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Power spectral density peak estimation from broadband data

Keiko Yoshida

Advanced Technology R & D Center, MITSUBISHI Electric Corporation, Amagasaki, Hyogo 661–8861, Japan

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Abstract

The power spectral density (PSD) peak estimation formula from response analysis results obtained from analysis with 1/3 octave bands or other broadband analysis bands for artificial satellites acoustic tests, is derived. The effectiveness of this formula by single-degree-of-freedom system response computations, and concerning the results of acoustic tests on an actual satellite panel, the PSD peak values estimated with this formula using loss factor obtained from experimental modal analysis are approximately same as the experimental results, is demonstrated. And the frequency resolution required for PSD peak estimation, are also investigated. Accuracy on the frequency resolution of practical test results, are shown.

1. Introduction

The sound produced during a rocket launch causes vibration in the structural panels of an artificial satellite. To ensure that the vibration will not damage or destroy equipments that are mounted on the structural panels, acoustic tests are performed in which the acoustic environment of a rocket launch is modeled by using a power spectral density (PSD) function to specify a certain acceleration level (referred to as simply 'spec' below). These tests can confirm in the initial stage of the satellite design that the structural panels will be subjected to no more than the spec vibration level. And equipments have to be confirmed no damages or destructions at that vibration level by vibration tests.

In the satellite acoustic tests, high acoustic pressure is generated in a reverberation room with the satellite placed at the center of the floor. The vibration response of each structural member is measured with an acceleration sensor and the PSD is computed from the data. An example comparison of the PSD of the acceleration response of a point near mounted equipment and the spec from the acoustic tests is shown in Fig. 1, where the thick line represents the spec values and the thin lines represent the acceleration response PSD at the point near the mounted equipments.

The analysis frequency bandwidth is 3.9 Hz, and max frequency is 2000 Hz. At 300 and 450 Hz, the measurement data exceed the spec. When the PSD exceeds the spec for a given frequency in the acoustic tests as shown in Fig. 1, it is necessary to modify the satellite structure so as to bring the value within the spec. That change in structure involves the drafting of countermeasures, analysis, change in design, implementation of countermeasures, acoustic tests and a large cost. Therefore, a great reduction in cost could be obtained by

E-mail address: Yoshida.Keiko@dw.MitsubishiElectric.co.jp

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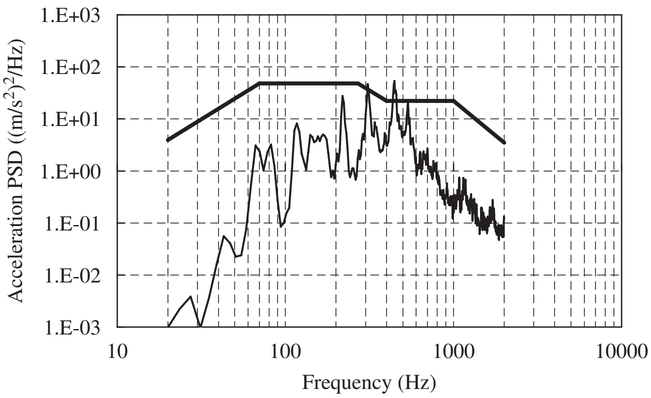

Fig. 1. Example of PSD and spec for measured acceleration response spec, acceleration response PSD.

predicting the value of the PSD of the acceleration response for each part of the structural panel and making the necessary changes in the design, before conducting the acoustic tests. With that objective, the Japan Aerospace Exploration Agency (JAXA) developed a system for predicting the panel vibration response with respect to acoustic vibration in the early stage of design [1]. That system employs the statistical energy analysis (SEA) [2] methodology as the method for prediction, so the response is computed for each 1/3 octave band in the analysis frequency band of the acoustic input. However, the analysis frequency bandwidth for the acceleration response PSD is usually a narrow 4 or 8 Hz (Fig. 1), and the peak response must be obtained in the narrow-band. Here, firstly a method for converting the response obtained for each 1/3 octave band, to the peak of a narrow-band PSD is derived. And the practicality of that method is discussed.

In this acceleration response evaluation method, the PSD analysis frequency band contributes greatly to the height of the peak. In Japan, the JAXA Artificial Satellite Design Standards [3] states that 'the recommended value for the resolution of the response PSD analysis is 8 Hz, however, that is believed to assume 512 FFT samples when the maximum frequency for evaluation is 2000 Hz.' On the other hand, in the US, MIL standard [4] states that 'although the analysis frequency bandwidth must not exceed 1/6 octave.' For example in Fig. 1, if the analysis frequency band is evaluated with a 1/6 octave band, the peaks at 300 and 450 Hz are within the spec, and no measures need be taken. In this way, the analysis frequency band is strongly related to the cost of the satellite. As I described above, if the mounted equipment is not damaged or destroyed when subjected to vibration tests to confirm reliability at the spec PSD, in which the total acceleration level applied to the mounted equipment with the spec of Fig. 1 is overwhelmingly larger than the acceleration levels in the acoustic tests. It is therefore difficult to believe that a partial deviation in the PSD peak would lead to damage with a high probability. More discussion of the analysis frequency band for the case of direct evaluation from the spec of the PSD are hoped for. When a slight peak deviation occurs in the acoustic tests in the evaluation by the spec of the acceleration response PSD, re-evaluation by random response spectrum (RRS) is often done. With RRS, the root mean square (rms) response for a single-degree-of-freedom system is calculated for each PSD response input. Although the peak frequency value is large, the overall total for the entire frequency band is calculated, so even if the peak deviates slightly from the spec, if the response for the frequencies other than the peak frequency is much below the spec, the spec RRS may be too small. The use of this method is based on the idea that the destruction of the equipment mounted on the panel is strongly related to the RMS of the acceleration, not the peak of the PSD. Even when RRS is used, if the PSD analysis frequency band is coarse, an accurate evaluation is not possible, so it is necessary that it be possible to at least estimate the resonance sharpness Q, and accurately measure the PSD peak. For brittle materials or other materials for which mechanical failure is problematic, have to be measured accurate PSD peak. Therefore, it is necessary to obtain an accurate low-frequency band peak and compute the stress from the shape of the vibration mode for evaluation. In that case, the analysis frequency band of the PSD peak must be such as to allow accurate obtaining of the resonance sharpness Q. In this report, the analysis frequency bandwidth that can accurately represent the peak, is considered.

