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UN MODELO DE SIMULACION DE ECOGRAMAS EN RECINTOS PARA EXCITACIONES CON IMPULSOS DEBILMENTE ALINEALES

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ABSTRACT
A new model to account for spatial and time distribution of weakly sound sources is presented. This model is based on an additional energy decay accounted by means of a nonlinearity parameter and on the main ideas involved in classical image source methods. Echograms of arbitrary signals can then be computed by using several partial 'energy based impulse responses' covering the frequency band of exciting signal. Computed results are compared to experimental ones obtained on a rectangular enclosure.

RESUMEN
Se presenta un nuevo modelo para similar distribuciones espaciales y temporales de señales débilmente alineales. Se basa en un factor de amortiguamiento función de un factor de alinealidad de nivel y usa la teoría de imágenes. Los ecogramas de una señal arbitraria pueden calcularse mediante las respuesta impulsivas parciales en un número suficiente de bandas de frecuencia que cubran el espectro de la señal. Se comparan resultados numéricos con resultados experimentales obtenidos en un recinto rectangular.

1. INTRODUCTIÓN

After Sabine[1] reverberation time of an enclosure is defined from the decay of steady state acoustic signals suddenly interrupted, usually white, pink noise filtered in frequency bands and burst tones. Later and mainly since the memorable work of Schroeder [2] pistol or crack reports, and electric sparks (mainly in scale models) are being used commonly not only to determine reverberation time but also to investigate most general acoustic properties of enclosures [3]. The proximity of acoustic responses obtained with that type of excitation signals to the impulse response of enclosures (for omnidirectional sources), joined to the rather simple and ease experimental arrangements and handling involved add further attractive to that impulsive signals.

On the other hand, crack reports of fractions of a gram of common powder give acoustic signals that in fact are within the range of level nonlinearity [4]. That nonlinearity leads to experimental results that can differ significantly from those of linear range.

Along this line in a previous work presented last year in the Acustica08 Congress, held in Coimbra [5] authors presented a theory of reverberation for weak nonlinear level sound signals. An equation relating 'nonlinear' reverberation time with reverberation time defined by Eyring's formula through a parameter of nonlinearity was derived.

In this paper main aspects of 'weakly nonlinear' impulse responses of enclosures, along the lines of image method, will be described and some echograms derived from that model compared with experimental results in a rectangular enclosure. Sound level variation with distance, a primary quantity in acoustic characterisation of families of enclosures [6] will be mainly dealt with.

2. ANTECEDENTS AND THEORETICAL FOUNDATIONS

2.1. Main aspects of nonlinearities of sound pulses caused by crack reports and electric sparks. A criterion to detect intensity nonlinearities

Perhaps the two more significant aspects of nonlinearities o sound pulses dues to crack reports and electric sparks are: a) deviation from *1/r law* of spherical propagation in free field, and b) presence of significant spectral components far beyond the limit straight line of -6 dB/octave slope proper of linear pulses [7], [8]. Both aspects can serve to detect nonlinearities in sound pulses but to our actual purposes a rather simple criterion derived from a) has been used. According to this criterion [4] the variation with distance (*r*) of either pulse pick value (in fact the product $r\,p_p$) or total sound intensity of non linear acoustic pulses deviate from a straight line of negative slope. Calling β to the excess of the exponent of distance *r*, over the usual value *2* for linear range, and *m* to the air attenuation, that is assumed to be equal to the linear range given the limitation to weak nonlinearities, the equation of the above criterion can be written:

$$2\lg(r \cdot p) = 2\lg(p1) - (2+\beta)\lg(r_1) - \beta\lg(r) - (m\lg(e)) \cdot (r - r_1)$$

where *p1* is the pic pressure at distance r1. A quite similar equation holds in terms of I(r) the total intensity of the pulse. Values of β up to *1* and more are typical of crack reports and up to *0.5* of electric sparks used in scale models.

2.2. Image models

Image theory has been and is being used as a powerful tool in predictive models and softwares to approach acoustic properties of rooms [9], [10], mainly combined with ray tracing methods in more recent models [11], [12]. Though modern computers have increased memory and speed up to limits unattended only a few years ago, the main problem continues to be the time consumed, and limitations to low orders of reflection have been introduced without significant loss of precision [13], [11]. Additional problems arise from wall (absorption and diffusion) coefficients and phases not yet solved. Nevertheless the usefulness of acoustic features afforded by these methods in common design practice of a large variety of rooms justifies in itself the actuality and general acceptance of these methods and models.

