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Perceptual Consequences of Structural Uncertainties

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Many studies have shown that industrial products can exhibit a great variability in their vibratory and acoustical behaviour; but the influence of this physical variability on the perception of sound emitted by these products has not yet been investigated. The aim of this study was to evaluate that influence in the case of a computed system, including a force source linked to a plate through three springs. The physical variability could affect the force amplitude, the stiffness of each spring, the thickness and damping of the plate. Two listening tests have been conducted : in the first one, a L_{18} fractional designed experiment was used for the sounds synthesis; 20 listeners had to evaluate the similarity between each sound and a reference one (corresponding to the nominal state of the system). The most important factors were identified (force amplitude, plate thickness and the stiffness of one of the three springs); psychoacoustical criteria representing the perception were Zwicker loudness and Aures roughness. In the second test, 38 sounds (including the 18 used in the fractional design) were categorized by listeners according to their timbre similarity; a three-dimensional perceptual space was built from the answers. The plate thickness appeared to be more influent in that case and was linked to the first dimension of the perceptual space; it was related to a spectrum balance which could be correctly described from the specific loudness curves. Loudness and roughness still described the two other dimensions of the perceptual space.

1 Introduction

Because of the mechanical uncertainties affecting their structures, "industrially" identical objects can exhibit large variabilities in their vibratory and acoustical behavior [1, 2]. Do this mechanical variability also generate a perceptual variability? Are the basic attributes of the timbre of an object affected by the scatter of its structure? To answer these questions, a mechanical research model, on which the mechanical variability could be controlled, wad used. Perceptual tests were conducted with sounds synthesized from this system to investigate the perceptual consequences of mechanical uncertainties.

2 Physical model for sound synthesis

The academic system was used to investigate the influence of mechanical variabilities on sound perception. 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. The subsystems were coupled by their mobility. The transverse velocity field on the plate was obtained by modal reconstruction, and allowed to compute the radiated pressure at the listening point using Rayleigh's Integral. The resulting sound was then synthesized in the time domain.

As shown in Table 1, a representative panel of structural uncertainties affected this system.

Table 1: Dispersion parameters

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

Sounds emitted by the device in various dispersion states were synthesized to look at the influence of these parameters over the timbre.

3 Test 1: Similarity evaluation

3.1 Listeners

Twenty listeners participated to this experiment. They were students aged from 22 to 25 (14 males and 6 females).They all reported to have normal hearing.

3.2 Stimuli

Eighteen sounds (i.e. variability configurations) were synthesized according to a special experiment layout, an L_{18} fractional factorial design. This approach enabled to extract relevant information from each of the 18 measurements. Each assessed sound delivered relevant information about the state of its source. The design factors were the dispersions described in Table 1. They were assumed independent and referred from A to G; 6 additional sounds were synthesized to check this assumption. The response (perceived similarity) had to be measured on a continuous scale.

3.3 Procedure

During this listening test, the listeners had to compare the twenty-four sounds (corresponding to perturbed states of the system) to a reference one (representing the ideal state of the object). Each sound had to be evaluated using a continuous similarity scale, presented on the screen. All sounds and answering scales were simultaneously presented to the listener. He could then freely listen to them as many times as he felt necessary, in order to help him in his task.

3.4 Results

An additive model of similarity arose from this test. The similarity for sound i could be obtained by adding the effects of the seven design factors (i.e. dispersion parameters) in the state i to the mean similarity:

$$S_i = \overline{S}_{1\to 18} + E_{Ai} + E_{Bi} + \cdots + E_{Gi} \qquad (1)$$

where S_i was the similarity score of sound i, the similarity score of a sound being the average of the listeners ratings for this stimulus. $\overline{S}_{1\to 18}$ was the mean similarity score, averaged over the 18 measurements of the design. E_{Ai}, E_{Bi}.... were the effects of the design factors in configuration i. The theoretical similarities of the whole set of sounds could be computed using Equation (1).

Figure 3 shows a very good agreement between the measured similarity and the one represented by Equation (1), even for sounds 19 to 24 that were not used to extract the factors effects. These configurations were then particularly suited to reveal unsuspected contribution to the measured response. Assuming that no other factor or interaction took any significant part to perceived similarity, the contribution of the design factors could be expressed as shown in Table 2.

