Auditory perception of structural uncertainty

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AUDITORY PERCEPTION OF STRUCTURAL UNCERTAINTY

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ABSTRACT

Because of structural uncertainty, an industrial object resulting from mass production can exhibit a large variability in its vibratory and acoustical behaviour. Some previous studies have focused on the variation in noise and vibration between structures with nominally identical design. Sounds emitted by these structures were also modified. Thus it might be thought that sound perception would vary as well because of structural variability. However, that problem has not yet been investigated. The aim of this study was to show how to assess the perceptual consequences of that physical variability. A mechanical model system, on which structural uncertainty could be simulated, was set up for sound synthesis. The sounds "emitted" by three different types of products were then assessed by a group of listeners performing a categorization task. The purpose was to determine if sounds stemming from nominally identical objects were always categorized together or if sounds emitted by nominally different objects could be confused. This experiment enabled to find the optimal partition of the stimulus set. Even though subclasses appeared within stimuli representing one type of object, sounds synthesized with different types of objects were not confused.

1 INTRODUCTION

Due to structural uncertainty, the vibratory and acoustical behaviour of “industrially identical” products may exhibit a large variability from one copy to another. The scatter of noise and vibrations has been studied by Bernhard and Kompella [1] on complex structures such as cars or by Gärdhagen and Plunt [2] on simple structures such as simply supported plates. Even though the consequences of structural uncertainty on sound radiation were studied and can be predicted, their perceptual consequences were not investigated so far. Nevertheless, some papers were devoted to study the influence of structural parameters variations over sound perception. These studies focused on sounds emitted by some basic structures like bars [3] and plates [4]. It was shown that small structural variations could be perceived by listeners. It may thus be thought that structural uncertainty is aurally noticeable and that this physical variability can also affect the product sound quality. In the present paper, stimuli were synthesized using a numerical model. They did not precisely represent sound quality of products. Nevertheless, a sound quality assessment procedure was proposed to determine if confusion was possible between objects with presumed different sound quality.

2 CATEGORIZATION TEST

2.1 Listeners

A group of 30 subjects (8 females and 22 males) took part in this experiment. They were students of the laboratory and their ages ranged from 23 to 30 years, average being 26 years and standard deviation 2.5 years. All reported having normal hearing.

2.2 Stimuli

Sounds to be assessed were synthesized using a mechanical model system. This numerical model was made up of an engine connected to a radiating panel via three elastic mounts. The engine exerted a harmonic complex force on the mounts, considered as pure springs, their nominal stiffness being 100 N/mm. The radiating panel was modelled as a simply supported square plate, its length was 500 mm. Three different types of “products” were modelled in order to synthesize stimuli with differences in sound quality. The three objects differed by their plate material and thickness. According to the object type, its properties are indicated in Table 1. Object type 1 (steel plate, 1 mm thickness) was already used in a previous study [1]. Object type 2 and 3 were made of an aluminium plate having respectively equivalent thickness and mass as the plate used for type 1.

Table 1. Material and thickness of the plate for each type of product.

Product type	Material	Thickness h
Type 1	Steel	1.0 mm
Type 2	Aluminium	1.0 mm
Type 3	Aluminium	2.7 mm

The structural uncertainty concerned only the stiffness of the mounts and the plate thickness which were supposed to vary within the common tolerance range encountered in industry. The tolerance range was 3.25 % for the thickness and 20 % for the stiffness. This variability was chosen to induce small but perceptible changes in sounds. Five synthesis configurations were set up for each object: the nominal state and four extreme configurations in which the two parameters are alternately at the upper and lower limit of the tolerance range. Sounds 1 to 5 were synthesized using object type 1, 6 to 10 using type 2 and 11 to 15 using type 3.

2.3 Apparatus

The categorization experiment took place in the laboratory. Listeners were seated in an isolated listening room. Sounds were reproduced for diotic hearing with a PC equipped with an Echo Digital Audio GINA24 soundcard via a set of Sennheiser HD600 headphones. Subjects had no information about the sound sources.