Image patterns and reflection order become crucial parts in the above models to reduce computing time mainly by suppression of invalid image sources and limiting the procedure to low order reflections.

2.3. An image model under weakly nonlinear conditions

Along the lines used in a previous work [5] it is possible to derive a compact formula to evaluate the sound level in a enclosure excited by weakly nonlinear signals and steady state conditions.

But like under linear range a level independent of distance results and our interest focus on variations of sound level with distance that have been detected by various authors [3], [6], the above numeric methods make evident. Experimental results in scale models with weakly nonlinear signals showed unexpectedly high attenuation with distance. They are suspected to be dues to nonlinearities of the excitation signal. This excess attenuation should be compensated in applications in the linear range.

Therefore, following hypothesis assumed on a previous work [5], our key energy algorithm on a receiving point related to an image source of an original weakly nonlinear source is:

$$E_{is} = E_0 (1/r_{is}^{2+\beta}) \cdot \exp\{-(m \cdot r_{is}) + \ln \prod_{j=1}^{is} (1-\alpha_j)$$

where β is the nonlinear parameter, r_{is} is the distance from image source *is* to the receiver and α_j*=1,2,. . ., is* are the absorption coefficients of the wall set involved in the path ; *is = 0* for the real source (direct sound).

This equation, that focuses on detailed information of intensity and time distribution of echoes, is able to render for enclosures excited by weakly nonlinear signals: a) the time history of energy variations and b) the energy dependence along distance to the source for given trajectories.

2.4. Variations concerning sound level distribution

The set of distances of image sources to the receiver, r_{is}, is completely determined by shape and dimensions of the enclosure. Although on average it is expected that enclosures of the same volume have quite similar 'echograms', some acoustic properties, manly those perceptive properties depending on the initial echogram pattern can differ strongly from an enclosure to another. Here, as already mentioned, the spatial distribution of energy is the main goal.

Choosing several different straight paths, the energy of echograms computed along a set of appropriate points are compared for linear and weakly nonlinear conditions. We are interested in knowing if results for different trajectories converge to a significant average. If so this average represents the variation of sound level with distance to the source of that particular enclosure. A priori it can be expected such result for 'diffuse enclosures' with homogeneously distributed absorption. In the opposite situation are enclosures where every trajectory has its own 'energy distribution law'.

In this way enclosures having sufficient nominal acoustic proximity can be analysed to confirm the existence of common 'laws' of sound level variation with distance, that in turn are 'equally affected' when passing from linear to weakly nonlinear conditions (of excitation signal levels).

In this work, and to avoid limitations due to the suppression of high order images and inclusion of 'impossible image sources' as well as to simplify computing time, rectangular enclosures will be considered. These volumes have 'exact patterns' of image sources that can be computed up to very high orders within a few ms. It holds similarly for straight prisms of triangular base.

Being so big the amount of parameters to be considered (f.e. size, shape, air absorption, wall absorption distribution, etc.), not yet sufficiently clarified, and the practical usefulness aimed in this work, computings will be limited to a simple enclosure and delayed to the appropriated point where they will be compared to experimental results carried out on a scale model.

3. COMPARISON OF COMPUTED AND EXPERIMENTAL RESULTS

3.1 Scale model, experimental set up, and typical echograms

A rectangular enclosure 1.6 x 0.5 x 0.29 m, was constructed on 2.5 inches wood agglomerate finished by melamine layers. Two 1/4 inches condenser microphones were used. One microphone placed at a fixed reference point and the other at successive reception points distributed along two nominal trajectories: a trajectory along the longitudinal plane of symmetry, 0.12 m height over the floor and other trajectory along the major diagonal and same height. An omnidirectional spark device was placed at the nominal source location of each trajectory. Signals picked up by micros feed a two channel FFT based signal analyzer (Data 600) with a dynamic range of 100 dB [14]. Digital files where then converted into compatible matlab and J files.

3.2. Matching times of first order experimental images

The first step in comparing computed and experimental echograms on nonlinear signals is to measure sound speed. It plays a main role in time sequences of echoes. Careful measurements by using the same excitation spark pulses under the above mentioned experimental temperature, atmospheric pressure and relative humidity gave the value 347.0 m/s.

