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Design and analysis of shock and random vibration isolation of operating hard disk drive in harsh environment

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Abstract. An effective vibration isolation system is important for hard disk drives (HDD) used in a harsh mechanical environment. This paper describes how to design, simulate, test and evaluate vibration isolation systems for operating HDD subjected to severe shock and random vibrations based on military specifications MIL-STD-810E. The well-defined evaluation criteria proposed in this paper can be used to effectively assess the performance of HDD vibration isolation system. Design concepts on how to achieve satisfactory shock and vibration isolation for HDD are described. The concepts are tested and further enhanced by the two design case studies presented here. It is shown that an effective vibration isolation system, that will allow a HDD to operate well when subjected to severe shock and random vibration, is feasible.

Keywords: Hard disk drives, vibration and shock isolation, MIL-STD-810E, vibration testing, isolation design

1. Introduction

The topic on how to design an optimum shock and vibration isolation for general type of devices has been discussed quite extensively in the literatures [1,2]. However, the vibration isolation design for sophisticated systems needs to be attended in a special manner. For instance, the design of vibration isolation for an infrared equipment has been discussed in detail in [3,4].

In this paper, the authors would like to focus on the design and analysis of shock and vibration isolation of hard disk drives (HDD). The vibration in HDD has been increasingly studied due to the fact that HDDs have been increasingly used in various mobile applications (e.g. portable communication and entertainment systems), in which the HDD may be subjected to severe shock and random vibration inputs. It remains a big challenge for HDD manufacturers to make the HDD robust to harsh environmental conditions. This is predominantly due to the fact that originally HDD used to be designed for operation in stationary environments.

There are basically three methods to handle the shock and vibration problems in HDD [5]. The first is to design a robust servo control mechanism to prevent read/write head error. The second is to design a robust mechanical system and slider/disk interface. The third is to design suitable vibration isolation for the HDD. The first and second methods have been widely used in the academic and industrial research, but the third has not been addressed sufficiently in the literature. Some research work done focused on vibration isolators installed inside the HDD [6]. But little attention is given to external vibration isolation of HDD. There has been a published work related to this specific area by the same authors [7]. However, the previous work did not address the shock problem.

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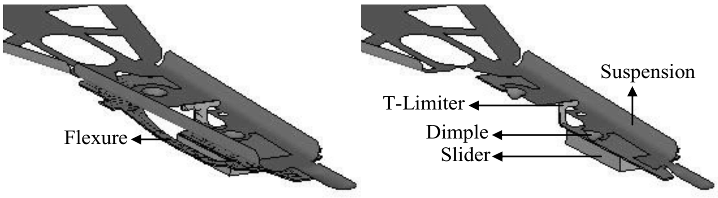

Fig. 1. Head-gimbal assembly device.

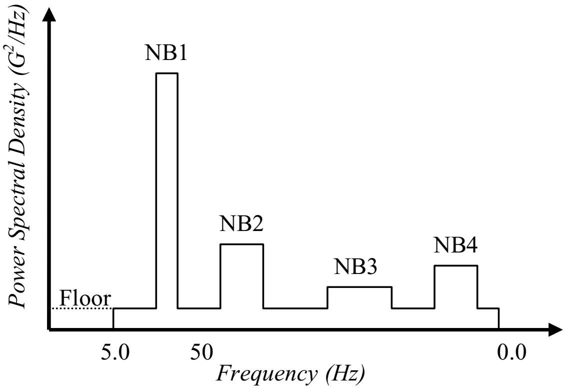

Fig. 2. Acceleration power spectral density.

This paper describes in more detail on how to design, simulate, analyse and evaluate vibration isolation systems of operating HDD subjected to not only harsh random-on-random vibrations but also severe shock. First, the shock and vibration profiles that might be experienced by HDD are described according to Military Standard (MIL-STD) 810E. Next, the authors propose vibration testing and evaluation criteria that can be used to assess the effectiveness of the shock and vibration isolation. Design concepts specially tailored to HDD vibration isolation systems are then proposed in the subsequent section. Next, two case studies are presented to test and augment the concepts.

2. Shock and random vibration profiles

The US Department of Defense has provided a series of guidelines for reliability and environmental testing under MIL-STD-810E [8]. Some of the tests given by the standard are vibration, water resistance, humidity, and temperature tests.

