AN ENERGETIC APPROACH ON SOUND PROPAGATION IN NATURALLY VENTILATED CONFINED SPACES

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Abstract. *With a view to sustainability and reducing energy consumption, techniques of passive cooling in buildings are often advised for countries such as Brazil, due to its hot and humid climate offering great amount of solar energy and impelling natural convection. However, natural ventilation openings in a building façade offer little resistance to the ingress of externally generated urban noise, reducing acoustical comfort indices. This work concerns the development of an alternative energetic approach for predicting acoustical conditions in confined spaces. Such method is based on the fundaments of Room Acoustics, yet the system, or room, is addressed by solving power flow equations, similar to the Statistical Energy Analysis' approach. Assumptions are adopted so that a complex system can be modeled by dividing it into simple subsystems, which relate to each other by means of power transmission equations. The proposed method can be applied, for example, into the study of classrooms and equipment partial enclosures, proving its simple and practical usage on the prediction of acoustical behavior of complex systems. Its main purpose is becoming a useful tool for engineers and architects to foresee potential high noise level problems in the design of buildings.*

Keywords*: Acoustics, ventilation, Statistical Energy Analysis*

1. INTRODUCTION

In antagonism with the countless benefits and the main purpose of improving the quality of human life, the urbanization process, associated with an increasing industrialization and with the expansion of transportation system, has been taking part in the generation of serious and progressive environmental problems. It is possible to observe changes in the urban noise, concerning its type, intensity and propagation.

The inconsequent use of noise sources and their incompatibility with space and with the period of the day are responsible for the significant raise of noise levels in the cities. Inhabitants of great urban centers are continuously exposed to noise levels generated by machinery, industries, civil constructions, aircrafts, local shops, amplified sound cars, churches, among others, which are way beyond bearable and recommended values.

In the last decades, noise has become one of the pollution types that affect the largest number of people in the world, right after air and water pollution. Since 1989, the problem has been treated by the World Health Organization as a question of public health.

The main source of disturb related to urban noise is cause by the vehicle traffic noise. It is due to the proximity between houses and streets and to the inefficient sound performance of building façades, which dispose of openings and windows. A highly efficient possibility for reducing noise levels inside buildings would be closing windows, but this would impose a raise on the energy consumption associated with cooling.

Concerns with the sustainable growth and the necessity of preserving energy sources indicate the use of renewable energy sources for the cooling of new and existent buildings. By these means, in countries such as Brazil, subjected by hot and humid climate, it is recommended to take profit of the great amount of solar energy offered by nature to stimulate natural convection, aiming natural cooling in edifications.

On the other hand, upon analyzing the acoustical comfort in a residential building refrigerated by natural ventilation, there is great permeability to urban noise. The current challenge is, therefore, to take profit from the local bioclimatic conditions and, at the same time, to solve problems of undesired noise infiltration. (De Salis, Oldham, Sharples, 2001)

This paper works on beginning the development of an energetic method of sound propagation for evaluating the acoustical quality of internal spaces that use natural ventilation for cooling. The proposed energetic method ought to use the traditional formulation of the Room Acoustics under the Statistical Energy Analysis (SEA) approach, by dividing complex systems into subsystems that are related to each other by simple equations.

The contents herein presented allow an estimation of resultant noise levels in spaces not yet constructed and aim to become a useful tool for a future integration between the work of engineers, architects, especially in the project of edifications and during the selection of the most suitable method for noise control.

2. PROPOSAL OF THE ENERGETIC METHOD

The sound field present in an enclosed space can be divided into two parts: one proceeding from the direct sound field and another from the reverberant sound field. Considering that the sound field at a given room "s" is completely diffuse and in steady-state, the general expression for the sound power level at the room (NWS^{s}) is given by Eq. (1). The *NWS* is a function of the sound pressure level resultant from the reverberant field (NPS^{s}_{REV}), the sound absorption coefficient α_i of each surface S_i of the room and the average sound absorption coefficient $\bar{\alpha}$ of the surfaces of the room.

$$NWS^s = NPS^s_{\mathrm{REV}} + 10\log\left(\frac{\sum_i S_i^s \alpha_i^s}{4\left(1-\bar{\alpha}^s\right)}\right) \quad (1)$$

From now on, the average sound absorption coefficient of the room's surfaces will be assumed to be small. Equation (1) can be rearranged in terms of partial sound power levels NWS_i^s, which represent the energetic contribution of each absorbent surface "i" of the room into the global level. The room's total power noise level can be then calculated by the logarithmic sum of the partial power levels of the room's surfaces, as shown by Eq. (2).

$$NWS^s = \sum_i NWS_i^s, \quad \text{when } NWS_i^s = NPS^s_{\mathrm{REV}} + 10\log\left(\frac{S_i^s \alpha_i^s}{4}\right) \quad (2)$$

2.1. System composed of two subsystems

The bidimensional system under analysis is represented in Fig. 1. The system is composed of two rooms interconnected by a common opening, through which the acoustical energy generated by the sound source W_1, located at room 1, is transmitted into room 2. The absorption coefficients of the surfaces are indicated in the figure.

