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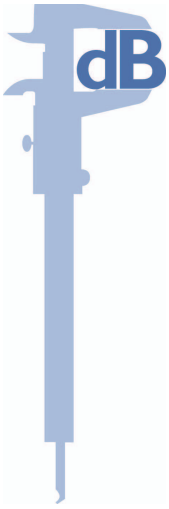
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## PERCEPTUAL ASSESSMENT OF SOUNDS EMITTED BY A SYSTEM SUBJECT TO STRUCTURAL UNCERTAINTIES

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### SUMMARY

This paper aims to investigate the consequences of faults in a mechanical system on sound perception. Because of mechanical variability affecting its structure, an object resulting from an industrial production can exhibit an important variability in its vibratory and acoustical behavior. However, are the main characteristics of the object timbre conserved? A dispersive physical model, on which structural uncertainties were simulated, was set up for sound synthesis. The “emitted” sound was then assessed by a group of listeners performing two different tasks. These tests enabled to determine which uncertainties did affect sound perception, as the way they were perceived by the listeners.

### INTRODUCTION

A number of studies [1-5] have shown that because of mechanical variability affecting their structure, “industrially identically fabricated” objects may exhibit large variability in their vibratory and acoustical behaviour. For instance, Kompella and Bernhard [1] showed that, on a large panel of cars, the frequency response functions due to air-borne and structure-borne excitations were subject to amplitude fluctuations and resonance frequencies shifts. But the perceptual consequences of structural uncertainties have not yet been investigated so far. Are the basic attributes of the object timbre affected by these uncertainties? The aim of this work was to study the behaviour of a elementary object modified by typical industrial uncertainties and to study their consequences on the perception of the sound emitted. For that purpose, a basic structure was modelled, its radiation being calculated to synthesize sounds “emitted” by this object at different stages of modification. Two listening tests have been set up to evaluate the perceptual contribution of the chosen uncertainties.

### PHYSICAL MODEL FOR SOUND SYNTHESIS

The modeled system is presented in Figure 1. It was made up of an engine connected to a radiating panel via three elastic mounts. The engine exerted an harmonic complex force on the mounts, considered as pure springs. The radiating panel was a square simply-supported plate.

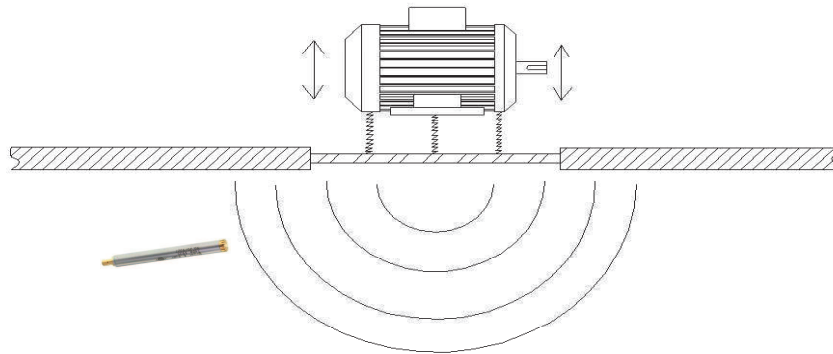


Figure 1: Academic structure for sound synthesis. The engine is connected to the plate via three mounts, the resulting radiated pressure is used to synthesize sound.

The subsystems were coupled by their mobility. The transverse velocity field on the plate was obtained by modal synthesis [6], and allowed to compute the radiated pressure at the listening point using Rayleigh’s Integral [7]. Uncertainties were introduced in the analytical calculation of the radiated pressure, affecting each component of the system, as described in Table 1. These uncertainties were within the common tolerance range encountered in industrial processes [8]. The two first ones affected the engine excitation spectrum, the three following ones changed the stiffness of the springs and the two last ones concerned the plate properties.

Table 1: Uncertainties and tolerance range.

Structural property affected by uncertainty	Nominal value and tolerance range
Global level	$\pm 1.5$ dB
Misalignment	+ 1.5 dB on even harmonics
Stiffness 1	100 N/mm ( $\pm 20$ N/mm)
Stiffness 2	100 N/mm ( $\pm 20$ N/mm)
Stiffness 3	100 N/mm ( $\pm 20$ N/mm)
Thickness	1 mm ( $\pm 0.0325$ mm)
Damping	3 % ( $\pm 1$ %)

The plate was a sandwich metal sheet with elastomer core, assumed to be square ( $L=500\text{mm}$ ). The damping of the plate was sensitive to temperature variations [9] and could thus vary between 2% and 4%. Its nominal thickness was 1mm, the tolerance range for this type of plate being 0.065mm, according to NF A 46-402 standard [10]. Each spring stiffness could differ from  $\pm 20\%$  from its nominal value.

