Structural vibro-acoustic response under high sound intensity environment

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Abstract: This paper investigates vibro-acoustic response characteristics of structures under high sound intensity, presents a response extrapolation method based on experimental data and the results of linear extrapolation, and discusses weak nonlinear characteristics of structures under high sound intensity environment.

Key words: vibro-acoustic; structure; response; extrapolation
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1 Introduction

Based on a large quantity of experimental data, this paper studies vibro-acoustic response of structures under high sound intensity environment based on statistical analytical theory. Through analyzing vibration response data of different acoustic loads, a structural vibro-acoustic response extrapolation method, under the specified acoustical environment as relevant to the experimental data, is presented. This paper also discusses the convergence of this method, and compares it with the linear extrapolation method.

2 Structure's response characteristics under sound load

It is important to decide whether the structural response under sound load is linear or nonlinear, which has important bearing on the response prediction of the structure. For convenience, we assume that the structural response has a relation with load as follows (see figure 1).

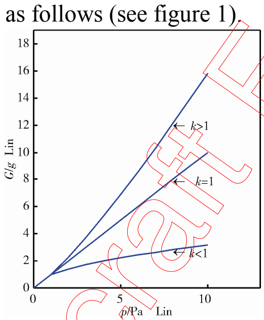

Fig. 1 The relation under linear coordinates system

$$G=A\cdot P^{k}, \tag{1}$$

where: G is power spectral density (PSD) root-mean-square (rms) value of structural vibro-acoustic response; A is coefficient; k is characteristic parameter; p is sound load.

In the logarithmic coordinate system, we have the following linear relation (See figure 2).

$$20\lg G=20\lg A+20k\lg P \tag{2}$$

$$R=kP+b\ , \tag{3}$$

where: R is power spectral density(PSD) rms value of structural vibro-acoustic response expressed in dB, R=20×lg(G/G_0), G_0=1g_{rms}; k is characteristic parameter; P is sound load expressed in dB, P=20×lg(p/p_0), p_0=2×10^{-5} Pa; b is coefficient related to k, A, G_0, p_0, b=20×lg$A$-20×lgG_0+20×$k$lgp_0.

It can be seen from figures 1 and 2 that if k=1, the relationship between structural response and load is linear; if k≠1, then the relationship is nonlinear. When k>1, the structure shows an intense nonlinearity; when k<1, a weak nonlinearity.

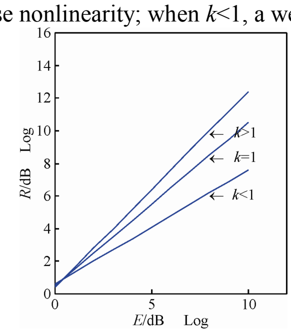

Fig. 2 The relation under logarithmic coordinates

A structure's acoustic experiment was carried out in dozens of states, with nearly 100 test points of response. In one state, the test was carried out on six different levels in the same spectral configuration, and the test points $d_j(p_i, g_i)$ (j=1,2…n, i=1,2…6) on six different levels are fitted into a straight line using the least-squares method, with k_j being the gradient of the straight line. The gradient of the point 'n' is shown in figure 3, whose mean value is 0.74, with a mean square deviation of 0.11. In figure 3, one can see that none of the test point gradient values is greater than 1, therefore, the structure is weakly nonlinear according to the mean value. In view of energy, the acceleration responses of all of the test points, under each state, expressed in dB, were added together as the energy E characterization of the structure under this load, and the following corresponding relations for above six test states were obtained(see figure 4).

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$$En_i = \frac{1}{n}\sum 20\cdot\lg(g_i/g_0)$$
$$P_i = 20\cdot\lg(p_i/p_0) \tag{4}$$

Where: i=1,2…6; j=1,2…96; G_0=1g_{rms}; p_0=2×10^{-5} Pa

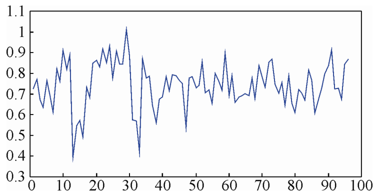

Fig. 3 Curve of test point responses' gradient

The gradient of the straight line, fitted with least-squares method, is 0.74. The structure is weakly non linear, in view of energy.

