Defence Science Journal, Vol. 66, No. 3, May 2016, pp. 210-215, DOI : 10.14429/dsj.66.8936

RESEARCH PAPER

Dynamic Analysis of HSDB System and Evaluation of Boundary Non-linearity through Experiments

K. Chandrakar*, P.L. Venkateshwara Rao, P. Rajendran, and C. Satyanarayana

Defence Electronics Research Laboratory, Hyderabad - 500 005, India

**Correspondence e-mail: kd211280@gmail.com*

ABSTRACT

This paper deals with mechanical design and development of high speed digital board (HSDB) system which consists of printed circuit board (PCB) with all electronic components packaged inside the cavity for military application. The military environment poses a variety of extreme dynamic loading conditions, namely, quasi static, vibration, shock and acoustic loads that can seriously degrade or even cause failure of electronics. The vibrational requirement for the HSDB system is that the natural frequency should be more than 200 Hz and sustain power spectrum density of 14.8 G_{rms} in the overall spectrum. Structural integrity of HSDB is studied in detail using finite element analysis (FEA) tool against the dynamic loads and configured the system. Experimental vibration tests are conducted on HSDB with the help of vibration shaker and validated the FE results. The natural frequency and maximum acceleration response computed from vibration tests for the configured design were found. The finite element results show a good correlation with the experiment results for the same boundary conditions. In case of fitment scenario of HSDB system, it is observed that the influence of boundary non-linearity during experiments. This influence of boundary non-linearity is evaluated to obtain the closeout of random vibration simulation results.

Keywords: Natural frequency, random vibration, finite element analysis, power spectrum density, printed circuit board

NOMENCLATURE

f_n	Natural frequency of PCB
D	Flexural rigidity of PCB
a	Length of the printed circuit board
b	Width of the printed circuit board
h	Thickness of the printed circuit board
E	Equivalent Young's modulus of PCB
υ	Equivalent poisson ratio of PCB
λ	Equivalent mass per unit area of PCB
E_k	Modulus of elasticity of the k^{th} layer of printed circuit board
d_k	Distance of k^{th} layer from neutral axis
μ_k	Density of the k^{th} layer of PCB
G_{rms}	Root mean square acceleration

1. INTRODUCTION

High speed digital board (HSDB) is used to perform accurate parameter measurement, classification, identification and determination of technical parameters of different type of radars. This system is developed as an independent entity that contains multi-layer PCB with different types of surface mount components and mechanical enclosure. The exploded view of HSDB system is shown in Fig. 1.The overall size of HSDB system is 253 mm x 180 mm x 22 mm. PCB is mounted on the cavity which is enclosed by connector panel and cover. The Connector panel has provision for connector to facilitate HSDB to connect with other systems. The cover acts as a lid for the entire cavity with PCB.

This system is exposed to harsh and high intensity vibration which could be harmful for electronic components packaged over the PCB. It could also cause some components in the PCBs to fail due to fatigue and tearing problem in lead wires and solder joints. Many studies have been done in the area of structural design, analysis and estimation of fatigue life of PCB components. Perkins and Sitaraman[1] investigated the failure of solder joint of packages due to the vibration in an electronic system. Sakri[2-3] has estimated the fatigue-life of electronic packages against sinusoidal and random vibration loads. Yeong[4], *et al.* and Weibin Tang[5], *et al.* have studied the reliability of the solder joint of plastic ball grid array under vibration load using numerical analysis and experimental test. Subramanaya[6], *et al.* studied the strength and stability requirement of the electronic packages to withstand dynamic load and discussed the cause of mechanical failures like solder joint fatigue failure, excessive deflection high stress level etc. They concluded that a proper mounting provision has to be incorporated to meet stiffness and strength requirement to protect the critical electronic components against high vibration level. The complex and fragile structure of electronic systems require a special attention in order to sustain the vibration level of the different platform. Dynamic analysis of electronic systems using analytical methods is very difficult

Received : 22 June 2015, Revised : 10 March 2016
Accepted : 31 March 2016, Online : 25 April 2016