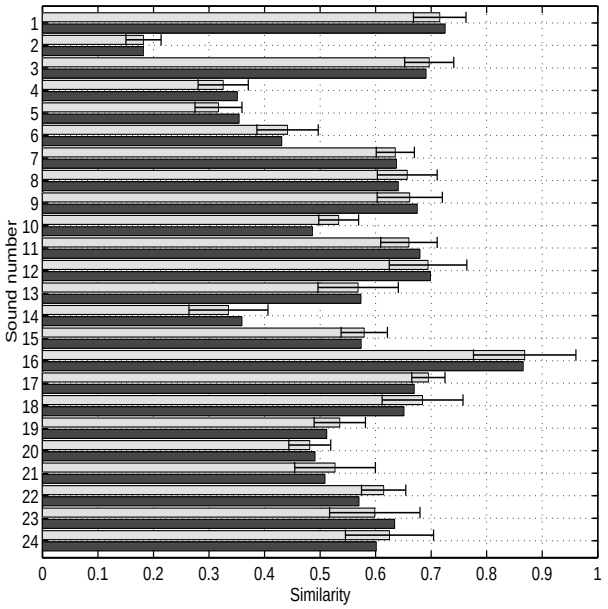


Figure 1: Comparison between the perceived similarities in their 95% confidence intervals (bright grey) and the computed similarities (dark grey).

Table 2: Effects of the factors on perceived similarity (contribution to explained variance)

Design factor	Contribution
A (Misalignment)	9.66%
B (Global level)	39.98%
C (Stiffness 1)	0.53%
D (Stiffness 2)	5.16%
E (Stiffness 3)	14.84%
F (Thickness)	21.57%
G (Damping)	5.46%

To determine the sound features used by listeners to discriminate the stimuli during the similarity evaluation, a forward linear regression was performed on the perceived similarities. A two-metrics regression model arose (R= 0.92, $F(2, 21) = 29.82$***, $p < .001$). Its inputs were ISO532-B Loudness N [4] and Aures Roughness R [5] computed with 01dB-dBSonic Software (Version 4.13).

4 Test 2: Categorization

4.1 Listeners

The same 20 listeners as for the similarity evaluation participated to this experiment.

4.2 Stimuli

Since the response to this test was not measured on a continuous scale, the fractional factorial design method could not be applied to this experiment. However the twenty-four sounds used in the previous experiment were used again for this test and fourteen additional configurations were added to the sound set to compensate this drawback.

4.3 Procedure

During the categorization task, listeners had to group sound items according to the similarity of their timbre. 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 sounds was evaluated in this experiment. The number of categories was not prescribed and hence could vary between one and thirty-height. Each listener had then to create his specific partition of the stimulus set, which could be formulated as a membership matrix a:

$$a(i,j) = \begin{cases} 1 & \text{\{i,j\} are in the same class} \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

A similarity (or distance) matrix d was reconstructed by adding the individual membership matrices.

$$1 - \sum_{l=1}^{N} a/N = \begin{bmatrix} d_{11} & d_{12} & d_{13} & \cdots & d_{1n} \\ d_{21} & d_{22} & d_{23} & \cdots & d_{2n} \\ d_{31} & d_{32} & d_{33} & \cdots & d_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & d_{n3} & \cdots & d_{nn} \end{bmatrix} \quad (3)$$

This distance matrix led to the agglomeration tree shown in Figure 2. The agglomeration schedule was hardly related to the dispersion parameters, except for the category of sounds at the bottom of the tree (in bold-italic). These nine sounds all corresponded to the thinest configuration of the plate. For the other parameters, a link with the dendrogram was not obvious. A multidimensional scaling [6] was carried out on the reconstructed distance matrix, enabling to reveal the common perceptual dimensions shared by the set of sounds. The first axis was well correlated to the plate thickness. Sounds from the group described above (thin plate) were all grouped at one end of this axis, the other configurations (nominal and thick plate) were grouped at the other end. When trying to correlate this physical dimension with a perceptual one, it appeared that the sounds emitted by the thin plate configuration were described as "hollow" by the listeners. The perceptual dimension representing this sensation was then related to the specific loudness in the low frequency range and was satisfactorily described by:

$$Dim_1 = \frac{N_{2\to 6Bark}}{N_{1\to 24Bark}} \quad (4)$$

The second and third axes of the perceptual space were still correlated to loudness and roughness.

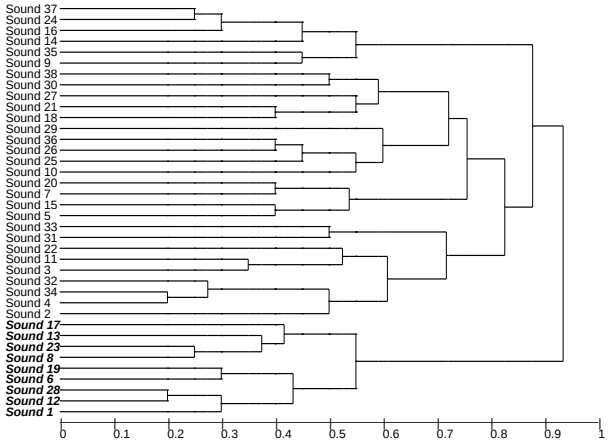


Figure 2: Agglomeration schedule (dendrogram) of the sound set over the 20 listeners, using average linkage method.

