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Using experimental design to characterize the effect of structural elements on acoustical response of hand-free phone

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ABSTRACT

This article presents an adaptation of the experimental design method (more precisely called "statistical design and analysis of experiments" and referred to as DOE) to acoustics. Experimental design is an efficient method to find an empirical relation whenever a theoretical one cannot be obtained or would be too difficult to obtain. This technique is not common in acoustics where it has been used in a few application cases to determine what product or process parameters affect the acoustic response. The response variable was single valued whereas, in the proposed method, it is an array of values, a frequency spectrum which constitutes a more practical tool for an advanced acoustic analysis. The results are presented on a spectrum plot where the factor effect is given in the physical quantity (dB) and the Fisher test of significance is presented as two plots of the lower and upper significance limits (also in dB). The method is applied to a hand-free telephone where, for subsequent modeling purposes, the method determines which structural factors affect the telephone acoustic response and what are the associated frequency ranges. This adaptation of the DOE method is validated with the verification of the results in three ways: first, with a complementary experimental design, second, with a more classical experimental method, and, third, with a computer simulation.

1. Introduction

Numerical techniques make it possible to develop acoustic models for products with complex geometries. However their use is limited by computer memory and speed, which makes it very important for the overall success of the model development to answer the following questions: which elements of the product need to be modeled, at which level of details, and what are the associated hypotheses and frequency ranges? The "statistical design and analysis of experiments" also called "experimental design" (which will be referred to as DOE in this article) should be a good approach to answer these questions as it is an efficient method to find an empirical relation whenever a theoretical one cannot be obtained or would be too difficult to obtain (a general presentation of the subject can be found in the introductory chapter of the book by Montgomery [1]).

The specific problem that brought about this general issue is acoustic modeling of a hand-free phone. What is important in the design is the acoustic quality that is defined in standard on their narrow-band [2] and wide-band [3] transmission characteristics. These standards defined upper and lower amplitude limits in dBs for the frequency responses. Consequently what is needed is a DOE method which will evaluate the statistical effet of a structural factor in terms of a physical variable expressed in dBs as a function of frequency.

A few papers can be found where DOE is used as a tool to solve an acoustics issue but they only partially meet this specific use. A few examples are given here after of the most commun case where the physical variable is a single valued such as an overall A weighted level or a band limited level. Ogle et al. [4] use an overall A weighted level for the analysis of the factors that affect the precision of a computer disk drive measurement system. Oberst et al. [5] use peak sound pressure level for the analysis of brake squeal noise. Landsberger et al. [6] use the NC (noise criteria) level for the analysis of the effect of installation parameters for the ductwork of variable air volume (VAV) units. Boulandet and Lissek [7] use the 50 Hz third octave band absorption coefficient to analyze the effect of the constitutive parameters of an electroacoustic

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absorber. Sgard et al. [8] use NRC (noise reduction coefficient) to analysis the effect of material parameters of porous materials. Yuksel et al. [9] use overall A weighted sound pressure level inside an automobile to analyze the effect of panel parameters.

There are a few cases where the physical variable is no longer a single value. Tarabini et al. [10] use third octave bands IL (insertion loss) between 50 and 300 Hz as well as the overall level in this range to analyze the effect of different set-up parameters on the active control of noise on a partition. Saha et al. [11] use third octave bands noise reduction between 125 and 8000 Hz to analyze the effect of various automobile door parameters. However the analysis is done in a qualitative manner without use of the usual DOE statistical analysis.

In all this references, analysis on physical variables are made on raw measured values and when the statistical analysis is carried out it is no longer in term of physical variable, hence it's difficult to juge the importance of an effect. Consequently, to determine which structural elements need to be included in the acoustic model of a product, there is a need to adapt the DOE methodology to obtain a frequency dependant significance limit in dBs. This is the general objective of the research presented in this current article. The first specific objective is to adapt the DOE technique to acoustical frequency response functions. The second specific objective is to apply this method to the hand-free telephone case. Finally, the third specific objective is the validation. This validation is done three ways: first, with a complementary DOE, second, with a more classical experimental method, and, third, with a computer simulation.