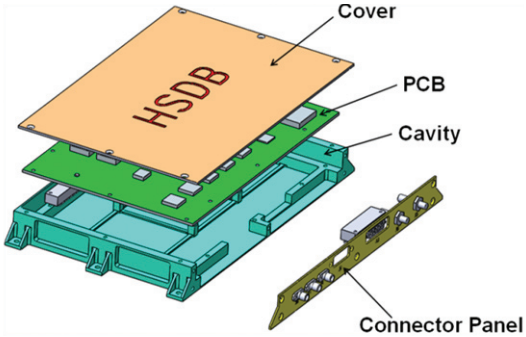

Figure 1. Exploded view of HSDB system.

and sometimes even impossible due to the complexity of today's electronic assemblies. Therefore, numerical simulations are generally preferred instead of dealing with complicated formulations. Eventually, conducting experiment is indispensable in order to validate computational results and they also lead to improvement of finite element model.

2. PROBLEM DEFINITION AND APPROACH

The objective of present work is to design and develop a light weight HSDB enclosure to meet the vibrational severity of the military environment which possesses a variety of extreme conditions that can seriously degrade or even cause failure of electronic components. The total weight of system is constrained to be within 1.4 kg including the electronic weight of 800 g approximately. Hence, the weight of housing is restricted to 600 g. The critical vibrational requirement for the system is that the natural frequency should be more than 200 Hz and maximum acceleration level on the PCB should be less than 50 G_{rms} against input load of 14.8 G_{rms}. The design approach of HSDB is mechanical configuration of enclosure, dynamic vibration (eigen value and random vibration) analysis and experimental validation. To make minimum dynamic response at component locations on the PCB, a systematic design approach of Veprin[7] and Cifuentes[8], *et al.* are followed. Experimental investigation of resonance frequencies and their couplings in the system to be explored in order to reduce the rms acceleration levels of surface mount packages (FPGA, oscillator etc.) over the 14 layers PCB. FE simulation tool is utilized to meet weight constraint of system and the rms acceleration level on the PCB within the designed limit for its safe operation.

3. THEORETICAL FORMULATION

The material used for the cavity, connector panel and cover is aluminium alloy AA 6351-T6. The PCB is a made of 14 conductive copper layers sandwiched with FR4 layers. The size of PCB is 233.4 mm x 160 mm x 2 mm. The theoretical formulation to find response of PCB against the dynamic load is estimated by considering the PCB as sandwich plate. Based on the Steinberg theory[9], natural frequency of a rectangular uniform plate fixed at all four edges is given as Eqn. (1)

$$f_n = \frac{\pi}{1.5}\left[\frac{D}{\lambda}\left(\frac{3}{a^4}+\frac{2}{a^2b^2}+\frac{3}{b^4}\right)\right]^{1/2} \quad (1)$$

where

$$D = \frac{Eh^3}{1.5\left(1-\upsilon^3\right)} \quad (2)$$

The natural frequency of sandwich plates is computed using the formula developed for homogenous plates by Blevins[10] and Aytekin & Nevzat[11]. The sandwich plate equivalent stiffness and mass per unit area are expressed as Eqn. (3) and Eqn. (4), respectively.

$$\frac{Eh^3}{12} = \frac{2}{3}\sum_{k=0,1,2} E_k\left(d_{k+1}^3 - d_k^3\right) \quad (3)$$

$$\lambda = 2\sum_{k=0,1,2} \mu_k\left(d_{k+1} - d_k\right) \quad (4)$$

The natural frequency of PCB evaluated by theoretical formulation using Eqn. (1) to Eqn. (4) is 416 Hz which gives an idea about the dynamics of PCB and based on that the dynamic analysis of subsystem can be done.

4. FINITE ELEMENT ANALYSIS

FE model of the system is generated with 8 nodes reduced order quad shell element (S8R) which utilizes quadratic interpolation due to midside nodes and support laminated composite. It provides robust and accurate solutions under all loading conditions. Finite element analysis (FEA) has been carried out using Abaqus[12] 6.13. The natural frequency and mode shapes are extracted using Eigen value analysis. The random vibration analysis is carried out for input PSD spectrum of 3 db/octave from 20 Hz to 100 Hz, 0.2 g^2/Hz from 100 Hz to 700 Hz and -6 db/octave from 700 Hz to 2000 Hz. The critical parameter which is to be monitored is the acceleration response on the PCB in order to achieve its defined level. The major assumption considered in FE analysis are:-

- The cavity is rigidly fixed on the bottom flange at six locations.
- Since the properties of FRP are orthotropic, the stress calculation is based on the assumption of plane stresses in each layer.
- Connections between the parts through fasteners are considered as perfectively rigid joints.
- The FE analysis is based on linear perturbation method which can be applied for linear system.

