} + \frac{1}{w^2}\right)\sqrt{\frac{Eh^3}{12\rho(1-\upsilon^3)}} \tag{1}$$

Here, λ is a constant influenced by factors like clamping, l and w represent the board's length and width respectively, E is Young's modulus, h denotes board thickness, while ρ and υ correspond to density and Poisson's ratio, respectively. Then, the measured acceleration (a) can be expressed in peak-peak displacement (d) at the center of the PCB (during its first resonance mode) using the following relation:

$$\mathrm{d} = \frac{a}{2\pi^2 {f_0}^2} \tag{2}$$

Due to the linear relationship between acceleration and peak-peak displacement, both are utilized interchangeably within the analysis of PCB vibration spectrum curves. The module board's dynamic response can be recorded using sensors, such as a lightweight piezoelectric-based accelerometer, and, or using LDV. These sensors are placed or focused at the center of the module board. A miniature lightweight piezoelectric based accelerometer used in this study weighs about 0.2 g. The results from these measurements are compared with those obtained from LDV. The LDV utilizes a He—Ne LASER beam of 633 nm wavelength. More details on the LDV can be found in [7].

Alternate sensors for measuring PCB dynamic response can include strain gauges and MEMS-based accelerometers soldered on the module board. In this case, a rosette strain gauge, designed for measuring strain in multiple directions is employed. It weighs about 0.03 g and features three interconnected strain gauges arranged in orientations at 45-degree increments. In contrast, the MEMS-based accelerometer is a semiconductor device that utilizes microscopic mechanical structures that are integrated with electronics to detect changes in PCB motion. This sensor is enclosed in a 16-pin Quad-flat no-leads (QFN) package which weighs about 0.02 g. The results from these sensors are compared to those obtained from the LDV.

A FEM is developed to mimic the PCB vibration measurement setups with accelerometers and without accelerometers. The Marc Mentat software estimates the PCB vibration response (at room temperature) in these configurations. Fixed boundaries are established at the bottom of the mounting pillars where the module PCB is mounted. The PCB and accelerometer undergo meshing by employing brick-and-penta-shaped elements. The dimensions and weight of the accelerometer are taken from the datasheet of the accelerometer. The PCB is modeled with linear elastic material properties. These are determined through Dynamic Mechanical Analysis (DMA). These properties are homogenized and provide input for configuring the resonance modal analysis.

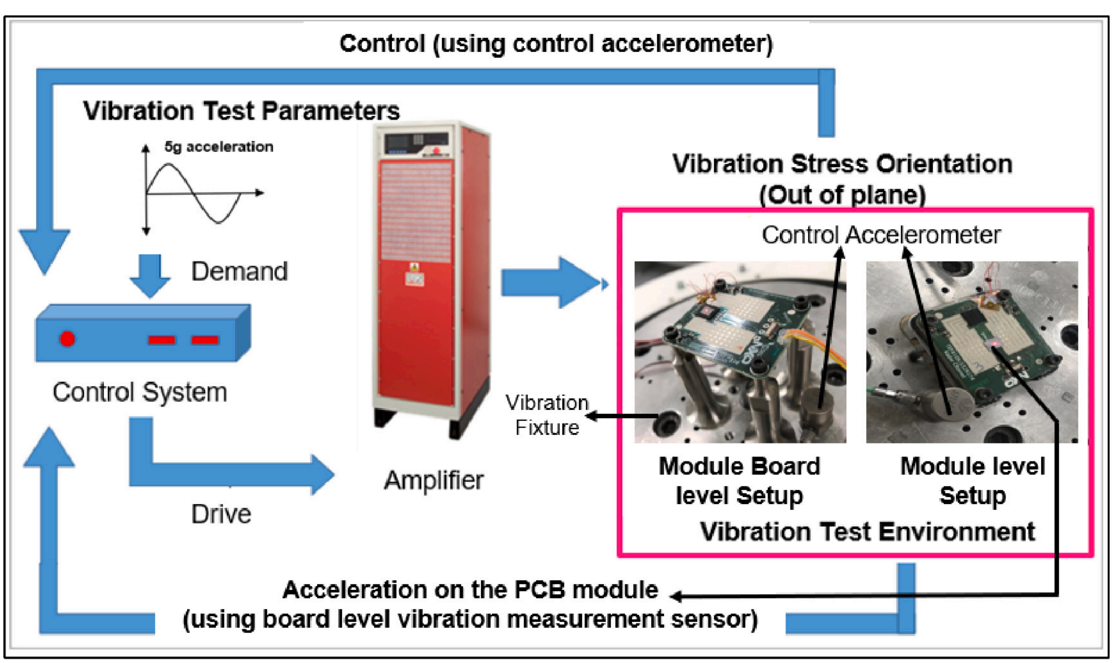

Fig. 3. Board Module, Module level vibration test setups.