2.4 Procedure

During this experiment, listeners had to assess 15 sounds and to gather them into equivalence classes, the equivalence relation being the perceived similarity. Sounds were presented on the test window at the same time. Each sound was represented by a dedicated button that could be freely moved on the screen. Listeners had to group buttons into clusters. Button numbers were randomly arranged. The number of categories was not prescribed and could hence vary between 1 and 15. Instructions were orally notified to listeners before the beginning of the test. Subjects could listen to each stimulus as many times as they wanted. This procedure was adapted from similarity or pleasantness assessment procedures where the listener was supposed to be always able to identify the sound source [6]. In our case, the listeners had no information about the stimuli and were not asked to recognize their sources. Nevertheless, it was expected that this experiment would enable to identify the latent equivalence classes within the stimulus range. The test duration varied from 8 to 15 min and was typically 11 min.

3 RESULTS

3.1 Partition analysis and optimal partition

Each listener created his specific partition of the stimulus set. The distribution of classes number in individual partitions is shown in Fig. 2. Each partition could be represented by a membership matrix [a], where:

$$a(i,j)=\begin{cases}1 & \text{if sounds } i \text{ and } j \text{ are in the same class}\\ 0 & \text{otherwise}\end{cases} \quad (1)$$

The sum of the individual membership matrices allowed to derive an incidence matrix [I] that could be transformed into a mean dissimilarity matrix [D]:

$$[D] = 1 - \frac{[I]}{n} = 1 - \frac{\sum_{l=1}^{n}[a_l]}{n} \quad (2)$$

where $[a_l]$ is the membership matrix for listener l, n being the number of participants.

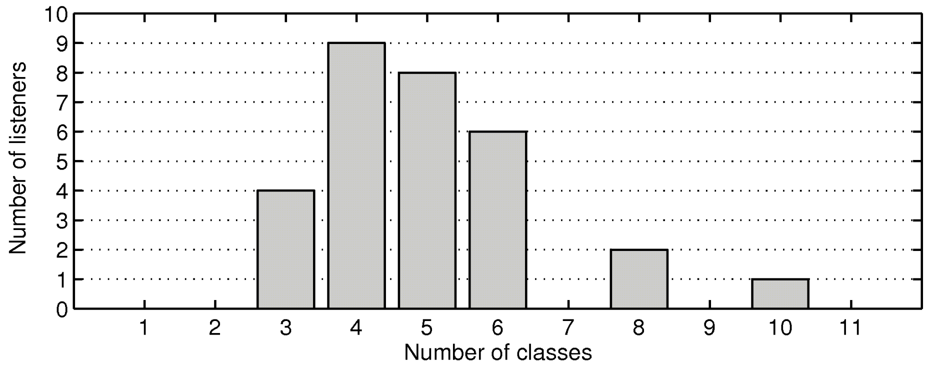

Fig. 2. Distribution of the number of classes among the 30 individual partitions.

Using mean linkage method, this distance matrix gave the agglomeration tree (dendrogram) shown in Fig. 2. It could be noticed that when cutting the agglomeration tree into 3 classes, the different types of objects appeared. It can then be concluded that different types of objects were not confused by listeners.