5 Discussion

The first dimension of the perceptual space of categorization was not used as a discrimination criterion for the similarity evaluation. Was it due to the task, to the stimulus range? Or did an experimental bias made listeners rate the annoyance instead of the similarity, which could explain the large contribution of loudness in the results of the first test? To check this assumption an other test was set up to look at the salient criterion for similarity and preference.

6 Test 3: Similarity and preference

6.1 Listeners

An other set of twenty listeners participated to this experiment. They were students aged from 23 to 27 (15 males and 5 females). They all reported to have normal hearing.

6.2 Stimuli

Twelve sounds, chosen among the twenty that were common to the similarity evaluation and categorization were selected for this experiment.

6.3 Procedure

The sounds were presented by pairs ($\frac{N(N-1)}{2} = 66$). The set of pairs was ordered according to Ross series, sounds being first randomly arranged from 1 to 12 [8]. After having at least listened once to the sound pair, the listener had to rate the similarity between the two stimuli on a continuous scale. The listener had then to listen to the pair again and to indicate his preference (tie answer being allowed).

6.4 Results

Results of the first test were analyzed using an Indscal procedure [7], which revealed the same perceptual space as the categorization. A principal component analysis (PCA) was carried out with the preference scores. The first principal component explained 90% of the variance, the second one only 4%. Further component only explained negligible parts. Therefore, the preference was quasi monodimensionnal and based upon the loudness.

As shown in Figure 3, the similarity measured during the first test was in good agreement with the first column of the distance matrix resulting from the paired comparison of similarity. Moreover, roughness did not appear to be a preference criterion. Therefore, listeners indeed assessed the similarity during the first test.

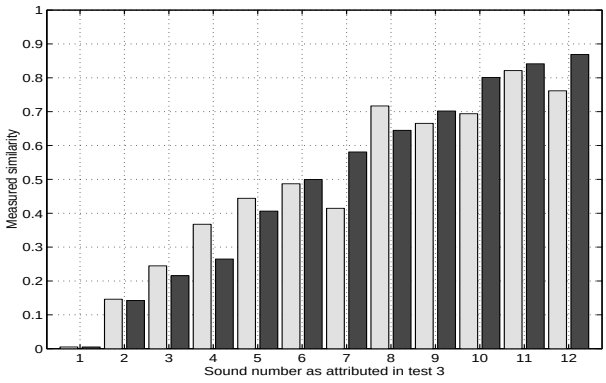


Figure 3: Comparison between the similarity measured during test 3 (bright grey) and the ones measured during test 1 (dark grey).

The reason why the sound feature described by Equation (4) was not used as a discrimination parameter during this experiment could be explained by the fact that all sounds were assessed in regard to one reference during this task. The reference having a weak loudness, this feature was then the most salient one for discrimination. To summarize, the similarity evaluation only gave information in regard to one reference, it hence corresponded to one single column of the distance matrix.

7 Conclusion

The categorization experiment enabled to determine the perceptual dimensions shared by the sound set. This test procedure is particularly suited to evaluate large stimulus ranges, and is therefore useful to determine the perceptual space which can be obtained from the structural uncertainties of a device.

During the similarity evaluation, listeners did not use the whole perceptual space determined by the categorization task. They only had to compare sounds to a given one (radiated by the device in its nominal state). On the other hand, the perceptual consequences of variabilities from this nominal state could be accurately predicted.

References

[1] R.J. Bernhard, M.S. Kompella, 'Measurement of statistical variation of structural-acoustical characteristics of automotive vehicles'. *Proc. SAE Noise and Vibr. Conf. 1993, paper 931272* (1993)

[2] B. Gärdhagen, J. Plunt, 'Variation of Vehicle NVH properties due to Component Eigenfrequency Shifting. Basic limits of predictability'. *Proc. SAE Noise and Vibr. Conf. 1995, paper 951302* (1995)

[3] G. Taguchi, S. Konishi, *'Taguchi methods. Orthogonal arrays and linear graphs. Tools for quality engineering'* American Supplier Institute Press, Dearborn MI, ISBN-094124301X (1987)

[4] E. Zwicker, H. Fastl, *'Psychoacoustics: facts and models'*, Springer Verlag, Berlin, ISBN-3-540-65063-6 (1999)

[5] W. Aures, 'Ein Berechnungsverfahren der Rauhigkeit', *Acustica* Vol. 58. No. 5. pp. 268-281 (1985)

[6] T.F. Cox, M.A.A. Cox, *'Multidimensional Scaling'*, Chapman & Hall, New York, ISBN-1584880945 (2000)

[7] J.D. Carroll, J.J. Chang, 'Analysis of individual differences in multidimensional scaling via an N-way generalization of "Eckart-Young" decomposition', *Psychometrika* Vol. 35. pp. 283-319 (1970)

[8] H.A. David, *'The method of paired comparison'*, Oxford University Press, New York, ISBN-0195206169 (1988)