The boundary conditions considered for FE analysis is linear constraint which is bounded without any separation for every step frame. Fixed constraints are applied on the FE model at mounting locations of the cavity. Tie constraint are used for connection between the parts at fasteners locations. The PCB is modelled with 29 layers of Cu and FR4 material as per construction (14 Cu layers and 15 FR4 layers). The various material considered in the design are given in Table 1.

5. EXPERIMENTAL TEST SETUP

The prototype of HSDB enclosure is fabricated for experimental test to meet vibration criteria. The HSDB system is mounted to vibration fixture using bolts of diameter 4 mm at the six locations and the vibration fixture is in turn mounted on an electro dynamic shaker (Spectral Dynamic USA, Model SD-40-370). The experimental setup is shown in Fig. 2. Two

Table 1. Material properties

	Density (kg/m^3)	Longitudinal & transverse modulus (GPa)	Shear modulus XY-dir. (GPa)	Shear modulus YZ & XZ -dir. (GPa)	Poisson ratio
FR4	1800	19.42	6.8	1.44	
Cu Alloy	8960	117	45		0.3
Al. Alloy	2700	70	27		

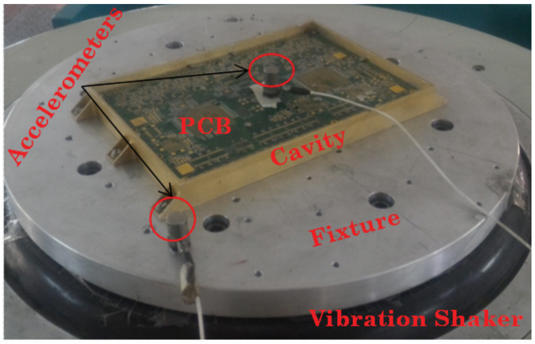

Figure 2. Experimental test setup.

accelerometers (PCB make, 352C03) are used in the experiment. One accelerometer is placed on the aluminium base plate fixture used for monitoring and controlling the input. Since, weight and location of the components on PCB are playing major role for the dynamic characteristics, accordingly, the second accelerometer is mounted for monitoring the response. Sine sweep and random vibration test are conducted as per the input profile. The system characteristics such as natural frequencies and acceleration response are obtained from the test by placing the sensors at different locations.

6. RESULTS AND DISCUSSION

The configuration of HSDB system is finalised by carrying out iteration for determining the optimum thickness of cavity, number of mounting screws, location to mount the PCB over the cavity and mounting arrangements for the cavity. The HSDB system is configured for cavity thickness of 1.2 mm along with ribs on bottom plate. Six mounting flanges have been provided on two sides of the cavity to achieve required stiffness, thermal path and symmetric load distribution. No mounting flanges are provided at other two sides of HSDB due to its electrical connectivity. Due to the limitation of FE analysis, fixed constraint are applied only at the mounting hole locations of the HSDB system, whereas, in real scenario, the bottom plate will have complete contact with mounting surface which is explained in evaluation of boundary nonlinearity section.

Initially, HSDB system is tested as per the simulation condition (fixed at 6 mounting holes) by keeping gap between the enclosure bottom plate and fixture. Sine sweep test is carried out on enclosure and obtained the first natural frequency of 329 Hz which is in good agreement with the natural frequency extracted from Eigen value analysis. Corresponding mode shape is shown in Fig. 3 and test result is shown in Fig. 4. The first four frequencies extracted from the analysis and testing are listed in Table 2.

