Proceedings of ICAD2000
First International Conference on Axiomatic Design
Cambridge, MA – June 21-23, 2000
ICAD055

IMPROVING AN EXISTING DESIGN BASED ON AXIOMATIC DESIGN PRINCIPLES

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ABSTRACT

This paper presents an application of axiomatic design principles to a Noise, Vibration, and Harshness (NVH) problem in the automotive industry. An approach is illustrated for improving the robustness of an existing system design by means of the axiomatic design "decoupling" philosophy. First, identify the relationship between functional requirements (FRs) and design parameters (DPs) in terms of percentage contribution of each DP to each functional response; then put these contribution values into a design matrix and rearrange the matrix to be as triangular as possible. The obtained matrix will demonstrate the relationship between FRs and DPs and guide engineers in making design improvements.

Keywords: axiomatic design, axioms, design improvement, CAE, NVH,

1 INTRODUCTION

In Axiomatic Design, the relationship between functional requirements (FRs) and design parameters (DPs) are represented in a design matrix. Good (decoupled) designs can be represented by nxn triangular matrices, e.g., all entries below the main diagonal are zero. The best (uncoupled) designs can be represented by nxn diagonal matrices, i.e., all entries off the main diagonal are zero. In the automotive industry, basic designs are frequently used over and over again--in which case an engineer's task is to make incremental improvement in existing designs, i.e., it is not to select a new design; rather it is to make an existing design more robust. Often these designs are redundant, they have more DPs than FRs and are represented by nxm matrices that can't be expressed in triangular form. Typically, the engineer has little latitude for removing DPs from these designs. Nevertheless, the decoupling
ideas of Axiomatic Design can still be used to determine a good approach for improving the design.

In this paper, we present an example in which Axiomatic Design principles are used to provide an approach for improving an existing system design. Functional requirements are given for various system responses that can be modeled using Computer Aided Engineering (CAE) tools. The CAE model is used to conduct a sensitivity analysis that identifies the relationship between DPs and system responses in terms of percent contribution of each DP to each response. (Contributions below a minimum cutoff level are treated as zero.) Contribution values are the entries in a design matrix that may be rearranged to be as triangular as possible. The obtained matrix provides design engineers a clear picture of the relationship between FRs and DPs and guides their strategy for making design improvements to the existing system.

2 EXAMPLE

2.1 BACKGROUND

Noise, Vibration, and Harshness (NVH) is a major attribute considered in vehicle design and analysis. It is a negative attribute in the sense that engineers strive to develop designs that minimize NVH experienced by vehicle drivers and passengers. Many different quantities contribute to the overall NVH of a vehicle such as sound pressure (Noise), steering wheel vibration, seat track shake (Vibration), and discomfort due to rough road (Harshness), etc. In our example, a vehicle CAE model existed in which more than 200 parameters were identified that could have an impact on 38 different NVH responses. Examples of the parameters are body gages, frame gages, windshield, elastomers, etc. Results of the CAE simulation showed that the nominal value of most responses for the baseline design met established performance targets by small margins. However, this raised a concern because the assessment did not take variability into account. The design engineers wanted to know whether, when variations in design parameters were considered, the upper bound of the response (e.g., 90th percentile) would also meet the target. Furthermore, they wanted to identify which design parameters have significant impact on response variation. Thus, a response variation assessment was required.

Input parameters fell into two categories: body and chassis. If body parameters were included in the analysis, obtaining a result for one design point would require about 20 hours of computer time. Because the analysis included a large number of parameters and computer run-time was high, a computer design of experiment (DOE) was considered too expensive. Therefore, a first-order approximation was used to evaluate response variation. Such an approximation assumes that

- The relationship between response and design parameters is close to linear for both body and chassis structure.
- Interactions between parameters are negligible.