3. Assessment of vibration measurement sensors for board modules

The vibration measurement sensor at the board-module level is at the core of the experimental test setup. It captures the actual vibrations experienced by the board module under test, providing precise data on the vibration load levels that are applied to a given component. The sensor's role is pivotal in understanding the dynamic response of the module board housed inside the enclosure. Some of the most prominent vibration characterization units described in [18] and its impact are investigated in this section.

3.1. Impact of accelerometer

A contact-based measurement method involving piezoelectric accelerometers is typically used to monitor vibrations at the fixture structural level. A lightweight accelerometer and LASER are suggested to measure board level vibrations [7]. However, it is not assessed on the board module used in this analysis. First, the resonance frequency is characterized using an accelerometer placed at the center of the PCB. Then, the LASER is pointed on top of the measurement accelerometer to assess the impact of the accelerometer. Finally, the accelerometer is removed from the PCB, and measurement is performed using LDV, without changing the measurement spot location. The results are shown in Fig. 4.

It can be observed that some measurement differences are observed between the two methods. The resonance frequency is reduced by 9 %. Whereas the peak-peak displacement is reduced by 42 %. It is attributed to the mass of the accelerometer with respect to the PCB stiffness that is being measured. The deviation becomes larger when measured on a bare board (lighter and less stiff board than the one assembled with components) residing inside the module structure. It is also in line with Eq. (1) [4] and has also been investigated using simulations (shown in Fig. 5).

As the accelerometer location is varied on the PCB, the differences observed in the PCB dynamic response change. It is illustrated in Figure. It shows that the mass of the lightweight accelerometer is large enough to induce perturbance in the PCB vibration spectrum. FEM results exhibit a measurement difference of 141 Hz when compared to the LDV measurements. It shows comparable agreements with the experimental outcomes, showing a measurement difference of 147 Hz. The differences between modeling and experiments are found in the absolute values of resonance frequency. It might be linked to the assumption of using homogenized material properties in FEM. To conclude, the LASER stands out as the preferred choice due to its non-perturbing nature that preserves the dynamic response of the PCB. Furthermore, it can be noted that the module board displacement and the resonance frequency found in these boards are much lower than those determined on the reliability test boards shown in [7]. These differences can be attributed to the PCB form factor, stiffness, and mass of the PCB under test.

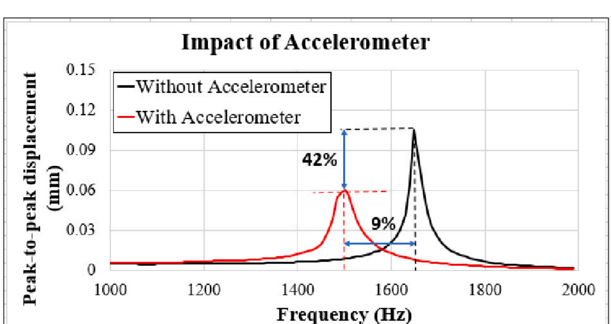

Fig. 4. Impact of light weight accelerometer on the dynamic response of functional board module.

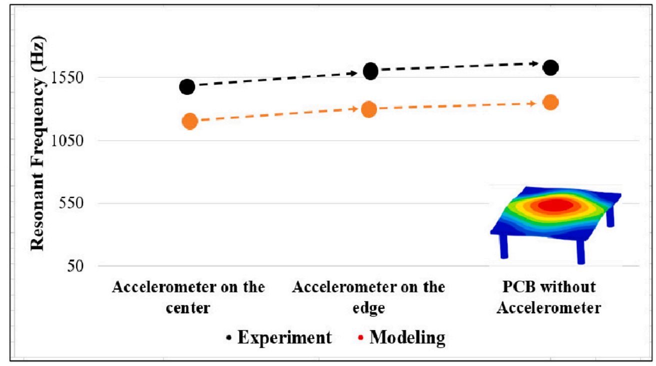

Fig. 5. Impact of accelerometer on resonance frequency (Experiment vs Modeling).

