

A Design of Experiments Analysis to Determine the Importance of Relevant Factors on the STL of an Acoustic Part

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ABSTRACT

This paper discusses a design of experiments (DOE) analysis that was performed to understand relevant factors that influence the acoustic performance of a sound package part used in the commercial vehicle industry for the floor mat application. The acoustic performance of the sound package part which is a double wall system and constructed of a barrier and cellular decoupler material is expressed in terms of sound transmission loss (STL). An experiment was designed using the Taguchi DOE technique with three factors and three levels to acquire the STL data and is discussed in the paper. The results of the DOE analysis and the confidence in the model are discussed as well as the benefits of predicting expected STL performances are mentioned in the paper.

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INTRODUCTION

With the advancement of manufacturing technology and the expectation to have a quiet ride in commercial vehicles, the trend is to come up with better sound package parts. As the sources are very noisy in heavy trucks, a significant improvement to interior acoustics is gained by using barrier materials. The barrier is separated from the body panels by some distance thus creating a double wall system which has the potential to provide high sound transmission loss (STL) performance. The space between the barrier and the body panel is filled with a decoupling material which in most cases is a closed cell foam. The acoustics of a sound package part made of a barrier and a decoupler system, depends on the surface density of the barrier material and thickness, density, and stiffness of the decoupler material. However the manufacturers have to go through understanding the impact of process and other variations that might impact producing the right product for the application. Based on a typical thickness and density information of a barrier and a decoupler one can predict the acoustic performance with confidence [1]. However, once the product is made, its performance needs to be verified to ensure that it delivers what it is intended to

deliver. Also one of the objectives of the part manufacturer is to understand what combinations of different design parameters will provide the best part performance.

A new product has been developed for the commercial vehicle industry application where the product provides 3D molded design features that are new in the industry compared to the traditional extruded flat floor mats [2]. This has many advantages including the ability to have a true molded part with deep draws and still maintain the thickness and surface density features which impact the acoustics significantly. Like with any new product development, studies were conducted to understand the acoustics of this product. This paper discusses the thought behind the set-up of the measurements, the measurement itself, and the analysis that were conducted to validate and predict the acoustic performance of the new molded floor mat product. For this study sound transmission loss (STL) measurements were conducted per the SAE J1400 test method [3].

There could be several variables that may affect the performance of a product. Therefore, the study included developing a reasonably small test matrix to understand the

impact of different variables using the design of experiments (DOE) tool.

BACKGROUND

Design of Experiments

The design of experiments (DOE) is a powerful statistical tool used in many applications to reduce the number of tests to understand the impact of different variables on the performance of a product. The product may range from a sound package part that may have only a few factors influencing the performance to an off-road vehicle vibration issue that may have several factors that have to be looked into [4].

The basis of the DOE is based on identifying variables (called factors in DOE) and the range of these variables (called levels in DOE) that impact the performance. The DOE examines how the levels and factors, and the interaction between them affect the performance or an objective function.

Therefore in a simple example, if there are two factors, such as density and stiffness, and each factor has a maximum and minimum level, there are four possible tests (in DOE it is called the factorial design or designs). Mathematically this is represented by

$$N=L^m,$$

Where, N = the number of possible designs

L = number of levels for each factor

m = number of factors

However, in another example, if there are 15 factors, each at two levels, the factorial design becomes 2^{15} or 32,768, and this will result in several experiments. Therefore at the onset of setting up a test matrix, one needs to identify the factors, levels, information on other variables, and then set-up the design of experiments on a fractional factorial basis. As the fractional factorial experiments study only a fraction of all possible combinations it may yield different results depending on the size of the fractional factorial experiments.

The Taguchi approach to the DOE that has been followed in this study is based on a very rigorous discipline on setting up the DOE. In this a special set of table called orthogonal array is introduced to represent the smallest fractional factorial experiment design [5]. Using, the Taguchi approach, the problem above for 15 two-level factors consists of only 16 test runs.

The Taguchi Approach for This Study

The performance of a sound barrier assembly (SBA) depends on the surface density of the barrier and on the thickness, surface density, stiffness of the decoupler material. For this study, the barrier consisted of a wear surface and a mass filled layer, such that the total thickness of the wear surface and the mass filled layer remained the same. The

decoupler was always of the same thickness but of different densities. Based on this, the number of factors for this experiment could be reduced to three. These are:

- Ratio of wear to mass filled layer density
- Mass-filled layer thickness, and
- Decoupler density

There were three levels of each factor whose range represented realistic manufacturability and in the range of what is used in the commercial vehicles today. These are:

- Low
- Medium
- High

Figure 1 shows the generic cross-section of the typical SBA samples that were tested in this case. The wear surface and the mass filled layers constitute the barrier layer, and the decoupler was a polyurethane foam material. The foam properties generally lend to form a skin on the exposed surface of the decoupler that will be laid against the floorpan of the vehicle.

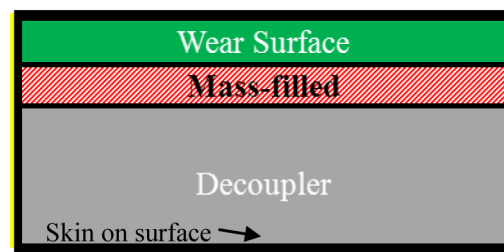


Figure 1. Cross Section of the SBA

A typical DOE for this problem would end up with 3^3 or 27 fractional factorial experiments. However, using the Taguchi orthogonal array approach the smallest fractional factorial experiment was 9×2 , or commonly called the L-9 array with two iterations of nine separate trial conditions. This included nine independent test samples (called trials in DOE). This many tests provide confidence to collect the performance variability information but still keeps the sample preparation and testing efforts under control.