The radiated pressure was then computed in the time domain to obtain the “emitted” sound. The sound emitted by the ideal (i.e. nominal) state of the system could then be compared to various uncertainty states.

## EXPERIMENTAL DESIGN AND SETUP

### Fractional factorial design

In order to limit the number of sounds to be rated, a fractional factorial design was used. In this systematic approach, all factors (i.e. uncertainties) were varied simultaneously according to a special experiment layout [11]. Each sound should then reveal relevant information about the uncertainties affecting the structure. The chosen design is referenced as  $L_{18}$  by Taguchi [12]. It enables to explore the effects of the design factors (i.e. uncertainties) on the measured response (i.e. perceived similarity) at various levels in only 18 measurements. As shown in Table 2 each factor, except factor A, had typically three levels: lower limit of the tolerance range, nominal value and upper limit of the tolerance range; as specified in Table 1.

Table 2: Descriptions of the factors and levels.

Factor designation	Corresponding mechanical dispersion	Level		
		1	2	3
A	Axial misalignment	0	+1.5dB	
B	Level of the spectrum	-1.5dB	0	+1.5dB
C	First engine mount	80N/mm	100N/mm	120N/mm
D	Second engine mount	80N/mm	100N/mm	120N/mm
E	Third engine mount	80N/mm	100N/mm	120N/mm
F	Thickness	0.9675mm	1mm	1.0325mm
G	Damping	2%	3%	4%

The sounds were synthesized according to this experimental design and presented to listeners for perceptual assessment. As shown in Figure 2 and 3, two listening tests were set up to investigate the influence of the design parameters over sound perception; the first one being a similarity evaluation and the second one a categorization task.

### Listeners

All 20 listeners participated in both experiments. They were students aged from 22 to 25 (14 males and 6 females). They all reported to have normal hearing.

### Stimuli

Synthesized sounds were presented for listening tests via a set of Sennheiser HD600 headphones. The sounds were stationary and their level (measured with Bruël & Kjør type 4100 artificial head) ranged from 74.7 to 84.1 dBA.

### Similarity evaluation procedure

During this experiment, listeners had to evaluate the similarity of 24 sounds to one reference sound: 18 sounds were synthesized according to the experimental design, 6 sounds from additional configurations, being different from the 18 ones chosen, were added to verify the assumption of design factors independence.

As shown in Figure 2, all 25 sounds (the reference sound, eighteen sounds from the varied design and six validation ones) were available on the test window at the same time. Sounds were presented in random order (the number given to each sound in the test window was arbitrary and had no link with its number in the experiment table). Sounds could be rated by listeners from 0 (identical to the reference) to 1 (very different from the reference) on a continuous scale. Sounds (which could be listened to as many times as the subject wanted), could as well be compared to the reference sound as well to any other one in order to allow for a more precise rating. To facilitate the task, subjects were given the opportunity of reordering sounds from the highest similarity to the largest dissimilarity to the reference sound. This test was set up to measure the effects of the design factors on the perceived similarity.