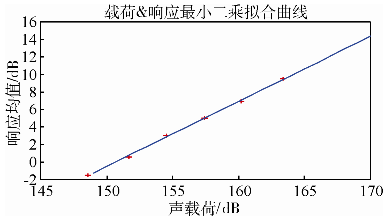

Fig. 4 Structure's characteristic curve obtained from 6 types of test states

3 The effect of sound load characteristics on structural vibro-acoustic response

The structure's vibro-acoustic response is related to the characteristics of the sound load, including the magnitude of the acoustic pressure, the shape of the sound spectrum and the spatial correlation of the sound load[1].

The sound pressure obviously affects the structure response. The larger the sound pressure level is, the larger the structural response will be. But it is more complicated to see how the sound spectrum configuration and the sound load spatial correlation affect the structure response, and the effects are found to be very significant. It can be seen from the actual experimental data that the structure's vibro-acoustic response is greatly influenced by the configuration of acoustic spectrum, because the local vibration makes different contributions to the overall vibro-acoustic response under the distributed load (see figures 5 and 6). That is to say that the structure's vibration response is sensitive to the frequency of the load, and it is also sensitive to the wavelength of the load, especially in high frequency region, when the load wavelength is described by the spatial correlation of the sound load. Therefore it is important not only considering the sound pressure, but also considering the shape of the acoustic spectrum and the spatial correlation of the sound load in the acoustical test.

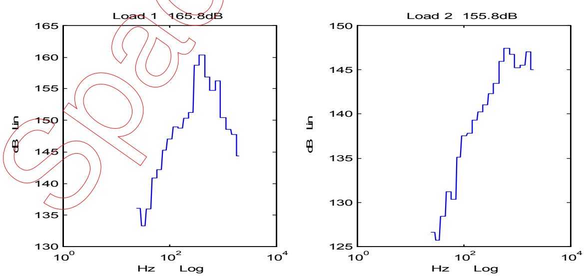

Fig. 5 Sound loads of two different spectrum configurations

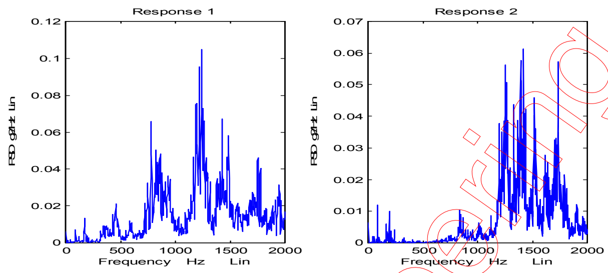

Fig. 6 Vibro-acoustic response under the loads of two different spectrum shape

4 Structural response extrapolation based on experimental data

The external load of high sound pressure, especially in high frequency range, may not be within the required range of the present test facilities. The vibro-acoustic response of the structure can be measured through several tests of different lower pressure levels by use of the present test facilities. To obtain vibro-acoustic response under the reference spectrum, a response extrapolation method based on experimental data is developed, named as the nonlinear extrapolation.