The random vibration test in MIL-STD-810E Method 514.4 is commonly used among mobile electronics manufacturers for ruggedisation testing. The vibration data in the standard is derived based on the interaction of vehicle structures with road and surface discontinuities. Due to the randomness and irregularity of data collected, the data is best simulated by superimposing narrowband random vibration over a broadband random base. Hence, the vibration data consists of random-on-random vibration data in 3 primary axes. Each axis has six phases which correspond to different speed of vehicle during military mission. Figure 2 shows a general power spectral density (PSD) profile described by the standard. The standard will be used to investigate the performance of externally isolated HDD. According to the standard, the HDD has to be able to run smoothly under the excitation of each random-on-random vibration profile.

The HDD also has to pass the shock tolerance requirements. The purpose of the shock tests is to ensure that the HDD can withstand the relatively infrequent, non repetitive shocks or transient vibration encountered in handling, transportation, and service environments. As described in the MIL-STD-810E, the shock tests are intended to assess equipment assemblies which in this case are the HDD together with the shock and vibration isolator systems, in their functional or operating modes. The applicable shock profiles for functional test are given in Table 1.

Table 1
Shock profile for functional shock test

Test procedure	Half sine peak acceleration	Pulse width	Cross over frequency
Functional test For ground equipment	40 G	6–9 ms	45 Hz
Crash hazard test For ground equipment	75 G	3.5–5 ms	80 Hz

(1 G = 9.81 m/s^2)

Table 2
Maximum GRMS that hard disk drive can withstand without vibration isolator

Manufacturer	Serial no	GRMS* (PSD profile is flat from 5 to 500 Hz)		
		x-axis	y-axis	z-axis
Hitachi	F4H23NTD	5.07	5.07	3.47
	F4H23NWD	5.05	5.22	3.47

*GRMS is the root-mean-square value of acceleration in G unit.

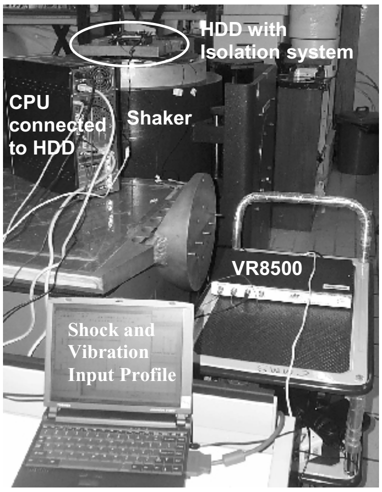

Fig. 3. Experiment set up for vertical random vibration.

3. Vibration testing and evaluation criteria

For testing the HDD, random-on-random vibration signals as specified by the power spectral density profiles of MIL-STD-810E are generated by a vibration controller (VR8500). The controller then excites a large electrodynamics shaker system to physically produce the random vibration. Figure 3 shows a typical experimental setup for random vibration.

For shock testing, a programmable shock table and dual-mass shock amplifier (Fig. 4) is used to produce the required shock magnitude and pulse width.

During shock/random vibration test, the functionality of the HDD is evaluated in terms of

1. Real time data recording to the HDD with constant data transfer rate.
   By using a multi-channel field data recorder, data (e.g. signals from accelerometers) is recorded and streamed in real-time to the HDD. The data transfer rate can be determined from the size of the data and the sampling frequency. The data written to the HDD is then verified. The HDD passes this test if the desired data recording rate can be maintained without loss.

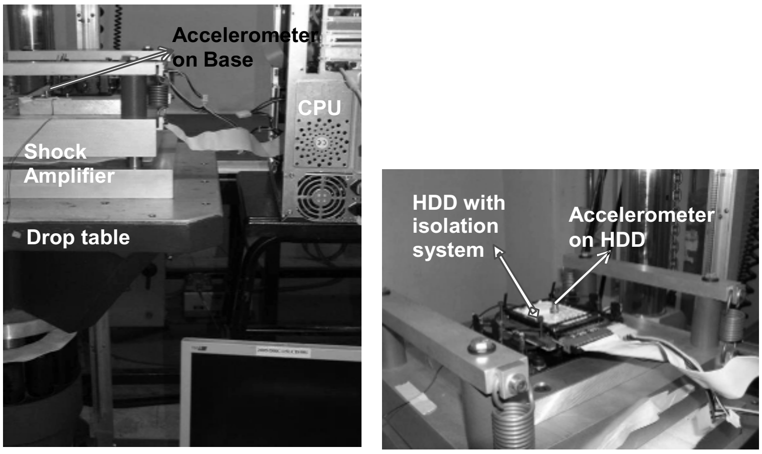

Fig. 4. Experiment set up for vertical shock test.

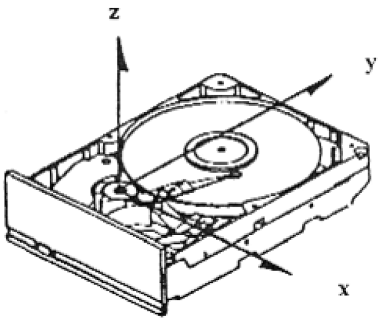

Fig. 5. HDD axes notation.