2. PSD peak estimation for 1/3 octave band analysis results

2.1. Derivation of the computational formula

Consider the case in which there are multiple vibration modes within the analysis frequency band. The results of calculating the response by SEA using the average of the loss factor values of all the vibration modes within the analysis frequency band, show that the calculated and measured results of the mean square values within the analysis frequency band agree. That is to say, the energy of the vibration modes is assumed to be uniformly distributed within the analysis frequency band.

Assume that N modes (1st, 2nd … kth, … Nth) are contained in the analysis frequency band. For the kth mode, the PSD peak value P_k, is given as follows:

$$P_k = \frac{S(f_k)}{(\eta_k K_k)^2}, \tag{1}$$

where f_k is the natural frequency of the kth mode, $S(f_k)$ is the PSD of the excitation force at f_k, η_k is loss factor for the kth mode, and K_k is the mode stiffness for the kth mode. From the assumption that the energy of the various modes is evenly distributed over the analysis frequency band, η_k and K_k for the kth mode in the analysis frequency band can be approximated by the mean value within the analysis frequency band η and k. Accordingly, the PSD peak in the analysis frequency band can equally be represented by P_b in the following equation:

$$P_b = \frac{S(f_k)}{(\eta K)^2}. \tag{2}$$

Furthermore, the excitation force is uniform within the analysis frequency band, so denoting the vibration amplitude as $S(f_b)$, Eq. (2) can be expressed as follows:

$$P_b = \frac{S(f_b)}{(\eta K)^2}. \tag{3}$$

On the other hand, integrating the power of the kth mode W_k, Eq. (1) over the entire frequency band gives the following equation:

$$W_k = \frac{\pi f_k S(f_k)}{2\eta_k K_k^2}. \tag{4}$$

If all modes are within the analysis frequency band, the loss factor is small, and most of the power of the modes is contained within the analysis frequency band, then the total power within the analysis frequency band W_b, can be expressed by the following equation:

$$W_b = \sum_k^N \frac{\pi f_k S(f_k)}{2\eta_k K_k^2}. \tag{5}$$

If η_k and K_k can be approximated by η and K as mean values in the analysis frequency band, and the excitation force PSD in the analysis frequency band is uniform and its vibration amplitude is expressed as $S(f_b)$, then Eq. (5) becomes as follows:

$$W_b = \frac{\pi S(f_b)}{2\eta K^2} \sum_k^N f_k. \tag{6}$$

Accordingly, from Eq. (6), which is the result obtained as the mean square value of the analysis frequency band, and using the following equation, the PSD peak level for Eq. (3) can be obtained

$$P_b = W_b \frac{2}{\pi\eta \sum_k^N f_k}. \tag{7}$$

When there is only one mode in the analysis frequency band and the resonance frequency is, Eq. (7) becomes

$$P_b = W_b \frac{2}{\pi \eta f_o}. \tag{8}$$

The natural vibration frequency of a plate increases linearly with frequency. Also for a honeycomb panel, an almost linear increase can be seen for a 1/1 octave and 1/3 octave range. For these kinds of structures, the number of modes per frequency (modal density) is a constant. Accordingly, the N modes in the analysis frequency band exist at equal intervals. If the frequency band is an octave band, the center frequency is f_o, the lowest frequency f_l is $f_o/\sqrt{2}$, and the upper frequency f_u is $f_o/\sqrt{2}$, the bandwidth Δf is then $f_o/\sqrt{2}$. The frequency interval between modes is assumed to be the bandwidth divided by $N+1, f_c/\sqrt{2}/(N+1)$. The kth natural frequency that appears in this analysis frequency band f_k, is expressed by the following equation:

$$f_k = f_l + \Delta f \frac{k}{N+1} = \frac{f_c}{\sqrt{2}} \frac{k}{N+1}. \tag{9}$$

Computing the total of Eq. (9) within the analysis frequency band yields the following equation:

$$\sum_k^N f_k = 1.06 f_o N. \tag{10}$$

Substituting Eq. (10) into Eq. (7) yields the following:

$$P_b = 0.94 W_b \frac{2}{\pi \eta f_o N}. \tag{11}$$

For the 1/3 octave frequency band, the minimum frequency f_l is $f_o/2^{-1/6}$, the maximum frequency f_u is $f_o \times 2^{1/6}$, and the bandwidth is $f_o/4.32$, so the kth natural frequency that appears in this analysis frequency band f_k, is expressed by the following equation:

$$f_k = f_l + \Delta f \frac{k}{N+1} = \frac{f_o}{2^{1/6}} + \frac{f_o}{4.32} \frac{k}{N+1}. \tag{12}$$

