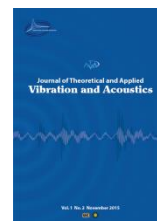




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# Vibration simulation and fatigue life estimation of a printed circuit board using a validated model

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### ABSTRACT

An electronic package consists of printed circuit boards (PCBs) placed in a casing joined together. Electronic circuit boards should operate properly in different conditions including thermal cycling, vibrations, and mechanical shock. Printed circuit boards require to be analyzed electrically as well as mechanically for optimized performance. In this paper, the finite element analysis (FEA) of a PCB is carried out in ANSYS and the results are validated utilizing modal testing. The natural frequencies and mode shapes of the PCB are determined, and the effect of mechanical shock on the PCB is also evaluated. The results demonstrate that the PCB has three resonance frequencies in the range of 0-1000 Hz. The mode shapes related to each natural frequency are also obtained employing ANSYS software. These data can be used for fatigue life estimation and mechanical shock analysis. In this work, the fatigue life estimation of wires and solder joints under sinusoidal and random vibrations are estimated as well by using the Steinberg's method. The results illustrate that random vibration has more impact than harmonic vibration on the fatigue life of solder joints and wires according to the Peugeot standard. Also, the results have passed the Peugeot standard qualification in both random and harmonic vibrations.

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## **1. Introduction**

Electronic equipment in automobiles is used to control and adjust the performance of subsystems and must be able to operate in harsh environments including shock and vibration. Mechanical shock occurs as a result of displacement or excessive force over a short duration which can cause the failure of the electronic circuit in a shorter time than the fatigue life of the part. Due to the different natural frequencies of each component, there is a possibility of failure of electronic circuit components. Increasing the reliability of electronic devices plays an essential role in the aerospace and automotive industries. The vibration loadings and thermal cycling, are the most significant external factors influencing the useful lifetime and the stability of power electronic systems in these industries. Hence, there is much interest in studying the fatigue life of electronic power devices [1, 2]. An electronic circuit includes various parts such as mechanical equipment, solder joints, retainers, etc. Salvatore et al. in [3] performed simultaneous testing of heat and vibration of solder joints using random excitation in eight electronic circuits with different solders and components on it, and then the fatigue life of each was extracted. In another study, Jiang Xia et al. in [4] performed a randomly excited vibration fatigue test on an electronic circuit using different frequency domains and compared the results. They also compared the test results with the Steinberg fatigue model and provided an accurate method for predicting the fatigue life of the electronic circuit. Another area of study is the fatigue analysis of PCB supports including solders filled in the board holes. In addition to the electronic connection, this also provides the mechanical connection of the heavy electronic components (such as capacitors) mounted on the PCB. If the PCB supports fluctuate, these lead wires may fail usually due to fatigue. These fluctuations usually occur at the lowest resonant frequency [5, 6].

In 1972, Eshleman et al. in [7] designed electronic circuits in the aerospace industry subject to high vibration and mechanical shock. Also, the effect of increasing the number of different electronic components, including resistor, capacitor, etc. on the vibrational performance of electronic circuits has been investigated. In 2000, Steinberg et al. in [8] proposed methods for designing and manufacturing electronic circuits for operating conditions with severe vibrations and mechanical shocks. This study described how to design and estimate the fatigue life of an electronic circuit with different components. Finite element simulation can be a more efficient way to study vibrations, fatigue life, mechanical shock, etc. on a printed circuit board. Thus, in 1990, Pitarresi et al. in [9] addressed the general considerations for modelling electronic circuits and various methods for simulating electronic components on electronic circuits. Also, numerical and laboratory methods have been proposed to calculate the natural frequencies and mode shapes of electronic circuits. Similar studies have been done to model electronic components on the board each using a specific type of modelling. The choice of each method depends on the operating conditions of the problem and the type of output data. A commonly used method of modelling electronic circuits is the Finite Element Analysis (FEA) [10-12]. Robin et al. in [13] worked on simplifying complex models of electronic boards and provided a convenient way to simplify different components. Simplifying electronic circuits causes errors in the obtained results. The above research describes how the error occurs due to various simplifications.