The aim of this method is using the structural characteristic parameter k, to extrapolate the vibro-acoustic response data, under the same load spectrum, in several different pressure levels, using an energy analysis, according to the sound transmission function and the required sound load spectrum. When k is equal to 1, to every point, there are linear dependence in log coordinate between the acoustic load and power spectral density (PSD) rms value of structural vibro-acoustic response,which is given by.

$$A = G_1 / p_1, \tag{4}$$

where G_1 is the power spectral density (PSD) rms value of structural vibro-acoustic response under the actual sound load p_1. In a linear extrapolation, the power spectral density (PSD) rms value of structural vibro-acoustic response under the specified load p_2 is

$$G_2^{'} = A\times p_2 = G_1\times p_2/p_1 \tag{5}$$

corresponding to each of spectrum density curves. Considering the structural characteristic k, the vibration response root-mean-square value of a nonlinear extrapolation under the specified load p_2, is

$$RMS_2 = 10^{(20\times\lg RMS_2^{'}-(1-k)\times(dB_2-dB_1))/20}$$
$$G_2 = G_2^{'}\times(RMS_2/RMS_2^{'})^2$$
$$R_{G_2} = 20\times\lg G_2 = 20\times\lg G_1 + 20\times\lg p_2 - 20\times\lg p_1$$
$$= 20\times\lg G_1 + P_2 - P_1 \tag{6}$$

The relationship of R_{G_2} and p_2 can see fig.7.the Equations above are correspond to every line spectrum of spectral density.

Considering the nonlinear behavior of structure, that is consider the situation of k>1 or k <1, is given by

$$\boldsymbol{A = G_l / p_l^k} \tag{7}$$

Where G_1 is the power spectral density (PSD) rms value of structural vibroacoustic response of actual vibroacoustic loads p_2, according to nonlinear extrapolation, power spectral density (PSD) rms value of structural vibroacoustic response $G_2^{'}$ under given loads p_2, is given by

$$G_2^{'} = G_1 \times p_2^k / p_1^k \tag{8}$$

$R_{G_2}^{'}$, The power spectral density (PSD) rms value of structural vibroacoustic response(dB) is given by

$$\begin{aligned} R_{G_2^{'}} &= 10\times\lg G_2^{'} = 10\times\lg G_1 + k\times 10\times\lg p_2 - k\times 10\times\lg p_1 \\ &= 10\times\lg G_1 + k(P_2 - P_1) \end{aligned} \tag{9}$$

The relationship of $R_{G_2}^{'}$ and p_2, see fig.7. The Equations above are correspond to every line spectrum of spectral density.

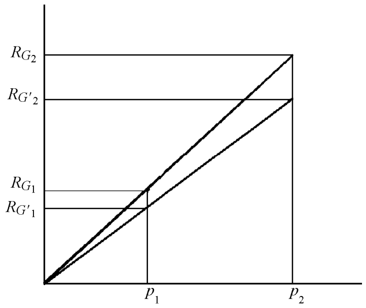

Fig. 7　Relation of R_{G_2}、$R_{G_2}^{'}$ and p_2

The power spectral density (PSD) rms value of structural vibroacoustic response(dB) difference in linear extrapolate and nonlinear extrapolate,are given by

$$\Delta = R_{G_2} - R_{G_2^{'}} = P_2 - P_1 - k(P_2 - P_1) = (1-k)(P_2 - P_1) \tag{10}$$

The following is how to obtain the nonlinear extrapolation vibro-acoustic response power spectrum density curve under specified load p_2.

To minimize the error due to spectrum effect, the spectrum p_1 should be consistent with the spectrum p_2 in application. Acoustic tests of three pressure levels were carriedout for a structure, whose load spectra are basically consistent with the required spectra in sound transmission function tests. The k value obtained here by fitting data (0.76) is basically consistent with the value mentioned in the section 2, which shows that the structure has a such characteristic parameter.

There are a hundred of points in the structure's sound test, some in the cabin wall and joint frame, and others in instruments and equipment. Therefore the characteristic parameters of the structure were obtained for sectors and by fitting data with this method. Table 1 shows the results. Structure's characteristic parameters, for the vibro-acoustic response to the same type of load, were obtained by fitting data for different points. The results in table 1 show that structure's characteristic parameters thus obtained are convergent.