Computing the total of Eq. (12) analysis frequency band yields the following equation:

$$\sum_k^N f_k = 1.005 f_o N. \tag{13}$$

Substituting Eq. (13) into Eq. (7) gives the following equation:

$$P_b = 0.995 W_b \frac{2}{\pi \eta f_o N}. \tag{14}$$

2.2. Verification for single-degree-of-freedom system response

Consider the vibration in a single-degree-of-freedom system that comprises a mass, a damper, and a spring. For force F, we denote the system mass as M, the resonance frequency as f_o, and the loss factor as η. The acceleration response at frequency f is then expressed as follows:

$$a = F \frac{-f^2}{M(f_o^2 - f^2 + jff_o\eta)}. \tag{15}$$

Accordingly, the acceleration response PSD $A(f)$ is as follows:

$$A(f) = F^2 \frac{f^4}{M\{(f_o^2 - f^2)^2 + (ff_o\eta)^2\}}. \tag{16}$$

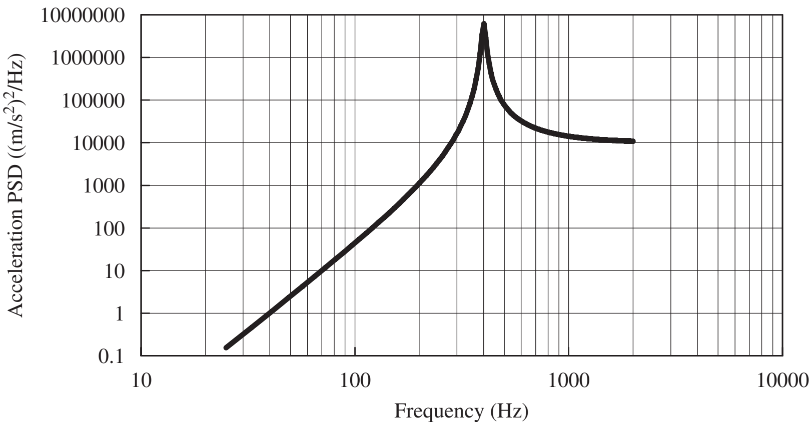

Fig. 2. Example of computed acceleration response PSD for a single-degree-of-freedom system ($f_o = 400$ Hz, $\eta = 0.04$, $B_e = 8$ Hz).

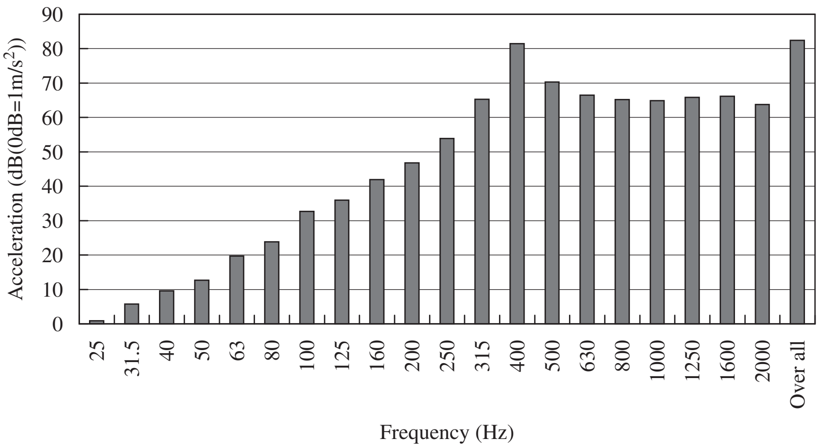

Fig. 3. 1/3 octave band analysis of acceleration response for a single-degree-of-freedom system ($f_o = 400$ Hz, $\eta = 0.04$, $B_e = 1/3$ oct).

In Eq. (16), consider the case in which $F = 100$, $M = 1$, $f_o = 400$, and $\eta = 0.04$. The computed values for the PSD of the narrow-band analysis frequency band $B_e = 8$ Hz are shown in Fig. 2.

The 1/3 octave band analysis results for Fig. 2 are shown in Fig. 3. The fact that the RMS shown on the right side of the bar graph in Fig. 3 is about the same as the center frequency component at 400 Hz shows that nearly all of the mode energy is contained within this analysis frequency band.

The estimated PSD peak obtained by substituting the 1/3 octave band analysis results from Fig. 3 into Eq. (14), the results obtained by simply dividing by the 1/3 octave bandwidth, and the calculated PSD from Fig. 2 are compared in Fig. 4. From Fig. 4, we can see that although the PSD peak estimation by Eq. (14) is the same as the actual PSD peak at 400 Hz, the result of simply dividing by the 1/3 octave band is not even 10% of the PSD peak. Fig. 4 satisfies the assumption made in the derivation of Eq. (14) that all of the modes are within the analysis frequency band and the coefficient of loss is small, the power of the modes is mostly contained within the analysis frequency band. Here, the 1/3 octave band analysis results for when the loss factor η, is taken to be 0.3 are shown in Fig. 5. The estimated PSD results are shown in Fig. 6. From Fig. 5, we can see that the 1/3 octave band component at 400 Hz and the rms are not the same, and that the mode energy extends over multiple 1/3 octave bands. This result is smaller than the PSD peak of Fig. 6 estimated by Eq. (14).