In this paper, a PCB is modelled by the finite element method. Due to the complexity of the model and a large number of electronic components on the PCB, the geometry of the components has been simplified and small parts with minimum effect on the vibration response have been ignored to simplify the simulation and reduce the calculation time. The natural

frequencies of the board are obtained from both experimental modal analysis and simulation. The mechanical shock response of the board is also simulated in ANSYS to study its behaviour in operating situations. Finally, the fatigue life estimation of wires and solder joints under sinusoidal and random vibrations are estimated using the Steinberg's method. The results show that random vibration has more effect than sinusoidal vibration on the fatigue life of solder joints and wires.

## **2. Modal Analysis**

Modal analysis is the process of determining the inherent dynamic characteristics of a system in the forms of natural frequencies, damping factors, and mode shapes and using them to formulate a mathematical model for its dynamic behaviour [14]. In this research, the modal parameters of the system are the natural frequencies extracted from the modal analysis of the PCB. In order to prepare an operational situation for the printed circuit board, the test was carried out with the PCB package. It contained the lower aluminium casing and upper plastic cover, as shown in Fig 1. or obtaining accurate results, the bolt and nut connection that attaches PCB to the lower casing must be completely rigid. Therefore, at first, bolts and nuts were screwed by a specific torque at four locations. Then, the PCB was excited by a shaker at a high-frequency level, and the torque of the bolt and nut connection was rechecked by a torque meter. As shown in Fig 1, the PCB package was installed on the shaker by a steel plate screwed to the vibration shaker. Also, the PCB with electronic components is shown in Fig.1. A single-axis miniature piezo accelerometer was mounted near the large capacitor since the Finite Element (FE) model showed more deflections in the vicinity of the large capacitor. The sine sweep excitation was applied in the modal testing in the 0-1600 Hz frequency range. The specifications and model numbers of the shaker and accelerometer used in the experiment are listed in Table 1.

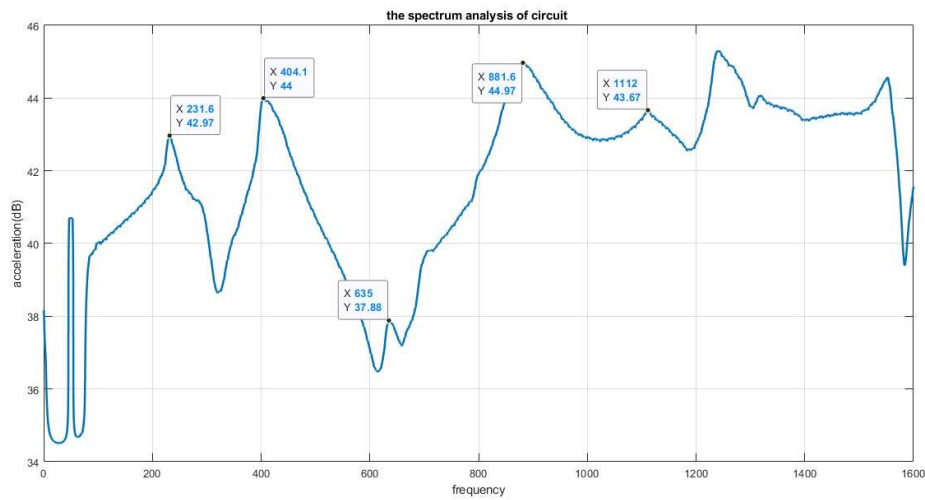


**Fig 1.** Lower aluminium casing and upper plastic cover

**Table 1.** Specification and model numbers of testing equipment

Equipment	Specs	Company and Model No.
<b>Shaker system</b>	Rated peak force: 1kN	TIRA TV 5220/LS-120
	Frequency range: DC-7kHz	
	Maximum acceleration: 60g	
<b>Miniature Accelerometer</b>	Linear frequency response range: 1 to 10000 Hz	ENDEVCO 2222C
	Sinusoidal vibration limit: 1000g pk	
	Weight: 0.5 gr	
	Charge sensitivity: 1.4 pC/g	

The natural frequencies of the PCB package obtained by the modal testing are reported in and Table 2.