2. Video streaming from HDD
   For example, the movie streamed may be a DVD video having a video bit rate of approximately 4 megabytes per second (MB/s). The HDD is considered to pass this test if there are no pauses in the movie being played continuously during the vibration test.
3. Video capture to HDD
   Using camera with video recording interface, dynamic events are captured to HDD. The HDD passes this test if there is no distortion in the video captured during playback.

4. Design concept

4.1. Threshold of bare HDD

This section aims to demonstrate that vibration isolation is necessary for HDD. The vibration tolerances of bare HDD (without vibration isolation system) in GRMS are determined based on the evaluation criteria given in Section 3 above. We called this maximum tolerable GRMS level of bare HDD as the threshold GRMS. Since the purpose is to find this threshold value, it is not practical to apply directly the power spectral density profile defined in MIL-STD-810E. Instead, by using the flat PSD profile, we can readily control the GRMS level in the threshold test and subsequently get the vibration tolerance level of bare HDD.

In our study, the bare HDD is subjected to the random vibration with flat power spectral density from 5 Hertz to 500 Hertz. The magnitude of power spectral density is increased until the HDD fails according to the given criteria.

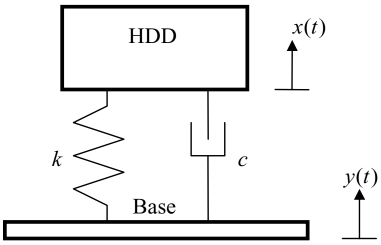

Fig. 6. HDD on vibration isolator mount.

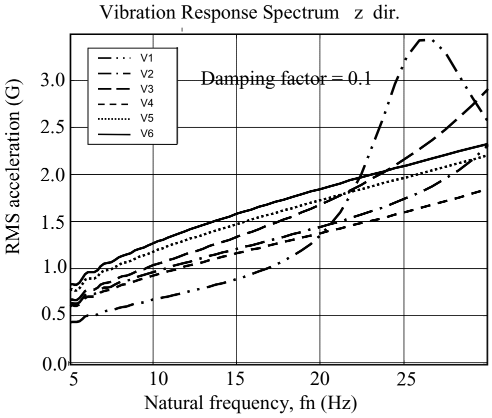

Fig. 7. Predicted RMS acceleration response of the HDD (z-direction).

Table 2 shows the experimentally measured acceptable limits of the bare HDD used in this study (the axes notation is given in Fig. 5). It can be seen that the x- and y-axes GRMS values for failure are higher than the z-axis; from the slider/disk interface point of view, the shock in z-direction has potential to cause more severe damage compared to x- and y-direction [5,9] because this is the direction where the slider will crash onto the disk. Additionally, the suspension (where the slider is attached to; see Fig. 1) is designed in such away that it is very stiff in the in-plane directions (x- and y-) but quite flexible in the z-direction so that the slider can follow the disk contour easily [10]. The high in-plane stiffness enhances the HDD shock robustness in x and y direction.

Since the random vibration inputs specified by MIL-STD-810E are up to 8.95 GRMS for z-axis and 12 GRMS for x-axis, the bare HDD would not be able to pass the MIL-STD-810E requirements. Hence, vibration isolation is necessary for the HDD.

4.2. Shock and random vibration isolation design

The modern HDD has a relatively high shock resistance. For example, Hitachi Travelstar 40GN can withstand up to 200G @ 2 ms (more than the shock tolerance required by MIL-STD-810E). Therefore, the HDD isolator mounts are primarily required to isolate random vibration. Basically, the isolator design should achieve transmissibilities for all three axes of motion that are low enough to provide the necessary vibration isolation in the 5–500 Hz frequency range. Since the HDD cover is relatively stiff (fundamental natural frequencies $>$3000 Hz), we can treat the HDD as a rigid body [2]. Referring to Fig. 6, the RMS value of the HDD acceleration can be predicted by the formula:

$$\text{RMS of HDD acceleration} = \sqrt{\int \left|Tr(\omega)\right|^2 S_{yy}(\omega)d\omega}, \tag{1}$$

where $Tr(\omega)$ is the frequency dependent transmissibility function, and $S_{yy}(\omega)$ is the power spectral density function for a random input vibration $y(t)$ to the base.