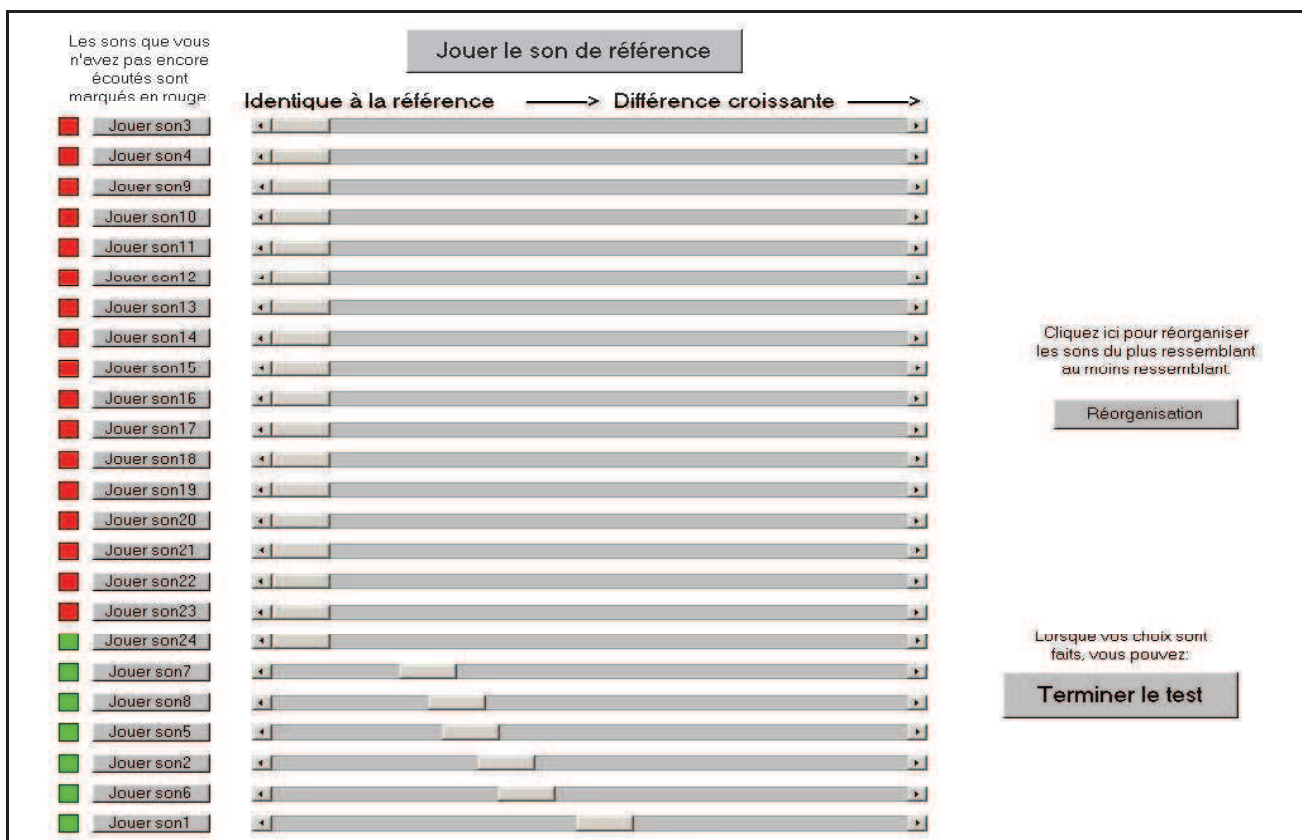


Figure 2: Screen shot of the similarity evaluation window. Each button on the left corresponds to a sound to rate, its evaluation cursor being placed beside. The reference sound is placed at the top of the window. A button on the left allows to reorder sounds according to the similarity ratings.

### Categorization procedure

In this test, listeners had to group sound items according to the similarity of their timbre (see Figure 3). Each button represented a sound and could be moved on the screen where the listeners had to group them into clusters. Either within a category or between categories, no distance between the sound was evaluated in this experiment. Since the response was not continuous (belonging to a cluster or not), this method could not be combined with the fractional factorial design technique. To compensate this drawback, the number of sounds was increased: 14 additional sounds were added to 24 previous ones. The number of categories was not prescribed and hence could vary between one and thirty-eight. Each listener had then to create his specific partition of the stimulus set. This experiment was to build up a perceptual space of the timbre of the sound emitted by the object.