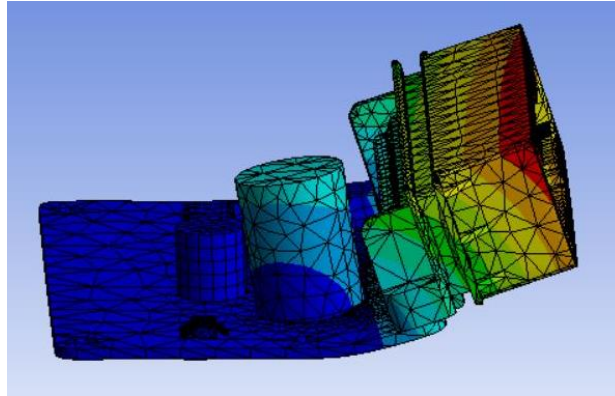
**Fig 2.** Acceleration-frequency figure of PCB package determined by modal testing

**Table 2.** First three natural frequencies of the PCB

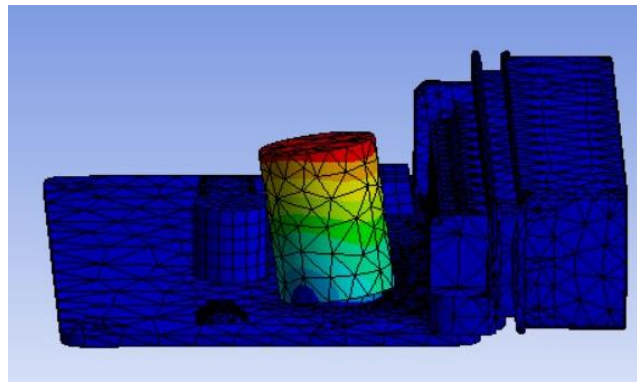
# natural frequency	Hz
1 <sup>st</sup>	231
2 <sup>nd</sup>	404
3 <sup>rd</sup>	635

### 3. Finite Element Modal Analysis

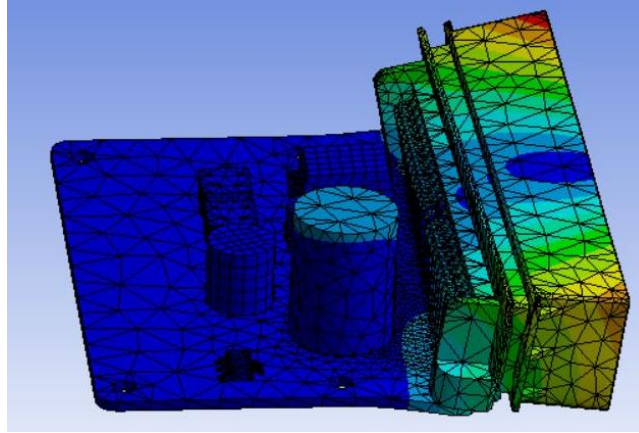
In order to obtain frequencies and mode shapes, the three-dimensional model was analyzed by modal analysis in ANSYS software; the three first natural frequencies were determined to be 232.72, 409.65, and 614.15 Hz, respectively. The frequencies are related to the connector, large capacitor, and twist of the connector, respectively. The corresponding mode shapes are shown in Figs. 3, 4, and 5.



**Fig 3.** First mode shape in 232.72 Hz



**Fig 4.** Second mode shape in 409.65 Hz



**Fig 5.** Third mode shape in 614.15 Hz

Table 3 compares the experimental and simulation results for PCB natural frequencies.

**Table 3.** Comparison of experimental modal test and simulation results

Natural Frequency	Experimental modal test	Simulation
1 <sup>st</sup>	231 Hz	232.72 Hz
2 <sup>nd</sup>	404 Hz	409.65 Hz
3 <sup>rd</sup>	635 Hz	614.15 Hz