3.2. Impact of strain gauge

LASER and strain gauge measurement methods are compared at both bare PCBs and boards with components. Strain gauges are widely used for measuring stresses in both laboratory settings and automotive applications [5]. Bare PCB is excited and measured using LDV and strain gauges. The measured signals from LASER and strain gauge align well when measuring the resonance frequency of the bare PCB. Both methods show a resonance of 1420 Hz. Then, the strain gauge measurement methodology is further assessed for the assembled module board.

Before studying this phenomenon on the application module board, it is examined using simulations and target experiments on a standard reliability test board designed in [26–28]. It is illustrated in the accompanying Fig. 6. Three rosette strain gages are mounted on this PCB. It carries a $15x15mm^2$ BGA component that is placed in the center of the PCB. The maximum principal strain is measured at the strain gauge locations described in Table 2. LDV measurements are performed over the component surface area. These measurements are carried out to scale the deformations calculated in simulations with peak-peak displacement values from LDV. This way, strain values can be extracted from simulations.

In both simulations and experiments, it is observed that the strain is smaller at the center of the package than at the corner (shown in Fig. 6). It indicates that the stiffness of the component limits the deflection of the PCB under the component at the resonance frequency. Higher strain levels found at the package corners might be linked to the abrupt change in PCB stiffness at these locations. Similarly, high-strain regions are found close to the PCB mounting screw holes. As a result, these locations can be susceptible to damage as found in [3]. Also, a significant variation of the strain measurements is observed at the package corners.

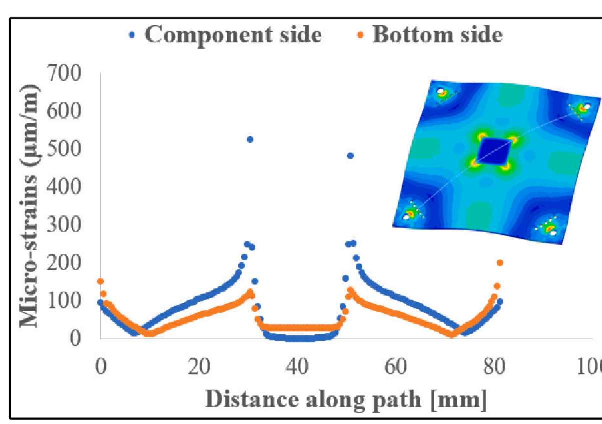

Fig. 6. FEM results showing the impact of strain gauge mounting location on measurements at board level.

Table 2
Strain Gauge Measurement Results: Experiments vs. Simulations.

Strain Gauge Location		Principal max. strain (μm/m)	
At Package	PCB side	Experiments	Simulations
Center	Bottom	23.5 ± 0.4	29
5.5 mm away from corner	Component side	91.3 ± 2.0	120
1 mm away from corner	Component side	208.8 ± 2.1	114

These variations tend to decrease after a distance of 5.5 mm from the package corner. It highlights that the small variations in the positioning of the strain gauge have a large impact on the strain measurements. Hence, It may introduce practical complexities in achieving repeatable strain results at some PCB locations.

Next, the strain gauge measurement methodology is verified on the assembled application PCB. The strain gauge is mounted in the center of the application module board. This location is 5.5 mm away from the package corner of the FO-WLP. The strain gauge measurements show a maximum principal strain level of 139 ± 2.3 μm/m. By the method used in [6,8], it is equivalent to a peak-peak displacement of 0.10 mm. It is summarized in Table 3 and coincides with the measurements from LDV.

3.3. Impact of MEMS accelerometer

The vibration measurement sensor assessment is further extended to include an IMU that can measure the vibration profiles at the module board level during vehicle operation. These sensors are equipped with MEMS-based accelerometers. A comparative analysis between MEMS accelerometers and LASER measurements is carried out. The results of this investigation are presented in Fig. 7 and summarized in Table 3. Both measurement units show similar resonance and acceleration levels. No differences between the two are observed. It can be concluded that vibration measurements during vehicle operation can be directly compared with the LASER measurements in the lab. Hence, the setup with the LASER measurement scheme is exclusively employed for measuring vibrations during module level vibration experiments. Also, MEMS accelerometers can be used for measuring board level vibrations in vehicles. It overcomes the shortcomings of other sensors, such as strain gauges and compact piezoelectric accelerometers. It can be attributed to the fact that the MEMS accelerometers are designed with low damping effects and involve very low mass and accurate mounting method.

