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Loudness models in the very low frequency range: application to the prediction of airplane cockpit noise comfort

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Aircraft interior noise is a major design stake with respect to airline requirements for passenger and crew comfort.

A study dealing with airplane cockpit noise annoyance had shown that loudness computed according to ISO 532-B standard was a good gauge of qualitative evaluation. This was not true for loudness computed according to ANSI S3.4 standard. It seems that this was due to differences of the two models for very low frequency sounds, as these models were adjusted to fit to different iso-loudness curves.

In order to check this hypothesis, direct loudness estimations will be presented in the low frequency range (from 35 Hz to 65 Hz). These estimations will be compared to predictions given by the two models.

1 INTRODUCTION

Loudness is a key factor of unpleasantness and annoyance. Two main models are available to predict loudness of sounds. They are both standardized and can be used by manufacturers for sound quality improvement. In this paper, the use of these models will be illustrated in the case of airplane cockpit noise. Some discrepancy has been observed between the models, especially for one sound with a very low frequency tone. In order to have a more clear understanding of this discrepancy, a second experiment was conducted, during which listeners had to estimate the loudness of very low frequency sounds (from 35 to 65 Hz).

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2 UNPLEASANTNESS EVALUATION

2.1 Experimental setup

Six stimuli were provided by Airbus corresponding to in-flight recordings with a microphone located in the cockpit of six aircraft ($f_s = 48$ kHz, 16 bits). One of the stimuli exhibited an abnormally high emerging frequency (63 Hz). An additional stimulus was created by filtering out this frequency; the spectra of the original and modified signals are presented in Figure 1.

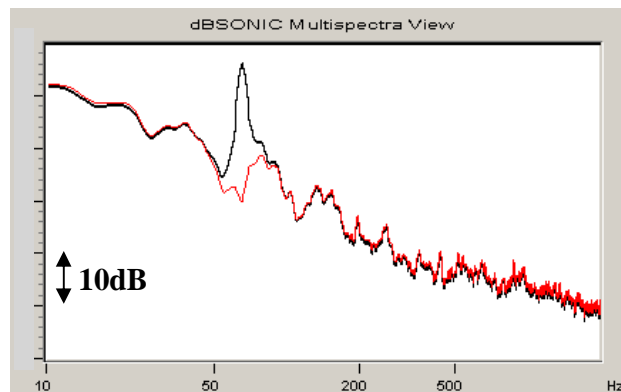


Fig. 1 - Examples of inside cockpit spectra of stimuli used in the experiment.

All stimuli had a duration of 5 seconds, including a 150 ms cosine in and out fading. These stimuli were played back by a couple of loudspeakers (Mackie Tapco S8) placed approximately two meters from the subject. The loudspeakers and the listener were placed at the edges of an equilateral triangle. This set up was arranged in a sound proof booth (approx. 3.5 m long and 2.5 m large).

The experiment was a pair comparison one. Each of the 21 possible pairs of different stimuli was played to the listener, plus two for training at the beginning of the experiment. The presentation order was randomized and arranged according to the rules of Ross' series. The listener was asked to compare the unpleasantness of the two sounds and had to give his answer on a continuous scale, which indicated five labels (from "A is much more unpleasant than B" to the reverse, including an equality label). He could play again the pair as often as needed before giving his answer. The whole experiment was conducted by the "*Jury Testing*" software (developed by 01dB-Metravib and running on a PC outside the booth).

31 subjects participated to the experiment: 15 students and 16 older searchers of the laboratory, 12 women and 19 men. They did not relate any hearing impairment, but their hearing ability was not checked.

2.2 Results

First of all, analysis of circular triads showed that all individuals could be considered as giving reliable answers, so that all subjects were considered in the following analysis. Then, a hierarchical cluster analysis of individual answers revealed a good inter-subjects agreement.

Therefore, the results of the 31 listeners were averaged, giving a set of 21 preference probabilities. These probabilities were analyzed using a BTL model, which gave the unpleasantness scores of sounds shown on figure 2. In this figure, the 95% confidence intervals of each score are also presented. They were estimated using a boot-strap technique (500 trials, 20 subjects, randomly selected with replacement).

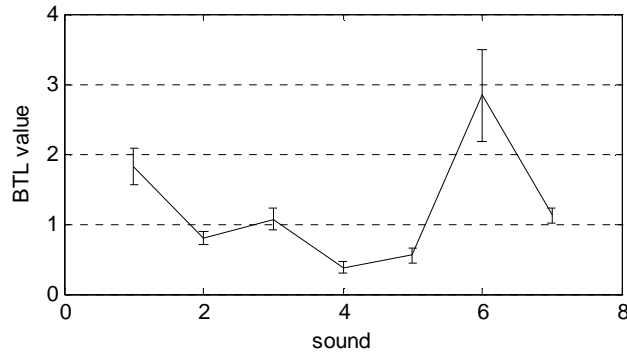


Fig. 2 – Merit scores of the 7 stimuli.

As can be seen in figure 2, filtering out the low-frequency component reduced the unpleasantness of sound n°6 (n°7 being the modified signal). 4 groups of sounds can be seen: n° 4 and 5, n° 2, 3 and 7, n°1 and n°6, these groups being ordered according to an increasing unpleasantness.