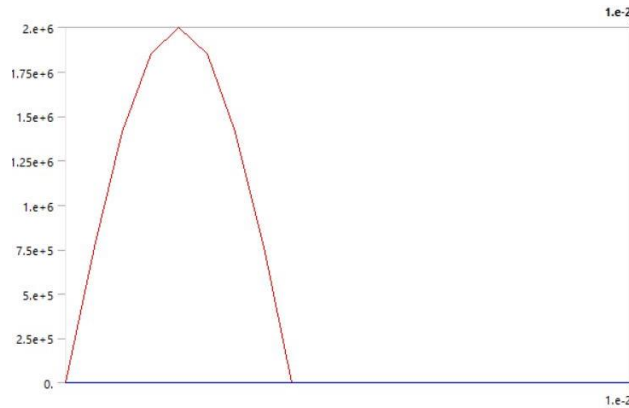
#### 4. Mechanical Shock Simulation

The use of PCBs in harsh environments with high levels of shock and vibration leads to high acceleration and consequently, more dynamic stress in electronic components. Therefore, the ability to predict and, if possible, reduce the amplitude of the dynamic response of this equipment is essential.

The shock response analysis is usually done in two ways: response spectrum analysis and time history analysis. The response spectrum analysis calculates the maximum response of the system to the applied load, but time analysis calculates the result at each time step and is more accurate than response spectrum analysis. For this reason, the response was solved in the transient structural environment of ANSYS Workbench.

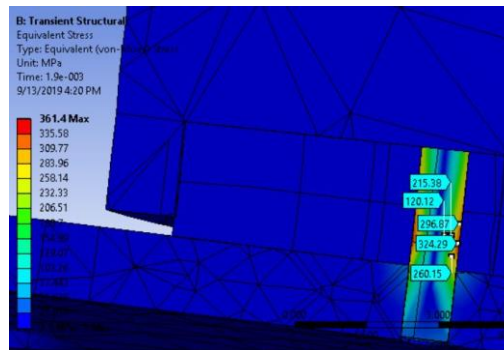
The shock response analysis was performed by a half-sine pulse force with a peak of 2,000 m/s<sup>2</sup> and a duration of 4 ms. The analysis was performed for 20 ms with a time step of 0.05 ms in three directions *x*, *y*, and *z*. The validated model by modal analysis was used to analyze the shock response.

The boundary conditions for this analysis are the same as for the modal analysis. The response of the PCB to shock load was derived from the superposition of the mode shapes obtained in the modal section. The acceleration input is shown in Fig 6.



**Fig 6.** Shock load time history (vertical axis: acceleration in mm/s<sup>2</sup> and horizontal axis in seconds)

The results of the analysis show that the von Mises stress at the lead wire of the parts has increased due to the shock. By applying the shock in  $x$  and  $y$  directions, only the lead wire of the capacitor is subject to significant stress of about 300 MPa (Fig7), and the stress is negligible in other places.



**Fig 7.** Stress analysis of the capacitor wire due to shock in the  $x$ -direction

By applying stress in the  $z$ -direction, the stress at supports and the Q701 and D701 components, as well as the capacitor lead wire, is noticeable, as shown in Figs 8 & 9.



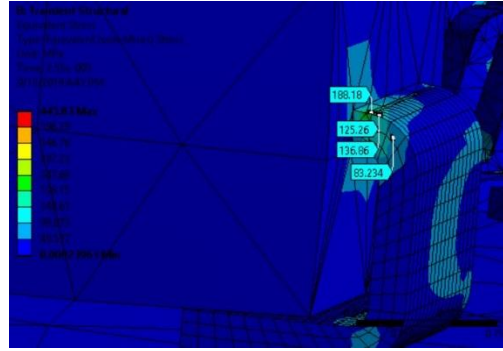


Fig 8. Stress analysis in D701 by applying shock in the z-direction

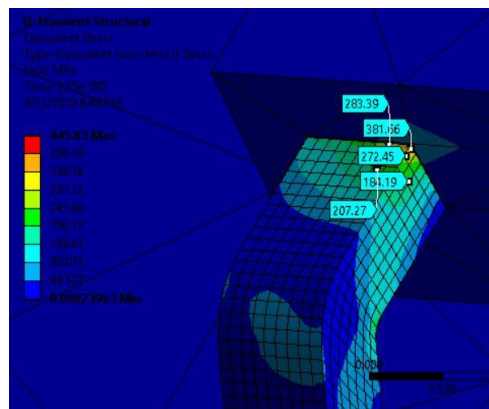


Fig 9. Stress analysis in Q701 by applying shock in the z-direction

## 5. Fatigue Life Estimation

Electronic equipment must work in severe vibration and thermal environments without any failure. Two primary types of vibrations are harmonic or sinusoidal excitation and random vibration. The test of electronic equipment and whose simulation using numerical software shows that the fatigue life of lead wires and solder joints is related to the relative motion of the PCB. Therefore, the resonant frequency of the PCB must be determined in order to obtain the approximate fatigue life relations.