4. Impact of module level elements

In this section, the focus shifts to comprehending the influence of module-level elements on the PCB vibration spectrum. These elements are depicted in Figure. It is assessed by exciting the module board that is mounted on top of the thermal heatsink and is embedded inside the housing shown in Fig. 2. PCB vibration spectrum analysis is used for assessing the implications of all module level elements (Fig. 8).

Table 3
Vibration characteristics of the measured application or module board.

Measurement methodology	Measured		FEM
	Peak-Peak Displacement [mm]	Resonance Frequency [Hz]	Resonance Frequency [Hz]
Piezoelectric based accelerometer	0.06 ± 0.03	1501 ± 1	1205
LASER doppler vibrometer	0.10 ± 0.01	1648 ± 2	1346
Strain gauge	0.10 ± 0.02	1648 ± 2	NA
MEMS based accelerometer	0.10 ± 0.01	1648 ± 1	NA

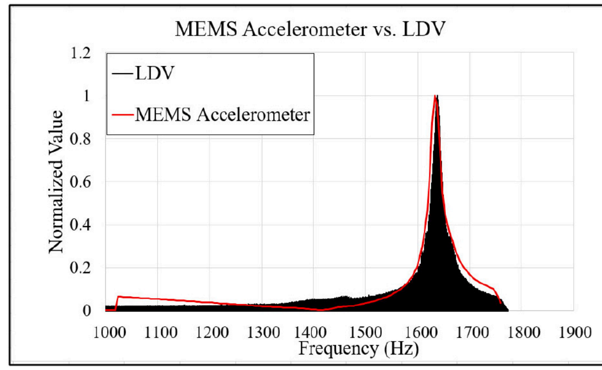

Fig. 7. MEMS accelerometer vs. LASER.

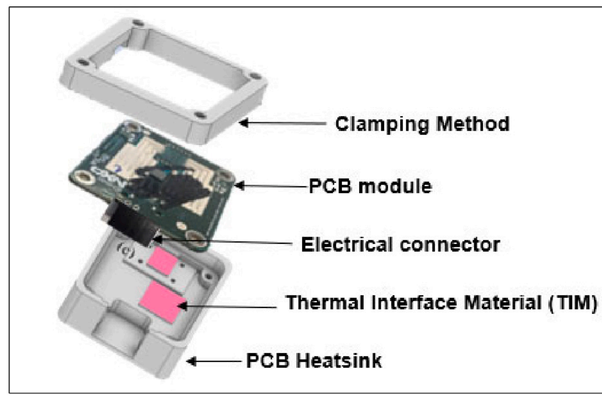

Fig. 8. Basic module level elements.

4.1. PCB heatsinks, TIM & enclosures

The PCB housing and heatsinks wield a significant influence on the PCB vibration response. Thereby, imprinting their impact on the board level reliability of components. The experimentation in this assessment encompasses diverse variations in heatsinks and PCB housings. It comprises of three distinct module design configurations. The first design is shown in Fig. 2. Then, the design of the heatsink is slightly modified by changing the depth profile in the heatsink. It is done to investigate the impact of the variation induced by testing one module to another module. These small changes in design features can either be introduced by design or by manufacturing. It is essential to take this variable into account as it might lead to distinctive loads at the component. It is called the second configuration. The third variant does not involve a heatsink. Instead, the module board is mounted on four pillars inside another PCB enclosure.

The PCB housing with heatsink shown in Fig. 2 mirrors the standard configuration showcased in automotive sensor module demonstrators [2]. Assembled PCB is mounted onto the heatsink-based module is called the module level configuration. The PCB vibration response from this setup is then compared to the PCB assembly mounted on four pillars (called module board level configuration). The findings on this module structure reveal a significant shift when compared to the PCB vibration spectrum at the module board level only. The resonance frequency experiences a slight increment, accompanied by a huge reduction in PCB displacement (shown in Fig. 9). This heatsink potentially imposes constraints on PCB motion, contributing to the observed alterations in the vibration response. Whereas, mounting the assembled PCB on pillars allows for greater PCB flexing and hence larger peak-peak displacement.