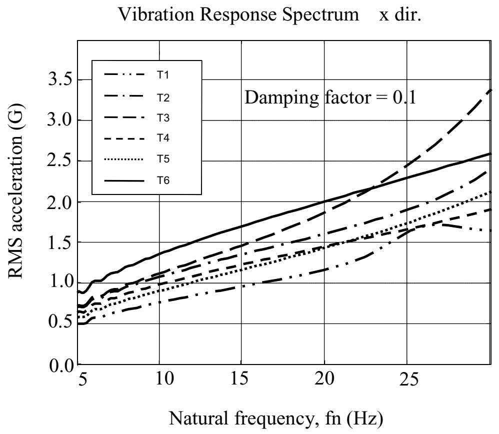

Fig. 8. Predicted RMS acceleration response of the HDD (x-direction).

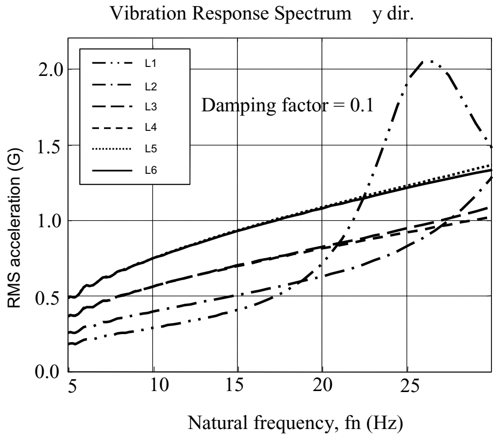

Fig. 9. Predicted RMS acceleration response of the HDD (y-direction).

The objective is to make sure that the RMS value of the HDD acceleration is lower than the acceptable limits given in Table 2. Using Eq. (1), the RMS acceleration response can be predicted if the transmissibility function *Tr*(ω) and the power spectral density input $S_{yy}(\omega)$ is known. *Tr*(ω) is a function of isolator system natural frequency ω_n and the damping factor ζ.

$$Tr(\omega) = \left(\frac{1 + (2\zeta r)^2}{(1 - r^2)^2 + (2\zeta r)^2}\right)^{\frac{1}{2}} ; r = \frac{\omega}{\omega_n} \tag{2}$$

$S_{yy}(\omega)$ is set according to the data given in MIL-STD-810E. The data consists of six phases of random vibration input defined in the z (vertical), x (transverse), and y (longitudinal) directions.

Figures 7–9 show the predicted RMS acceleration response of the HDD versus the isolator's natural frequency for damping factor of 0.1, for the given power spectral density input as defined in Mil-STD-810E Method 514.4. V1 to V6 correspond to $S_{yy}(\omega)$ in the six phases of vertical random vibration data. T1 to T6 correspond to $S_{yy}(\omega)$ in six phases transverse of random vibration data. L1 to L6 correspond to $S_{yy}(\omega)$ in six phases of longitudinal random vibration data.

From Figs 7–9 it can be inferred that the vibration isolation design must have relatively low natural frequency. For example, in vertical direction, a natural frequency of 20 Hz or below will give an RMS acceleration response under 2 G. In the x and y directions, a natural frequency of 30 Hz or below will give an RMS acceleration response under 3.5 G. A well-damped system (damping ratio $\geqslant$0.1) with natural frequencies between 10 to 20 Hz is expected to give good random vibration isolation.

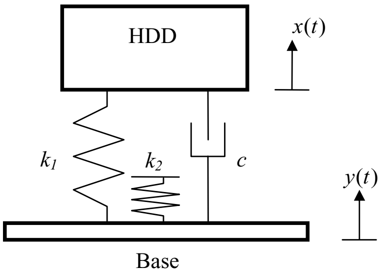

Fig. 10. Vibration isolator mount with additional stiff isolator (k_2).

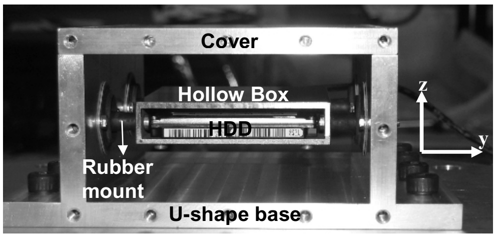

Fig. 11. Vibration isolation system I.

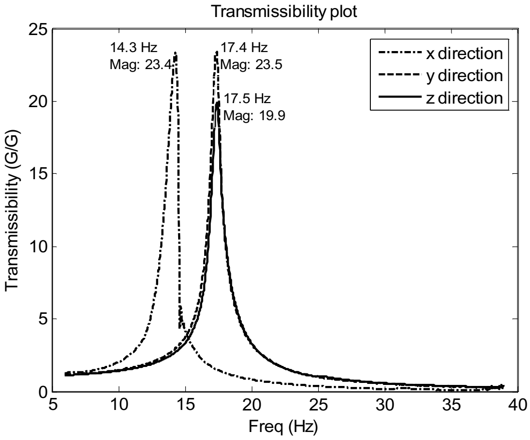

Fig. 12. Transmissibility plot for vibration isolation system I.

