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AUDITORY EVALUATION OF SOUND SIGNALS RADIATED BY A VIBRATING SURFACE[†]

S. MEUNIER, D. HABAULT AND G. CANÉVET

CNRS, Laboratoire de Mécanique et d'Acoustique, 31 *chemin Joseph-Aiguier,*
13402 *Marseille cedex* 20, *France. E-mail*: *habault@lma.cnrs-mrs.fr*

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This paper presents a combination of vibroacoustic and psychoacoustic studies of sounds radiated by a vibrating structure. The calculated sound field is the sound pressure radiated by a baffled thin-plate structure immersed in a fluid, on the surface of which the acceleration is given. Various configurations are selected for the time and space functions of the acceleration variable, each configuration leading to a particular acoustic signal (a low-frequency tone complex in our case). These signals are then transformed into sound files, which are used as test signals in psychoacoustic experiments for assessing their perceptual attributes and quality. Two experiments were run. In the first one, the unpleasantness of a series of signals at different levels was measured by direct estimation and compared with their calculated loudness and sharpness using Zwicker's model. The same measurements were repeated with the signals set to the same maximum amplitude. In the second experiment, the pleasantness of another series of sounds at equal loudness was measured, as well as dissimilarity and preference on pairs of these sounds. An MDS analysis was run to extract auditory attributes that could account for the perceived differences between sounds and correlate with the estimated pleasantness. The results from the first experiment show that pleasantness is always highly (and negatively) correlated with loudness. The same holds for sharpness, when sounds are played at the same maximum amplitude. The second experiment shows that the perceptual attributes revealed by the MDS analysis are related to pitch and timbre, the latter being highly correlated with pleasantness. Overall, this study confirms the interest of extending vibroacoustic studies to a more complete "psychomechanical" investigation of the whole process of sound generation. It is suggested that such investigations may apply to product sound quality and to active or passive noise control, by providing psychoacoustic feedback to the design of the vibrating structures or of the noise-control systems.

1. INTRODUCTION

Most studies on acoustic radiation by vibrating bodies have focused on the physical aspects of either the vibration itself (displacement, velocity of the vibrating structure) or the acoustic field radiated outside the structure. However, if the spectrum of the radiated field lies within the frequency range of human hearing, a sound is created. This sound therefore carries auditory attributes and information, which contribute to the acoustic environment created by the vibration. This acoustic environment has an impact on humans; it can be perceived as pleasant or unpleasant, depending on the evaluation of the auditory attributes by the listeners. As a consequence, when studying a vibroacoustic problem, it may be useful to include an auditory assessment of the signals produced.

[†] This paper is dedicated to the memory of Ingrid Richard.

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Increasing interest for auditory attributes of acoustic signals can be seen in the literature, mainly in the field of environmental acoustics (see references [1–4] for example), but also in that of sound quality of industrial products (see references [5–8] for example). Sound quality is thought to depend on a series of auditory attributes (so-called psychoacoustic criteria of sound quality), the validity of which was attested by psychoacoustic experimentations (see reference [8] for a review). Among all possible auditory attributes, it seems broadly accepted that loudness, fluctuation strength, roughness and sharpness are of particular importance for sound quality. These four attributes are therefore most relevant for assessing sounds produced by mechanical vibrations. Algorithms or programs are available to calculate the magnitude of these attributes for any given acoustic signal.

Relations between the mechanical characteristics of vibrating structures and the perceptual features of the corresponding generated sounds have also been studied recently [9–13]. In particular, Roussarie *et al.* [13] investigated the auditory perception of synthesized sounds simulating those of vibrating bars and plates. The models used for synthesis have been developed by Chaigne and his colleagues [14, 15]. They are based on a finite-difference method to solve the equations for the displacement in the time domain. Auditory evaluation was made by judging perceptual distances (dissimilarity) between pairs of synthesized sounds. Specific auditory attributes that explained the differences observed between sounds were identified with the help of a multi-dimensional scaling technique. The authors then related these attributes to the mechanical parameters of the structures such as damping factor and Young's modulus.

In the present article, a study is described that combined vibroacoustics and psychoacoustics. One aim was to evaluate the validity of the above-mentioned psychoacoustic criteria in predicting the overall pleasantness of sounds simulating the acoustic radiation of vibrating plane surfaces. In this paper, the word "pleasantness" ("agrément" in French) is used as an equivalent to the word "Wohlklang", originally used in the German literature on sound quality (see reference [16] for example). The sounds were synthesized waveforms, representing the sound pressure radiated by the surface. They were obtained as an integral of the acceleration on the surface. A second aim of this study was to correlate the various physical parameters of the sound signals and their perceptual attributes, in order to identify which physical parameters in the acceleration function are influent in the resulting sound quality. Such an identification might make it possible, in turn, to improve the quality of the radiated sound by optimizing the geometric and mechanical characteristics of the structure.

The psychoacoustic tests consisted of two main experiments. In the first experiment, considered as a preliminary test, eight different synthesized sounds were played to a group of listeners, who were asked to rate the unpleasantness of the sounds. The method of magnitude estimation was used, that is the subjects were requested to estimate the unpleasantness by assigning numbers proportional to it. On the other hand, the loudness and sharpness of the sounds were calculated with the help of a program based on models by Zwicker [17, 18], by Bismarck [19] and by Aures [16]; the values for roughness and fluctuation strength are not considered here since they were close to zero for the signals selected for the two experiments. Unpleasantness was found to be essentially correlated to loudness, as expected, and to sharpness as a second-order effect. A second experiment was then run, with a set of 15 sounds (including the first eight) for which the levels had been set so as to reach equal loudness for all sounds. A moderate value was chosen for the average loudness level, so that the sounds would be perceived as less unpleasant. The experiment then consisted of three parts, each measuring a different attribute. In one part, the pleasantness was estimated by magnitude estimation. In the second part, the distance between two sounds presented in pairs was rated, using a method that will be described below, in view of a multi-dimensional scaling analysis. Finally, the subjects' preference was asked, for the same set of pairs of sounds. As will be shown in the text below, setting the loudness to a (moderate) common value made possible the appearance of interesting secondary criteria for perceived quality.

Section 2 describes the physical characteristics of the radiated sound signals. Sections 3 and 4, respectively, describe experiments 1 and 2 and present their results. Section 5 contains the conclusions of this study.