Then the experimental (or the computed) echogram should be delayed to obtain the superposition of direct sound (first isolated pulses). Pulses of the first order image sources (6 in our case of a rectangular enclosure) of one set should then match each other. Some changes of coordinates of source and reception points in computing program, bounded to error limits in positioning source and micros in the experimental set up, lead quite easily to reasonably good time matchings. The good this fitting be made the better would be the matching between computed and experimental echograms. Fig.1 shows the cases of points p10, p12 and p17.

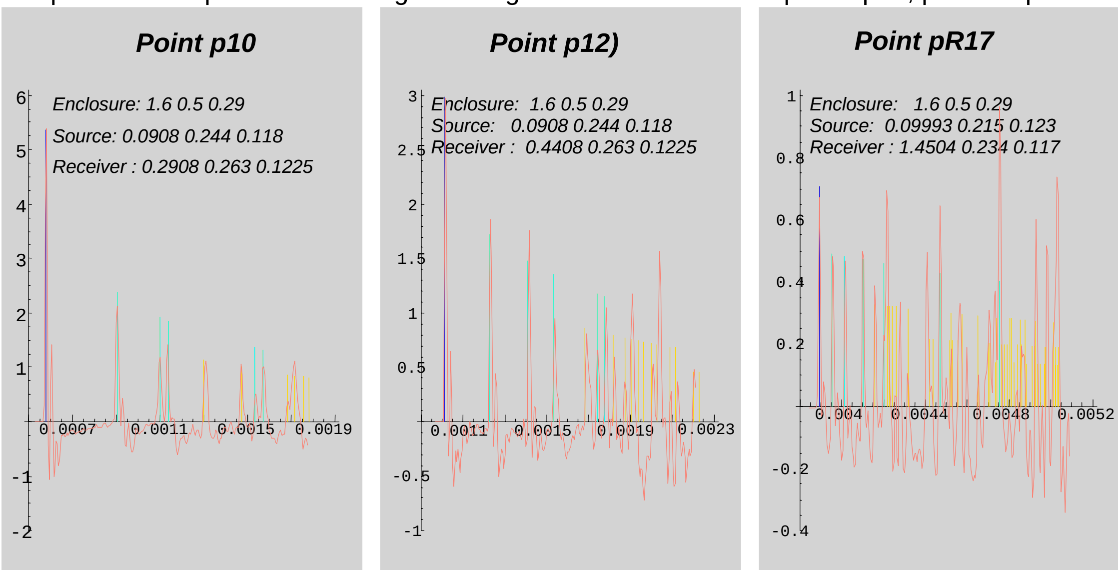

Figure 1. Matching arrival times of computed image sources (blue: direct; green: first order; yellow: second and higher orders) to experimental echograms (red)

3.3. Determination of wall absorption, nonlinear parameter and air absorption

Air absorption can be obtained from standard ISO 9613-1. See table 1.

When comparing computed and experimental echograms it is convenient to obtain values of β from sets of echograms obtained at different distances from the source taking only the direct part of the signal. Values should be duly corrected to compensate potential variations of the excitation signals at every reception point. Signals picked up at a fixed reference position simultaneously to the responses at different distances can serve to that purpose. For a set of reception points p10, p11, p12, p13, p14, p15,p16 and p17, along a straight line 0.12 m from the floor, in the longitudinal plane of symmetry of the enclosure, at nominal distances 0.201, 0.251, 0.351, 0.550, 0.748, 0.949, 1.154, 1.351 from the source located to 0.1 m from the nearest wall, the set of values in table 1 were obtained.

If absorption coefficients are known only for linear range, equation

$$T_a = \frac{T^{1-(0.053\beta+0.0514\beta^2)}}{e^{0.41\beta+0.083\beta^2}}$$

can be used to obtain the corresponding ones to be used: apparent absorption coefficients under weakly nonlinear conditions [5]. Otherwise they can be determined from experimental echograms by conventional methods.

Frq. band	1.25 kHz	2.5 kHz	5 kHz	10 kHz	20 kHz	40 kHz	Complete signal
M	0.0023	0.00605	0.0196	0.0604	0.1343	0.1979	0.188
β	0.3156	0.1066	0.0800	0.0595	0.0715	0.1728	0.158928
$\alpha_{Ey,med}$	0.013	0.013	0.024	0.026	0.029	0.067	0.066

Table 1. Values of m,b and a in our experimental arrangement

For the complete signal (non filtered), for example, previous values can be optimized by means of a fitting function that simultaneously takes into account the amplitudes of direct and first echoes for the ensemble of reception points. Figure 3.2.2 summarizes the final result.