2. Adaptation of DOE to acoustics with a frequency spectrum as dependent variable

The statistical design and analysis of experiments is based on the measurement of a dependent variable (or response variable) under a specially defined set of values of the controlled factors. It uses a factorial design where the different combinations of values of the factors are chosen so that the factors and interactions effects can be evaluated with orthogonal contrasts. Compared to a one-factor-at-a-time experimental scheme, it is more efficient as it provides more information for the same number of experiments, the effects are evaluated independently from one another and it is valid over a wider range of experimental conditions.

The kind of DOE relevant to the decision to be made on which factor affect the response variable is called a factor screening study. It often uses two well separated levels for each factor as it is the simplest way to decide if a factor has an effect or not. The number of experiments required for k factors is 2^k for a full factorial design. However this number of experiments can be reduced by 2^p in a fractional factorial design (2^{k-p} experiments) if one is willing to accept it will no longer be possible to separate some effects from each other, as they are aliases. The traditional presentation of the DOE results has been modified in two ways to facilitate the interpretation in the case of an acoustic frequency spectrum. The two modifications are presented, respectively, in Sections 2.1 and 2.2 hereafter.

2.1. Presentation of the DOE results using the physical variable

The physical variable used is the sound pressure amplitude as the ITU standard [2,3] base the phone transmission characteristics on the frequency response amplitude. This sound pressure amplitude is usually measured as a sound pressure level in dB. Because we want to judge directly in dB what are the uncertainty interval and the magnitude of the effect, a representation of the statistical results directly in the physical variable in dB was judged more appropriate than using the Fisher test directly. A significance limit is derived for each factor in dB and the factor effect in dB is compared to this limit. Rather than giving directly the significance limit expression, a simple two-factor case is used to derive this expression and, at the same time, define the basic terms and formulas of the statistical analysis of experiments, which might be useful to acousticians less familiar with the concepts of DOE. The notations used are taken from the 2^k factorial design example in Montgomery [1].

The main data elements for this example case are presented in Table 1. There are two factors A and B and the acoustic response (sound pressure level L_p in dB) has been evaluated twice (two replicates, i.e. two independent runs of each factor combination) for each of the four treatment combinations. The treatment combinations are the arithmetic sums of the levels obtained for each replicate. Since all the treatment combinations are tested, this is a full factorial design.

The factor and interaction effects are evaluated with contrasts using the table coefficients. For example, for the factor A, the contrast C_A is:

$$C_A = ab + a - b - (1), \\ = Lp_4 + Lp_8 + Lp_2 + Lp_6 - Lp_3 - Lp_7 - Lp_1 - Lp_5, \tag{1}$$

and the effect of the factor A is:

$$A = \frac{C_A}{2^{k-1}n}, \tag{2}$$

where n is the number of replicates.

The significance of the effect of A is determined by comparing the mean square of A (MS_A) to the mean square of the error (MS_E) using the Fisher test.

To evaluate MS_A , the sum of squares for A is computed:

$$SS_A = \frac{C_A^2}{2^k n}. \tag{3}$$

Then the mean square is computed by dividing the sum of squares with the number of degree of freedom of A $df(A)$:

$$df(A) = \text{number of levels} - 1 = 2 - 1 = 1, \tag{4}$$

which gives

$$MS_A = \frac{C_A^2}{2^k n}. \tag{5}$$

To evaluate MS_E, the sum of square of the error is obtained by subtracting the sum of squares of the various effects and interactions from the total sum of squares (SS_T):

$$SS_E = SS_T - SS_A - SS_B - SS_{AB}. \tag{6}$$

Then the mean square is computed by dividing with the number of degree of freedom of $E(df(E))$, $n-1$ degrees of freedom for each of the 2^k treatments:

Table 1
Example case of an DOE with 2 factors (A and B, number of factors $k = 2$), 2 levels (+ and −), and 2 replicates (I and II, number of replicates $n = 2$).

Signs for factors and interactions evaluation			Treatment combinations	Replicates	
A	B	AB		I	II
−	−	+	$(1) = L_{p1} + L_{p5}$	L_{p1}	L_{p5}
+	−	−	$a = L_{p2} + L_{p6}$	L_{p2}	L_{p6}
−	+	−	$b = L_{p3} + L_{p7}$	L_{p3}	L_{p7}
+	+	+	$ab = L_{p4} + L_{p8}$	L_{p4}	L_{p8}