2. VIBRATION MODES AND RADIATED SIGNALS

The study concerns a baffled thin-plane structure immersed in a fluid. This structure is called "vibrating panel" or "panel" throughout the article. The sound signals used in the experiments correspond to the acoustic pressure radiated by this panel.

To compute the sound pressure radiated by a fluid-loaded thin structure, it is necessary to solve a coupling problem where the unknowns are the displacement on the surface of the structure and the sound pressure in the fluid (see reference [20] for example). The data are the dimensions of the structure and its mechanical characteristics (such as Young's modulus and damping). Here, to reduce the amount of computation, instead of solving the coupling problem, it was chosen to impose the acceleration (function of space and time) on the surface of the structure. Because of the baffle, the acoustic pressure is directly obtained as an integral of the acceleration on the surface of the panel. The data are the dimensions of the panel and the acceleration function.

More precisely, $\hat{v}(M, t)$ denotes the acceleration on the panel. When $\hat{v}(M, t)$ is known, it is possible to compute the sound pressure radiated at any point Q of the half-space on both sides of the structure through the classical Kirchhoff–Helmholtz representation [21]

$$p(Q, t) = \frac{\rho}{2\pi} \iint_{\Sigma} \frac{\hat{v}(M, t - R(Q, M)/c)}{R(Q, M)} \, \mathrm{d}\sigma(M), \tag{1}$$

where Σ represents the surface of the structure, ρ is the air density, c is the sound speed in air. $R(Q, M)$ is the distance between the point M on the structure and the observation point Q above the structure (see Figure 1).

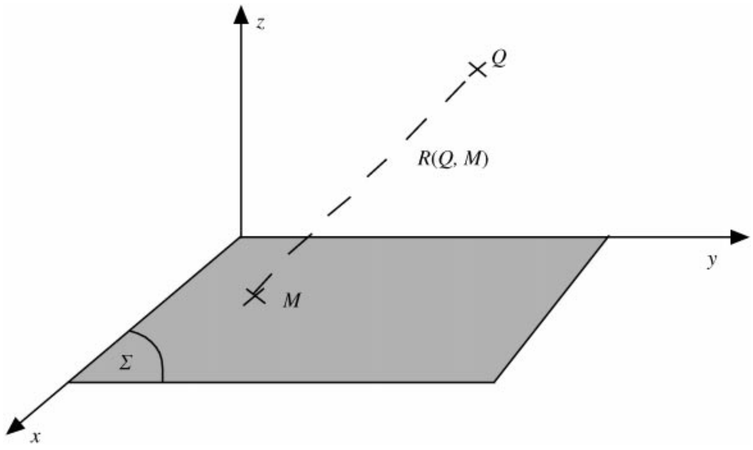

Figure 1. Geometry of the problem.

The acceleration function on the panel was chosen as the product of two functions: $\hat{v}(M,t) = V(M)F(t)$. To simulate a classical radiation problem, $V(M)$ has been chosen as a sum of cosine functions of the space variable. The time function $F(t)$, which can be seen as the excitation on the structure, has been chosen independently of the space variation. It is expressed as a sequence of concatenated Ricker signals with a centre frequency v_0 of 500 Hz. More precisely, F is equal to one of the two functions

$$F_1(t) = \sum_{j=1}^{N} f(t-(j-1)\alpha) \quad \text{and} \quad F_2(t) = \sum_{j=1}^{N} (-1)^j f(t-(j-1)\alpha), \tag{2}$$

where $f(t)$ is a Ricker signal defined by the formula

$$f(t) = (1-2\pi^2(v_0t-1)^2)\exp(-\pi^2(v_0t-1)^2).$$

Here $v_0 = 500$ Hz and therefore α, the duration of the Ricker signal, is equal to 4 ms.

The reason for the choice of a Ricker signal as a stimulus was that it has a bounded support both in frequency and in time. This makes it an easy tool for numerical developments. However, for the present study, it was decided to use a concatenation of such elementary signals because the psychoacoustic tests and calculations required signals of longer duration. On the one hand, the models and algorithms available to us for calculating loudness were only valid for stationary sounds, or at least for sounds longer than 200 ms. On the other hand, the duration for the auditory tests was chosen equal to 1·5 and 2 s. Therefore, the number N of Ricker signals was chosen equal to 375 and 500.

The panel was assumed to be a square, represented in space by $x = 0$ to d and $y = 0$ to d. Radiated sound signals have been computed for a large series of conditions $(V(M), F(t))$. Many of them lead to fairly similar signals. A subset of 15 conditions were then selected that provided signals sufficiently different, from an auditory point of view. For each of these 15 signals, the acceleration was defined as $V(M)F(t) = v(x)v(y)F(t)$. Both functions v and F and the length d are given in Table 1.

TABLE 1

Physical characteristics of the vibration modes

Signal	$v(x)$, for $x = 0,\ldots,d$ $a = \pi/2d$	$F(t)$	d (m)
s1	1	F_2	4
s2	$\cos(ax) + 2\cos(3ax) + \cos(5ax) + \cos(7ax)$	F_2	4
s3	$\cos(7ax)$	F_2	4
s4	$\cos(ax)$	F_2	4
s5	1	F_2	8
s6	$\cos(ax) + 2\cos(3ax) + \cos(5ax) + \cos(7ax)$	F_2	8
s7	$\cos(7ax)$	F_2	8
s8	$\cos(ax)$	F_2	8
s9	$\cos(6ax)$	F_1	4
s10	$\cos(\mathrm{ax}) + \cos(2ax) + \cos(4ax) + \cos(5ax) + 2\cos(6ax)$	F_1	4
s11	1	F_1	8
s12	$\cos(ax) + \cos(2ax) + \cos(4ax) + \cos(5ax) + 2\cos(6ax)$	F_1	8
s13	$\cos(ax) + \cos(2ax) + \cos(4ax) + \cos(5ax) + 2\cos(6ax)$	F_2	4
s14	$\cos(2ax) + \cos(4ax) + 2\cos(6ax)$	F_2	4
s15	$\cos(6ax)$	F_2	4

