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THE LIMITS OF PREDICTABILITY DUE TO MANUFACTURING AND ENVIRONMENTALLY INDUCED UNCERTAINTY

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INTRODUCTION

When predicting the behavior of vibro-acoustics systems, one certainty is the uncertainty of the prediction. Some of this uncertainty is due to imprecise knowledge of material properties, cross section dimensions, and damping. These types of uncertainty are addressed in detail elsewhere. However, vibro-acoustic systems are also subject to uncertainty due to manufacturing variations and to environmental effects which cause parts of the system to change behavior. For static conditions or low frequency vibro-acoustic behavior, the response of the system is generally not sensitive to these variations. However, at frequencies typical of the audible frequency range for systems such as automotive vehicles and appliances, there is significant sensitivity to these variations. The limits of predictability of vibro-acoustic systems are generally due to the uncertainty of the model caused by variation across the population of samples and by environmental conditions. In this paper, a number of case studies will be shown to demonstrate the uncertainty inherent in systems and how the uncertainty affects the predictability of vibro-acoustic systems.

AUTOMOTIVE VEHICLE CASE STUDIES

Several investigations of the variation of the vibro-acoustic characteristics of nominally identical automobiles have been reported [1-4]. These results are believed to be typical of the variation found in most vibro-acoustic systems, with the exception that the frequency range of certain types of behavior is expected to shift higher or lower depending on the overall stiffness and mass of the structure. A typical result, the frequency response data from Kompella and Bernhard for sound pressure response at the driver's ear location due to mechanical excitation of the wheel for a population of 98 nominally identical Rodeo light utility vehicles, is shown in Figure 1 [3,4]. At the lower end of the frequency range shown, variation in the frequency response functions are small. Above 200 Hz, the frequency response functions vary by 20 dB or more. This variation is due to the shifting of the natural frequencies of the modes from vehicle to vehicle. As the modal density increases with frequency, it is more likely that the resonance of one sample of the population will coincide with a frequency of minimum response for another sample of the population.

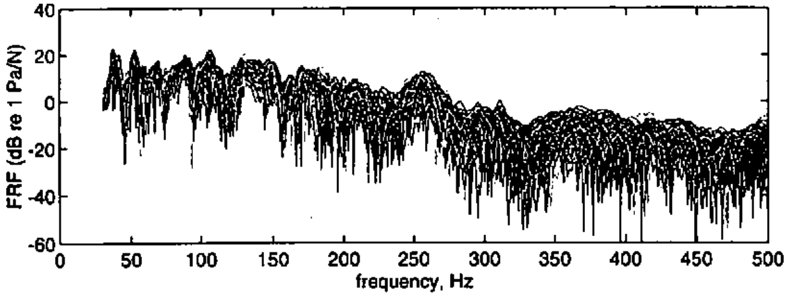

Figure 1 Structure-borne frequency response functions for 98 Isuzu Rodeos

To illustrate the limits of predictability of the models of these automobiles, two consecutive frequency response functions from the same data set are shown in Figure 2. These two vehicles were tested in nearly identical environmental conditions. For narrowband analysis, a perfect model of one of these vehicles would not be a very good model of the other vehicle, particularly at frequencies above 125 Hz.

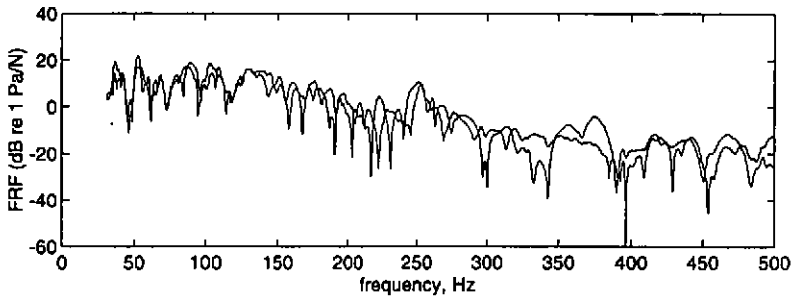

Figure 2 Structure-borne frequency response functions for Rodeos #2 and #3

It should be pointed out that frequency averaged methods, such as the statistical energy analysis method, would also not be entirely satisfactory. Near 250 Hz there is a clear feature in the data that resembles modal response. This response is likely to be important and a method that does not include modal response would not be useful for predicting the vibro-acoustic behavior of this system.

