Technical Paper
Journal of Aerospace System Engineering
Vol.15, No.4, pp.40-46 (2021)

EISSN 2508-7150
http://dx.doi.org/10.20910/JASE.2021.15.4.40

Development of an Efficient Notching Toolkit for Response Limiting Method

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Abstract

At launch, satellites are exposed to various types of structural loads, such as quasi-static loads, sinusoidal vibrations, acoustic/random vibrations, and shocks. The launch environment test is aimed at verifying the structural stability of the test object against the launch environment. Various types of launch environments are simulated by simple vibration, acoustic, and shock tests considering possible test conditions in ground. However, the difference between the launch environment and the test environment is one of the causes of excessive testing. To prevent overtesting, a notching technique that adjusts the frequency range and the input load considering the design load is applied. For notching, specific procedures are established considering the satellite development concept, selected launch vehicle, higher system requirements, and test target level. In this study, the notching method, established procedure, and development of a notching toolkit for efficient testing are described.

Key Words: Launch Environment Test, Structural Stability, Over Test, Response Load, Notching Method

1. Introduction

Satellites and payloads are exposed to various types of structural loads during the launch phase. Structural loads are classified into quasi-static loads, sinusoidal vibrations, acoustic/random vibrations, and shocks. The quasi-static load in the low frequency band is applied in the form of steady-state acceleration. The sinusoidal vibration is a transient quasi-harmonic load generated by the dynamic mode of the projectile in the frequency band of 5 to 100 Hz. Acoustic/random vibration is a structural load that occurs in conjunction with other vibration and depends on the size of the satellite: acoustic loads are applied to large satellites, whereas random vibrations are applied to small satellites. The impact occurs in the form of a high load in a short window of time when the restraint device is separated (e.g., separation of the satellite from the launch vehicle, deployment of the antenna of the satellite). The launch load is simulated as a launch environment testing that can be implemented on the ground, as summarized in Table 1 [1].

Table 1 Launch Environment Test [1]

Test	Type	Frequency [Hz]
Sine Burst	Quasi-static	10–50
Sine Vibration	Sine Vibration	5–100
Random Vibration	Random Vibration	20–2,000
Acoustic	Acoustic	10–10,000
Shock	Shock	100–10,000

In the vibration test that simulates the launch environment, transient state tests are conducted for the following reasons [2]. First, there is a difference between the constraints of the launch and the test configuration. Within the launch configuration, the launch vehicle and the satellite, the satellite and the payload, and the payload and the mounting equipment have structural influence on each other. Fig. 1 shows a simplified two-degree-of-freedom system of the launch vehicle (M1) and satellite (M2). Vibration applied to the satellite from the outside induces a dynamic absorber effect based on the structural effect of the launch vehicle.

For the vibration test, test objects such as satellites, payloads, and on-board equipment are assembled on the vibration tester (including the vibration test jig) with high structural rigidity, as shown in Fig. 2.

Received: Jan 26, 2021 Revised: Apr. 29, 2021 Accepted: Apr. 29, 2021
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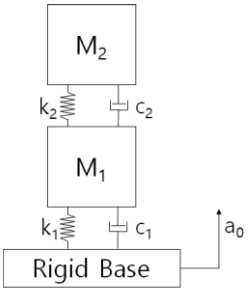


Fig. 1 Two-degree-of-freedom System

Fig. 2 Shaker with Slip Table

Fig. 3 shows the resonance search results from a single trial test (high stiffness constraint in black) and a test assembled on a high-level structure (dynamic damping effect constraint in red) on the same test object. The response from the test object appears relatively high in natural frequency and amplification ratio under high stiffness constraint. This results in the transient state test that causes damage or malfunction of the test object.

