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# SPATIAL IMPRESSION EVALUATION WITH OMNIDIRECTIONAL MICROPHONES

J D Polack et X Pelorson

Laboratoire d'Acoustique de l'Université du Maine, CNRS-UA 1101,
BP 535, 72017 Le Mans Cédex (France)

Spatial Impression arises in an enclosure when a listener perceives sound coming from the sides. Extensive experiences in the past years showed it happens when lateral reflections are sufficiently loud, and it is enhanced by the overall loudness of the sound inside the enclosure.

Attemps to characterize Spatial Impression by means of acoustical measurements drew heavily on our knowledge that lateral sound sources create both level and phase differences at the two ears. It was therefore quite logical to use directional microphones, or even a dummy head, for designing measures of Spatial Impression.

Unfortunately, there are cases where directional microphones, not to speak of dummy heads, are not available. This happens in small scale models - let say at scale 1:50 - which have proved very valuable in designing concert halls when an acoustical feedback is required as early as the conceptual stage. We therefere felt the need for some new developments on that topics, and we were keen to test their validity by means of subjective listening. This paper presents the steps we went through in order to derive, test, and refine an acoustical measure of Spatial Impression will omnidirectional microphones.

## DERIVING A MEASURE

Careful review of the literature [1-7] convinced us that Spatial Impression is a low frequency effect. At low frequency, the head shadowing only plays a small rôle upon the perception of lateral sound, leaving phase differences almost unperturbated [1]. Hence measurements solely based on phase differences between two omnidirectional microphones where likely to be successful.

The arguments that led us to derive a new measure run on the following line :

i/ Of all simple acoustical parameters related to Spatial Impression, only one has been thoroughly investigated by means of subjective listening : the Lateral Energy Fraction $L_f$ [2,3]. Unfortunately making use of discrete reflections, $L_f$ cannot be measured in real enclosures where diffraction occurs and breaks up the reflections.

ii/ There are strong evidences in the literature that Spatial Impression arises from a cross correlation process of the two ear signals [1-4]. Barron [5] was thus able to derive a relationship between $L_f$ and the normalized cross correlation K of two microphone signals :

$$k\, L_f = (1 - K)$$

where k is a constant depending on the signal used for measuring the correlation. It turns out that k = 1 for a square pulse of duration equal to the maximum time taken by sound to travel from one microphone to the other. This proves that Spatial Impression is a low frequency effect.

iii/ Cross correlations reflect differences of arrival times, therefore phase differences [6]. Hence level fluctuations between the two microphones should play little rôle.

The technique we selected consists in placing two omnidirectional microphones at right angle with the source direction, and separating them by a distance roughly equivalent to the spacing of the ears in the head (175 mm for our tests). Wanting to assess the effect of phase fluctuations, the most relevant assumption was to consider all logarithmic spectra as gaussian processes. Hence we write :

- cross spectrum : $S_x(\omega) = \exp\{\Gamma_x(\omega) + i\varphi(\omega)\}$

- auto spectra : $S_i(\omega) = \exp\{\Gamma_i(\omega)\}$ , $i=1,2$

where $\Gamma_x = (\Gamma_1+\Gamma_2)/2$ and $\Gamma_1, \Gamma_2, \varphi$ are centered gaussian variables. Tedious calculations lead to the following mean spectra :

$$< S_x(\omega) > = \begin{cases} \exp\{-[\sigma_x^2 - \sigma_\varphi^2 + 2i\sigma_{x,\varphi}]/2\} & \omega > 0 \\ \exp\{-[\sigma_x^2 - \sigma_\varphi^2 - 2i\sigma_{x,\varphi}]/2\} & \omega < 0 \end{cases}$$

$$< S_i(\omega) > = \exp\{\sigma_i^2/2\}$$

where $\sigma_x^2$, $\sigma_i^2$, $\sigma_\varphi^2$ are the variances of $\Gamma_x$, $\Gamma_i$ and $\varphi$ respectively, and $\sigma_{x,\varphi}$ the covariance of $\Gamma_x$ and $\varphi$. Thus the correlation functions at time origine can be written as :

- cross correlation : $< \phi(0) > = \exp\{[\sigma_x^2-\sigma_\varphi^2]/2\}\cos\sigma_{x,\varphi}$

- auto correlations : $< \varphi_i(0) > = \exp\{\sigma_i^2/2\}$

and the normalized cross correlation as :

$$K = <\phi(0)>/[<\varphi_1(0)><\varphi_2(0)>]^{1/2} = \exp\{[\sigma_x^2-(\sigma_1^2+\sigma_2^2)/2-\sigma_\varphi^2]/2\}\cos\sigma_{x,\varphi}$$