Table 1　Structure's characteristic parameters obtained by fitting data under different states

	10	30	50	70	90	On frame	Out of frame	All
k	0.67	0.74	0.74	0.74	0.76	0.75	0.74	0.74

5　Comparison of linear and nonlinear extrapolations

Figure 8 shows the specified load spectrum for a structure's acoustic test, which is out of the range of the present experimental facilities. Therefore, the sound transmission function test was conducted first in the actual tests. Figure 9 shows the actual load spectrum with the same configuration as required. From the sound vibration response of each point, the structure's response is extrapolated with linear and nonlinear extrapolations. Table 2 shows the results.

Table 2　Comparison between linear extrapolation (①)and nonlinear extrapolation(②)（Unit: g_{rms}）

		1x	1y	1z	2x	2y	2z	3x	3y	3z	4x	4y
164.7dB	①	10.1	8.2	5.2	10.8	18.4	5.1	62.6	52.6	41.0	4.8	3.6
	②	7.6	6.2	3.9	8.2	13.9	3.9	47.6	39.8	31.0	3.6	2.7
167.5dB	①	14.0	11.3	7.2	14.9	25.4	7.0	86.4	72.6	56.5	6.7	5.0
	②	9.7	7.9	5.0	10.4	17.7	4.9	60.2	50.6	39.3	4.7	3.5
169.0dB	①	16.6	13.4	8.6	17.8	30.2	8.3	103	86.3	67.2	7.9	5.9
	②	11.1	8.9	5.7	11.9	20.1	5.5	67.2	57.5	44.7	5.3	3.9

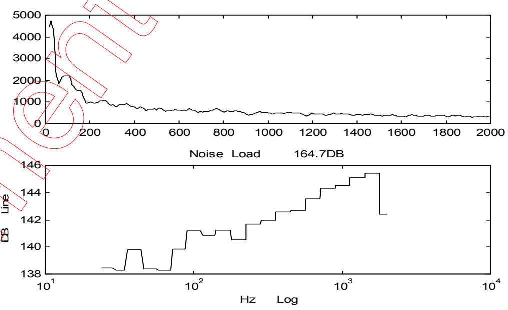

Fig. 8　Pressure spectrum density curve under the required test load and 1/3 OCT

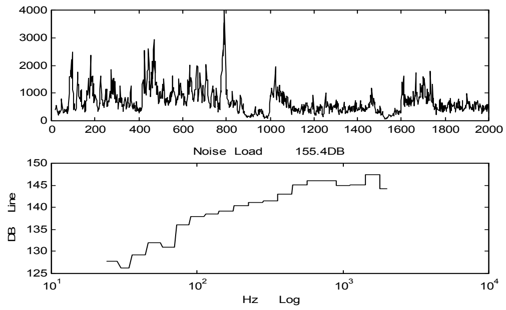

Fig. 9　Pressure spectrum density curve of sound transmission test and 1/3OCT

From the table, it is shown that some vibro-acoustic response of structure exceeds $100g_{rms}$, using the structural linear extrapolation method. According to engineering experience, it is impossible. With nonlinear extrapolation, the structure's characteristic parameter is first obtained, and then structure's acoustic vibration response is extrapolated, and the structure's vibration response is significantly reduced.

6　Conclusion

Based on data analysis of structure's sound vibration response, this paper shows that sound load characteristics, especially, the sound load spectrum and the spatial correlation of the sound load, have a great effect on the vibro-acoustic response; a structure's vibro-acoustic response extrapolation method is proposed. It is shown that this response is usually not linear; parameter k is defined to describe this characteristic. This method is used in the actual experiment, and the results are compared with linear extrapolation, and the structure's response is significantly reduced.

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结构在高声强环境下声振响应研究

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摘要： 文章研究了结构在高声强噪声环境下的声振响应特性，给出了一种以试验数据为基础的响应外推方法，与线性外推方法进行了比较，并研究了结构在高声强噪声环境下结构弱非线性特性。

关键词： 声振；结构；响应；外推

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