The damping observed in Fig. 9 is further enhanced when the module is excited with the thermal interface material (TIM) that is placed in between the heatsink and the component. It is shown in Fig. 10. Also, the

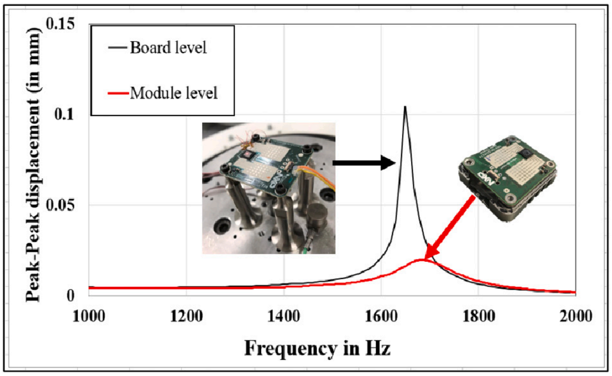

Fig. 9. PCB dynamic response in Board level vs. Heatsink based module level.

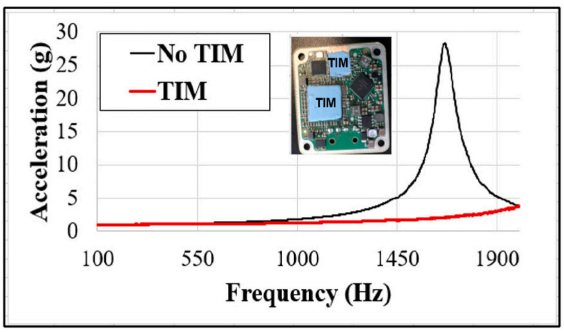

Fig. 10. Impact of TIM on the PCB dynamic response.

resonance frequency is shifted to larger values when compared to the configuration without the TIM. It can be noted that the acceleration levels measured in these boards are much lower than the acceleration level measured on the board level vibration test boards used in [7]. It can be concluded that the module used in this study exerts lower stresses on solder joints when compared to the reliability test boards used in [7].

Then, small design variations are introduced by altering the depth profile of the heatsink (also called the second configuration). The depth profile or the gap between the PCB and the heatsink body is increased by 0.30 mm. As a result, there is a corresponding decrease in the resonance frequency and an augmentation in PCB displacement (illustrated in Fig. 11). The heightened PCB displacement can be understood as a consequence of the increased PCB flexing. The larger gap between the PCB and heatsink body offers reduced PCB constraints. It also results in a reduced PCB resonance frequency under the influence of external vibration loads.

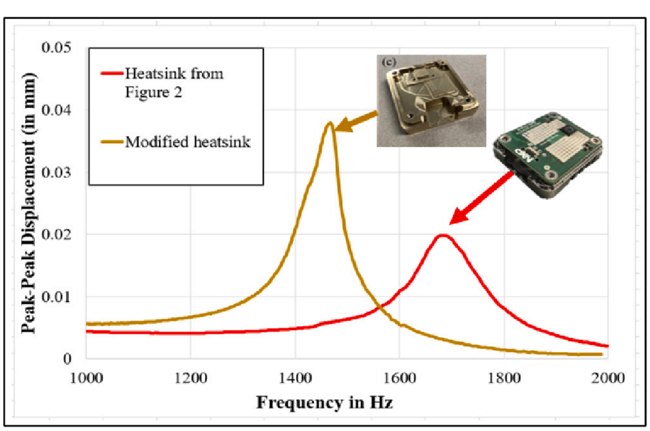

Fig. 11. Impact of heatsink design feature.

Then, another PCB housing is introduced to investigate the extent of influence a housing can impose on the PCB vibration response. It is called the third module configuration. In this equipment, the PCB is encased within a housing, mounted on pillars without a heatsink, and securely screwed onto these four pillars. It is shown in Fig. 12. The results revealed an amplified resonance frequency and heightened displacement (as shown in Fig. 12). This result may be ascribed to the interaction between the resonance characteristics of the housing and the PCB.

The increase in resonance frequency and peak-peak displacement can lead to higher strain rates at the solder joint level. In this case, these strain rates are estimated to be greater than when the same module board is mounted without the PCB enclosure. It can be attributed to the fact that the enclosure has a significantly higher mass or stiffness compared to the PCB. Also, the boundary conditions imposed by the enclosure may alter the PCB vibration modes and frequencies more significantly than the changes in the PCB form factor alone. Furthermore, a slightly asymmetric PCB vibration spectrum is observed when it is excited inside this PCB enclosure. It might be linked to nonlinearity in the system. It may manifest in different ways during vibration testing. It may include material damage or deformation, enclosure mounting method on the test fixture, and structural dynamics such as mode coupling and energy transfer mechanisms. It may arise due to nonlinear interactions between different vibration modes of the PCB and the enclosure itself.