However, a system with low natural frequencies may suffer from high displacement response under a shock input. A high displacement response is not desirable because there may not be enough space around the HDD to accommodate peak-to-peak displacement. In order to restrain displacement response, relatively stiff isolators can be added to the vibration isolation system (Fig. 10). The HDD can still function normally when it hits the stiff isolator due to its high shock tolerance.

5. Design case studies

5.1. Design I

Figure 11 shows a vibration isolation system for a 2.5” HDD. The HDD is secured inside an aluminium box. The box is supported by four low damped rubber mounts; two at the left side and two at other side. Figure 12 shows the

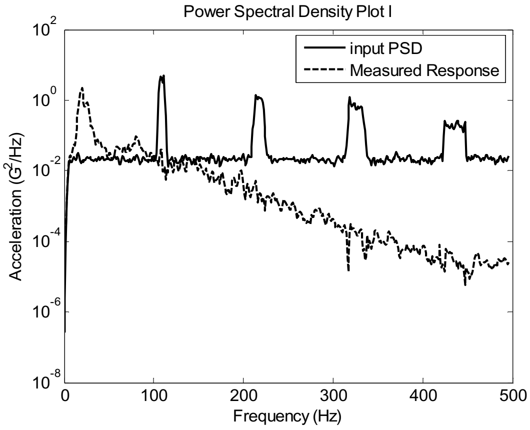

Fig. 13. PSD plot for vibration isolation system I.

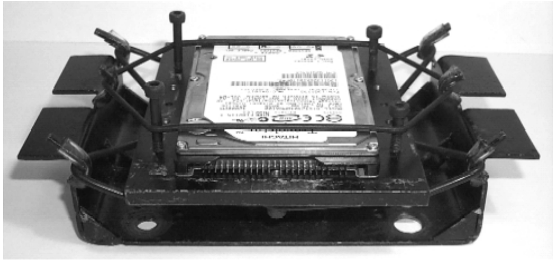

Fig. 14. Components of vibration isolator system II.

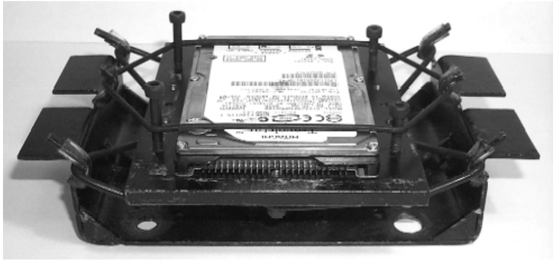

Fig. 15. Vibration isolator system II.

measured transmissibilities of the system in the x, y and z directions. The damping ratios for all three directions are less than the values that are predicted to give satisfactory vibration isolation, as explained in Section 4.2. Figure 13 shows a typical vibration PSD of the excitation and the corresponding response of the HDD. The HDD isolation system did not pass the random vibration tests according to the criteria defined in Section 3.

5.2. Design II

Figures 14 and 15 show another vibration isolation system for a 2.5” HDD. The HDD is secured to a metal base and suspended by rubber O-rings. Figure 16 shows the measured transmissibilities of the system in the x, y and z directions. The natural frequencies and damping are well within the ranges that are predicted to give satisfactory vibration isolation. Figure 17 shows a typical vibration PSD of the excitation and the corresponding response of the HDD. It is observed that the HDD passes all the random vibration tests according to the specified criteria.

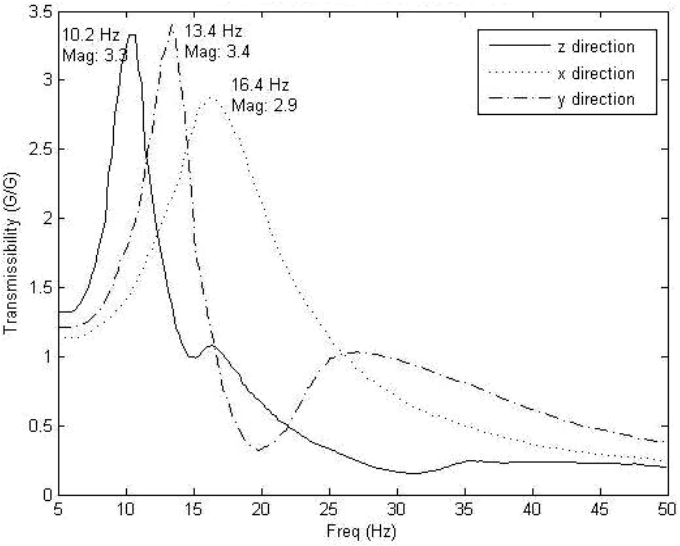

Fig. 16. Transmissibility plot for vibration isolation system II.