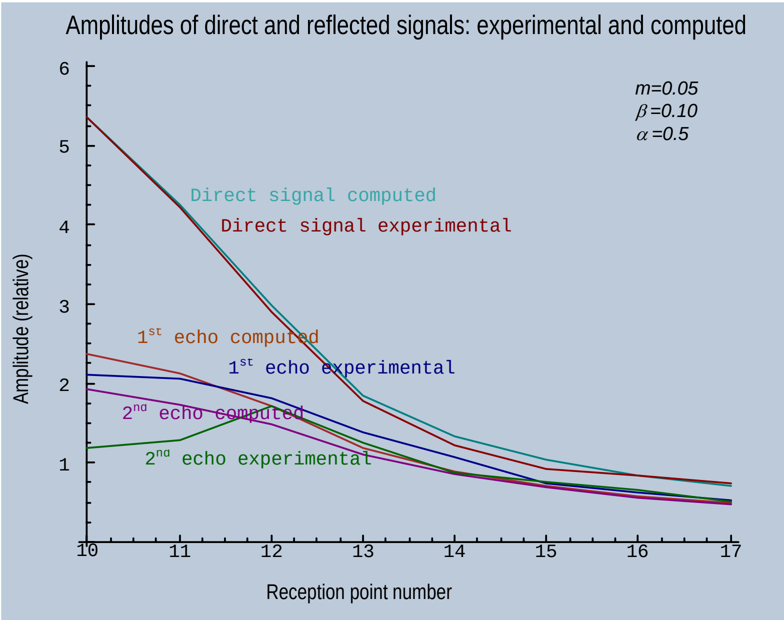

Figure 3.2.2. Global optimization of m, β and α for the complete signal in experimental study to match simultaneously amplitudes of direct signal and first two echoes

3.4. Comparing computed and experimental echograms

Te convolution of the excitation signal with the ‘energetic approach of impulse response’ results in turn a reasonably good approach to experimental echograms. Figure 3.4.1 gives the results for points p10, p12 and p17 for the complete signal.

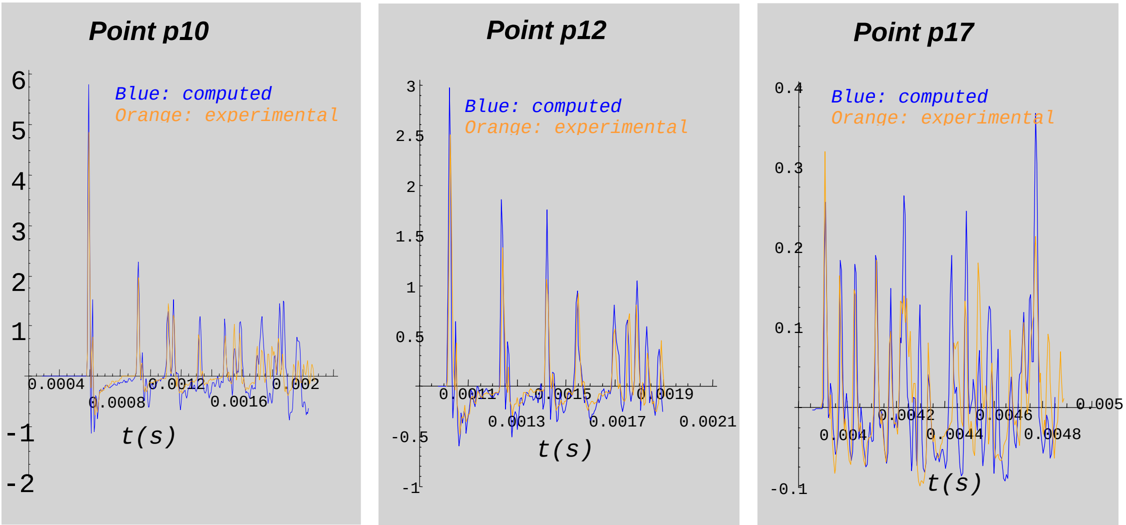

Figure 3.4.1. Comparison of experimental and computed echograms in points p10, p12 and p17 for the complete signal.

It is to mention in point 17, that the third of first order echoes is more intense than the two previous ones because the convolution process accounts for the negative effect of the tails of preceding echoes, given its relative nearness.

3.5. Sound levels as a function of distance to source

Weak nonlinearities of the excitation signal level cause changes on spatial sound level distribution with regard to linear range. In many problems it comes important to account these changes as a function of distance. Obviously that variation is mainly dependent on the acoustic characteristics of enclosures and sometimes it is so high that averages and other statistical estimators are nonsense.