2.3 Metrics

In most cases, unpleasantness is strongly related to loudness (some examples concern noise in trains¹ or in cars²). Therefore, loudness metrics were natural candidates for the description of subjective/qualitative results. Two models were used. They are described by two standards: ISO 532-B³ and ANSI S3.4 – 2005⁴. It appeared that ISO model represented results in an accurate way (figure 3). The left part of the figure shows loudness values of sounds (X-axis) and BTL scores (Y-axis), indicating a high correlation between the two sets of values ($R = 0.86$, $p = 0.013$). The right part of figure 3 shows the ratio of the loudness of sounds in each of the 21 pairs presented to listeners (X-axis) and the preference probabilities in pairs (Y-axis). The relation is still clear, the ISO-loudness can be used to predict unpleasantness of sounds in airplane cockpits.

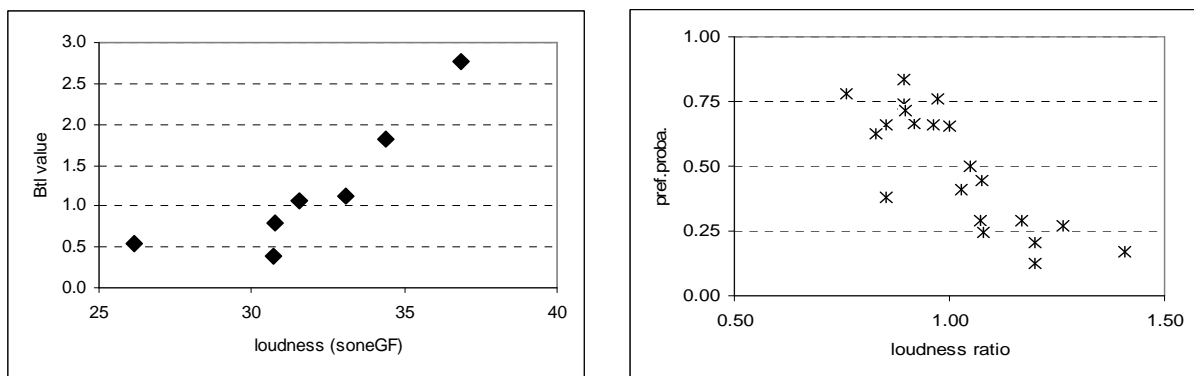


Fig. 3 - Relation between ISO-loudness values of sounds and subjective unpleasantness. Left: BTL scores; right: preference probabilities.

On the other hand, ANSI loudness failed to represent unpleasantness (figure 4). Namely, this is mainly due to sound 6, whose loudness is underestimated by this model.

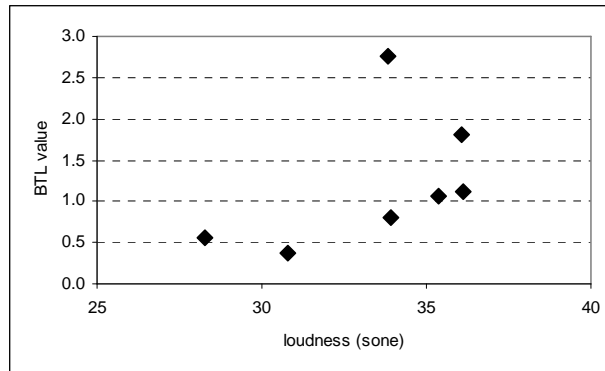


Fig. 4 - Relation between ANSI-loudness values of sounds and unpleasantness.

Indeed, the relation between sound pressure level and loudness of a 63 Hz pure tone is different in the two models (figure 5). Loudness computed according to the ISO model is approximately twice loudness computed according to the ANSI one. This is certainly due to the fact that these two models have been adjusted according to different equal-loudness level contours. This difference in loudness values can be observed in different versions of the ISO 226 curves^{5,6}.

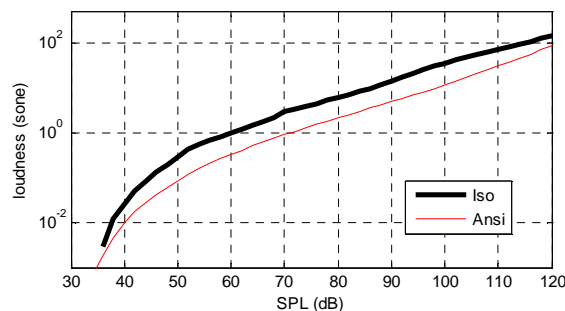


Fig. 5 – Loudness of a 63 Hz pure tone, as predicted by the two standardized models.

3 LOUDNESS EXPERIMENT

The goal of this experiment was to evaluate the loudness of very low frequency sounds, in order to get a better idea of the validity of the two loudness models in that frequency range. Very few studies have been conducted to establish the relation between sound pressure level and loudness for frequencies lower than 100 Hz (which was the lowest frequency used by Hellman and Zwislocki⁷). As perception of very low frequency sounds can be extra-auditive⁸, it was decided to use a loudspeaker, as in the previous experiment.