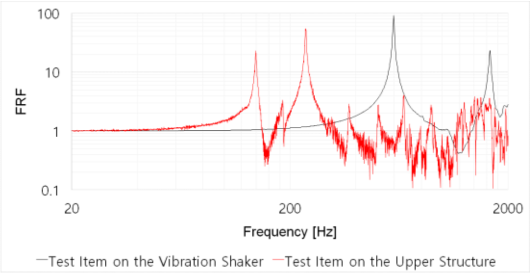


Fig. 3 Modal Survey Result for Boundary Condition (FRF: Frequency Response Function)

The second reason is a comprehensively defined test condition. The test conditions are derived based on the results measured in the launch environment and the response results obtained from the high-level system vibration test. Test conditions are specified to include the peak values from the measurements and test data, considered for simplifications and margins. The local maxima (peak) are reflected, whereas local minima (valley) are not considered, as shown in Fig. 4.

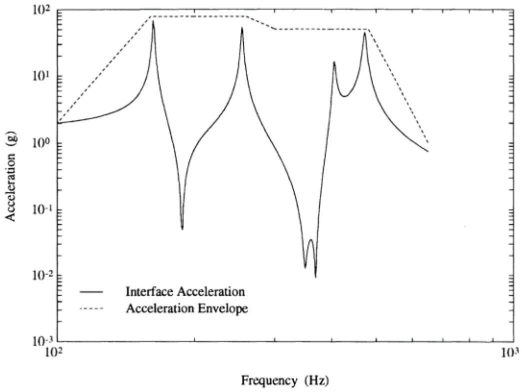


Fig. 4 Envelope Synthesis [2]

The test conditions derived as described here result in a transient state test that causes damage and malfunction of the test object due to the excessive load over the limit of the launch environment. To prevent transient state tests, the test conditions are adjusted considering the results measured in the launch environment and the response results obtained in the high-level system vibration test. The adjustments are made on the test frequency range and maximum applied load, which is called notching [3, 4]. As notching must satisfy the requirements of the high-level system, approval from the person in charge of launching vehicles for the satellite, satellite for the payload, and payload for the on-board equipment must be obtained.

In the present study, the current notching procedure is summarized and a notching toolkit of the response limit technique for user convenience and time efficiency is described. A toolkit for one response was developed, and corrections/supplements and utility were confirmed through unit level tests. Based on these results, it was expanded to a toolkit for multi responses and its effectiveness was verified through high-level assembly-level tests.

2. Notching based on Response Limit Technique

There are two approaches to notching depending on the response being considered. The first approach is a response limit technique that considers the response acceleration obtained from the center of gravity of the test object. The second approach is a force limit technique that considers the response load obtained from the interface of the test object [5, 6]. There is no generally applicable notching procedure. Based on these two approaches, it is necessary to establish specific notching procedure factoring in the satellite development concept, selected launch vehicle, high-level system requirements, and level of the test object. In this study, the notching procedure and toolkit based on the response limiting technique are described.

Structural stability is verified through structural analysis and launch environment tests. The verification through analysis estimates the stress for the design load, and is evaluated in terms of the margin of safety (MoS > 0) shown in Eq. 1 based on the allowable strength for different materials and safety factors. The safety factors are determined based on the uncertainty of the material as specified in specifications, such as those of the European Space Agency (ESA) and NASA. The safety factor of the ESA specification is 1.25 for metal, 2.0 for bonding, and 2.5 for glass based on yield strength [7].

$$\text{MoS} = \frac{\text{Allowable Strength}}{\text{Maximun Stress } \times \text{Safety Factor}} - 1 \tag{1}$$

For test objects whose structural stabilities have been verified analytically, the final verification of structural stability is made through sine wave and random vibration tests. In the same test, the difference in constraints between the launch and the test configuration and comprehensively estimated test conditions are the causes behind the transient state tests. Notching with response limiting technique is applied with the design load as the evaluation criterion to prevent transient state tests. The acceleration response for notching is obtained at the center of gravity of the test subject. Determination of frequency band, load level, and rate of change for notching varies depending on the development policy. Using the ESA specifications, notching frequency bands are estimated using $\Delta f = 3\,f_0/Q\ [Hz]$ (where f_0 is the natural frequency and Q is the amplification ratio), and the load levels are determined based on the levels allowed in the high-level system. Maximum of ±25 dB/oct was suggested for the load change rate *vs.* frequency based on the specifications of the testing equipment [8]. Wijker determined the notching frequency band as $\Delta f = f_0/Q\ [Hz]$ and determined the rate of change according to the amplification ratio and allowable load level as shown in Fig. 5 [9].