By introducing the level difference of the two spectra : $\Gamma_y = (\Gamma_1-\Gamma_2)/2$, we obtain :

$$\sigma_x^2 = -\sigma_\varphi^2 + (\sigma_1^2+\sigma_2^2)/2 \ ;$$

and $$K = \exp\{-[\sigma_y^2 + \sigma_\varphi^2]/2\}\cos\sigma_{x,\varphi} \qquad (1)$$

In theory, the normalized cross correlation K depends on level well as phase differences, thus it was a goal of our investigation to analyse to which extend the different terms appearing in Eq (1) are contributing to Spatial Impression, or alternately to its acoustical correlate $L_f$ (cf[7]).

## SUBJECTIVE LISTENING

In order to test the relevance of Eq (1) to Spatial Impression, we simulated in an anechoic chamber simplified sound fields consisting of a direct sound and two equally loud lateral reflections (Fig.1), the angle of incidence of which could be varied. This simple arrangement was selected for compatibility with the literature [3]. Important parameters are : i) the delay angle of incidence of the lateral reflections, either 30° or 70° ; ii) the delays $\tau_1$ and $\tau_2$ of the reflections, fixed at 32 ms and 33 ms respectively ; iii) the attenuation $\Delta L$ of each reflection relative to direct sound ; and iv) the overall leval L of the sound field. Several listening tests were run at different levels L and different attenuations $\Delta L$ with excerpts from an anechoic recording of the $4^{th}$ mouvement of Mozart's Jupiter Symphony [8]. A-B comparisons were first used to check the coherence of the test, sort out the most favorable excerpts, and determine practical values for level and attenuation increments. As a result, the last 10 s of the Symphony were selected for the final test.

In the final test, listeners had to assess 18 different sound fields on a discrete scale ranging from "no Spatial Impression" (0) to "too much Spatial Impression" (6). The sound fields were characterized by four values of $\Delta L$ (0,4,6,8 dB) and five values of L (75,80,85,90,95 dB). 25 listeners attended the test for reflection angles $\alpha = \pm 70°$, but only 8 for $\alpha = \pm 30°$.

Fig.2 shows the results for $\alpha = \pm 70°$. It plots the mean Spatial Impressions attributed by all listeners to each of the 18 sound fields as a function of the overall level L. Parameter is the attenuation $\Delta L$. Notice that the scale we chose for Spatial Impression depends on the arbitrary range chosen for the subjective tests ; but comparison with the literature leads to estimate one unit as 1.8 degree of Spatial Impression [3]. Not plotted in Fig.2 are the standard deviations : they are found quite high, varying between .4 and 1.3, with an average of .8 . The standard deviation therefore is notably larger than 1 degree of Spatial Impression. Paying due respect to this large standard deviation, the regression slopes can be considered as constant, as stated in the literature [9] : the mean slope of .13 is consistent with available estimates [3].

Fig.2 also confirms the observation [9] that Spatial Impression sets on at a certain overall level $L_0$ depending on the attenuation $\Delta L$. Since in normal situations, reflections are not as loud as the direct sound, it confirms the finding that Spatial Impressions never arises when music is played pianissimo.

The results for $\alpha = \pm 30°$ are similar. In fact, we found virtually no differences between mean Spatial Impressions for $\alpha = \pm 30°$ and $\alpha = \pm 70°$, except for attenuation $\Delta L = 0$ dB where Spatial Impressions is lower for $\alpha = \pm 30°$. The results were probably biased by the example played before each test, where the attenuation varied from no lateral sound to no direct sound at constant overall level, thus giving references for the two extremes of the scale. Besides, the two lateral loudspeakers were different from the central one.

A phantom source for the direct sound proved unusable since it provided either no spatial impression, or too much, without intermediate value. It confirmed the very critical range of $\Delta L$ with phantom sources [9]. Placing the two microphones at the listening position immediately revealed the reason of this inadequacy : phase differences proved to be very unstable and to depend heavily on the position of the microphones in the room. Moving them sideway by as less as 30 mm completely changed the phases for frequencies as low as 500 Hz, because of the interference pattern created by the two sources.