MEASUREMENTS AND DATA REDUCTION

The STL measurements were conducted to generate data for statistical analysis. Measurements were conducted per the SAE J1400 test method where the source room was a 200m³ reverberation room and the receiving room was an adjacent anechoic chamber connected to the reverberation room via an opening in between. The test samples were mounted on a frame in this opening to evaluate the acoustical performance. The samples included various factors and levels of the SBA

materials placed against a 0.8 mm thick steel panel (20 ga or 7.3ksm) that faced the sound source and the barrier faced the receiving room. The edges of the sample were sealed to prevent any flanking of sound into the receiving room. For this study, measurements were conducted over a broad frequency range of 125 to 8000 Hz $1/3^{\text{rd}}$ octave band frequencies.

Test Results

Figure 2 shows the STL performance of all 18 samples. The results show that the performance of all 18 samples is close to each other and in most cases these are within 10 dB.

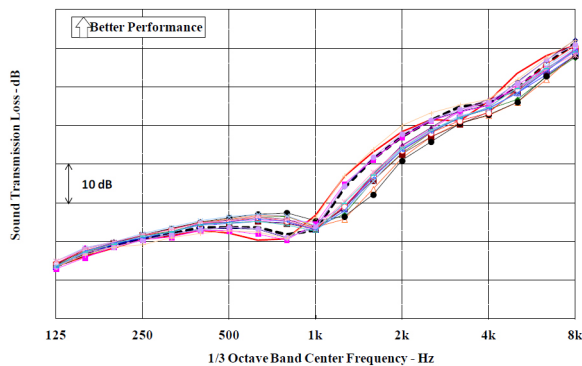


Figure 2. STL performance of 18 samples.

Figure 3 shows the average performance of all 18 samples. This figure is important for two reasons. These are:

- To understand whether the basic measurement is correct and consistent (i.e., the interpretation of the measurement)
- To decide how to statistically analyze the data from the DOE measurements.

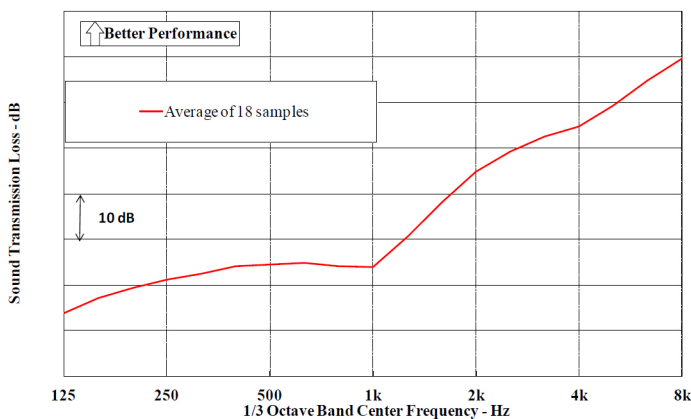


Figure 3. Average performance of 18 samples.

Interpretation of the measurement

The STL of a barrier decoupler system, such as the floor mat of a commercial vehicle when tested with the body sheet metal goes through several regions in the frequency domain [1] and these regions are shown in Figure 4.

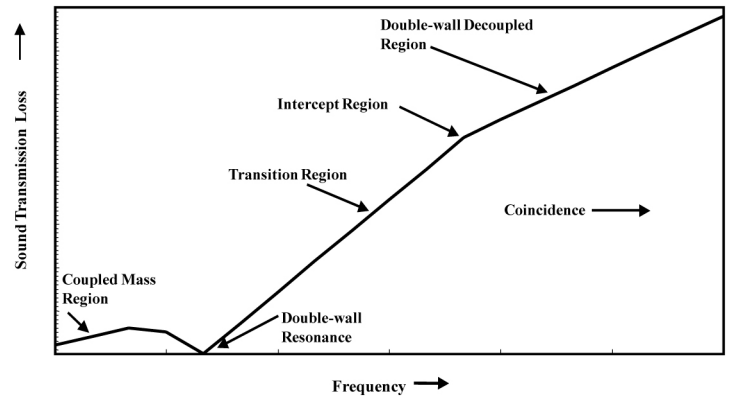


Figure 4. Several regions of a double wall test sample [1]

The one of particular interest in this case is the double wall resonance. After the double wall resonance frequency, the performance is much higher and the system has a much steeper slope.

The typical double wall resonance frequency for nominal barrier and decoupler assemblies that were studied in this case is expected to be around 300 Hz which is in the frequency band of the 315 Hz $1/3^{\text{rd}}$ octave band center frequency. However, the measured data show the average double wall resonance frequency to be around 1000 Hz $1/3^{\text{rd}}$ octave band frequency. This is identified by the dip in performance at 1000 Hz in Figure 3. This was a concern. However, further investigation revealed that the foam self-skins against the tool surface. For the STL tests, the skin is against the steel panel and the skin affects the STL performance by shifting the double wall resonance to 1000 Hz $1/3^{\text{rd}}$ octave band center frequency. Figure 5 shows the measurements made on a sample with the skin and after breaking up the foam skin. Tests conducted with the foam skin broken up show that the double wall resonance of the same sample shifts down to 315 Hz $1/3^{\text{rd}}$ octave band center frequency, which is close to the predicted value of 300 Hz. This shift is thought to be associated with the interfacial stiffness of the foam-skin decoupler in association with the steel panel. One thing should be noted that although the double wall resonance frequency has been shifted to a higher frequency the slope after the double wall resonance frequency of the samples with and without the skin is the same both in the transition and in the double-wall decoupled region. However, performance is obviously restricted by the presence of the skin.