Two types of mounting configurations of PCB are studied. First configuration of the PCB mounting is edge mounting (PCB is mounted along the edges) and second one is edge with centre mounting (PCB is mounted along the edges and middle).The first natural frequency of the PCB obtained for edge mounting is 268 Hz and edge with centre mounting is 304 Hz. It is observed that by providing extra mounting at the centre of the PCB, the natural frequency is increased. The list of natural frequencies extracted for both fixing cases are listed in Table 3. The rms acceleration response is dictated by

Table 2. List of natural frequencies of enclosure

Mode No	Extracted from modal analysis (Hz)	Extracted from vibration testing (Hz)
1.	327	329
2.	603	556
3.	694	732
4.	935	1015

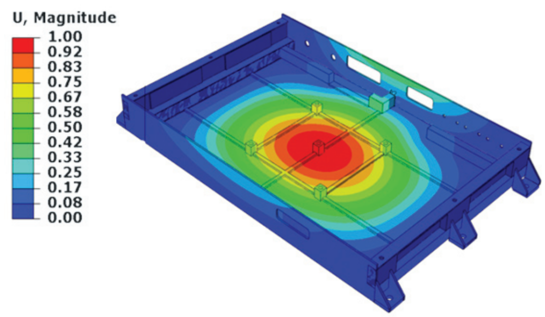

Figure 3. First mode shape at 327 Hz of enclosure.

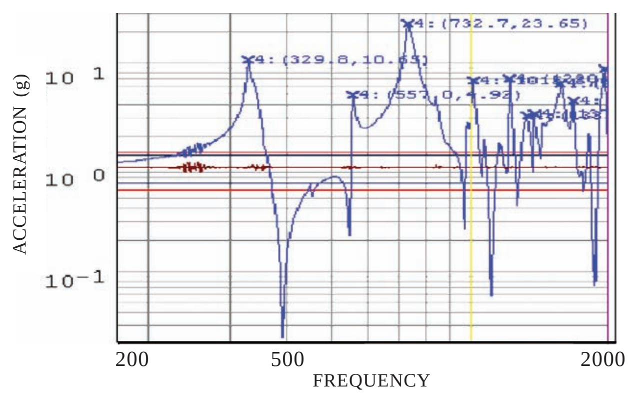

Figure 4. Sine sweep test result of the enclosure mounted in a gap with fixture.

Table 3. List of natural frequencies of PCB

	Edge mounting		Edge and centre mounting	
Mode No	Extracted from modal analysis (Hz)	Extracted from vibration testing (Hz)	Extracted from modal analysis (Hz)	Extracted from vibration testing (Hz)
1.	269	240	304	330
2.	429	408	505	510
3.	490	545	537	510
4.	646	611	621	670

the damping (material damping and structure damping). The modal damping found out from the experiment, varies from 3 per cent to 6 per cent which is a crucial input for random vibration analysis. In simulation, the maximum acceleration observed over the PCB for edge mounting is 106 G_{rms} and for edge along with centre mounting is 86 G_{rms}. The rms acceleration contours of FE simulation for both fixing conditions are shown in Fig. 5 and Fig. 6, respectively. A significant reduction in acceleration response is observed by comparing their acceleration PSD response at critical node as shown in Fig. 7.

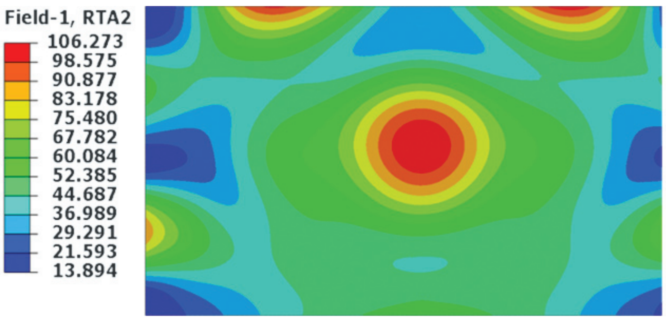

Figure 5. RMS acceleration over PCB for edge mounting.

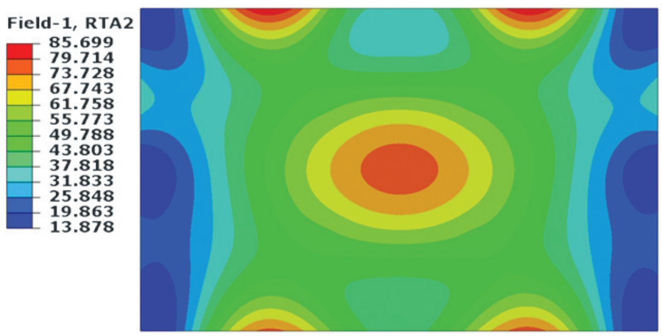

Figure 6. RMS acceleration over PCB for edge and centre mounting.