## REFINING THE MEASURE

Computer simulations of the sound fields used for the subjective testing were carried out to gain a better understanding of how the normalized cross correlation relates to lateral energy fraction. It turned out that keeping the phase variance only in Eq (1) gives the best correlation with $L_f$, provided only frequencies below the inverse duration of the maximum travel time between the two microphones (cf[5]) were kept for the calculation. Then holds the relationship :

$$L_f = 1 - \exp(-\sigma_\varphi^2/2) \pm .1 \qquad (2)$$

Accordingly, we next measured $L_f$ for as some sounds field used in the subjective testing ($\alpha = \pm 70^\circ$). They are plolted in Fig.3, where the solid line gives the theoretical $L_f$ calculated from the attenuations. The results from computer simulation are also shown in Fig.3, pointing out the good agreement between simulations and measurements. Typically, errors are less than .07, a value considered as the difference limen for $L_f$ in [3]. Agreement is poorer between simulations (or measurements) and the theoretical $L_f$. Interpolating the measured $L_f$ values from Fig. 3 for the relevant attenuation values, it is possible to plot the Spatial Impression as a function of the measured lateral efficiency. Fig. 4 presents the mean results. Taking into account the large standard deviation, it proves possible to join the data corresponding to the same overall level L by straight lines. Except for 95dB, this lines are running quite parallel, confirming the linear relationship between Spatial Impression and $L_f$ with a mean slope of 7.5. We can therefore write down :

$$SI = 7.8\ (L_f - 0.05) + 0.13\ (L - 85) \qquad (3)$$

Eq.(3) lead to estimate our units to 1.9 degree of Spatial Impression, and it relates very well with the expression found in the litterature [3]. It also indicate that $L_f$ measures Spatial Impression at a level of 85dB, well within the range proposed in [3]. Attempts to plot Spatial Impression against calculated $L_f$, or even against theoretical values, proved less successful. Just as disappointing were all plots drown for $\alpha = \pm 30^\circ$, although the standard deviations make it always possible to fit straight lines. Lack of proper equipments for matching different incidence angles $\alpha$ in one single listening test prevented us from investigating further the poor results for $\alpha = \pm 30^\circ$.

## CONCLUDING REMARKS

Giving due consideration to all findings gathered in this lacunal survey of Spatial Impression, it seems that our estimate of the lateral energy fraction is sufficient for its primary goal of small scale model measurements. This was confirmed by computer simulation of various oddly shaped halls, where agreements between calculated and theoretical $L_f$ remained within the range given by Eq.(2). And this is further confirmed by comparisons between correlation measurements carried out with a dummy head and two omnidirectional microphones [10]. In fact, we believe that any monotonous estimator of Spatial Impression is good enough for prediction purposes, probably explaining while Lateral Efficiency is so widely used despite its lack of subjective validation.

But our investigations confirmed that Spatial Impression is predominantly a low frequency effect created by phase differences at the two ears. Further, it is a wide band effect, and attempts to measure the lateral energy fraction using one period of a sinus wave basically confirmed it.

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SPATIAL IMPRESSION EVALUATION