The results show that the method employed for clamping the PCB within the module is also significant. It is further investigated by employing another PCB clamping system. In this mounting configuration, a metallic frame is employed to hold the entire edge of the PCB from all four sides (as shown in Fig. 13). The PCB dynamic response results are also shown in Fig. 13. It reveals that the configuration with the metallic frame exhibited an increased resonance frequency compared to the one with conventional corner clamping. Additionally, there is a noticeable increment in the PCB displacement. It can be attributed to the altered stiffness and boundary conditions introduced by this clamping method. The metallic frame placed at the edge of the PCB increases the rigidity of the electronic system.

Another impact of the PCB clamping method can be drawn from the simulation results shown in Fig. 13. It can be seen that the PCB area close to the mounting screws shows large strain gradients. Such large strain gradients can cause PCB or solder damage in these areas when the PCB assembly is subjected to vibration tests for 24 h. In [3], 100 μm-deep PCB cracks are revealed near the mounting holes of the test board designed in accordance with [29]. A similar trend is expected for components placed close to the PCB clamping frame. In this case, the entire PCB edge is expected to suffer large strains. The clamping method is also expected to impact the mechanical properties of the PCB assembly after some time of operation. Such changes in resonance frequency can be taken into account by using the resonance tracking functionality as used in [30–32].

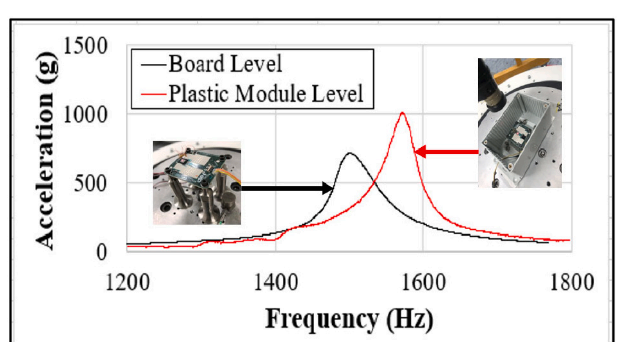

Fig. 12. Impact of PCB enclosure design.

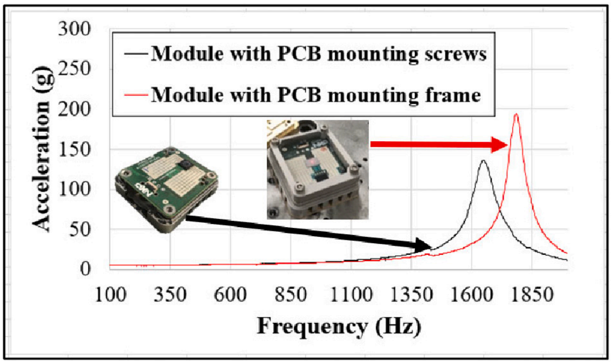

Fig. 13. Impact of changing PCB clamping method.

4.2. Assembled components on board

This section focuses on the interaction of electronic components that are mounted at the functional PCB level. It encompasses the final assembled PCB with electronic components on both sides of the PCB. In addition, it involves the integral electrical connector interfacing with the car architecture. The assessment spans both at board level and module level, where the PCB is placed inside a typical heatsink housing shown in Fig. 2. Comparisons are drawn with the bare PCB to unravel the impact of electronic components on the PCB vibration response.

Board level results unveil a notable correlation between increased PCB mass and a decrease in resonance frequency and displacement, with a further reduction observed in the presence of a big electrical connector. This shift of about 27 % in resonance (shown in Fig. 14(a)) can be explained by the Eq. (1). This trend also persists when the PCB is excited with the standard heatsink-based module (shown in Fig. 2). The trend is shown in Fig. 14(a). However, the reduction in resonance is about 20 % in this case. In contrast, it is found that the presence of electrical and electronic components distorts the vibration signal at the module board level (shown in Fig. 14(b)). Thereby, it impacts the distribution of forces and bending moments across the PCB. The integration of electronic components on the PCB introduces additional mass and changes the overall stiffness of the assembly. When placed within a module, the interaction between the housing and other module board-level elements could induce different vibrational modes.