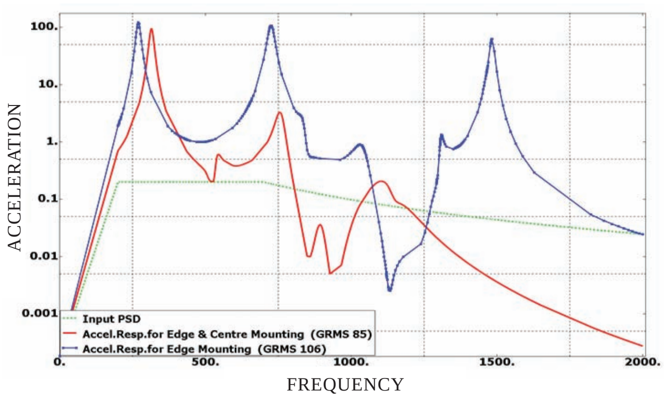

Figure 7. PSD response of critical node over PCB.

The acceleration response at the centre of PCB computed from the experiment are 74 G_{rms} and 70 G_{rms} for edge and edge along with centre mounting conditions as shown in Fig. 8 and Fig. 9, respectively. Experimental and simulation results show that edge along with centre mounting of PCB experienced lesser rms acceleration level than edge mounting. A marginal deviation in FE and experimental results of rms acceleration response is observed which may be due to modelling

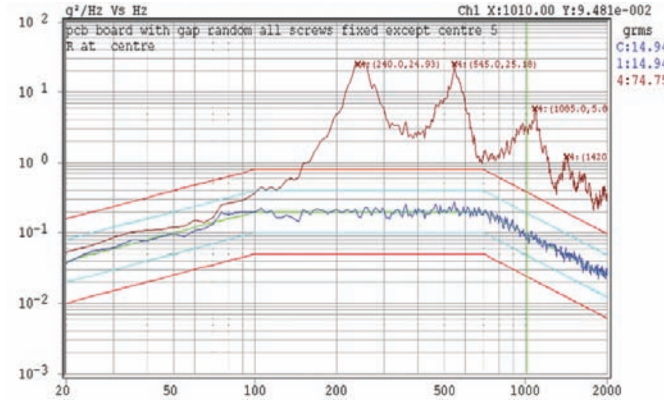

Figure 8. Tested PSD plot at centre of PCB for edge mounting.

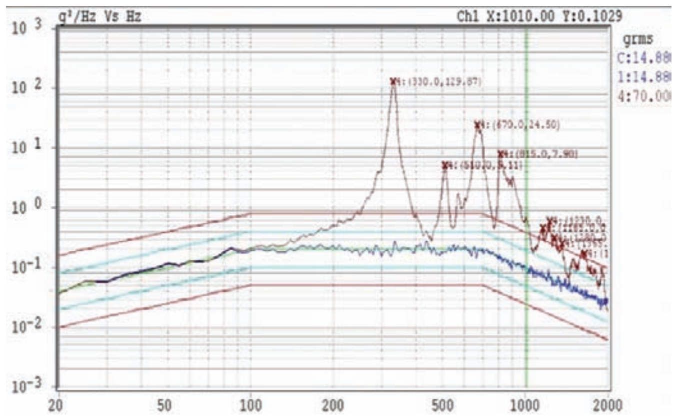

Figure 9. Tested PSD plot at centre of PCB for edge and centre mounting.

assumption, manufacturing and testing variability. These source of errors have been already reported by Robin Alastair Amy[13] using simplified FE model and experimental test.

7. EVALUATION OF BOUNDARY NON-LINEARITY

In reality, the bottom surface of HSDB is in contact with the mounting panel, hence it is experimentally investigated for sine sweep and random vibration tests by maintaining the cavity base in contact with fixture plate. The first natural frequency of the cavity obtained from sine sweep test is about 660 Hz which is improved compare to the gap mounting condition. The first natural frequency over the PCB for edge mounting and edge along with centre mounting are 235 Hz and 350 Hz, respectively. From the test results, it is observed that a significant improvement in natural frequency of cavity due to surface contact between cavity base and fixture which affect its natural frequency. But for the PCB, the improvement was observed only at higher frequencies. The first natural frequency of the PCB has little impact from surface contact of cavity. The maximum acceleration obtained from random vibration test for edge mounting and edge along with centre mounting of PCB are 53 G_{rms} and 44 G_{rms} are shown in Fig. 10. and Fig.11 respectively. These results also show a significant improvement in rms acceleration response compared to FE simulation.