Next, consider the case in which the PSD analysis frequency band is too wide, and the PSD does not realize the actual peak. The PSD for when the analysis frequency amplitude is 32 Hz and the PSD peak estimated

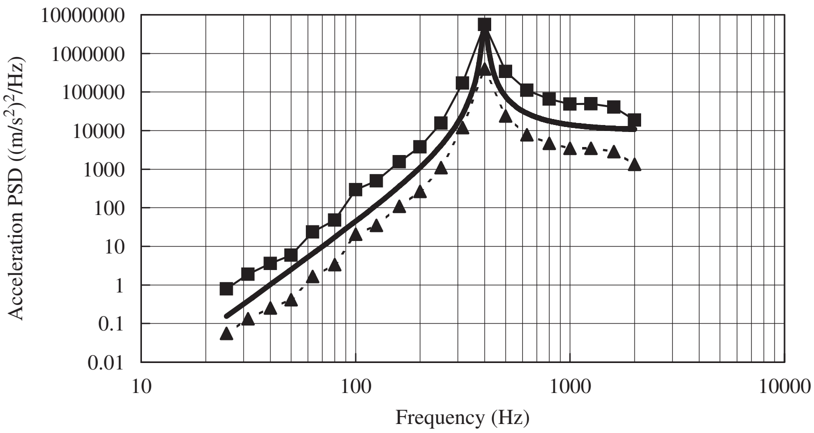

Fig. 4. PSD estimated from 1/3 octave band analysis results ($f_o = 400\,\mathrm{Hz}, \eta = 0.04, B_e = 8\,\mathrm{Hz}$), ▬ PSD theory, — calculation results by Eq. (14), - - - calculation results obtained by simply dividing by the 1/3 octave bandwidth.

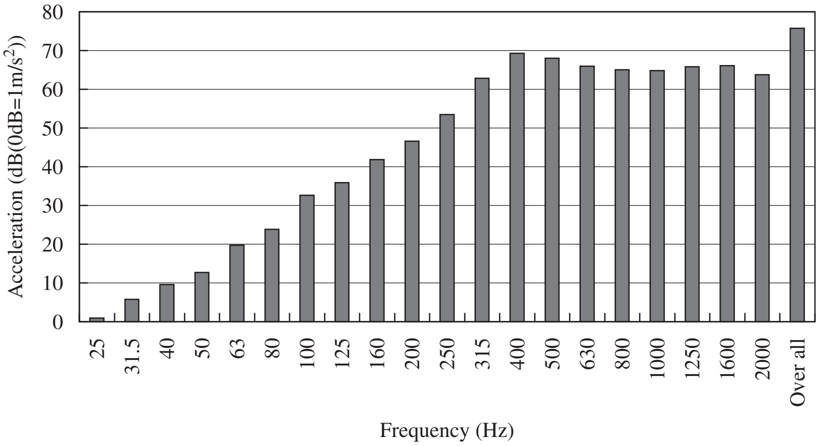

Fig. 5. 1/3 octave analysis results for $\eta = 0.3$ ($f_o = 400\,\mathrm{Hz}, \eta = 0.3, B_e = 1/3\,\mathrm{oct}$).

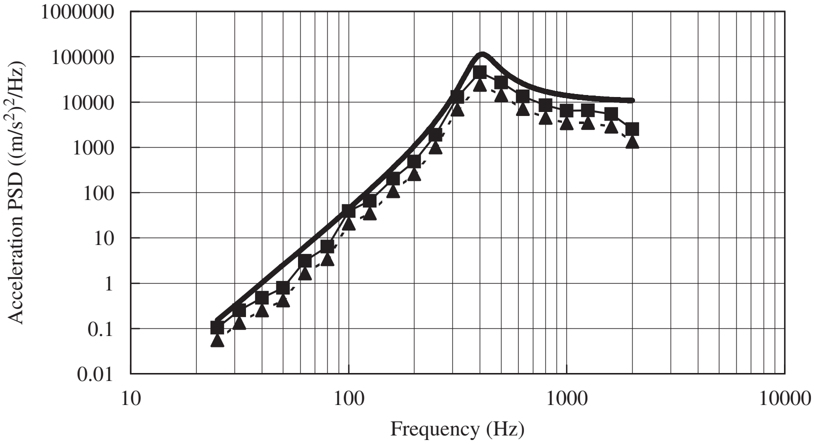

Fig. 6. PSD peak estimation results for $\eta = 0.3$ ($f_o = 400\,\mathrm{Hz}, \eta = 0.3, B_e = 8\,\mathrm{Hz}$), ▬ PSD theory, — calculation results by Eq. (14), - - - calculation results obtained by simply dividing by the 1/3 octave bandwidth.

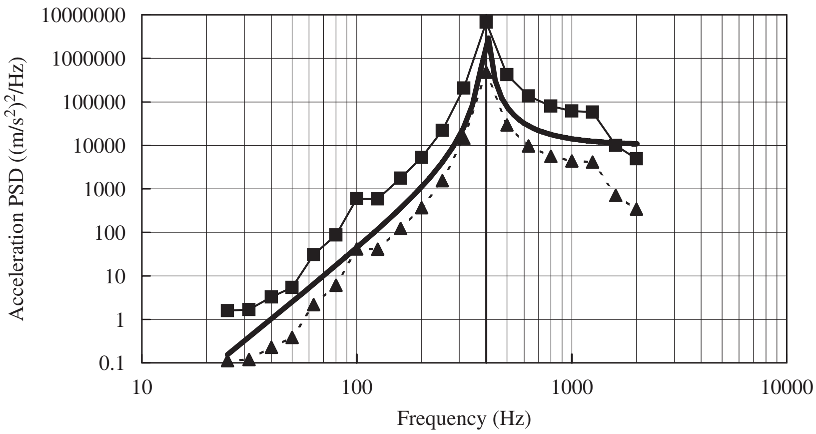

Fig. 7. PSD for 32 Hz analysis frequency band compared with 1/3 octave band analysis ($f_o = 400$ Hz, $\eta = 0.04$, $B_e = 32$ Hz), ▬ PSD theory, —— calculation results by Eq. (14), - - - calculation results obtained by simply dividing by the 1/3 octave bandwidth.