With the above assumptions, only a single 20-hour CAE run was required to compute nominal response values along with variation based the following formula:

$$\sigma_i = \sqrt{\sum_{j=1}^{n} \left(\frac{\partial f_i}{\partial x_j} \right)^2 \sigma_j^{\,2}} \,, \qquad (1)$$

in which σ_i is the standard deviation of response i
f_i is response i
x_j is parameter j
σ_j is the standard deviation of parameter j
$\partial f_i/\partial x_j$ is the sensitivity of the response f_i with respect to parameter x_j.

2.2 ANALYSIS

A vehicle system CAE model was used to perform the NVH response analysis. Input to the model included nominal design parameter values. Output of the model included sensitivities of responses with respect to design parameters for each frequency within a specified range. Standard deviations of design parameters were estimated using tolerance data provided by design engineers. A *C* computer program was written to combine sensitivity and standard deviation data and conduct the calculation in Equation (1). Response variation was computed for each response at the frequency of peak response. This obtained variation was then applied to responses across the rest of the frequency range in order to approximate response variation at frequencies where responses are less significant. A sample plot of response vs. frequency is shown in Figure 1.

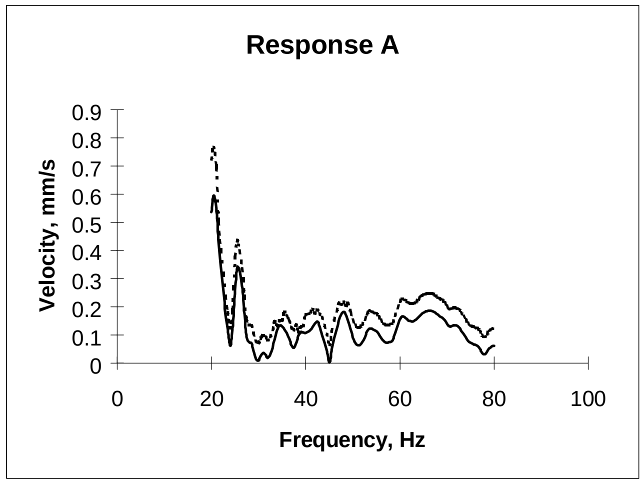

Figure 1. NVH Response vs. Frequency

This is a typical NVH response plot. The actual physical response is a measure of left front seat vibration in the vertical direction. In the plot, the solid line represents nominal value, i.e., 50th percentile of the response, and the dotted line represents 90th percentile. A response peak occurs at frequency 20 Hz, and variation at this frequency was used to approximate variation for the other frequencies in the range.

The contribution of each parameter to response variation can be calculated using the following formula:

$$r_{ij} = \frac{\left(\frac{\partial f_i}{\partial x_j} \right)^2 \sigma_j^{\,2}}{\sum_{k=1}^{n} \left(\frac{\partial f_i}{\partial x_k} \right)^2 \sigma_k^{\,2}} \times 100\ \% \qquad (2)$$

in which r_{ij} is the contribution value of the jth parameter to variation in the ith response. It should be apparent from the equation that, for each response, the total contribution from all parameters must add up to 100%.

A pareto plot is shown in Figure 2 to display the individual parameter contributions to Response A in terms of percentage. Examples of design parameters include engine and body mount stiffness and gages.