4.3. Component location and symmetry

The location of electronic components on the functional PCB within the module is also a critical factor influencing the stresses on components. In this investigation, the FO-WLP component is positioned off-center, while the BGA IC is situated near the center of the PCB on the opposite side. The study compares the PCB vibration spectrum at the center versus the off-centered location where the FO-WLP device is placed. The results reveal that the component placed in the middle of the PCB experiences higher stress levels than the off-centered location where FO-WLP is placed. PCB flexing is maximized at the central location in comparison to the other measured location on the PCB (it is shown in Fig. 15(a)). So, the BGA component is expected to receive more stress than the FO-WLP placed in this specific module configuration. Another consequence of this phenomenon is shown in Fig. 15(b). It can also be seen that the BGA experiences asymmetrical stresses. Solder joints close to the center of the PCB (top and bottom right) receive more stress than the ones situated closer to the edge of the PCB. So, it is expected to induce more solder failures at this location than compared to other PCB locations.

4.4. Summary of module level effects

The implications of all module level elements on PCB displacement and resonance are summarized in Table 4. A comparison between these

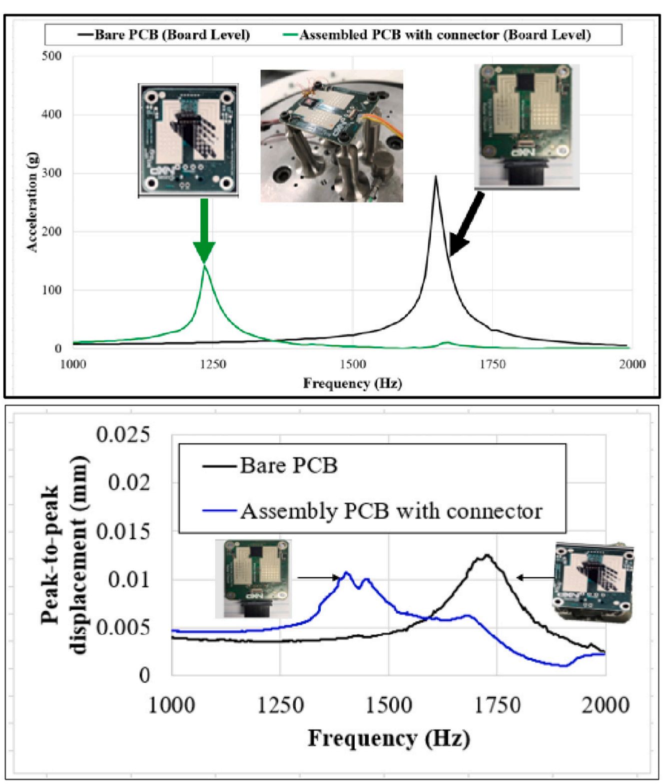

Fig. 14. Impact of component assembly on PCB dynamic response (a) PCB without heatsink (b) PCB with heatsink.

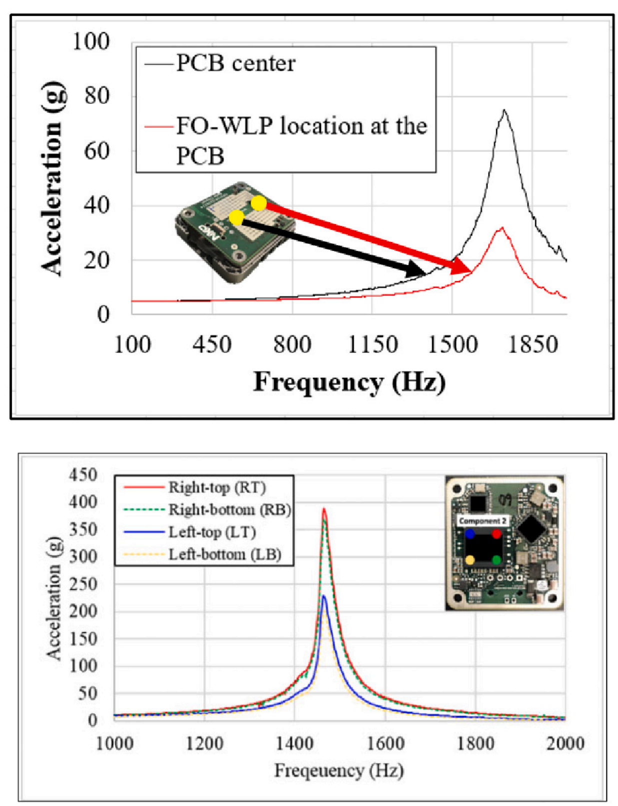

Fig. 15. Impact of component location and symmetry (a) For FO-WLP (b) For BGA.