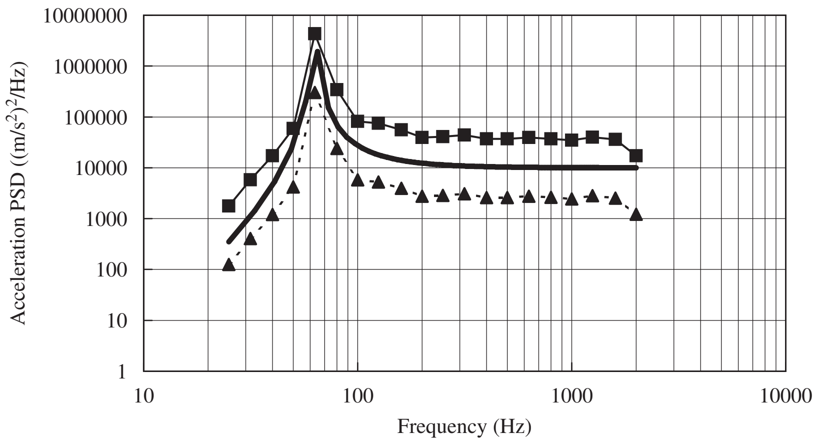

Fig. 8. PSD for 8 Hz analysis frequency band compared with 1/3 octave band analysis results ($f_o = 63$ Hz, $\eta = 0.04$, $B_e = 8$ Hz), ▬ PSD theory, —— calculation results by Eq. (14), - - - calculation results obtained by simply dividing by the 1/3 octave bandwidth.

from the PSD and 1/3 octave band analysis are compared for $F = 100$, $M = 1$, $f_o = 400$, and $\eta = 0.04$, in Fig. 7. From Fig. 7, we can see that the PSD peak is smaller than the PSD estimate. This is not because the accuracy of estimation by Eq. (14) is poor, but because the resolution of the PSD is low and thus cannot express the peak. The analysis frequency band problem arises when the resonance frequency is low. For $F = 100$, $M = 1, f_o = 63$, and $\eta = 0.04$, the PSD when the analysis frequency band 8 Hz is compared with the PSD peak estimated from the 1/3 octave band analysis results in Fig. 8.

In representing the power of one resonance mode, at least the resonance peak -3 dB frequency, which is to say the half-bandwidth Δf for calculating the resonance sharpness Q, should be represented. In this example, however, the analysis frequency band is coarser than this frequency band, so because the measured PSD peak itself is low, and the estimated 1/3 octave band analysis results are higher than the actual power of the PSD, and the 1/3 octave band analysis results the estimates obtained using Eq. (14) are larger than the PSD peak. To accurately obtain the PSD peak restricted to the low-frequency band requires that the measured maximum frequency be made small and the frequency resolution be increased.

The above results show that the peak estimation obtained with Eq. (14) is effective when all modes are within the analysis frequency band the loss factor is small, and the power of the mode is mostly contained in analysis frequency band.

2.3. Example of application to practical acoustic tests

Consider the PSD estimates from the acoustic tests on satellite structure panels conducted with narrow-band and 1/3 octave band analysis frequency bands and the results for the PSD peak estimated from the 1/3 octave band measurements by the proposed method using Eq. (14). Usually, the satellite acoustic test is conducted in the big chamber which volume is about 1500 m^3. But this experimental test aim is not a satellite quality assurance, but verification of Eq. (14). Therefore, the chamber did not have to be so large, and the sound pressure level did not have to be rocket noise environment lebel.

In the experimental tests, the white noise sound was generated in the small chamber, and the test panel was hung from the ceiling center of the chamber, and the vibration level of it was measured. To avoid the influence of the reflection of the sound, the panel located at the point which is almost same distance from the floor, the walls, and the ceiling of the chamber. The test circuit is shown in Fig. 9.

The measuring instruments used in Fig. 9 circuit, is shown in Table 1.

The specification of the echoic chamber, is shown in Table 2. Because of this chamber's volume, the room resonance is clear and modal density is low under 100 Hz. And so, the acoustic test targeted upper 100 Hz.

The sound pressure lebel was measured by two microphones which located 1 m away from the test panel. Microphone 1 and Microphone 2 were located each sides of the panel. 1/3 octave band sound pressure lebels are shown in Fig. 10.

The physical properties of the test panel are listed in Table 3.

In Table 3, size values are measured value, and physical properties values are examined in the material catalog.

The resonance frequencies and the loss factor for below 2000 Hz obtained from a mode analysis performed prior to the acoustic tests are listed in Table 4.

The PSD obtained from the acoustic tests for this panel with analysis frequency bands of 1.5625 Hz and 1/3 octave and the PSD peak values estimated from 1/3 octave band measurement results using Eq. (14) are shown in Fig. 11. Two cases are plotted in the figure for the PSD peak estimation using Eq. (14), one in which the

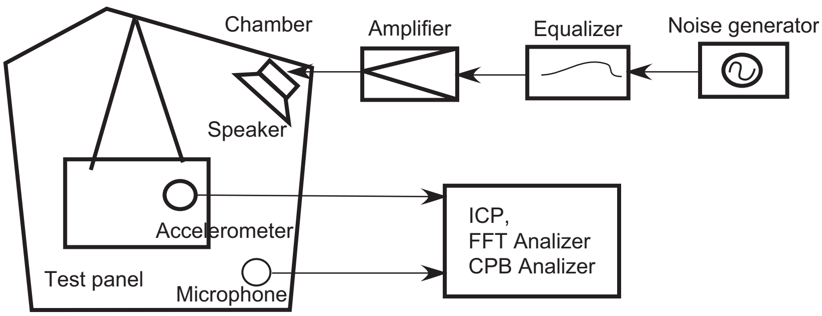

Fig. 9. Test circuit.