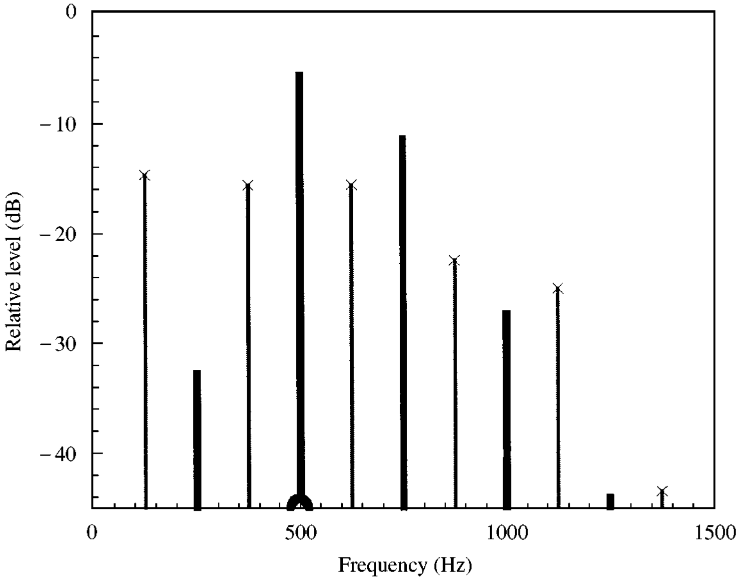

Figure 2. Spectra of signals s6 (—×—) and s9 (▬).

The spectra of the radiated signals are directly related to the choice of the acceleration function $\hat{v}(M, t)$. The spectral components are determined by the choice for $F(t)$, and the level of each component is directly linked to the choice of $V(M)$. Because of the time dependence of the acceleration given by formula (2), the radiated signals are harmonic. The choice of $F_1(t)$ and $F_2(t)$ leads to two sequences of spectral components, $(n + 1)250$ and $(2n + 1)125$ Hz, for n equal to or greater than 0. The acceleration as a function of space $v(x)v(y)$ has an influence on the energy distribution in the spectra of the signals. Figure 2 illustrates an example of this influence. It presents the spectra of signals s6 and s9; the amplitudes are expressed in dB (relative amplitudes for a reference equal to 1). The first three components of the spectrum of signal s6 have very close levels (around − 15 dB). Signal s9 is characterized by a very low level in its fundamental frequency (250 Hz) and a high level at the second frequency. Signals s6 and s9 are extreme cases of such energy distribution. The other signals lie more or less regularly in between these two extreme cases. This feature turned out to be an important characteristic in separating the signals as demonstrated in section 4.

It must finally be pointed out that, from an auditory point of view, the sound signals synthetised for this study do sound close to sounds heard when exciting metallic structures in real life including some harmonic features.

In experiment 1, each of the eight signals used was presented at two different sound–pressure levels. The first level, termed “original”, was the level directly computed with the characteristics defined in Table 1. The second level, termed as “normalized”, was obtained in the following way. Since the signals are similar to sine functions (i.e., with values continuously oscillating from a maximum to a minimum value), they have been normalized by keeping, for each signal, its maximum value equal to 1. The loudness levels of the signals are not then equal, but quite close to each other.

Table 2 presents the “original” sound levels (linear and A-weighted level in dB) of the signals along with their values of loudness and sharpness. Table 3 presents the same characteristics for the “normalized” sound levels. The loudness and sharpness values were obtained by using algorithms developed by Zwicker and his colleagues [22–24] for

Table 2

Acoustic characteristics of the signals—Experiment 1—"*original levels*"

Signal	*SPL* (dB)	*N* (dB (A))	Loudness (sones)	Loudness levels (phons)	Sharpness (acums)
s1	74·5	68·3	14·7	78·8	0·73
s2	91·0	86·7	38·6	92·7	0·66
s3	71·2	69·0	11·0	74·6	0·98
s4	69·8	60·8	9·0	71·7	0·78
s5	90·2	86·4	39·4	93·0	0·65
s6	87·8	83·5	42·5	94·1	0·71
s7	79·2	75·9	17·5	81·3	0·85
s8	81·1	76·5	23·7	85·6	0·68

Table 3

Acoustic characteristics of the signals—Experiment 1—"*normalized levels*"

Signal	*SPL* (dB)	*N* (dB (A))	Loudness (sones)	Loudness levels (phons)	Sharpness (acums)
s1	84·5	78·5	27·7	87·9	0·59
s2	87·0	82·8	29·3	88·7	0·64
s3	87·7	85·5	29·6	88·9	0·74
s4	87·3	78·8	29·3	88·7	0·53
s5	86·2	82·4	30·1	89·1	0·63
s6	83·8	79·5	33·2	90·5	0·71
s7	85·1	81·8	27·2	87·7	0·74
s8	87·1	82·6	36·5	91·9	0·66

stationary signals. As an example, Figure 3 presents the specific loudness curves of signals s6 and s9. The shape chosen for the acceleration functions is the reason why some characteristics of the signals do not differ a lot from one to another. In particular, the sharpness values for the normalized levels vary between 0·53 and 0·74 because of the choice of the excitation $F(t)$. However, this range of variation appeared to be sufficient to create clear perceptual differences among sounds, as shown in section 3.

As a complement to the auditory tests, we tried to find out if there exist simple relations between, on the one hand, the acceleration function and the dimensions of the structure and, on the other hand, the spectra of the signals. Such relations do not show up in any obvious way. It can be noticed, however, that for $v(x) = \cos(n\pi x/2d)$ with $n = 6$ or 7 (i.e., high-order harmonics), the fundamental frequency of the signal corresponds to a low level (signals s3, s7, s9, s15). On the other hand, signals s11 and s12 have quite similar spectra although they were computed from two different functions $v(x)$ (see Table 1). Relations between the acceleration shape and the psychoacoustic criteria are easier to point out, as seen in section 4.

3. EXPERIMENT 1. ESTIMATED UNPLEASANTNESS VERSUS CALCULATED LOUDNESS AND SHARPNESS

When setting up this first experiment, it appeared that most of the selected sounds, if played at their original levels as indicated in Table 2, sounded rather unpleasant or