3.1 Experimental setup

Experiments took place in the same sound proof booth. The first resonance frequency of the room is approximately 43 Hz. A subwoofer was placed in a corner of the room. This subwoofer has been designed by Ph. Herzog (Laboratoire de Mécanique et d'Acoustique, Marseille) and built by the Centre de Transfert et de Technologie du Mans (CTTM). It is made of a 30 cm loudspeaker (PHL Audio W384) mounted in a vented wooden box. The first requirement was to place the listener at a position at which the level of the sound did not vary too much with the exact position of the subject. The opposite corner of the room was a good candidate position. A set of 27 microphones was placed in an arrangement made of 3 sets of 9 microphones located at three different heights (1 m, 1.1 m, 1.2 m), which described the range of the head of the sitting subject. In each plane, 8 microphones were arranged in a circle (with a 11 cm radius) and another one located at the center of the circle. This center was 33 cm far from the two walls defining the corner of the room.

A white noise generator was used for this experiment and the frequency response function was measured for each microphone. In figure 6, the median, minimum and maximum values of these functions are shown.

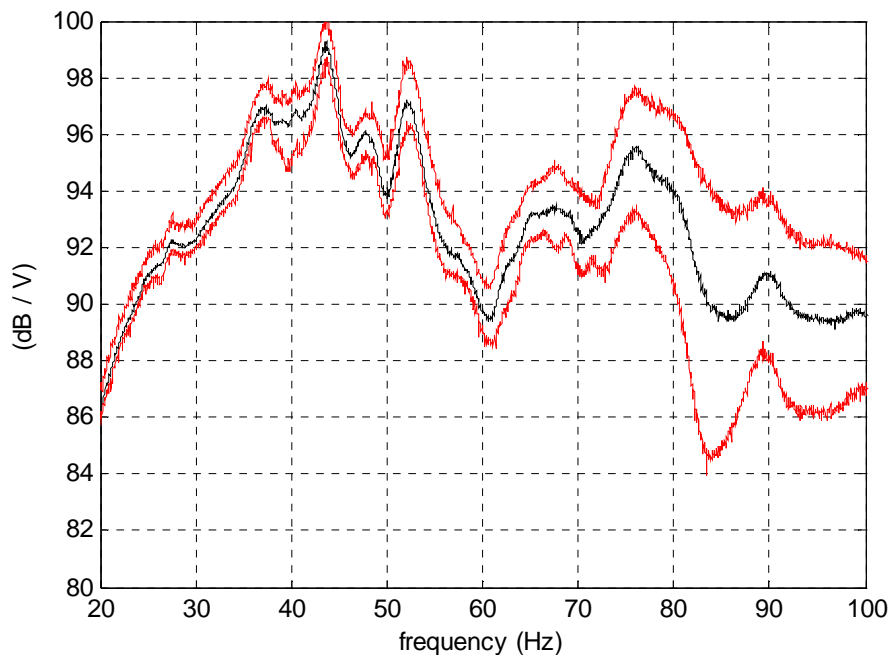


Fig. 6 - Median (black curve), minimum et maximum (red curves) of the frequency response functions measured in the room.

As it can be seen in figure 6, the useful frequency range was limited to 30 – 65 Hz. Below 30 Hz the level was too low and above 65 Hz the spatial variation was considered as too important.

It was decided to use pure tones as stimuli. In order to reduce the number of experiments, three frequencies were considered: 35, 45 and 65 Hz. In a second step, harmonic distortion of the subwoofer was measured. For each frequency, the maximum level was selected so that the level

of all higher harmonics was below normal hearing threshold. These maximum levels can be seen in table 1.

Table 1 – Sound pressure level range for each tone

Frequency	Max. level	Max. level
35 Hz	63 dB	85 dB
45 Hz	60 dB	85 dB
65 Hz	47 dB	83.5 dB

For each frequency, 10 levels were selected, going from slightly above normal hearing threshold to maximum level. These levels were equally distributed between the minimum and maximum values of table 1. A set of 10 signals was prepared, with a duration of 3 seconds each, including a 100 ms in and out fading.

3.1 Procedure

The procedure consists in absolute magnitude estimation, as it has been shown by Boulet⁹ that it gives reliable results with a limited duration of the experiment. When hearing a sound, the listener was asked to give a number representing loudness. Three experimental sessions were conducted (one for each frequency). In each session, each stimulus was presented four times to the subjects, so that the session was arranged in four blocks of 10 stimuli. In each block, the presentation order was randomized. The sessions order (there were 6 possible orders) was balanced within listeners and 30 subjects participated to the experiment.

3.2 Results

The experiment has just been conducted and its results will be presented at the conference. Subjective loudness evaluations will be compared to the predictions given by the two models.

4 CONCLUSIONS

These two experiments give a deeper knowledge of unpleasantness of low frequency sounds. More precisely, 2 questions shall be addressed: (1) was the unpleasantness of sound 6, as determined in experiment 1, related to loudness only, or did the tonal character of that sound contribute to unpleasantness ? (2) Which of the two standards should be recommended for the prediction of loudness of such sounds? We hope answering from the analysis of the related experiments.

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