Table 1
Measuring instruments used in the experimental test

Instrument	Manufacturer and model
Noise generator	NF 1360
Equalizer	JBL 5547A
Amplifier	YAMAHA PC2002M
Speaker	JBL E-114,2445J
Accelerometer	B&K 4507 (TEDS)
Microphone	B&K 4190
ICP, Analyzer	B&K PULSE

Table 2
Specification of echoic chamber

Physical property	Value
Shape	Scalene heptahedron
Material	Reinforced concrete
Wall thickness (mm)	200
Volume (m^3)	40
Surface area (m^2)	80
Averaged absorption coefficient (250 Hz)	0.01

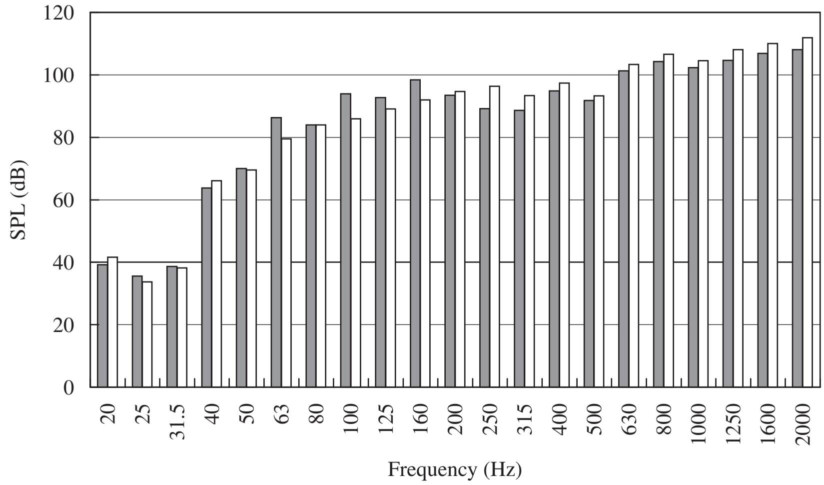

Fig. 10. Sound pressure label analyzed on 1/3 octave band of two microphones. Gray bars are microphone 1, white bars are microphone 2.

Table 3
Physical properties of test panel

Physical property	Value
Face sheet thickness (mm)	0.364
Face sheet Young's modulus (Pa)	6.4×10^{10}
Core thickness (mm)	20
Core shear modulus (Pa)	1.05×10^{8}
Area (m $\times$ m)	0.66×0.72
Mass per area (kg/m^2)	5.04

number of in-band modes for each band was estimated by mode analysis and one in which the number of modes of the honeycomb panel was estimated by theoretical formula [5]. From Fig. 11, we can see that the PSD obtained with the 1/3 octave analysis frequency band is 10% or less of the narrow-band estimates, and the peak cannot be estimated. In comparison with that, the peak can be roughly estimated above 300 Hz using Eq. (14). For an actual satellite, experimental mode analysis up to the high frequency of 2000 Hz is seldom performed, so the theoretical values for number of modes must be used. Nevertheless, we have seen that the error when the theoretical values are used, is smaller than the error when estimates from experimental mode analysis are used. In addition to the resonance peak estimates at 159 Hz being larger than the PSD, peaks were observed in the region from 200 to 300 Hz, where there is no resonance frequency. This is regarded as the

Table 4
Resonance frequency and loss factor of test panel estimated by experimental modal analysis

Natural frequency (Hz)	Loss factor
159	0.0041
312	0.007284
420	0.005033
458	0.010414
614	0.012984
634	0.011137
769	0.010907
820	0.016042
1028	0.0161
1141	0.008136
1196	0.025288

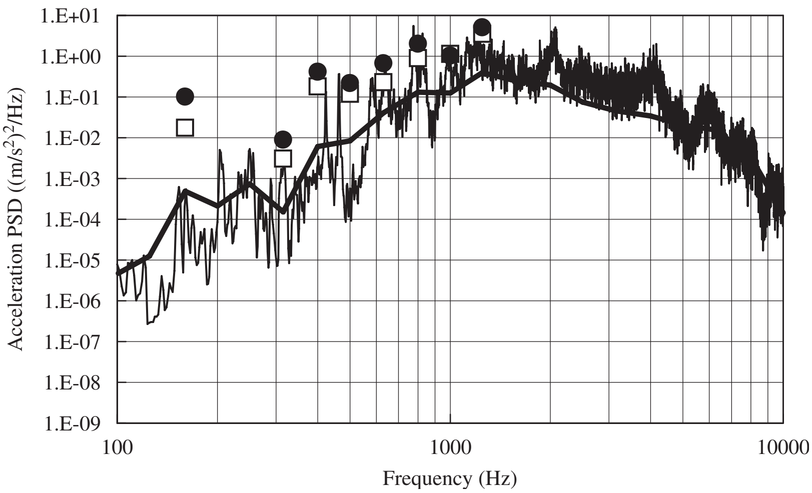

Fig. 11. Example of PSD peak estimation of a practical panel ━ PSD of 1.5625 Hz bandwidth, ▬ PSD of 1/3 octave band, □ proposed estimation (by actual mode number), • proposed estimation (by analytical mode number) dividing by the 1/3 octave bandwidth.

appearance of modes of the reverberation room as peaks, because the reverberation room in which the experiments were conducted was only 40 m^3 in size. These results confirm the utility of Eq. (14) in actual acoustic tests.