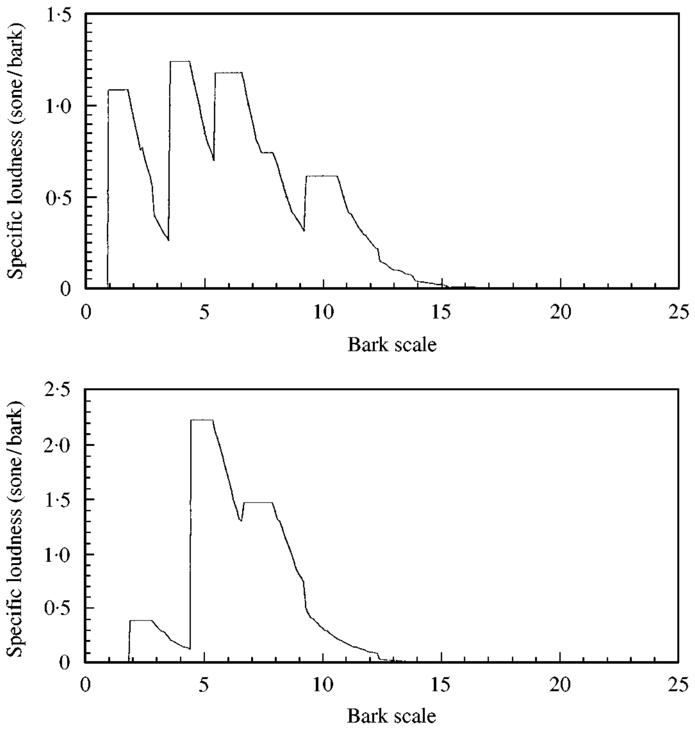

Figure 3. Loudness density of signals s6 and s9, as a function of critical band rate.

aggressive. Furthermore, the most intense sounds were also the most unpleasant. Therefore, it was decided to estimate unpleasantness, and to compare the results with the calculated values of loudness and sharpness, which were supposed to be the major ingredients for the observed unpleasantness. Pleasantness, the fundamental vector of sound quality, will be studied in experiment 2 with another set of signals.

3.1. STIMULI AND APPARATUS

This experiment was run on the eight signals described in Tables 2 and 3. For each signal, two sound files were created, one corresponding to the original level (Table 2), the second to the normalized level (Table 3), as described in section 2. These sound files were played from an APOS sound card of a Tucker Davis psychoacoustic workstation (TDT). Sounds were presented binaurally to the listeners, over a duration of 2s, through headphones Stax Lambda Pro calibrated with the help of a dummy head HRS II from Head Acoustics. The levels of presentation, on each ear, were set to the values displayed in Tables 2 and 3. The sounds were converted to analogue signals via a TDT digital–analogue converter (DA3). Electronic switches (TDT ESW) were used to insert a 50-ms rise and fall time in the signal. Then, the signal was filtered using a PF1 TDT filter, loaded so as to compensate for the transfer function of the headphones. Thus, the acoustic signal was a close image of the computed signals.

Before starting the measurements, the set-up had been calibrated with a reference sinusoïd at 1 kHz and set to 94 dB on the headphones. A PA4 TDT attenuator was used to set the level of the reference at this level.

3.2. SUBJECTS

The subjects were unpaid students and members from the laboratory. There were seven men and three women, with ages ranging from 23 to 61 and an average of 43 yr. Most of them had long experience in psychoacoustic testing.

3.3. PROCEDURE

The method of magnitude estimation developed by Stevens [25] was used to measure unpleasantness. According to this method, the subject is asked to evaluate the magnitude of the auditory attribute under study (unpleasantness here) and to express this magnitude by assigning a number proportional to it. The stronger the attribute, the bigger the number. Each subject ran two sessions, one for the original signals, the other for the normalized ones. Half of the subjects ran the session with original signals first; the other half started with the normalized signals. In any given test session, the eight sounds were presented twice, with different orders, so that two estimations were collected from each subject for each sound.

3.4. RESULTS

The geometric means of estimated unpleasantness, as a function of the loudness level of the sounds, appear in Figures 4 and 6, respectively, for original and normalized signals. The numbers opposite to the data points correspond to those in Table 2 or 3. Note that, for the sake of clarity, letter "s" is omitted in the figures. In Figures 5 and 7, the same values of unpleasantness are plotted versus calculated sharpness.

As in all previous studies on the annoyance or unpleasantness of sounds, loudness is found to play a major role [26–28]. In the present set of data, estimated unpleasantness

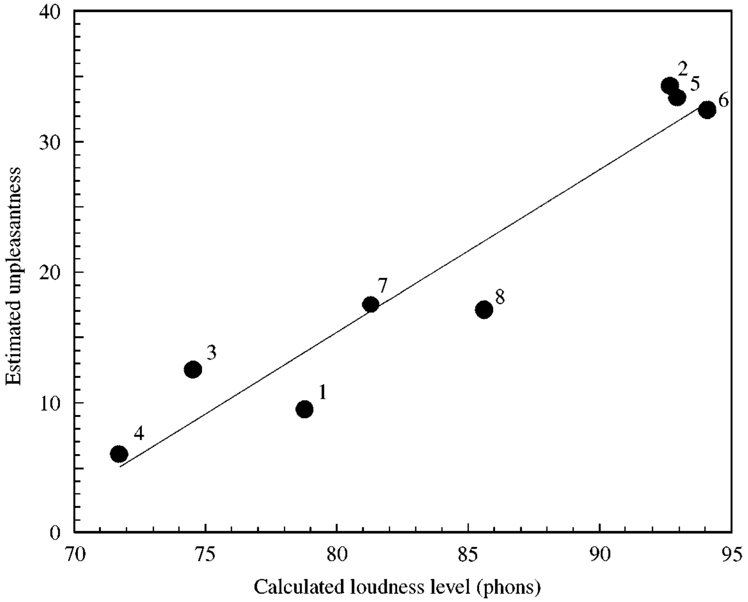

Figure 4. Estimated unpleasantness of the original signals s1–s8 (Table 2), plotted against their loudness level calculated according to Zwicker's model. Mean data from 10 listeners. $R = 0{\cdot}96$. In the signal numbers, the letter "s" is omitted.

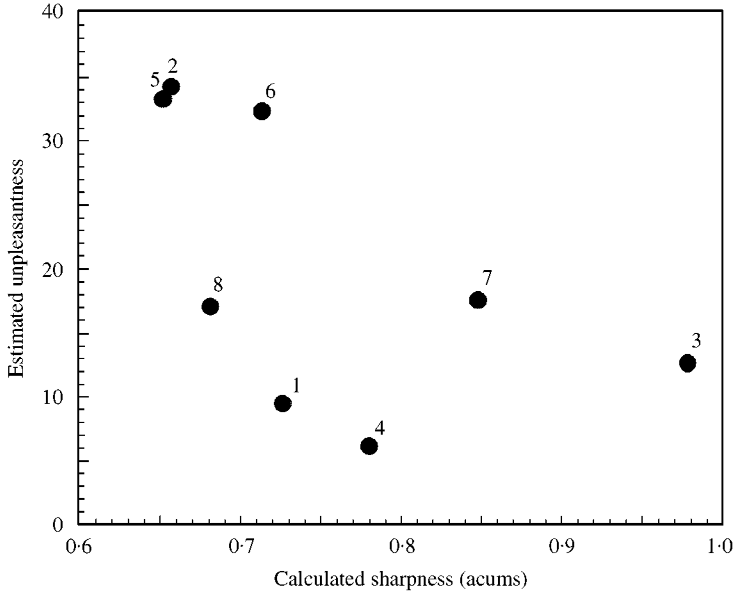

Figure 5. Same as Figure 4, except that unpleasantness is plotted against calculated sharpness.