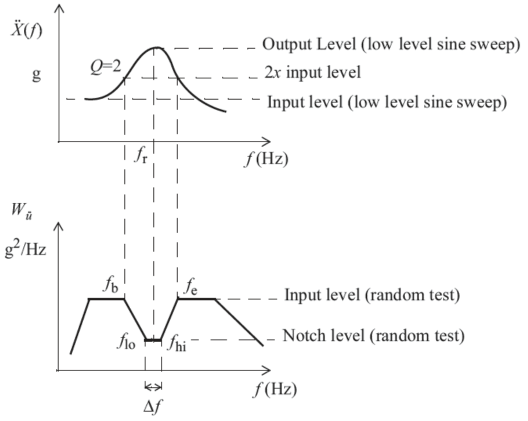


Fig. 5 Random Vibration Test Notching [9]

In this study, the notching criteria are the frequency range and change rate within the controllable level of the vibration tester, and the load level at the minimum load or minimum response required by the high-level system. As sinusoidal vibration is described in terms of frequency (Hz) and acceleration (g), notching is attained through a direct comparison with the design load (g). As random vibration, defined in frequency (Hz), and power spectrum density (PSD: g^2/Hz) are not suited for a direct comparison with the design load, notching is performed based on the response load (g) estimated from the average response load (grms) and statistical probability over the entire frequency range, as in in Eq. 2.

$$a_i = \left\{ \begin{array}{c} \left[\frac{y_i}{f_i{}^N}\right]\left[\frac{1}{N+1}\right]\left[f_{i+1}{}^{N+1} - f_i{}^{N+1}\right], for\ N \neq -1 \\ [y_i f_i]\left[\ln\left(\frac{f_{i+1}}{f_i}\right)\right], for\ N = -1 \end{array} \right\}$$

$$a_{RMS} = \sqrt{\sum_{i=1}^{m} a_i}$$

$$a = acceleration(g), y{:}\,PSD(g^2/Hz), f : frequency(Hz), N{:}\,Slope \tag{2}$$

The maximum load that can occur in random vibration has a Gaussian distribution and the following probabilities:

1 1σ: 68.3%
2 2σ: 95.4%
3 3σ: 99.7%

where σ is the average response load. In this work, the expected maximum load was calculated with 3σ.

3. Notching procedure

Notching is a method to determine the optimal frequency range and load level that meet the design load and allowable conditions under constrained conditions. A range of conditions manifest depending on the structural characteristics of the test object, and as the test level rises, the response characteristics (natural frequency and amplification ratio) change, requiring numerous trials and errors. The notching procedure formulated in the present work is shown in Fig. 6.

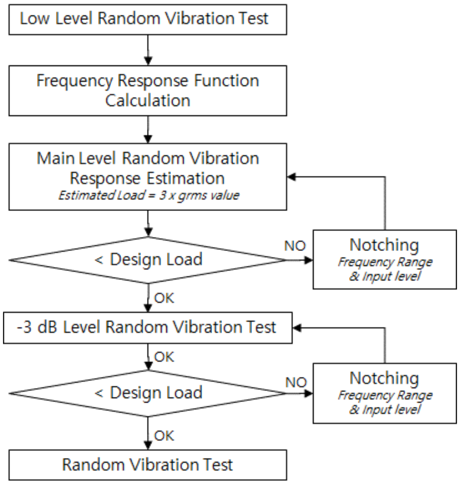


Fig. 6 Response Limit Notching Flow

1 Low Level Random Vibration Test

Input/response results are obtained by performing random vibration tests at the lowest possible level considering the performance of the vibration tester

2 Frequency Response Function Calculation: Frequency Response Spectrum

The frequency response function (FRF) of the test object is calculated from the obtained results.