The analysis result using Eq. (14) on 800 Hz, is 3 dB less than the practical peak. This is because the 769 Hz mode peak is influenced by 820 Hz mode. Eq. (14) is derived from the summation of single degree of freedom system. So, if each mode is not well separated, the analysis value using Eq. (14) may be under estimation for the practical value.

3. Analysis frequency band capable of expressing the peak

3.1. Estimation accuracy in a single-degree-of-freedom system

Given adequate frequency resolution, the height of the PSD peak can be represented with equal fidelity, even if there are differences in frequency resolution. If the coarseness of the resolution exceeds a given threshold, however, the peak height will be lower than the actual value. For example, comparing the peak heights for narrow-band PSD and 1/3 octave band PSD, we see that when the coefficient of loss is small, the 1/3 octave band peak height is often low. The frequency resolution that is capable of highly faithful representation of the peak height is strongly related to Q, which is the reciprocal of the coefficient of loss, and the half width, Δf, for estimating Q. Up to now we have estimated the accuracy ε between the PSD value estimated and the actual value for the case in which peak is at the center of the frequency band by using the following equation [6]:

$$\varepsilon = \frac{B_r}{B_e}\tan^{-1}\left(\frac{B_e}{B_r}\right), \tag{17}$$

where B_r is the value of the resonance frequency f_o divided by Q and resonance frequency. For the resonance mode at f_o, the PSD peak estimation accuracy for the cases in which B_e is 1/3 octave band and 8 Hz is evaluated by the following equation.

$$\varepsilon = \frac{P_o}{\frac{1}{B_e}\int_{f_o-B_e/2}^{f_o+B_e/2}\mathrm{PSD}(f)\,\mathrm{d}f}. \tag{18}$$

Here, the numerator P_o represents the true PSD peak at the resonance frequency, and the denominator is the PSD peak estimated from the analysis frequency band B_e. PSD(f) represents the PSD at frequency f. The results of computations by Eq. (17) and Eq. (18) for f_0 values of 100, and 1000 Hz and Q values of 1, 10, 20, 50, and 100 are compared in Fig. 12.

From Fig. 12, the accuracy can be estimated by Eq. (17) in these cases.

However, the PSD peak may occur at the minimum value or maximum value of the frequency band rather than at the center. In that case, the estimated accuracy of the peak is worse than indicated by Eq. (17).

When the resonance peak is at the lowest frequency of the analysis frequency band width, the estimation error is evaluated by the following equation:

$$\varepsilon = \frac{P_o}{\frac{1}{B_e}\int_{f_o}^{f_o+B_e}\mathrm{PSD}(f)\,\mathrm{d}f}. \tag{19}$$

The results computed with Eqs. (17) and (19) for f_o values of 45, 89, and 890 Hz and Q values of 1, 10, 20, 50, and 100 are shown in Fig. 13.

From Fig. 13, we can see that when B_e/B_r is more than 1, the calculated accuracy by Eq. (19) is lower than Eq. (17).

3.2. Error in the acoustic tests

The PSD values measured in the acoustic tests described in Section 2.3 for the various resonance frequencies and the analysis frequency bands of 1.5625, 6.25, 12.5 Hz, and 1/3 octave band are shown in Fig. 14.

From Fig. 14, we can see that coarser frequency resolutions are generally accompanied by smaller PSD peak measurements. The estimated accuracy values obtained from substituting the loss factor values from Table 4

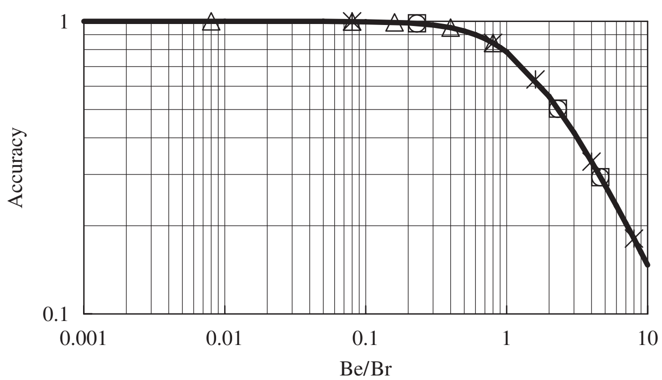

Fig. 12. PSD peak estimation accuracy due to bandwidth and Q when the PSD peak is at the center of the analysis frequency band, □ 1/3 octave band and $f_o = 100$, ○ 1/3 octave band and $f_o = 1000$, × 8 Hz bandwidth, $f_o = 100$, △ 8 Hz bandwidth, $f_o = 1000$, ▬ Eq. (17).

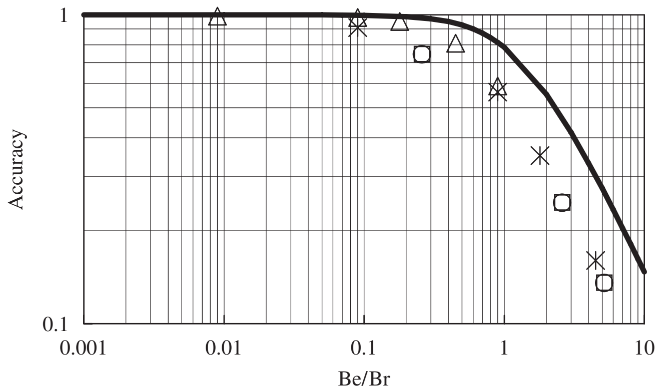

Fig. 13. PSD peak estimation accuracy due to bandwidth and Q when the PSD peak is at the minimum frequency of the analysis frequency band □ 1/3 octave band and $f_o = 89$, ○ 1/3 octave band and $f_o = 890$, × 8 Hz bandwidth, $f_o = 89$, △ 8 Hz bandwidth, $f_o = 890$, ▬ Eq. (17).