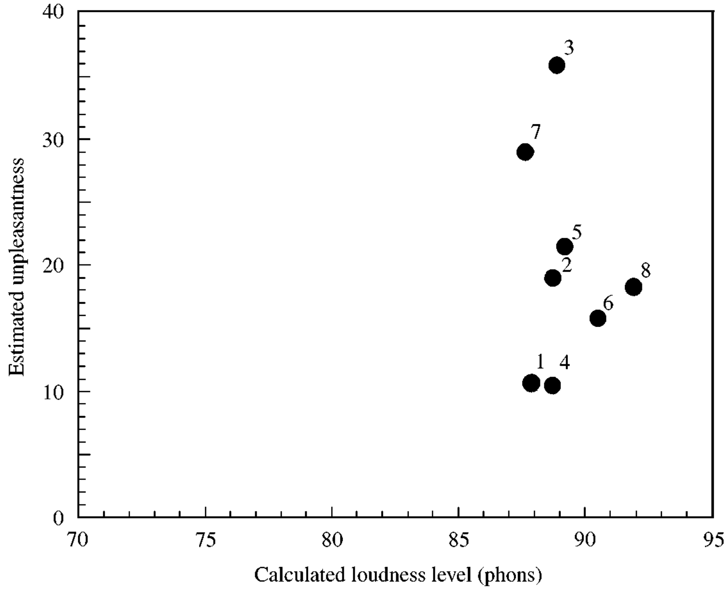

Figure 6. Same as Figure 4 for unpleasantness versus loudness level of normalized signals (Table 3).

correlates at about 96% to loudness level of the original sounds (Figure 4). On the other hand, it is also clear in Figure 6 that loudness is not the only cause of unpleasantness. When normalized to the same maximum amplitude, the sounds still remain unequally unpleasant although their loudness levels are much closer to each other. This question will be developed further in section 4.

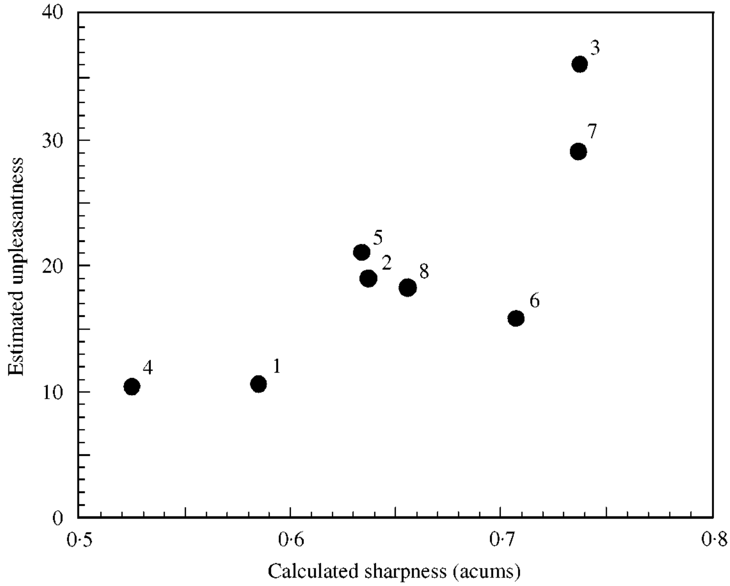

Figure 7. Same as Figure 5 (unpleasantness versus sharpness) for normalized signals. $R = 0{\cdot}82$.

Part of the unpleasantness certainly comes from the sharpness of the sounds, as evidenced by Figures 5 and 7. When played at the original loudness, sounds are clearly not perceived as unpleasant because of their sharpness; the trend is even the opposite, showing a lower unpleasantness for more acute sounds (see for example sound number s3, rightmost point in Figure 5, compared with sound numbers s5 or s2). But when loudness variations are eliminated, at least for the most part, by amplitude normalization, it seems that sharpness does influence unpleasantness. The data in Figure 7 show a correlation of about 82% between the two variables.

4. EXPERIMENT 2. DISSIMILARITY AND PREFERENCE OF SOUNDS AT EQUAL LOUDNESS

The aim of this second experiment was to explore further the intrinsic properties of sound signals that influence their perceived quality. From the first experiment, we had some indications that, by reducing the influence of loudness, it was possible to reveal the effect of sharpness on unpleasantness, albeit to a lesser degree. In this second experiment, the loudness was set equal for all sounds, at a value sufficiently comfortable for long-lasting psychoacoustic tests (around 70 phons). Three types of tests were then run. The first test measured similarity between sounds, presented in pairs. This test was designed in view of developing a multi-dimensional analysis, and if possible to identify parameters other than loudness and sharpness that would be dominant in judging sound quality. The second test measured individual preferences between sounds, also presented in pairs. The third test measured directly the auditory pleasantness of the sounds (rather than unpleasantness because, at the moderate loudness chosen, none of the sounds was perceived as particularly unpleasant). This third test was planned to provide a basis for comparison between auditory attributes and estimated quality.

4.1. STIMULI AND APPARATUS

The stimuli used in this experiment are presented in section 2, and their physical parameters are defined in Table 4. Their sound pressure levels should have been set so as to get exactly the same loudness level for all sounds. However, it appeared that equal *calculated* loudness did not produce exactly equal *perceived* loudness. Such a discrepancy has been found on occasions for environmental sounds [29]. Some slight alterations of the levels were therefore made, by the experimenter, to improve loudness equality between sounds. All values in Table 4 correspond to these approximately adjusted loudness. Sound duration was 1·5 s, with an R/F time of 50 ms. The apparatus was the same as described in section 3.1.

4.2. SUBJECTS

Fifteen subjects participated in the similarity experiment; 14 of them also ran the preference experiment. Another 15 subjects participated in the pleasantness experiment, eight of them being common to the first two tests. Ages had averages around 32 yr, and ranged from 20 to 58. As for experiment 1, all were members of the lab or students receiving training in acoustics or psychoacoustics. Most had long practice in hearing testing.