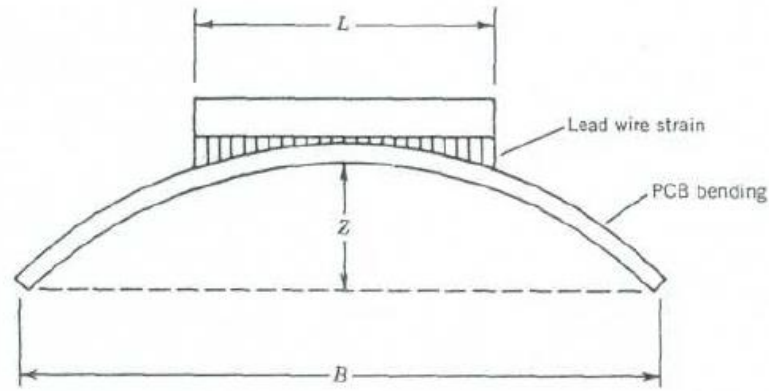
Steinberg et. al in [3] have developed a fatigue model that predicts the life of electronic components attached to a PCB where only a few parameters of the component and the PCB need to be known. Steinberg's model has the advantage of estimating directly the survival of the joints between electronic components and the PCB subjected to dynamic loads like random vibration and shock. In the following, a review of the Steinberg's method will be presented.

### 5.1. Steinberg's Method – Sinusoidal Vibration

Extensive electronic vibration testing data and analysis techniques, using the Finite Element Method (FEM), have shown that the fatigue life of electronic components can be related to the



dynamic displacements developed by PCBs. These studies have shown that lead wires and solder joints will fail long before any failures in the printed circuit etched copper traces on the PCB. These studies also showed that the electronic components could achieve a fatigue life of about 10 million stress reversals in a sinusoidal vibration environment when the peak single-amplitude displacement of the PCB is limited to the value shown in Eq. (1) for PCBs excited at their resonance frequency, as shown in Fig 10, when the component is mounted at the center of the PCB [15].



**Fig 10.** Schematic of PCB displacement in resonance frequency

$$Z_{\text{initial}} = \frac{0.00022B}{chr\sqrt{L}} \quad (1)$$

Where  $Z_{\text{initial}}$  is the maximum PCB displacement which results in 10 million cycles failing under random vibration loading and 20 million cycles failing under sinusoidal vibration. Parameters  $c$  and  $r$  are related to component type and relative position factors, respectively, and their different values are listed in Tables 5 and 6.



**Table 4.** Definition of parameters

Parameter	Definition	Unit
$B$	length of the PCB edge parallel to the component	in
$L$	length of the component body	in
$h$	height, or thickness of PCB	in
$c$	component type	--
$r$	relative position factor	--
$Z$	maximum desired PCB displacement	in

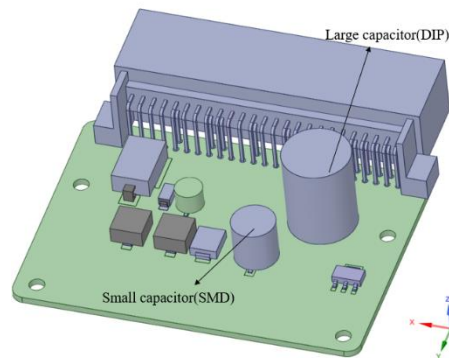
**Table 5.** Example of relative position factor ( $r$ )

Component location	$r$
1/4 point on X-axis and 1/4 point on Y-axis	0.5
Component located near one side of the PCB	0.707
Component located at the center of the PCB	1