The variation of the responses shown in Figure 1 is not due solely to manufacturing variation. For the tests done by Kompella, one of the Rodeo vehicles was used as a reference vehicle. Its response was measured at regular intervals throughout the test. In total, 12 measurements were made of the reference vehicle.

The data for the same frequency response function shown in Figure 1 are shown in Figure 3 for the reference vehicle. Although the variation is smaller for the reference vehicle, there is still significant variation above 250 Hz despite the fact that the same vehicle was used for each test.

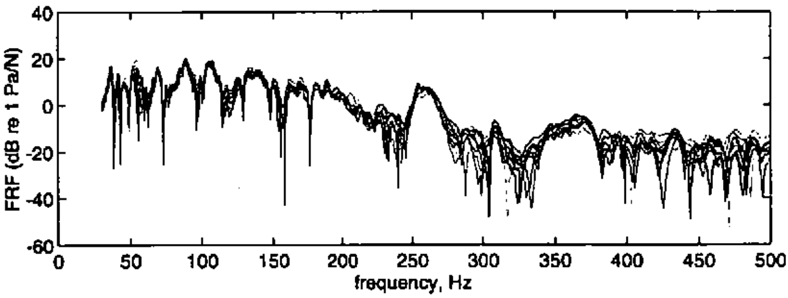

Figure 3 Structure-borne frequency response functions for the reference Rodeo

To further illustrate the effect of temperature, the data from the second and sixth test are shown in Figure 4. These tests were conducted on different days but the interior temperatures for these tests were similar, 31.3°C and 31.2°C, respectively. The temperatures are relatively close and the data have relatively small variation. In Figure 5, the data for the sixth and eighth test (40.5°C) are shown. For larger temperature variation there is a larger variation in the frequency response function. While these response variations are not as significant as the manufacturing variation, the variations are large enough at the highest frequency shown here such that predictive models of behavior will be of limited value for narrowband analysis.

SIMPLE CASE STUDIES

To understand the type of behavior observed in the studies of automotive vehicle variation, Gardhagen and Plunt developed analytical models of both 3-beam systems and two-plate systems for which response variation could be studied [5]. The analytical models of the systems were developed for a broad frequency range. Several parameters of the system were randomly varied. The resulting behavior of the predicted response is similar in many ways to the behavior of the Rodeo vehicles. The results of a similar analysis done by Huff are shown in Figure 6 [5]. Three collinear beams with the average properties shown in Table 1 were used. The response of 25 beam systems with sample lengths varying according to a uniform distribution with a variation equal to 2% of the length of each beam are shown. At low frequency the variation is small and the average response of the entire population is dominated by modal response. At the high frequencies shown, the response variation is significant with no apparent dominant modal features. In the middle of the frequency range shown, near 250 Hz, 700 Hz, and 1100 Hz, significant modal response due to the short beam are superimposed on the large variations of the long beams.

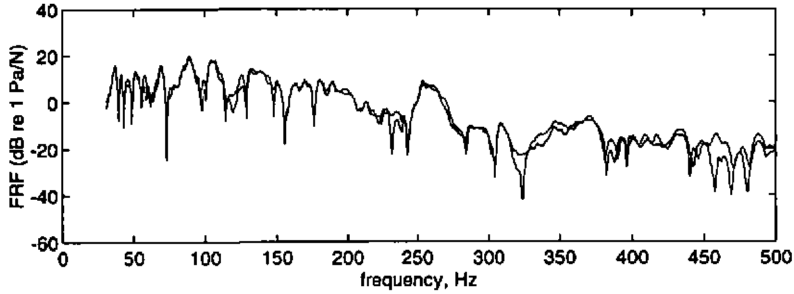

Figure 4 Structure-borne frequency response function for reference tests #2 and #6