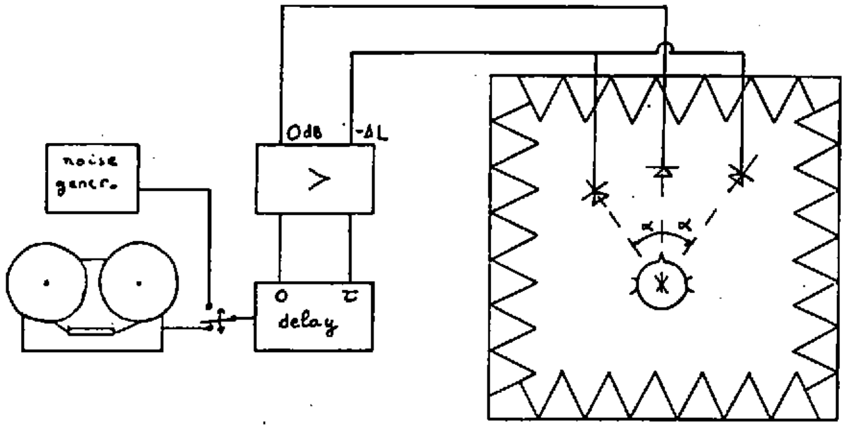


Fig.1 : Sound field simulation for subjective listening

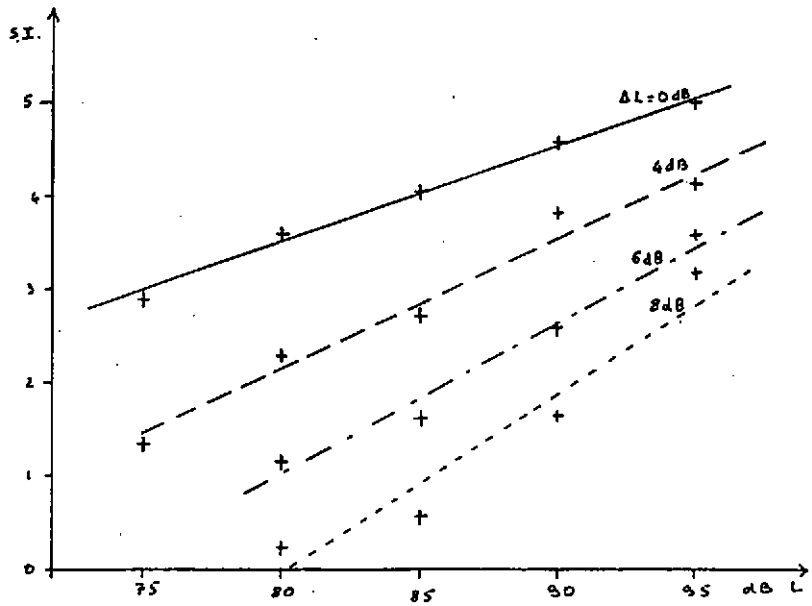


Fig.2 : Spatial Impression vs. Level

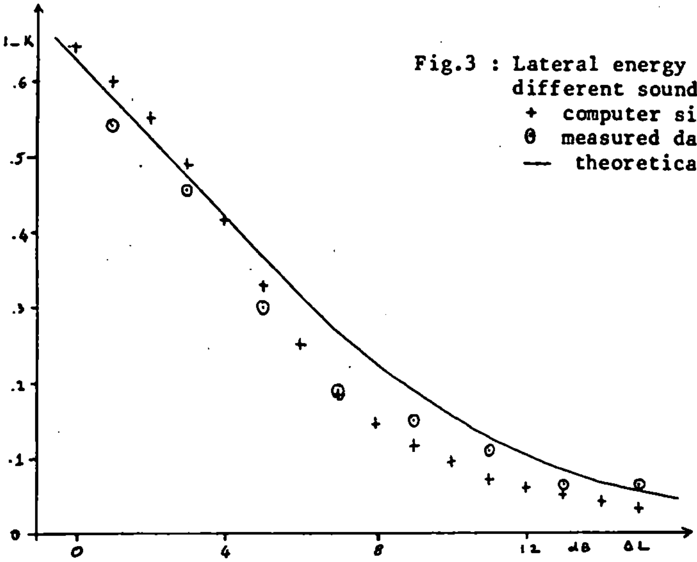


Fig.3 : Lateral energy fraction for different sound fields
+ computer simulation
θ measured data
— theoretical expectation

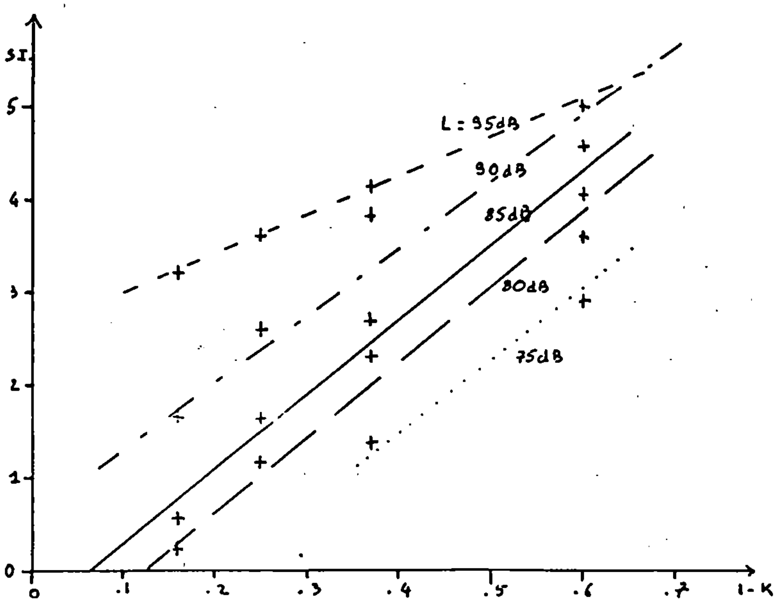


Fig.4 : Spatial Impression vs. measured correlation