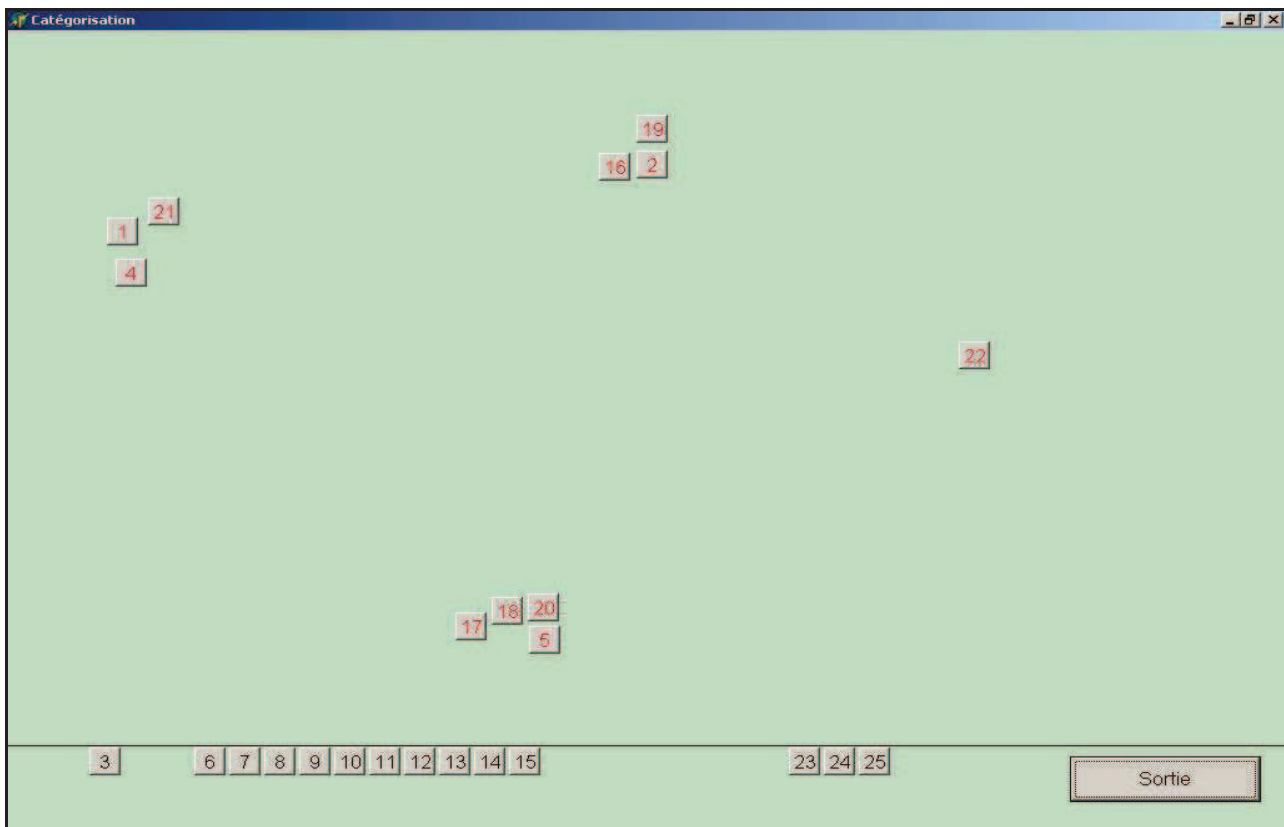


Figure 3: Screen shot of the categorization window. Each button corresponds to a sound and can be freely moved on the screen to be gathered with items having similar timbre.

## RESULTS

### Similarity evaluation

The additivity of the factorial contributions (i.e. the factors independence) was checked with the additional configurations (leading to the sounds 19 to 24). The analysis of the results of this evaluation combined with the fractional factorial design approach allowed to extract the influence of each design parameter (i.e. structural uncertainties) on the perceived similarity.

As could be suspected, the most influential factor, is the global level of the excitation spectrum. It did affect the level of the transfer function radiated pressure/input force. In the second place ranged the plate thickness. As shown in [2], this uncertainty generated magnitude fluctuations and resonant frequency shifts.

Table 3 Factors effects

B (Spectrum level)	39.98%
F (Thickness)	21.57%
C (Mount 3)	14.84%
A (Misalignment)	9.66%
G (Damping)	5.46%
D (Mount 2)	5.16%
E (Mount 1)	0.53%



It could be noted that the mount influence depends on its position on the plate. The less influent position was the connection to the plate at its middle position ( $x=250\text{mm}$ ,  $y=250\text{mm}$ ). When looking at the transfer function *radiated pressure/input force* for each connecting point (see Figure 4), it could be stated that this excitation point did not excite much plate modes. On the other hand the third position excited less modes than the second one, but at larger modal amplitudes. The influence of a spring was then determined by the number of modes excited but also by their modal amplitudes. The third position was thus the one having the larger influence (see Table 3).