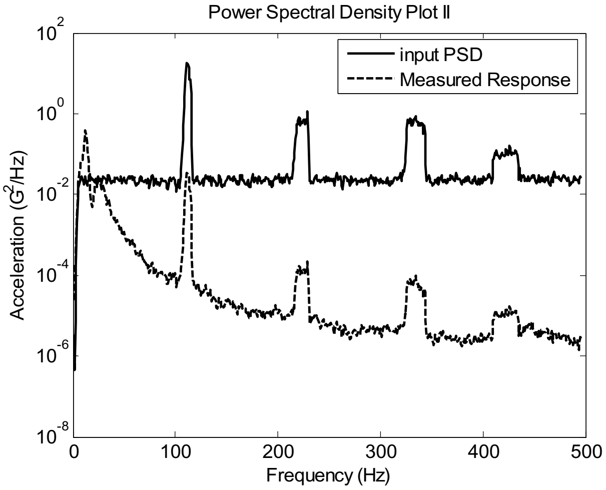

Fig. 17. PSD plot for vibration isolation system II.

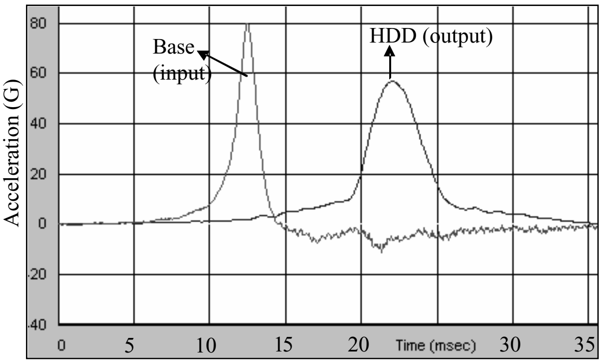

Fig. 18. HDD crash hazard test result.

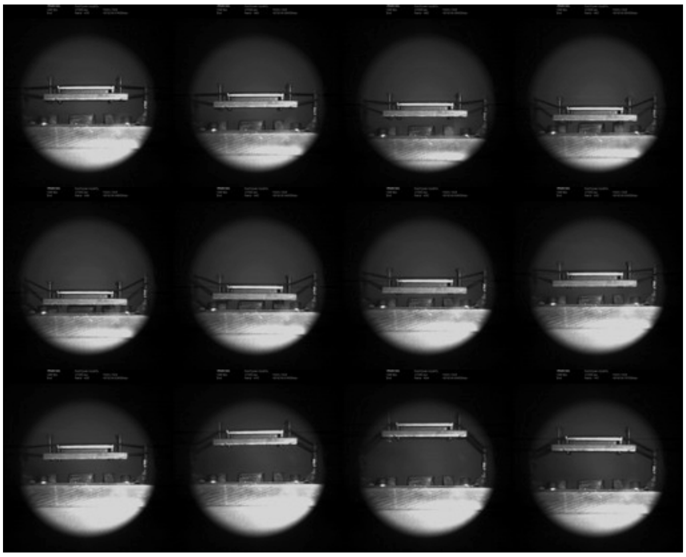

Fig. 19. Snapshots of shock response of HDD.