4.3. PROCEDURES

4.3.1. *Similarity*

The procedure for measuring similarity was as follows. Sounds were presented in pairs to the subjects, with an 800-ms interstimulus interval. The subjects were then asked: (1) to locate a cursor on a line displayed on their response terminal, the two end points of the line

Table 4

Acoustic characteristics of the signals—Experiment 2

Signal	SPL (dB)	N (dB (A))	Loudness (sones)	Loudness levels (phons)	Sharpness (acums)
s1	66·7	60·5	8·3	70·5	0·49
s2	67·8	63·5	8·3	70·6	0·55
s3	68·4	66·2	8·0	70·0	0·69
s4	68·4	59·8	8·3	70·6	0·44
s5	66·8	62·9	8·6	71·0	0·56
s6	63·5	59·0	8·4	70·7	0·64
s7	67·6	64·2	8·7	71·2	0·64
s8	65·6	61·0	8·8	71·4	0·59
s9	69·5	66·9	8·7	71·3	0·71
s10	67·0	61·7	8·8	71·4	0·58
s11	67·1	62·4	9·1	71·8	0·59
s12	66·8	62·8	9·0	71·7	0·60
s13	69·9	65·3	8·7	71·3	0·55
s14	70·1	65·7	9·1	71·9	0·60
s15	69·8	67·1	9·4	72·3	0·66

being labelled “very similar” and “very dissimilar”, and (2) to hit a key to validate their judgements. The abscissa of the cursor in its final position (0 for very similar and 1 for very dissimilar) was taken as a measure of similarity.

4.3.2. *Preference*

Preference was evaluated by using a paired-comparison procedure. A pair of sounds was presented to the subjects, again with an interstimulus interval of 800 ms. The subjects were asked to indicate which of the two sounds they liked better, by hitting key 1 or 2 on the keyboard; the value 1 was then assigned to the preferred sound and the value 0 to the other. A preference score was then computed by summing up all these values for each sound. All sounds were paired once with all others in one test. The measurements of similarity and preference were performed in the same session, with a pause between the two tests.

4.3.3. *Pleasantness*

Pleasantness was measured in a different session, by direct magnitude estimation. The procedure was the same as for unpleasantness (see section 3), which means that each sound was estimated twice during the test. Besides, this test was repeated once, on a different day, so that four estimates were collected for each sound and each subject.

4.4. RESULTS

4.4.1. *Similarity results*

A multi-dimensional analysis was run on the similarity data. The judgements made by the subjects, as defined in section 4.3.1, were pooled into a lower half-matrix and submitted to multi-dimensional scaling (MDS) using Statistica software. The MDS computed by Statistica is a non-metric unweighted MDS based on Kruskal’s model [30].

A three-dimensional solution was found to be most appropriate, based on the analysis of stress-scree elbow and interpretability. Distributions of the data points along the three dimensions appear in Figures 8 and 9.

Dimension 1 clearly separates the set of sounds in two groups, one with abscissae between -1 and $-1{\cdot}3$, to the left of Figure 8, the second one around $+0{\cdot}5$, to the right. All four data points on the left portion of Figure 8 correspond to sounds that have a fundamental frequency of 250 Hz ($F_1(t)$ in Table 1), all others, on the right of Figure 8, to a fundamental frequency of 125 Hz ($F_2(t)$ in Table 1). Dimension 1 can therefore be attributed to judgements based on the pitch of the sounds (correlation of $-0{\cdot}93$).

Dimension 2 seems to be related to a “spectral balance” between the amplitude of the fundamental frequency and that of the harmonics, if we refer to the spectral characteristics of the signals. For example, the lower data points on the right of Figure 8 (sounds s4, s6 …) correspond to sounds whose fundamental frequency has a relatively high level (see signal s6 in Figure 2). On the contrary, sounds s3 and s15 (higher portion of Figure 8) have the least intense fundamental frequency compared with the rest of their spectrum. It thus seems reasonable to relate the signal distribution along Dimension 2 to judgements based on an attribute somehow related to timbre. To quantify this “spectral balance”, the difference between the level of the fundamental frequency and that of the sum of the harmonics (F/H ratio) has been calculated for each signal. This difference is highly correlated with Dimension 2 (Figure 10; $R = -0{\cdot}92$).

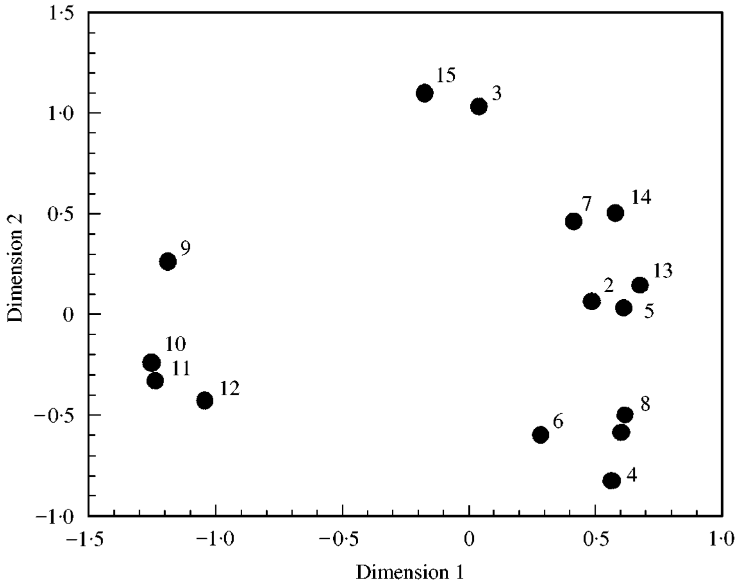

Figure 8. Spatial distribution of signals s1–s15 (Table 4) along Dimensions 1 and 2 revealed by MDS analysis.