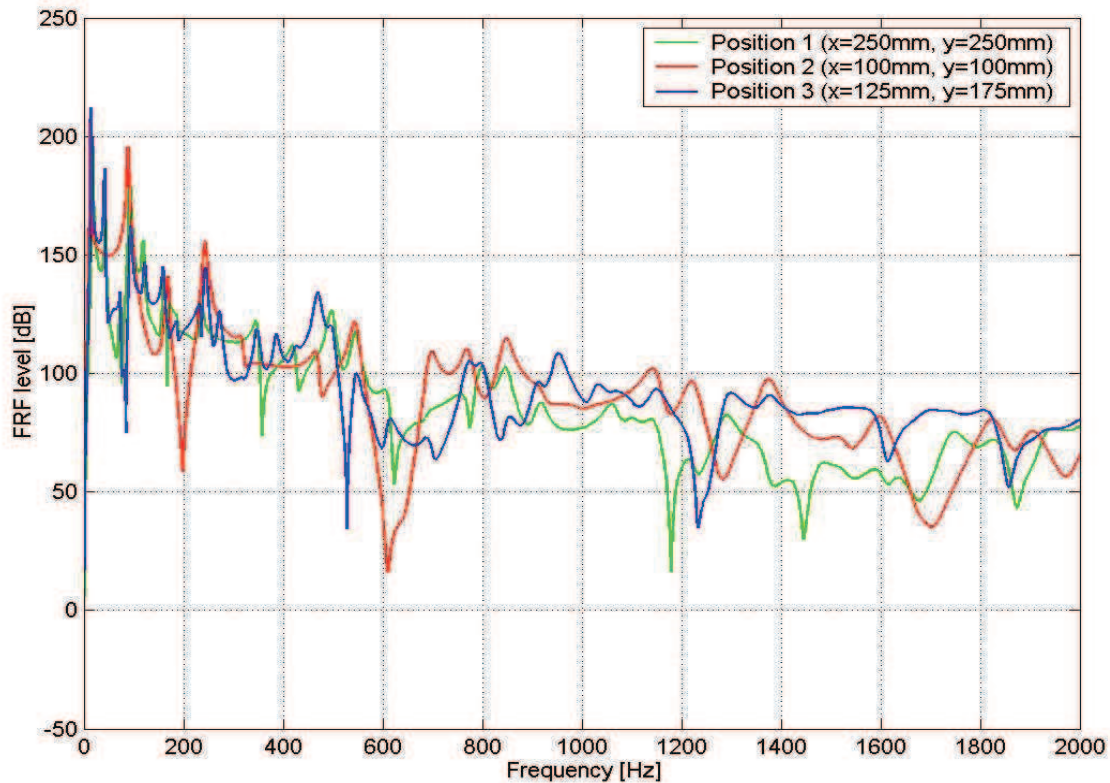


Figure 4: Transfer functions *radiated pressure/input force* at each connecting position.

The acoustic parameters used by listeners to discriminate sounds could give further information to understand the influence of the mechanical variability. A forward linear regression indicated a two-metrics regression model for dissimilarity ( $R=0.92$ ,  $F(2,21)=29.82^{***}$ ,  $p<.001$ ), for which inputs were Zwicker Loudness  $N$  [16] and Aures Roughness  $R$  [17] computed with 01dB dB Sonic software (Version 4.13).

### Categorization

Each individual partition could be represented by a membership matrix  $a$ , where:

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

The sum of the individual membership matrices allowed to reconstruct a dissimilarity matrix, which gave the mean agglomeration tree. The Rand Index [14,15] gives an indication about the concordance of two partitions. In this case, it indicated that the best cutting level for the agglomeration tree was seven classes; the resulting partition being the one fitting at best the listeners answers.