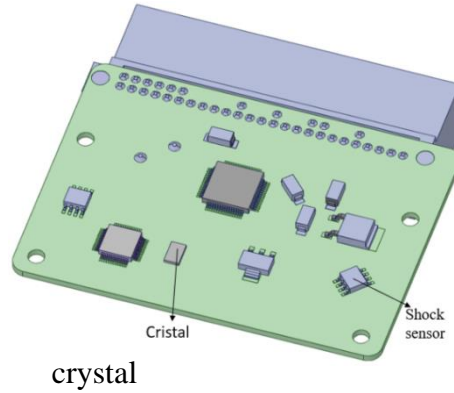
**Table 6.** Constant ( $c$ ) for the different types of components [8]

C	Component	Image
0.75	Axial leaded through hole or surface mounted components, resistors, capacitors, diodes	
1.0	Standard dual inline package (DIP)	

A printed circuit board as a case study is shown in Figs. 11 and 12.  $Z_{\text{initial}}$  was calculated for four important components mounted on the PCB; large capacitor, a small capacitor, crystal, and a shock sensor (See Table 7).



**Fig 11.** PCB 3D model (top) – location of electronic components on the board



**Fig 12.** PCB 3D model (bottom) – location of electronic components on the board

**Table 7.** Calculation of  $Z_{\text{initial}}$  for different components under sinusoidal vibration

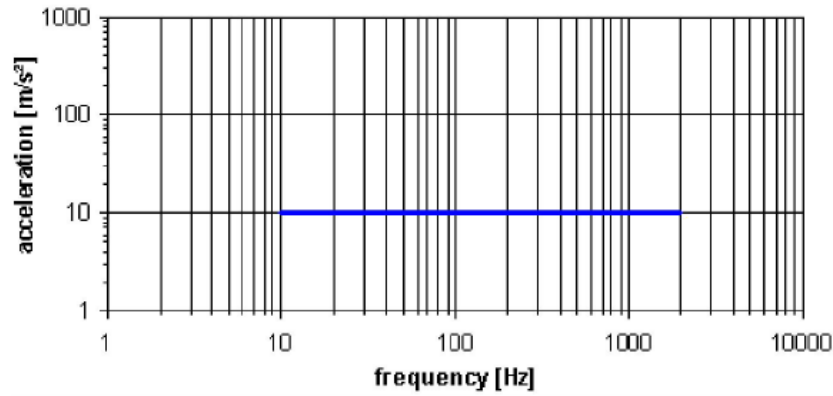
#	Component	$c$	$r$	$h$ (in)	$L$ (in)	$B$ (in)	$Z_{\text{initial}}$ (in)
1	Large capacitor	0.75	0.492	0.0618	0.62	3.13	0.0383
2	Crystal	0.75	0.795	0.0618	0.2	3.13	0.0417
3	Shock sensor	1	0.274	0.0618	0.19	3.13	0.0932
4	Small capacitor	0.75	0.766	0.0618	0.4	3.13	0.0306

The maximum single-amplitude displacement expected at the center of the PCB during the resonant condition can be obtained by assuming the PCB acting like a single-degree-of-freedom system as follows [15].

$$Z_{\text{final}} = \frac{9.8G}{f_n^2} \quad (2)$$

where  $G$  is the standard acceleration and  $f_n$  is the natural frequency. It should be noted that Eq. (2) assumes the worst case of resonance without damping in determining  $Z_{\text{final}}$ . Therefore, the obtained results for the fatigue life of the components are conservative and their actual lifetime is longer.

The Peugeot standard was used to determine the standard acceleration in Eq. (2). In Fig 13, the acceleration versus natural frequencies under sinusoidal vibration is presented. The standard acceleration was determined using Fig 13 and then  $Z_{\text{final}}$  was obtained to be  $6e - 6$  in for all components assuming the resonant frequency of 404 Hz.



**Fig 13.** Acceleration of PCB in different resonance frequencies according to Peugeot standard

After determining  $Z_{\text{initial}}$  and  $Z_{\text{final}}$  from Eqs. (1) and (2), the number of cycles to fail ( $N_2$ ) can be obtained for lead wires and solder joints under sinusoidal vibration using Eq. (3) [15].

$$N_1 Z_1^b = N_2 Z_2^b \quad b = 6.4 \quad (3)$$

Tabel 8 shows the number of cycles to fail ( $N_2$ ) for different components under sinusoidal vibration.