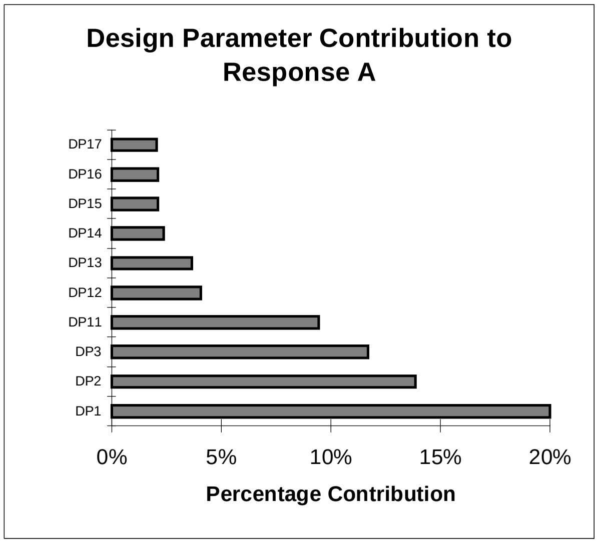

Figure 2. A Pareto Plot of Response A

In order to focus the design engineer's work on improving the most important aspects of the design, data of this type was collected for the six responses considered most important to customers. For each of these responses, individual parameter contribution values of less than 10% were considered insignificant and treated as 0% in order to simplify the analysis. The results are collected in Table 1.

This is the original matrix arranged according to alphabetical order of response and design parameter labels. Only the 10 parameters that contribute at least 10% to the variation of one of the 6 selected responses have been preserved. (If all parameters had been retained and contributions less than 10% had not been cutoff, each row in the matrix would sum to 100%.) As is, the matrix shows which DPs have a significant effect on Responses A-F. For example, entries in the last column of the matrix indicate that DP10 has significant impact on Responses B, C, and D. Entries in the third row indicate Response C is significantly affected by DP4, DP5, DP6 and DP10. However, the matrix does not indicate the best order for changing DPs to most effectively improve the entire set of responses.

Table 1. DP Percent Contribution to Response Variation

DP: Resp.	1	2	3	4	5	6	7	8	9	10
A	20.0	13.8	11.7							
B										19.2
C				16.9	13.3	10.5				12.6
D				20.6		11.9				27.4
E							27.1	12.7		
F									30.0	

2.3 AXIOMATIC DESIGN PRINCIPLES

In this example, the engineer had no latitude for removing DPs. The existing set of DPs defined a design planned to be used in production. The best the engineer could hope for was to be able to tune the DP's in such a way that all FRs related to the responses would be met. In this situation it was possible to use the decoupling ideas of Axiomatic Design to determine a good approach for tuning the design within the constraints faced by the engineer. The original matrix was rearranged into a new matrix by making it as triangular as possible. The rearranged matrix is shown in Table 2.

Table 2. Rearranged "Design Matrix"

DP: Resp.	10	4	6	5	1	2	3	7	8	9
B	19.2									
D	27.4	20.6	11.9							
C	12.6	16.9	10.5	13.3						
A					20.0	13.8	11.7			
E								27.1	12.7	
F										30.0

The matrix gives a good idea of how to go about improving the design if necessary. Response B is affected only by DP10. In order to improve Response B, DP10 should be tuned. In order to improve Response D, the new value of DP10 should be kept unchanged and parameters DP4 and DP6 should be tuned. Once the settings of DP10, DP4, and DP6 are fixed, Response C could be improved by tuning DP5. To improve Response A, whichever of DP1, DP2, or DP3 is easiest to adjust could be tuned. Similarly, DP7 and DP8 are available to tune to improve Response E. Finally, DP9 controls Response F.

3 SUMMARY

In this paper we use the concept of DP contribution to response variation to identify the relationship between DPs and responses. Learning this relationship requires knowledge of DP variability and sensitivity of responses with respect to DP settings. The contributions can be collected in a matrix which may be simplified by treating insignificant contributions as 0. Following the decoupling idea of Axiomatic Design, the relationship matrix can be rearranged to be as triangular as possible. The resulting matrix may not be a design matrix in the strict sense of Axiomatic Design, but it can provide an engineer with a clear strategy for tuning the design to achieve desired functional requirements.

In the simple case discussed here, the matrix rearrangement can be done manually. In general, some sophisticated axiomatic design software may be needed to perform the rearrangement according to decoupling principles.

4 ACKNOWLEDGEMENTS

The authors would like to thank Kar Chueng of the Ford NVH CAE organization for providing the CAE model and analysis and Dr. D.J. Li of Ford Research & Vehicle Technology Quality for proposing the response variation evaluation method and conducting part of the analysis.

5 REFERENCES

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