3 Expected Maximum Response Load Estimation

The maximum response load is predicted using the calculated FRF and random vibration test conditions:

Maximum response load (g) = 3 × average response load (grms)

4 Notching (Frequency Range and Load Level)

The frequency range and load level satisfying the design load and allowable conditions (±10%) are set (requires high-level system approval).

5 -3 dB Level Random Vibration Test

The random vibration test is performed while increasing the load from a low level to a high level. The final notching conditions are determined after confirming the adequacy of notching at the level of -3 dB as the response results (natural frequency and amplification ratio) may change with increasing levels, as shown in Fig. 7.

6 Random Vibration Test

The random vibration test is performed, verifying the response result with the final notching conditions.

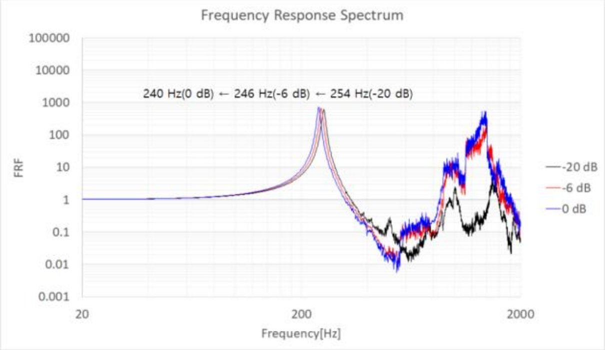


Fig. 7 FRF Change for Test Level

The notching conditions (frequency range and load level) can change the random vibration test requirements, requiring the approval of the high-level system. The high-level system conditions in this work are as follows:

1 Apply the response result from the excitation axis;
2 Higher than 80% of the standard condition of random vibration test for the load applied for notching;
3 Minimum applied load for each frequency;
4 Minimum response load applied when condition ③ is not met;
5 Consult with the higher-level system when condition ④ is not met.

The response to the excitation axis is predominantly based on the response of this axis meeting the first condition, but the result from the three axes is also considered when the response from other axis is relatively large depending on the test object.

4. Notching toolkit

Two notching toolkits are proposed in this study: one intended for a single response and the other intended for multiple responses. The utility of the toolkit for one response was confirmed through unit level random vibration test, where corrections/supplements were derived. In sequence, this toolkit was improved to become a toolkit for multi responses by considering and implementing the identified corrections/supplements and test objects beyond the assembly that requires multiple responses.

4.1 Toolkit for one response

Fig. 8 shows the screen composition of the initial implementation of the toolkit for one response. To use this toolkit, it is necessary to prepare a FRF (Excel format) of the test object by performing a low level random vibration test. The main features of the toolkit are as follows:

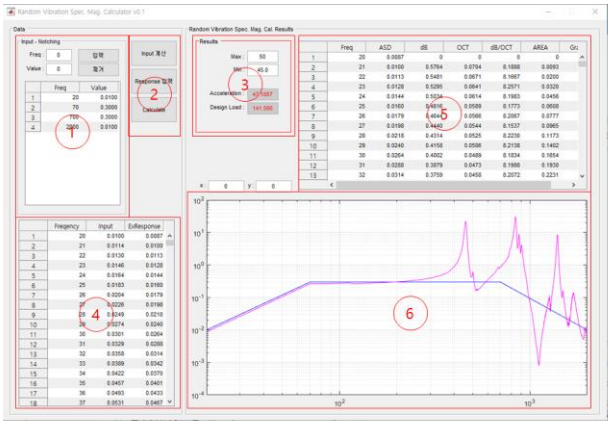


Fig. 8 Initial Notching Toolkit for One Response

1 Applied load: input frequency (Hz) and load level (g^2/Hz);
2 Response calculation: calculate the response to the input through the FRF prepared in Excel format;
3 Average response load (grms) and maximum response load (g) calculation: calculate the average response load of the responses calculated in conditions ① and ② and the maximum response load with 3σ;
4 Response load results for each frequency: present the calculated response load for each frequency;
5 Cumulative average response load: present cumulative average response load for each frequency;
6 Input and response graph: present the input load and response load results as graphs and check the

frequency and load values in the response graph.

The unit level random vibration test on the initial toolkit showed that the time required for notching was reduced by approximately 50% compared to the time required before using the toolkit. The following corrections/supplements were derived for improved convenience.

1 Feature to modify input frequency and load level in the applied load input table;
2 Saving/loading feature of notching conditions for input/output convenience;
3 Load calculation function for arbitrary frequencies under conditions with load on a slope.

The random vibration condition can be divided into three intervals of load increase, stagnant load, and load decrease. Notching during the stagnant load interval can be applied intuitively, but the load for frequency in the load decrease and increase intervals requires a separate calculation. Fig. 9 shows the interval where the load decreases as the frequency increases under random vibration conditions. Considering the frequency (f_l) and load (PSD_l) at the starting point of the decrease and the frequency (f_h) and load (PSD_h) at the end point of the decrease, the slope (m) considering the log scale and the load (PSD_x) at an arbitrary frequency (f_x) are calculated using Eqs. 3 and 4, respectively.

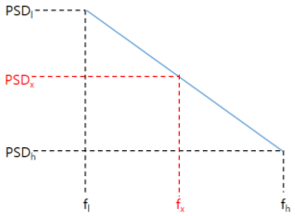
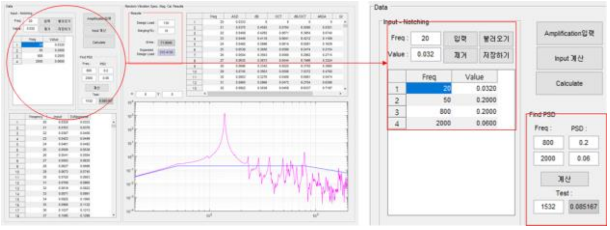


Fig. 9 Response Limit Notching Flow

$$m = \frac{\log(PSD_h/PSD_l)}{\log(f_h/f_l)} \tag{3}$$

$$PSD_x = PSD_l \times \left(\frac{f_x}{f_l}\right)^m \tag{4}$$

Fig. 10 shows the screen configuration of the toolkit for one response that includes the feature that enables the modification of applied load, saving/loading of notching conditions, and calculation of the load for an arbitrary frequency.



Freq : 20

Value : 0.032

	Freq	Value
1	20	0.0320
2	50	0.2000
3	800	0.2000
4	2000	0.0600

Freq :	PSD :
800	0.2
2000	0.06

Test : 1532 0.085167

Fig. 10 Updated Notching Toolkit for One Response

The random vibration test for unit level performed using the outlined notching toolkit for one response is shown in Fig. 11.