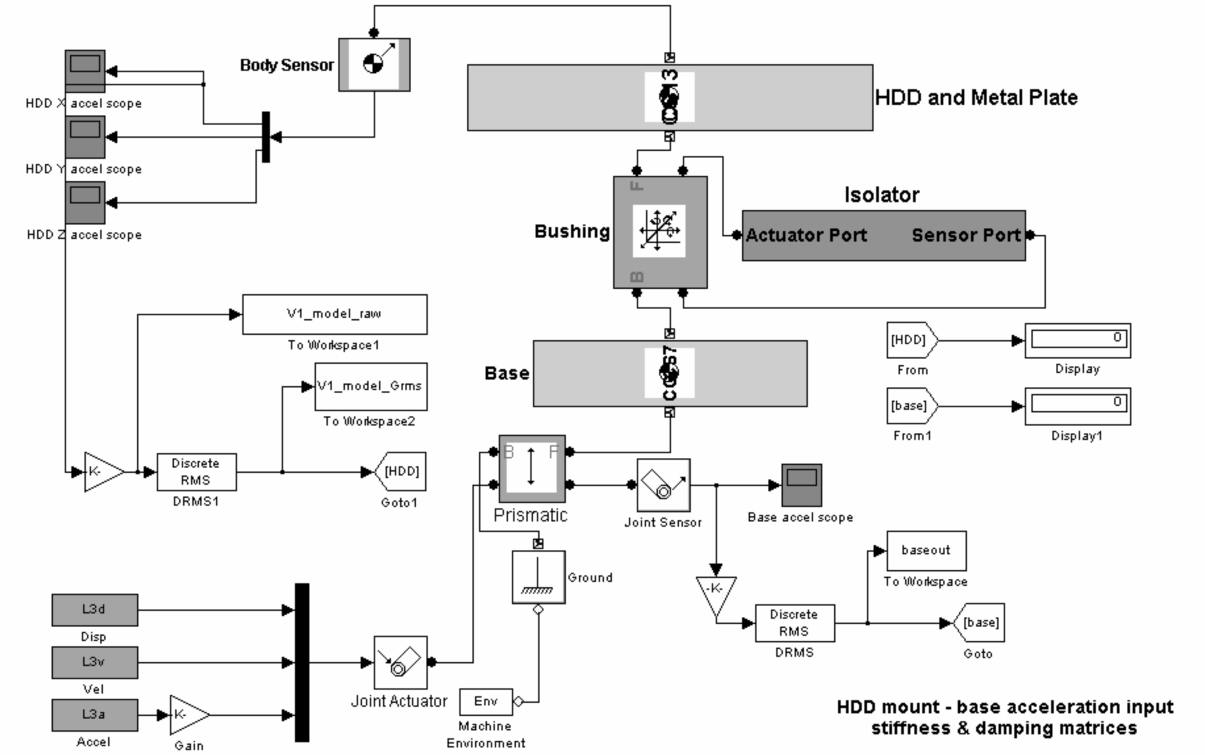

Fig. 20. SimMechanics model of design II.

Figure 18 gives the acceleration time history of the base and of the HDD during the crash hazard test. The acceleration of the HDD is below its critical level (200 G). Design II passes the criteria described in Section 3 in all the shock tests. Figure 19 shows the snapshots of the shock response of the HDD to 80 G @ 3.5 ms shock input. It is seen that the stiff isolator helps reduce the peak-to-peak displacement.

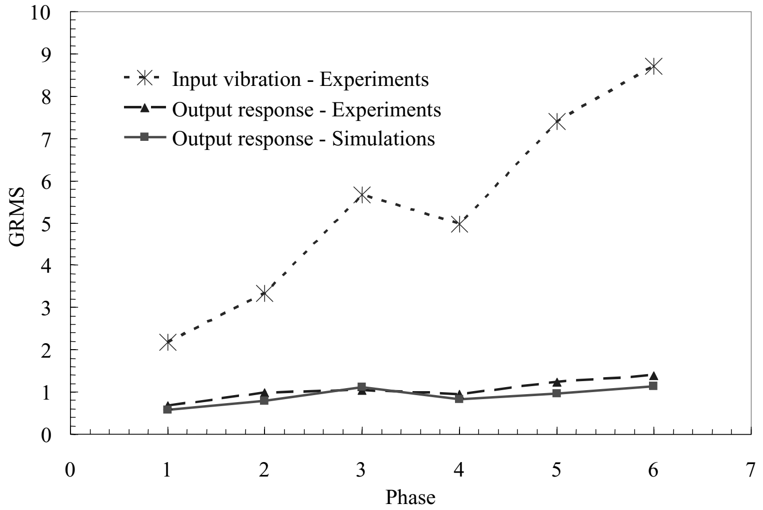

Fig. 21. Measured and predicted RMS acceleration.

The input shock level defined in MIL-STD-810E is 75 G @ 3.5 ms. In the experiment it is difficult to get exactly 75 G input due to the limitation of the test equipment. However, if the system passed the shock test at 80 G, it should be able to pass the test at 75 G also.

The volume of space that the isolation apparatus consumes in the actual installation is 0.15 m (length in x-direction) × 0.1 m (width in y-direction) × 0.06 m (height in z-direction). Additional space (0.04 m–0.05 m) should be provided above the HDD to allow it to sway vertically during shock.

A computer simulation model of the HDD vibration isolation system (Fig. 20) has been developed using SimMechanics. This model takes input in the form of vibration time history data generated from the PSD profiles defined in MIL-STD-810E Method 514.4 and then predicts the output responses. Figure 21 shows the measured and predicted RMS acceleration levels of the suspended HDD for the six random vibration test phases in the vertical (z) direction. Comparing with the RMS levels of the input excitation, it can be seen that substantial vibration isolation has been achieved.