But when shapes and sound absorption are quite similar, averages and deviations are proper parameters of sound levels distributions. In our case of rectangular enclosures variation of sound level with distance becomes plenty of sense and differences between linear and nonlinear ranges present regular evolutions as a quite simple function of the nonlinear parameter.

Figure 3.5.1 gives differences on sound level between nonlinear and linear excitation signals as a function of distance for different frequencies and combinations of air absorption, wall absorption coefficient and nonlinear parameter (se table 1) for a path along the longitudinal plane of symmetry. Derivation of this figure and algorithm implies comparison with experimental results obtained in the scale model.

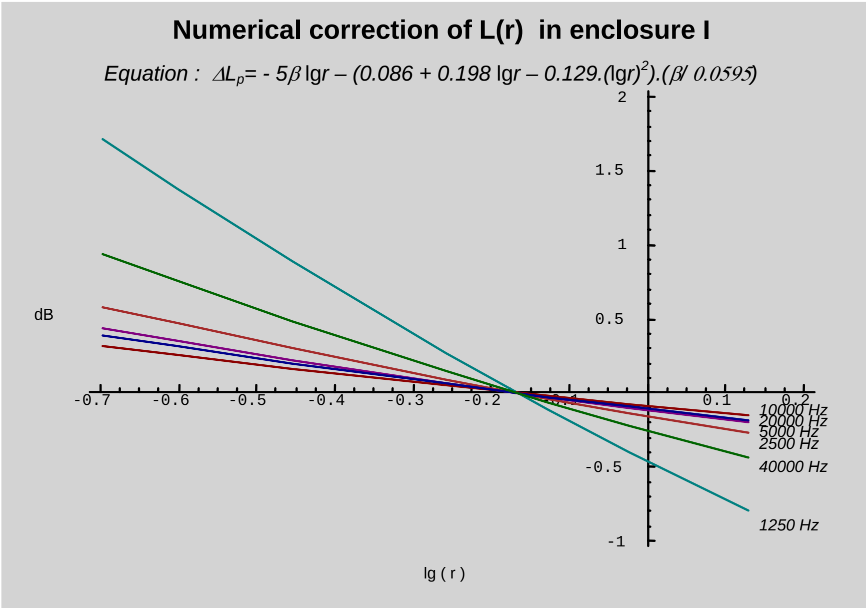

Figure 3.5.1. Differences on sound level as a function of distance in rectangular enclosures

The predominant effect of b is very clear. However the remainder parameters and mainly the shape and size of the enclosure also play a role conforming the basic shape represented by the polynomial of coefficients *0.086, 0.198 and –0.129*.

4. CONCLUSIONS

A new model of sound propagation in enclosures for sound signals with weakly nonlinear level has been presented. It considers spatial distribution of sound level and is a complement of a previous one devoted to time variations (mainly reverberation).

[1] W. C. Sabine, Collected papers on acoustics, Dover 1965//[2] M. R. Schroeder, J. Acoust. Soc. Am., 37, 409-412, 1965//[3] M. Barron, L. J. Lee, J. Acoust. Soc. Am.,84(2)618-828,1988//[4] A. Moreno, C. Colina, F. simón, Proc. 16th ICA Congress, Toronto , Vol I, 125-126,// [5] A. Moreno, R. M. Rodriguez-Alves, Proc. Acústica 2008, Coimbra//[6] J. J. Sendra, T. Zamarreño, Proc. Tecnicústica 95, 87-90, 1995//[7] F. B. Frungel, High speed pulse technologiy Vol I, Cap I, Accademic Press, New York 1965//[8] A. Moreno, C. Colina, F. Simón, J. Pfretzschner, Revista de Acústica, vol XVIII, núms. 3-4, 1997, 11-13//[9] H. Kuttuff, Room Acoustics, Applied Science, London 2nd Édition, 1979//[10] A. Krokdtad, S. Strom, S Sorsdal, J. Sound Vib. 8, 118, 1968//[11] M. Vorlander, J. Acoust. Soc. Am.,86(1),172-178, 1989//[12] W. Ahnert, S. Feistel, O. Schmitz, XIII Session of the Russian Acoustical Society, Moscow 29-29,2003//[13] H. Lee, B. H. Lee, Applied Acoustics 24(1988)87-115//[14] R. M. Rodriguez-Alves, Final Project of DEA, ETS Arquitectura, Madrid, 2006