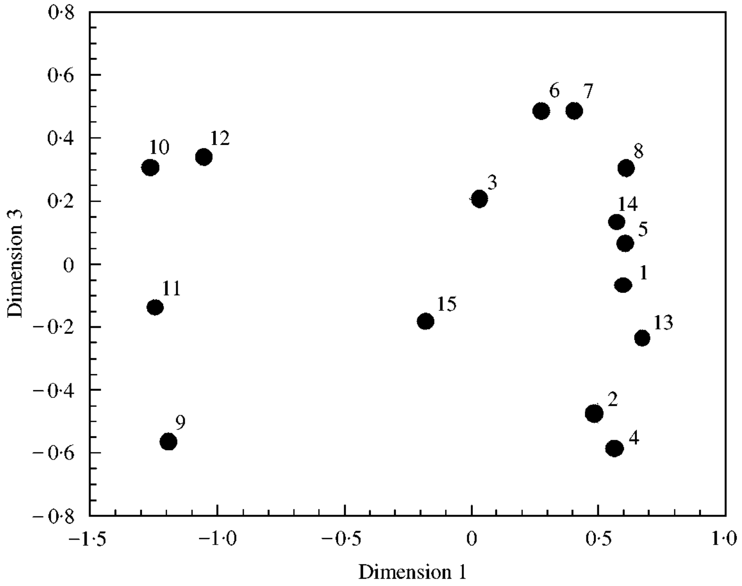

Figure 9. Same as Figure 8 for Dimensions 1 and 3.

A third dimension was calculated and is presented in Figure 9. The meaning of this third dimension is not so clear but should be taken into consideration. We found, by observing the specific loudness and time–frequency representations of the signals, that spectral spread could be related to Dimension 3. Figures 9 and 3 illustrate this relation: signals s6 and s9 are opposite on Dimension 3; loudness density of s6 clearly extends over a broader range than that of s9. However, this relation does not hold for all signals. For example, as stated before,

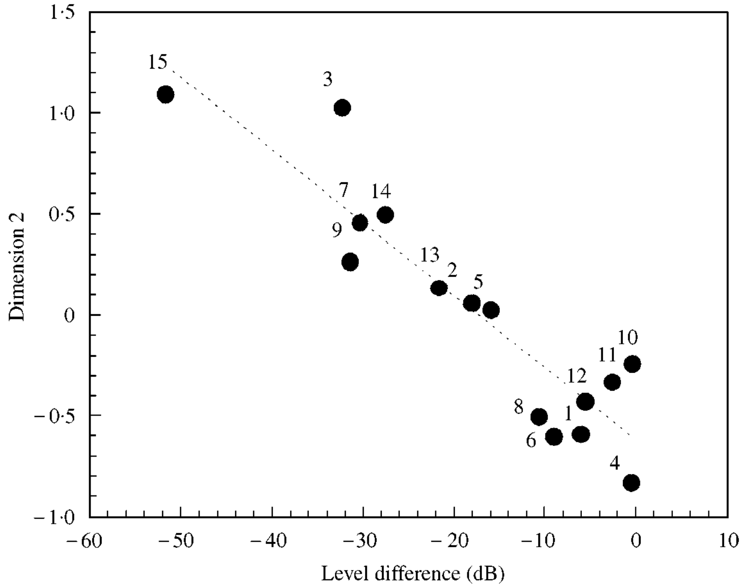

Figure 10. Comparison of level differences (fundamental/harmonics) and co-ordinates along Dimension 2 for signals s1–s15 (Table 4). $R = -0{\cdot}92$.

s11 and s12 have fairly similar physical features and, still, they are separated along Dimension 3. These are the first observations. To get a more precise identification of this Dimension and its influence, more signals should be tested.

4.4.2. *Preference and pleasantness*

Preference and pleasantness are strongly correlated ($R = 0{\cdot}96$), as expected; this is attested by Figure 11. The variability that is visible in the figure is probably partly due to the fact that the two tests were not run by exactly the same subjects. Both sets of data, preference scores and estimated pleasantness, are therefore equivalent in assessing the auditory quality of the sounds tested. But it is worth noting the advantage of direct estimation, in terms of test duration, compared to a method based on paired comparison. Besides, the average estimates given by the subjects can be considered as a direct measure of quality, in contrast to preference which gives access only to a ranking of the level of quality.

Estimated pleasantness or preference scores can then be compared to MDS results, to find out whether some physical parameters, in addition to making sounds dissimilar, make them also sound pleasant or not. It turns out that no correlation was found between pleasantness and Dimension 1: The partition of the sounds in two groups simply based on pitch characteristics does not give any advantage to either group. On the contrary, as Figure 12 illustrates, preference is fairly highly correlated to Dimension 2 ($R = -0{\cdot}84$). As a consequence, preference is highly correlated to F/H ratio ($R = 0{\cdot}86$). The signals with a weak fundamental relative to the harmonics (abscissa around − 50 dB in Figure 10), are clearly judged as less pleasant, probably because they sound somewhat distorted.

It should be mentioned that sharpness is also correlated to Dimension 2 ($R = 0{\cdot}72$) and therefore to preference ($R = -0{\cdot}92$). Besides, the F/H ratio is also correlated to sharpness

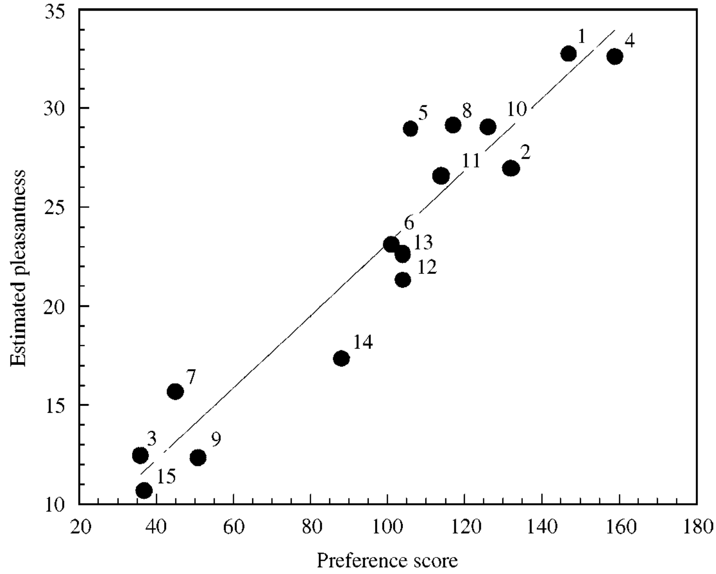

Figure 11. Estimated pleasantness of signals s1–s15 (Table 4) plotted against the corresponding preference scores. Both sets of data are mean values from 15 observers. $R = 0{\cdot}96$.