**Table 8.** Fatigue life calculation for different components under sinusoidal vibration

Component	Large capacitor	Crystal	Shock sensor	Small capacitor
<b>Fatigue life (year)</b>	$4.70 \times 10^{13}$	$8.15 \times 10^{13}$	$1.39 \times 10^{16}$	$1.125 \times 10^{13}$

## 5.2. Steinberg's Method – Random Vibration

In this section, the fatigue life of wires and solder joints under random vibration is determined. Here, Eq. (4) is used instead of Eq. (2) to determine  $Z_{\text{final}}$ .

$$Z_{\text{final}} = \frac{9.8 G_{\text{rms}}}{f_n^2} \quad (4)$$

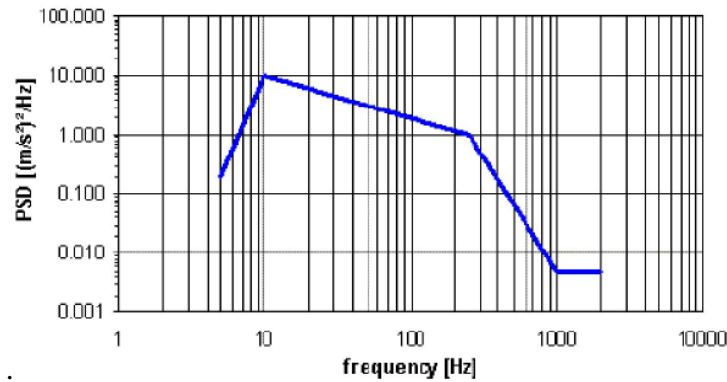
$$G_{\text{rms}} = \sqrt{\frac{\pi}{2} p f_n Q} \quad (5)$$

$$Q = \sqrt{f_n} \quad (6)$$

In order to determine different values of Power Spectral Density (PSD) in Eq. (4), the Peugeot standard was used. The PSD for devices on the sprung mass versus natural frequencies for random vibration is presented in Fig 14.

**Table 9.** Definition of parameters in Eq. (5)

$p$	Power Spectral Density (PSD)	$\frac{G^2}{Hz}$
$f_n$	Natural frequency	Hz
$Q$	Displacement factor	--

**Fig 14.** Different values of power spectral density in different natural frequencies under random vibration

It is noted that a Factor of Safety (FoS=5) has been considered for PSD values.

**Table 10.** Grms for different electronic components under random vibration

#	component	$f_n$	Q	Grms
1	Large capacitor	404	20.1	112.91
2	Crystal	404	20.1	112.91
3	Shock sensor	404	20.1	112.91
4	Small capacitor	404	20.1	112.91

After determining  $G_{rms}$ ,  $Z_{final}$  was recalculated similarly and fatigue life of wires and solder joint under random vibration is obtained as in Table 11.

**Table 11.** Fatigue life calculation for different components using Equation (3) under random vibration

Component	Large capacitor	Crystal	Shock sensor	Small capacitor
<b>Fatigue life (year)</b>	102.85	178.15	30423.83	<b>2.59</b>

## 6. Conclusion

In the current study, a reliable three-dimensional finite element model was obtained for an electronic board for vibration analysis purposes. The model can be used to calculate the stresses

in the wires and solder to determine their fatigue life. The 3D model of this electronic board was modeled in ANSYS software, and finite element analysis was performed to determine the natural frequencies of the PCB that matched closely to the obtained values from experimental modal analysis. The equality of the three first natural frequencies in both experimental and finite element methods indicated that the finite element model and the supports and contacts between the parts were correctly defined. To evaluate the mechanical shock, the obtained model was used as a simulator. A half-sine shock load was applied to the PCB in different directions and the response was determined. The fatigue life estimation of lead wires and solder joints under random and sinusoidal vibration was carried out as well. In order to estimate the fatigue life, the Steinberg's method was used. In this method, for calculating the fatigue life of the wires and solder joints, it is sufficient to calculate the stresses caused by the thermal or vibrational load. The results showed that random vibration makes lead wires and solder joints fail sooner than sinusoidal vibration. In other words, random vibration has more effect on the fatigue life of PCB components according to the Peugeot standard.

## **Acknowledgement**

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