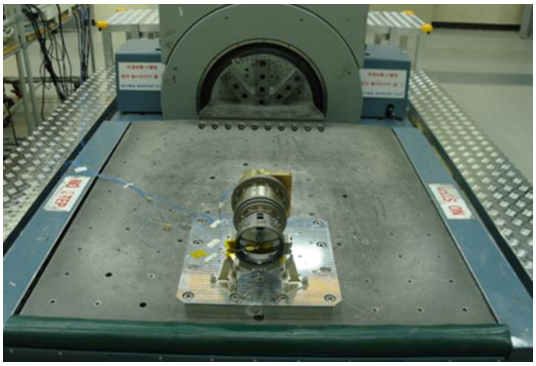


Fig. 11 Random Vibration Test for Unit Level

The FRF was calculated by performing a random vibration test at a low level (-20 dB) that can be realized in the vibration tester based on the standard test conditions (16.75 grms, black in Fig. 12). The primary notching (15.04 grms, black in Fig. 12) was performed such that the maximum response load became 95% of the design load by applying the obtained FRF, and a random vibration test was performed up to -3 dB. The expected maximum response load at -3 dB was 125% of the design load, exceeding the rated operating condition (±10%). This was different from the value initially expected (95%). Hence, the secondary notching (14.24 grms, red in Fig. 12) was performed to achieve 97% of the design load by applying the -3-dB FRF. The test was completed after confirming that the response load was 99% of the design load at 0 dB in terms of the secondary notching standard.

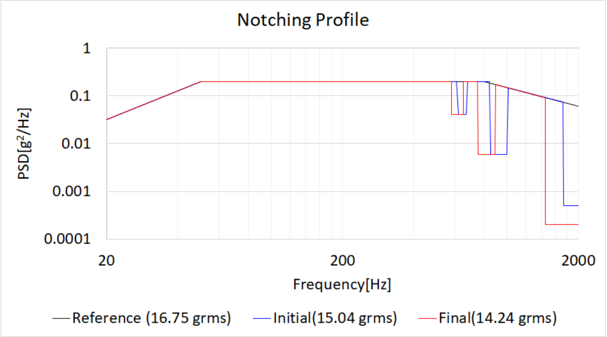


Fig. 12 Updated Notching Profile for Input Level

The change in the maximum load was estimated from the change in the structural characteristics (reduction of natural frequency and increase in amplification ratio) of the test object as the load increased. Through this test, the utility of the improved toolkit for one response was verified, and the time required for notching was reduced by approximately 65% compared to not using the toolkit.

4.2 Toolkit for multi response

Notching of an assembly equipped with multiple units must be conducted such as to meet the design load and rated operating conditions of the assembly and unit. Therefore, multiple responses should be considered. For this, a toolkit for multi response was developed. The screen configuration is shown in Fig. 13.

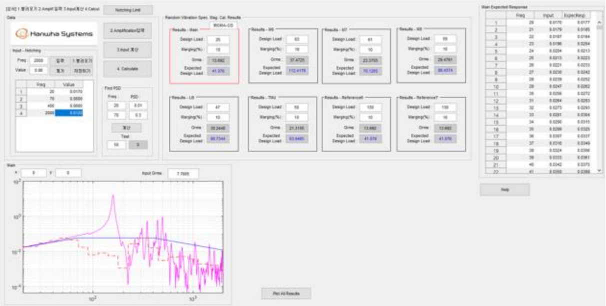


Fig. 13 Notching Toolkit for Multi Response

The overall configuration is similar to that of the toolkit for one response, and the following items were added:

1. Input and display of minimum applied load condition;
2. Display multiple response load results;
3. Display multiple response graphs.

The minimum applied load conditions required by the high-level system was input (Notching Limit in Fig. 14) and shown as a graph (red dotted line in Fig. 14), providing a visual tool for determining the frequency range and load level.

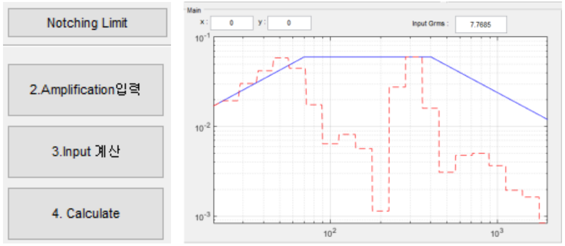


Fig. 14 Minimum Notching Level on the Graph

The response graph on the main display shows a response that should be considered first. The system is configured to show other response graphs in a separate window, as shown in Fig 15. Each graph is implemented such that it can be enlarged/reduced to check the frequency and response load. The frequency of interest and the load from a total of eight response graphs including the main display can be observed.