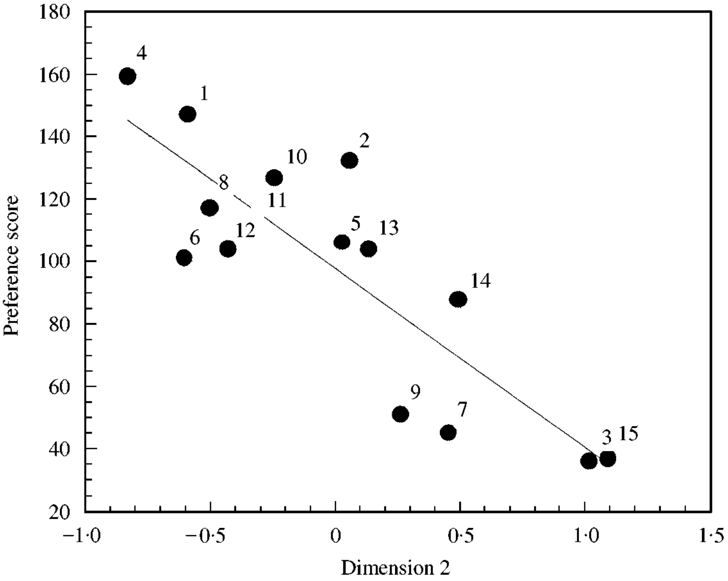

Figure 12. Comparison of preference scores and co-ordinates along Dimension 2 for signals s1–s15 (Table 4).

($R = -0{\cdot}76$). This is not surprising, considering the signals used in this experiment. Indeed, there were two classes of synthesized sounds, each with a different fundamental frequency (125 or 250 Hz). It is then obvious that the louder the fundamental frequency, the lower the sharpness. However, listening to the sounds, as distributed along Dimension 2, leads us to conclude that distortion due to the variation of F/H ratio must be the parameter for that dimension. The sounds sounded different because of different distortion rate, not because of different sharpness. Moreover, sharpness varies only from 0·5 to 0·7 acums, which is a very small variation and it does not seem reasonable to take this 0·2-acum variation in sharpness as responsible for the variation in preference. To summarize, we think that sharpness is correlated to preference because it is correlated to F/H ratio in the particular set of sounds used in our experiment.

4.4.3. *Relations between physical and perceptual characteristics*

One aspect of our study was to examine the relations between the mechanical characteristics of the structure and the perceptual characteristics of the signals. Two main features can be pointed out. The first one is that the signals computed with a function $v(x)$ including terms such as $\cos(n\pi x/2d)$ with $n = 0$ or 1 were definitely preferred by the subjects. These signals are those for which the F/H ratio is > -25 dB. They also correspond to the lowest values along Dimension 2; this is not surprising since Dimension 2 is closely related to preference scores. The second feature is that, within this class of signals, those computed with $d = 4$ m obtained the highest preference scores. It can also be noticed that the set of four signals with the highest values for Dimension 3 correspond to $d = 8$ m. Thus, the size of the vibrating surface is an influent parameter on the perception of the signals. More tests for a larger number of signals are needed to eventually confirm and generalize these first observations.

5. CONCLUSION AND PERSPECTIVES

The study presented in this paper was meant to illustrate how a theoretical calculation in vibroacoustics can be extended to the psychoacoustic assessment of the radiated sound signals. Vibroacoustics provides tools for calculating the sound field originating from a mechanical vibration. Psychoacoustics provides the methods for studying the relationships between this sound field and its auditory attributes and quality.

In the present study, we concentrate on the case of a vibrating panel, immersed in a fluid, and we assume that the vibration function over the surface of the panel is known. From the acoustic pressure calculated for a variety of vibration modes, sound files are created and used for auditory testing. The main perceptual parameter under study was the possible pleasantness (or unpleasantness) perceived on listening to such sounds. As pleasantness, and in general sound quality, is known to depend on some specific psychoacoustic attributes, the results from our auditory tests were compared with the values predicted from Zwicker's model for those specific psychoacoustic attributes. In addition, similarity and preference among signals were estimated by listeners, and the data used for a multi-dimensional analysis in order to identify possible complementary attributes, specific to the present class of sounds.

The first major result is that when sounds differ in loudness, pleasantness is always highly (and negatively) correlated with loudness. This has been found consistently in the past, and demonstrated for example by Berglund *et al.* [26], among others, for community noise, and more recently by Canévet *et al.* [31] in a study on environmental noises and by Altinsoy *et al.* [32] in a study on noise produced by vacuum cleaners. Sharpness also contributes markedly to unpleasantness, but usually to a lesser extent. This was first observed by Terhardt and Stoll [33] for environmental sounds. It is attested once again by the recent results from Altinsoy *et al.* [32]. In our study, the influence of sharpness appears only after loudness has been eliminated by setting all loudness levels to about the same value.

Since our signals are complex harmonics, they may be partly considered as musical sounds. And indeed, some of the perceptual attributes revealed by the MDS analysis are related to pitch and timbre perception. This is also an important result to emphasize in terms of sound quality because, even though they are based on a simulation, these signals are fairly close to some kinds of real sounds generated by mechanical vibrations. Therefore, it seems clear enough that when designing a mechanical structure which is due to vibrate and create sounds, care should be taken of the spectral balance of these sounds, and thus, of the corresponding vibration modes of the structure. In other words, a complete study of the problem should include a "psychomechanical" investigation of the whole process of sound generation.

As far as vibration models are concerned, our next step will be to use sound signals emitted by a fluid-loaded thin elastic plate. The physical parameters are then the thickness and the bending stiffness of the plate, a damping factor and the boundary conditions on the boundary of the plate. To these parameters can also be included the characteristics of the excitation, usually a force on the plate or an incident sound pressure. The sound pressure radiated by the plate can be conveniently represented in the time domain, by using expansions in series of resonance modes [34, 35]. This kind of technique is similar to the one presented by Morse and Ingard [36] in room acoustics.

Finally, two major practical applications of these vibro- and psychoacoustics studies must be mentioned. One concerns passive and active noise control, which leads to spectral modifications of the sounds and usually induces a change of quality. A perceptual study could thus be incorporated in the process, on synthesized sounds simulating the radiation of vibrating structures. The other application concerns simulation of sound landscapes in virtual reality. The calculations necessary for accurate simulations are quite time consuming, especially if vibrating structures have to be simulated. It is therefore necessary to introduce as many approximations as possible in the computations. Combining vibroacoustic and psychoacoustic approaches can be useful to determine the kind of approximations to introduce, in order to optimally achieve to the desired perceptual effect.

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