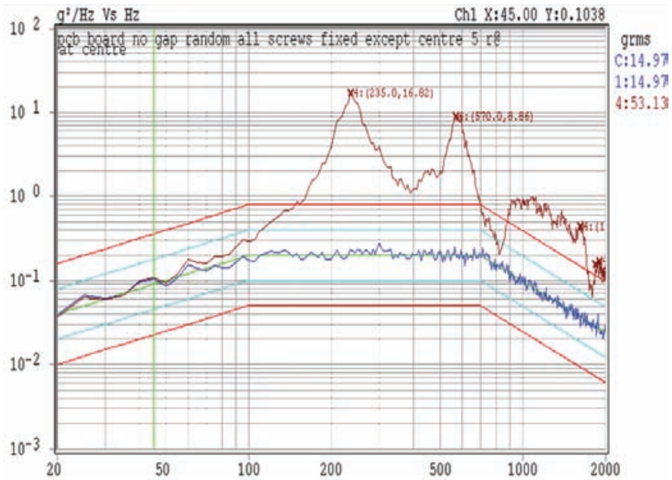

Figure 10. Tested PSD plot with bottom plate of housing contact with fixture plate (edge mounting of PCB).

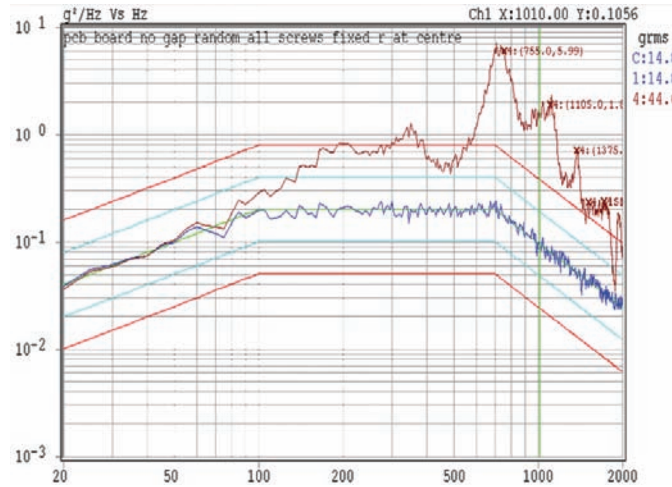

Figure 11. Tested PSD plot with bottom plate of housing contact with fixture plate (edge and centre mounting of PCB).

8. CONCLUSION

The HSDB system is developed based on FE simulation and experimental tests for the configuration of edge along with centre mounting of the PCB over cavity of 1.2 mm bottom wall thickness with ribs. The total weight of HSDB enclosure achieved is 500 gram which is well below the target weight. The FE simulation results are validated with the experimental test for the same boundary conditions. For the condition of surface contact between cavity base and fixture, a significant improvement in natural frequency and rms acceleration response are obtained through experiment as compare to FE analysis. This difference between experiment and FE analysis is attributed to a linear eigen value study which is not capable of capturing boundary non linearity. Boundary non linearity is playing a vital role for the systems which has base surface contact along with mounting. It is inferred that the cavity has absorbed maximum input PSD and has transmitted only partially to the PCB.