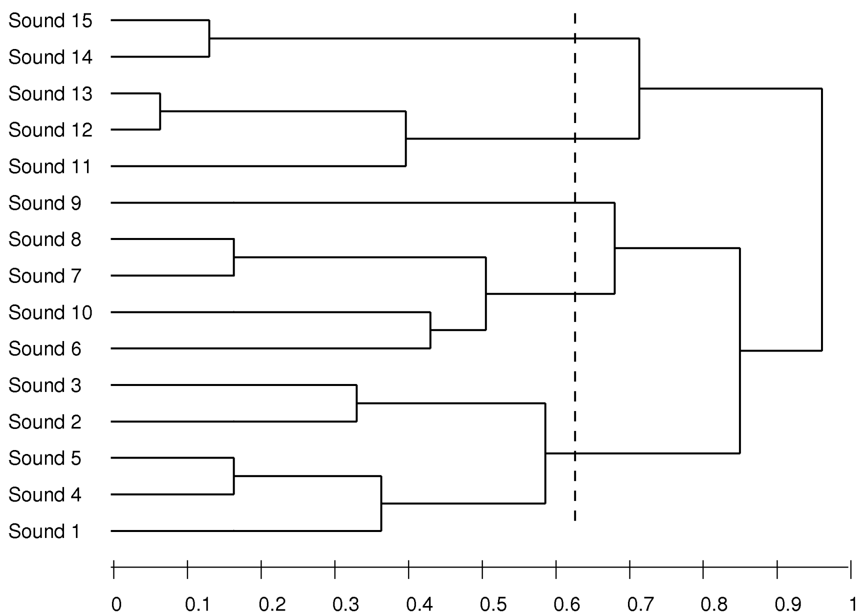

Fig. 3. Mean agglomeration tree for the stimulus set of categorization test, obtained from the distance matrix using average linkage method. The dashed line shows the optimal cutting level as indicated by the corrected Rand index.

The optimal partition was selected so as to match the individual ones as well as possible. Mean partitions of the stimulus range (containing from 1 to 15 classes) could be obtained by cutting this tree at various agglomeration levels. The Rand index [7] is an estimator of the concordance between two partitions. Hubert and Arabie [8] developed a corrected version of this index, enabling to compensate the fact that partition correspondence could be due to chance. The corrected Rand index was computed to estimate the concordance between each mean partition (resulting from the dendrogram and containing from 1 to 15 classes) and the 30 individual partitions. As shown in Fig. 3, the best mean concordance appeared when partitioning the stimulus set into five classes according to the agglomeration tree. The best cutting level on the dendrogram is indicated by the dashed line in Fig. 2. According to the resulting partition, subclasses were perceived within a family of sounds.

Fig. 3. Corrected Rand index for each of the 15 mean partitions.

3.2 Perceptual space of similarity

A multidimensional analysis was carried out to determine the perceptual space of similarity for the categorization task. Using MDSCAL algorithm [9], the reconstituted distance matrix [*D*] revealed the axes of the perceptual space. A 3-dimensional perceptual space (explaining more than 80% of the total variance) resulted from this analysis. This perceptual space was validated using a paired comparison test. For that purpose, 9 sounds were selected for a paired comparison of similarity. Each class was represented by 2 sounds, except sound 9 that was a class by itself. Multidimensional scaling (INDSCAL [9]) of the individual distance matrices revealed a 3-dimensional perceptual space very close from the one obtained from categorization data and explaining more than 85% of the total variance. The dimensions were respectively related to spectral centre of gravity (*SCG*, $R^2 = 0.89$***), loudness (*N*, $R^2 = 0.91$***) and roughness (*R*, $R^2 = 0.71$***). Sound differences due to structural variability were perceived by the sound timbre (*SCG*, *R*) and level (*N*).

4 CONCLUSIONS

The perceptual task of categorization enabled to determine the optimal partition of the stimulus set. This partition made possible to immediately identify the confusions or separations in the sound set that were caused by structural variability. In our case it appeared that the differences between the various types of sounds were too large to create confusion caused by structural uncertainty. Nevertheless, subclasses appeared within the predefined types of sound which showed that listeners identified differences in timbre among these objects.

The perceptual space of similarity could be obtained when transforming individual partitions into a mean distance matrix. That perceptual space proved to be consistent with the one obtained with individual distance matrices. Sounds were distinguished by their timbre and level.

It would be interesting to apply that method on sounds emitted by real products to study the evolution of sound quality over a panel of industrially identical items.

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