Table 4
Vibration characteristics for the measured module compared to the enclosed application board level.

Module level elements	Peak-Peak Displacement	Resonance Frequency
Heatsink	Decreased by 98 %	Increased by 12 %
Heatsink-Heatsink variation	Increased by 90 %	Decreased by 7 %
TIM	Decreased by 80 %	Increased by 15 %
PCB enclosure	Increased by 43 %	Increased by 6 %
PCB dimensions (when compared to PCB in [7])	Increased by 92 %	Decreased by 70 %
Assembled module board	Decreased by 9 %	Decreased by 16 %
Component close to center	Increased by 60 %	Similar
PCB clamping method change (from point to edge)	Increased by 33 %	Increased by 6 %

parameters at the module level and those at the module or application board level is conducted. So, the application board level is taken as a reference. An increment in peak-peak displacement in combination with a rise in resonance frequency is expected to induce more damage at the solder joint levels than those in the application board level tests. According to Table 4, the major impact is induced by the heatsink, PCB enclosure, TIM, component location, and the PCB construction itself. Moreover, the test frequency applied during this board level vibration testing may or may not account for this modified resonance frequency of the PCB. Therefore, the translation of lifetime in board level vibration tests to the actual lifespan of solder joints might be inaccurate. These changes in the PCB vibrational motion can also impact the failure location and failure mode when compared to those obtained in application board level vibration test studies. So, there are some module level elements for which the reliability risks are not covered by the application board level vibration tests. These features include heatsink hardware, PCB enclosure, and component placement location concerning the PCB clamping method. So, it necessitates stress evaluations at the module level by the electronic module designer such that it is validated in the final application. Based on these investigations, it might be possible to define a worse-case application board level vibration test as an envelope for the module.

5. Conclusion & outlook

Overall, this investigation lays a foundation for automotive application-driven vibration testing. This reliability test methodology demands vibration stress measurements both in the lab and real-world automotive environments. It also necessitates a well-characterized vibration test setup that can replicate the stresses undergone by components in the final application. This study correlated the PCB vibration measurement sensors used in labs (such as LDV) to those employed in real-world vehicle applications (such as MEMS accelerometers). LDV measurements complement well with the MEMS accelerometers. The formulation of a vibration test method at module board level also revealed inherent pitfalls in the test methodology. For example, changes in strain values emerge when the strain gauge is employed on PCBs with components. The differences are primarily attributed to the specific location of components on the PCB, which in turn affects the amplitude of strain gauge signals.

A module level vibration test method is developed to determine board module stress interaction. The PCB vibration spectrum analysis is used to link the stresses transferred onto the solder joints. This investigation elucidated the impact of module level features present within them. The PCB form factor, PCB enclosure, small variations in the heatsink, TIM, and component location emerge as pivotal factors. It is expected to exert a significant influence on the failure mode and lifespan of solder joints. By understanding the stress profiles in automotive module applications, electronic components, and modules can be designed to provide optimal reliability in a cost-effective manner.

Board level reliability testing with the standardized board is vital because it enables the comparison of vibration performance of surface-mounted components. However, the module design also plays a crucial role in either reducing or increasing the stresses on components. In instances where these stresses may surpass those experienced during board level vibration testing, the conventional standardized board level vibration testing may not adequately address the reliability concerns. Therefore, in those cases, board module level vibration testing is anticipated to cover solder joint reliability risks effectively. These scenarios can be determined by correlating the PCB vibration spectrums of the module board when it is residing in a given enclosure and the reliability test board used in board level vibration testing.

The evaluation of the solder joint reliability risks for automotive components will involve two primary steps. Firstly, understanding the board level vibration stresses endured by components in automotive applications is essential. Secondly, a comparison of these so-called application mission profiles with loads applied during accelerated vibration testing in the lab is imperative. This correlation is expected to enable the assessment of solder joint reliability in automotive applications. These are some of the major foundations for an automotive application-driven vibration test approach. Future studies will delve into these aspects further.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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