REFERENCES

1. Perkins,A. & Sitaraman, S. Vibration-induced solder joint failure of a ceramic column grid array (CCGA) package. *In* proceedings of conferences on Electronic components and technology. 2004, **54**(2), 1271-1278. doi: 10.1109/ECTC.2004.1320277
2. Sakri, M.I.; Saravanan, S.; Mohanram, P.V. & Syath Abuthakeer, S. Estimation of fatigue-life of electronic packages subjected to random vibration load. *Def. Sci. J.*, 2009, **59**(1), 58-62. doi:10.14429/dsj.59.1486
3. Sakri, M.I.; & Mohanram, P.V. Experimental investigations on board level electronic packages subjected to sinusoidal vibration loads. *Int. J. Current Engineering and Technology*, 2014, Spl. (2), 427-431. doi: 10.14741/ijcet/spl.2.2014.79
4. Yeong, K. Kim & Hwang, Do Soon. PBGA packaging reliability assessments under random vibrations for space applications. *Int. J. Microelectron. Reliability*, 2015, **55**(1), 172-179. doi:10.1016/j.microrel.2014.09.022
5. Weibin, Tang; Jianfeng, Ren; Gangying, Feng & Limei, Xu. Study on vibration analysis for printed circuit board of an electronic apparatus. *In* Proceedings of IEEE, International conferences on Mechatronics and Automation, 2007, pp. 855-860. doi: 10.1109/ICMA.2007.4303657
6. Subramanya, K.P.; Jiwan Kumar Pandit; Prasad, C.S. & Thyagaraj, M.R. Vibration analysis study of spacecraft electronic packaging. *Int. J. Sci. Eng. Tech. Res.*, 2014, **3**(3), 503-507.
7. Veprin, A.M. Vibration protection of critical components of electronic equipment in harsh environmental conditions. *J. Sound Vibration*, **259**(1), 2003, 161-175. doi: 10.1006/jsvi.2002.5164
8. Cifuentes, A.O. & Kalbag A. Dynamic behavior of printed wiring boards: Increasing board stiffness by optimizing support locations. *In* proceedings of 43rd conf. on Electronic components and technology, 1993, 270-275. doi: 10.1109/ECTC.1993.346830
9. Steinberg, D.S. Vibration analysis for electronic equipment: John Wiley & Sons, 2000, pp. 226-227A.
10. Blevins, R.D. Formulas for natural frequency and mode shape: Krieger Publishing Florida, 1995, pp. 236-237
11. Aytekin, B. & Nevzat, Ozguven H. Vibration analysis of a simply supported PCB with a component–An analytical approach. *In* proceedings of10th conf. on Electronics Packaging Technology,2008,1178-1183. doi: 10.1109/EPTC.2008.4763589
12. Abaqus user manual, V6.14
13. Robin Alastair Amy; Guglielmo S. & Aglietti, Guy Richardson. Accuracy of simplified printed circuit board finite element models. *Int. J. Microelectron. Reliability*, 2010, **50**(1), 86-97. doi:10.1016/j.microrel.2009.09.001

ACKNOWLEDGEMENT

Authors are thankful to Dr C.G. Balaji, Distinguish Scientist & Director, DLRL for providing opportunity and giving acceptance to publish this paper. Authors are grateful to Mr M. Balachary, Scientist 'G' and Addl. Director, Mr CVH Prasad, Scientist 'F' and Group Director and Dr Lachiram, Scientist 'F'and Division Head for their constant support.

CONTRIBUTORS

Mr K. Chandrakar has graduated from MP Christian College of Engineering and Technology, Bhilai, Chhattisgarh, India in 2002 and received his Masters from IIT Madras, Chennai, in 2011. Currently working as Scientist-D in the structural analysis group in DLRL. He has carried out the structural analysis of the HSDB subsystem using FE tool.
In current study, he has validated the FE result using experimental tests and studied the effect of boundary non linearity.

Mr P.L. Venkateshwar Rao has graduated from JNTU College of Eng. Hyderabad, India in 1997 and received his Masters from Osmania University College of Eng. Hyderabad, India in 2013. Currently working as Scientist at Defence Electronics Research Laboratory in 1992. He is a Member of Institute of Engineers (India). He has generated the solid modeling of the HSDB system.
In current study, he has coordinated with CNC manufacturing centre for development of prototype and also contributed for conducting the experimental tests of system.

Dr P. Rajendran received the BE in Mechanical Engineering from Madurai kamaraj University, Madurai, India in 1992, ME from Anna University, Chennai in 1998 and PhD from the Osmania University, Hyderabad in 2008. He is senior scientist at Defence Electronics Research Laboratory. He is the author and co-author of over 20 technical publications. He is core project member and configured the HSDB system with suitable mounting for PCB and enclosure.
In current study, he has contributions lead to develop light weight prototype hardware against high intensity vibration level.

Mr C. Satyanarayana has graduated from Osmania University, Hyderabad, India in 1995 and received his Masters from Regional Engineering College, Trichy, in 1997. He is senior scientist at Defence Electronics Research Laboratory. He is Member of Institute of Engineers (India). He is head of the structural analysis group in the lab. His contributions are providing suitable design approach, finalisation of configuration and development of mechanical hardware.
In current study, he has also reviewed the analysis results of HSDB.