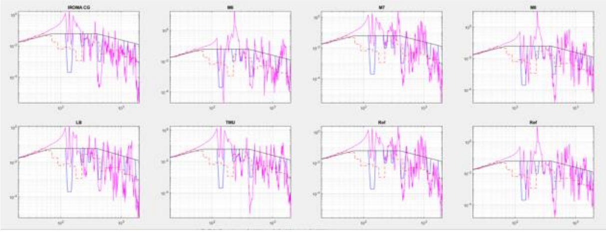


Fig. 15 Separated Multi Response Graph

A random vibration test at the assembly level requiring six responses was performed using the notching toolkit for multi response, and the test configuration is shown in Fig. 16. Responses were obtained from an assembly and five mounted units. The FRF of the test object was calculated by performing a low level random vibration test that can be implemented in the vibration tester. Notching was performed such that the response load of the assembly and five units satisfied the design load and rated operating conditions. Oddities and corresponding solutions from this test were as follows. The response was 135% of the design load at point A, exceeding the rated operating condition (±10%) by 25%, and 93% of the design load at point B, which was within the rated operating condition. If an additional notching is performed to reduce the response at point A to be within the rated operating condition, the response at point B would be reduced below the rated operating condition (-10%). To overcome this problem, the frequency range with the difference in amplification ratio was determined by comparing the response graphs at points A and B. In the frequency range 1300–1600 Hz, amplification ratio at point A was 10 or more and 1 or less at point B. By performing notching in the aforementioned frequency range, the response at point A was reduced by 27% to 108% of the design load, whereas the response at point B was reduced by 2% to 91% of the design load; notching was successfully conducted at points A and B to meet the rated operating conditions.

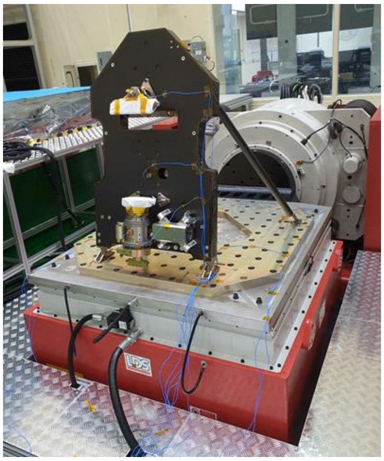


Fig. 16 Random Vibration Test for Assembly Level

From this test, the utility of the toolkit for multi response was demonstrated, and the time required for notching was reduced by approximately 65% compared to not using the toolkit.

4. Conclusion

In the present study, the notching technique, implemented to prevent transient state test that causes damage and malfunction to the test object during the vibration test, was described. Transient state test is caused by the difference in constraints between the launch and test environments and the comprehensive determination of the test conditions. Notching can be classified into response-limiting and load-limiting techniques. In this study, response-limiting techniques based on acceleration and design load were described. With notching, various conditions emerge depending on the structural characteristics, and these characteristics of the test object vary with the applied load level, requiring a trial and error approach and a considerable amount of time. The notching toolkit was developed for user convenience and shortening of test time considering the development concept, high-level system requirements, and test object level.

User convenience and time reduction were confirmed and details for corrections/supplements were obtained through the vibration test using the initially developed toolkit for one response. Unit level vibration test using the supplemented toolkit showed that the required time was reduced by approximately 65% compared to the time required when the toolkit was not used. Based on this, a toolkit for multi response was developed, and an assembly level vibration test requiring six responses was performed. The specificities and solutions related to the rated operating conditions of the response, which occur in the random vibration test using multiple responses, were presented. From this, the effectiveness of the toolkit for multi response and the time reduction effect of approximately 65% were verified.

The notching toolkit of the response limiting technique proposed in this study is used for diverse random vibration tests in our facility, and it has potential to be expanded to other applications depending on the required response quantity of the test object and additional requirements.

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