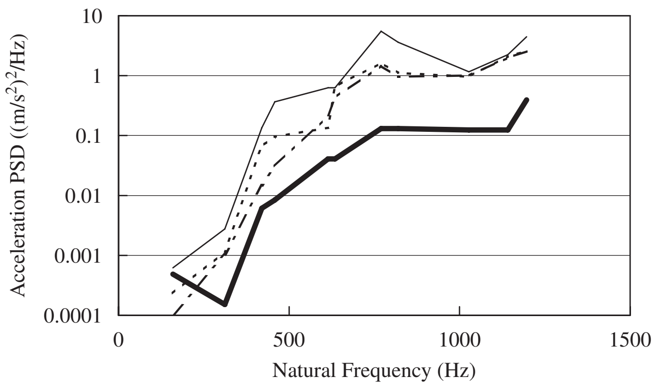

Fig. 14. Differences in PSD peak measurements by analysis frequency band —— $B_e = 1.5625$, ··· $B_e = 6.25$, - · - · - $B_e = 12.5$, ▬ B_e =1/3 octave band.

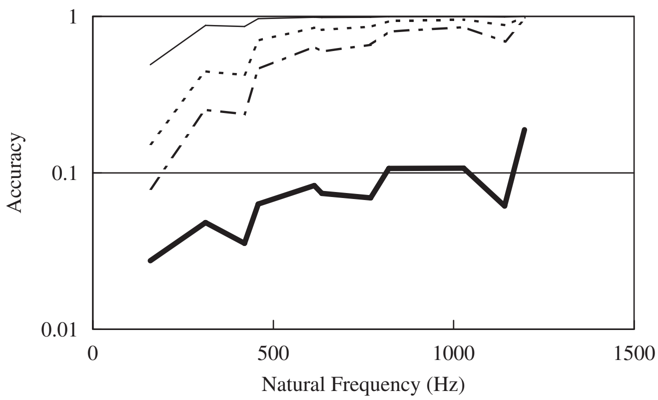

Fig. 15. Accuracy estimated by substituting loss factor from Table 4 and the various analysis frequency bands into Eq. (14) —— $B_e = 1.5625$, ··· $B_e = 6.25$, - · - · - $B_e = 12.5$, ▬ B_e =1/3 octave band.

and the various analysis frequency bands into Eq. (17) are presented in Fig. 15. The accuracy values of each analysis frequency band actual values divided by the actual values of 1.5625 Hz in Fig. 14, are shown in Fig. 16. There are some differences between Fig. 15 and 16, but the tendency is the same or similar.

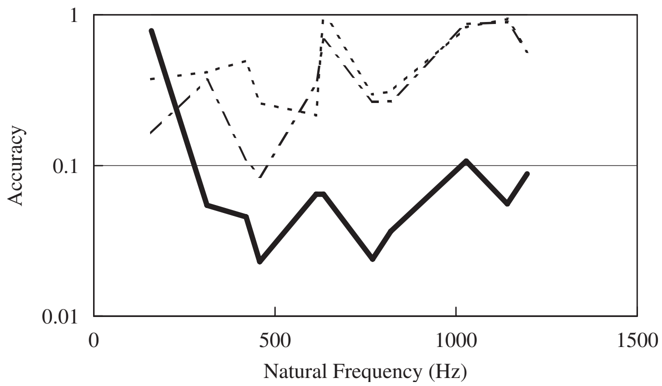

Fig. 16. Accuracy calculated taking the 1.5625 Hz analysis frequency band values tentatively as the actual values —— $B_e = 1.5625$, ··· $B_e = 6.25$, - - - - - $B_e = 12.5$, ▬▬ B_e =1/3 octave band.

As I described in Section 2.3, there is a measurement error originating in the size of the reverberation room in the low frequency band below 300 Hz. At higher frequencies, error is believed to come from the peak not being at the center of the band.

4. Conclusions

PSD peak estimation formula by response analysis results which were obtained from 1/3 octave analysis or other broadband analysis, was derived. Moreover, single-degree-of-freedom system response computations demonstrated the effectiveness of this formula. However, when the loss factor is large, this formula may underestimate, and when the PSD frequency resolution is coarse, the PSD peak itself cannot be represented. In consequence, the results differ from the peak estimation of this formula.

Concerning the results of acoustic tests on an actual satellite panel, the PSD peak values estimated with this formula using loss factor obtained from experimental mode analysis are approximately same as the experimental results. Furthermore, no problem arose from using the theoretical number of modes of the honeycomb panel. When the PSD peak is near a boundary frequency of a 1/3 octave band, this formula produced under estimates.

Investigation of the frequency resolution required for PSD peak estimation yielded the following conclusions. The conventional accuracy estimation formula can be used without problem when the PSD peak is at the center of the analysis frequency band. However, accuracy may be worse when the peak is not at the center. This conventional accuracy estimation can estimate accuracy roughly in acoustic tests on an satellite panel, but actual accuracy may be poorer because of the peak position declination in frequency band region.

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