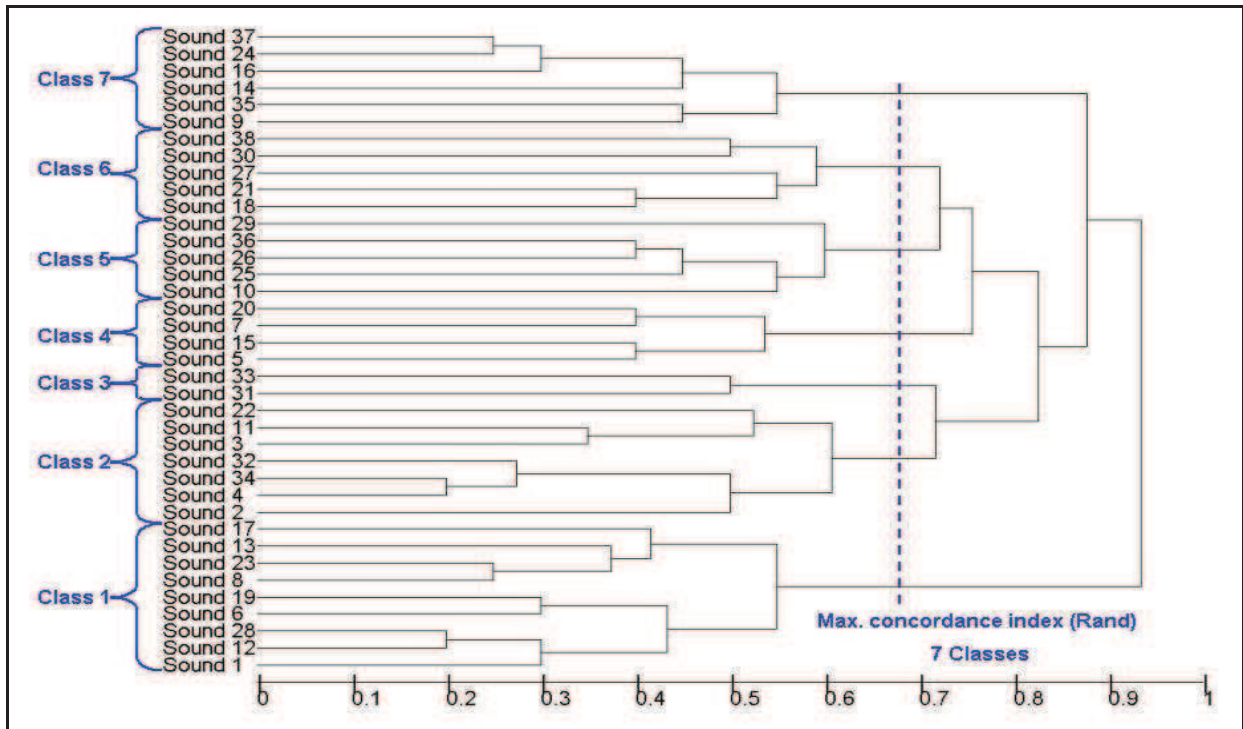


Figure 5: Mean agglomeration tree (average linkage method). The optimal partition is seven classes according to Rand index.

It can be noted that sounds belonging to Class 1 corresponded to the thinnest configuration of the plate. Such a simple physical description could not be found for the other classes.

Multidimensional scaling [18] of the distance matrix enabled to find out the axes of the perceptual space which were also the main attributes of the object timbre. A 3-dimensional perceptual space resulted from this analysis. The first axis was strongly related to a fractional loudness in a specific Bark range (see Equation 1). This dimension determined the presence of the sounds in the first class and was then related to the plate thickness. Sounds in this class were described by the listeners as “hollow”.

$$Dim_1 = \frac{N_{2 \rightarrow 4Bark}}{N_{1 \rightarrow 24Bark}} \quad (1)$$

The two other axes were related to still loudness and roughness. Since these two indicators were the same as the ones used in the first experiment, it could be assumed that the uncertainties contribution were the same within the six remaining classes.



## **Comparison**

In the second experiment, one additional discrimination indicator, defining an own separate class, appeared. This axis of the perceptual space was not salient in the similarity evaluation. Since this axis was related to the plate thickness, the influence of the uncertainty affecting this parameter should then be revalued in comparison to its contribution to the first listening test.

During this first experiment all sounds were compared to a reference one. This answer was adequate to a single column of the distance matrix. Obviously, a single column could not contain as much information as the whole matrix. Nevertheless, the two discrimination parameters corresponded to two axes of the perceptual space of timbre. This indicated that even though one of the axes was not salient for this task the acoustical parameters employed for sound discrimination were the same in the two experiments.

## **CONCLUSION**

These listening tests allowed to quantify the influence of structural uncertainties on sound perception, as well as the acoustical parameters used for sound discrimination. The main attributes of the object timbre and the way they were affected by the uncertainties were revealed.

This study enabled to point out the uncertainty parameters that had a negligible effect on sound perception, and also the sensitive parameters affecting the acoustical parameters used by listeners for sound discrimination. These sensitive uncertainties are the ones that should be controlled in order to preserve the object timbre.

These parameters could then be reused in a test involving nominally different objects; the scope being to check that variation of the objects would not produce similar (or nearly identical) timbres that would cause a wrong identification of an original source.

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