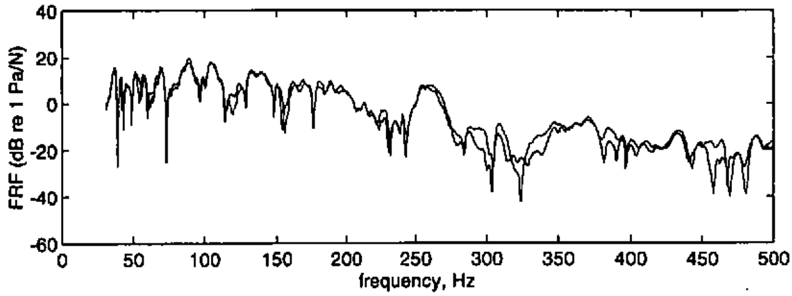

Figure 5 Structure-borne frequency response function for reference tests #6 and #8

To better understand the variation due to manufacturing, Unglenieks has done a study of the sensitivity of the response of a bolted, two-beam system to reassembly. The tests were done while repeatedly disassembling and reassembling the beams. Care was taken to reproduce the bolt torque and alignment of the beams. The resulting power reflection coefficients at 3100 Hz are shown in Table 2. The variation in the data is significant. It would be difficult to predict the behavior of these beams well at this frequency for any random assembly using traditional prediction methods.

Table 1 Average Beam Properties for the Variation Study [6]

	Beam 1	Beam 2	Beam 3
Density (kg/m^3)	7850	7850	7850
Loss Factor	0.003	0.020	0.003
Young's Mod. (GN/m^2)	195	195	195
Width (mm)	2.54	10.2	2.54
Height (mm)	2.54	10.2	2.54
Length (m)	3.0	1.5	2.0

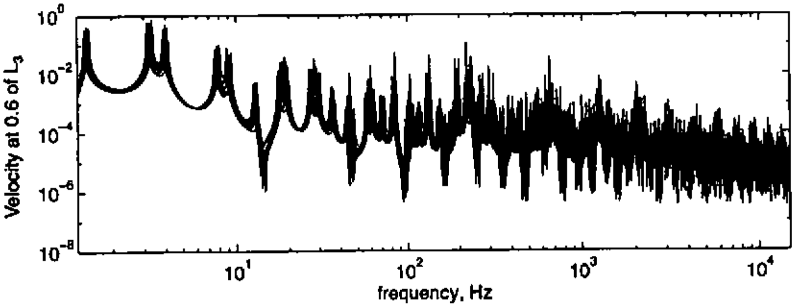

Figure 6 Velocity response of the 3 beam system, at 60% of beam 3

Table 2 Variation of reflection coefficients for reassembled beams	
Run	Power Reflection Coeff.
1	0.3302
2	0.4108
3	0.3467
4	0.3583
5	0.3492
6	0.3808
7	0.3429
8	0.3585
9	0.3621
10	0.3850
Mean	0.3625
Std. Dev.	0.0237

CONCLUSIONS

In summary, variation in vibro-acoustic systems due to manufacturing and environmental conditions is commonplace. The variation of the response due to these parameter variations grows as frequency increases. This response variation must be considered and treated. Several steps are necessary;

1. As a community we must determine whether response variations similar to those shown in this paper make a difference in the perception of the noise. In the author's experience, there has been significant conflicting input about this issue. Some manufacturers claim frequency averaged results in one-third octave bands are sufficient for evaluation. Others point to examples where relatively high frequency, narrow band features of a sound spectrum are important.
2. As a community we must better understand the variations which occur in vibro-acoustic systems including parameter variation of components.

3. New and existing analytical method should be evaluated for their applicability to the problem of predicting the response and its potential variation.

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