6. Conclusion

An effective suspension system is necessary to isolate the HDD from the strong vibration transmitted from the ground, vehicle engine, etc. Procedures for vibration testing, evaluation criteria, design concept, modeling and simulation for the external vibration isolation system for the HDD have been presented. Two example designs have been used as case studies to demonstrate and verify the design concepts. The natural frequencies of the external vibration isolation system should be between 10 to 20 Hz. The damping properties of the system is required to be relatively high ($\geqslant$10%). To reduce the peak-to-peak displacement during shock event, relatively stiff isolators can be used. Experiments and simulations have confirmed that effective vibration isolation can indeed be designed to isolate the operating HDD from severe shock and random vibration.

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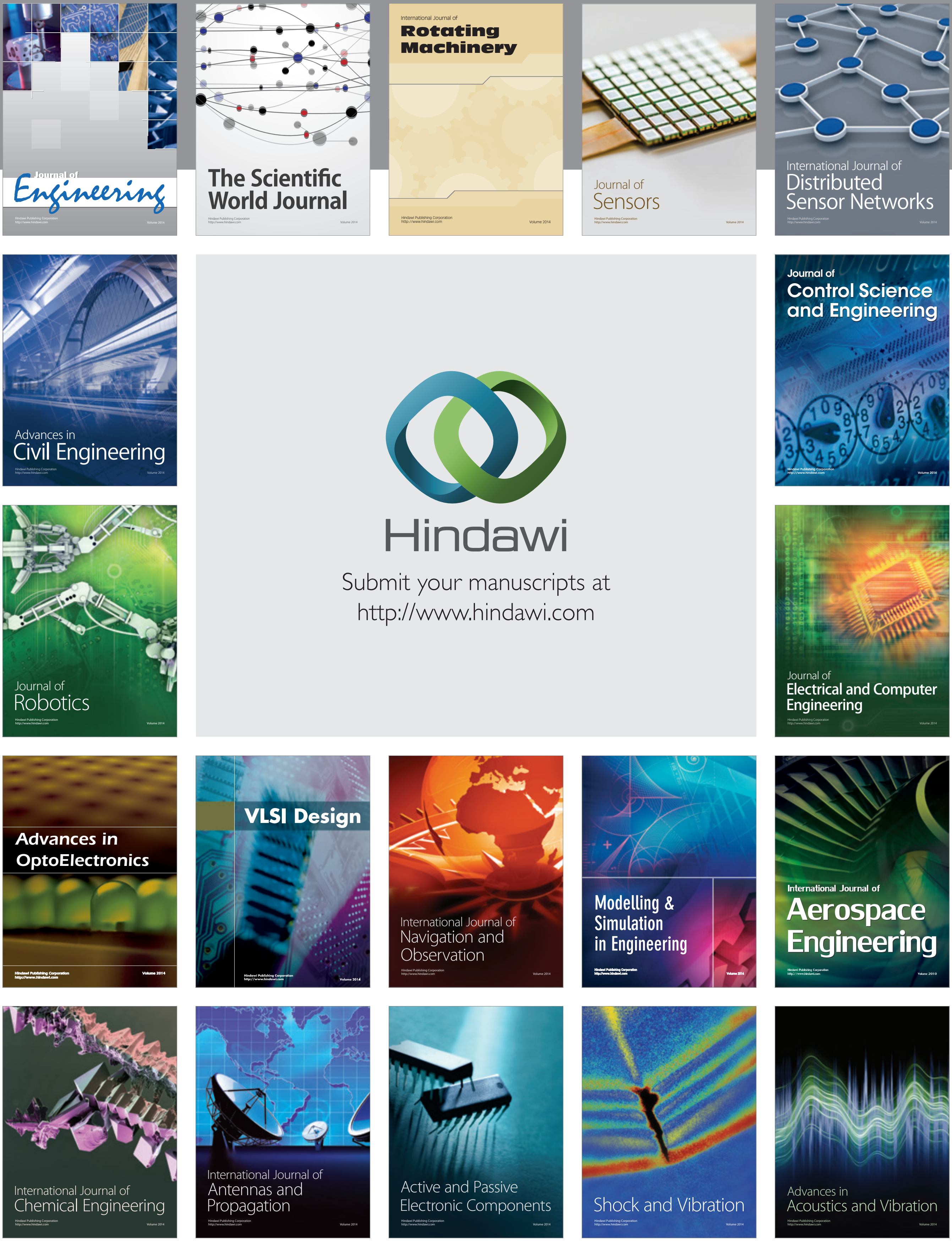
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