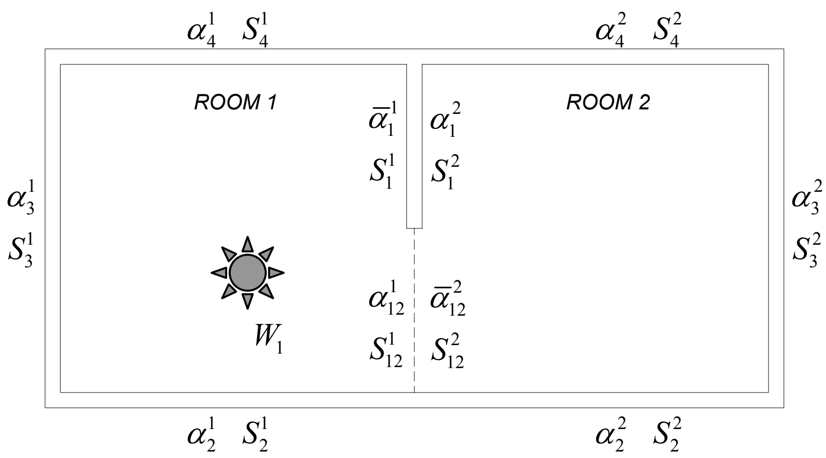

Figure 1. System composed of two rooms connected by an opening.

The notation adopted to represent the proprieties of the rooms' surfaces uses sub- and superscripted indexes. For instance, the sound absorption of surface "3" of room "1" is represented by α_3^1. For the opening, common to both rooms "1" and "2", the subscripted index "12" was adopted.

The sound absorption coefficient of the opening is one, meaning that the opening absorbs no energy – all energy incident onto the area is completely transmitted into the adjoining room.

In the proposed model, it is assumed that the energy generated in room 2 is transmitted into room 2 exclusively through the opening. For this consideration, the rooms' surfaces shall have high sound transmission losses and there shall be no flanking transmission between the interface walls. Therefore, the acoustical energy transmitted directly through the opening will be much higher than the energy transmitted through the walls of the rooms.

The expression for the sound power level in room 1 can be developed according to the steps shown in Eq. (3) and (4). By these means, a relation can be established between the power generated by the sound source W_1, the power absorbed by the surfaces and the power transmitted from room 1 into room 2.

$$10\log\left(\frac{W_1}{W_o}\right)=10\log\left(\frac{p_1^2}{p_o^2}\right)+10\log\left(\frac{\sum_i S_i^1\alpha_i^1}{4}\right) \quad \therefore \quad \frac{W_1}{W_o}=\frac{p_1^2}{p_o^2}\sum_i\frac{S_i^1\alpha_i^1}{4} \tag{3}$$

$$\frac{W_1}{W_o}=\frac{p_1^2}{4p_o^2}\left(S_1^1\,\alpha_1^1+S_2^1\,\alpha_2^1+S_3^1\,\alpha_3^1+S_4^1\,\alpha_4^1+S_{12}^1\,\alpha_{12}^1\right) \tag{4}$$

The last term of Eq. (4), dependent of the area of the opening S_{12}^1 between the rooms, describes the parcel of power that is transmitted into room 2 throughout the opening. The other terms represent partial power absorbed by room 1's walls.

It shall be noted that, in order to complete the power balance in room 1, the power that is transferred from room 2 into room 1 throughout the opening must be accounted for. A last term shall be added up into Eq. (4), completing room 1's power flow balance:

$$\frac{W_1}{W_o}=\frac{p_1^2}{4p_o^2}\left(S_1^1\,\alpha_1^1+S_2^1\,\alpha_2^1+S_3^1\,\alpha_3^1+S_4^1\,\alpha_4^1+S_{12}^1\,\alpha_{12}^1\right)-\frac{p_2^2}{4p_o^2}S_{12}^2\,\alpha_{12}^2, \tag{5}$$

where p_1^2 and p_2^2 are the quadratic pressures in rooms 1 and 2, respectively.

Keeping in mind that the opening's absorption coefficient is equal to one and that the areas S_{12}^1 and S_{12}^2 are identical ($S_{\text{open}}=S_{12}^1=S_{12}^2=S_{12}$), Eq. (6) can be found by grouping the terms dependent of the opening area.

$$\frac{W_1}{W_o}=\frac{A_1}{4}\frac{p_1^2}{p_o^2}+\frac{A_{12}}{4}\left(\frac{p_1^2}{p_o^2}-\frac{p_2^2}{p_o^2}\right) \tag{6}$$

A_1 is the total absorption area of room 1's walls and derives from the result of the product of each surface area of the room's wall by its sound absorption coefficient. A_{12} is the opening's total absorption area, which is, as a matter of fact, equal to the opening area between the rooms ($A_{12}=S_{12}\cdot\alpha_{12}=S_{12}$). Such terminology will be used henceforth.

Observing Eq. (6), the following interpretation can be given to each of its terms: the one that is a function of A_1 represents the power dissipated due to the interaction between the absorbent walls of room 1 and the other one, which is a function of the opening area A_{12}, represents the power flow between rooms 1 and 2.

For the subsystem room 2, a similar equation can be reached:

$$\frac{W_2}{W_o}=\frac{A_2}{4}\frac{p_2^2}{p_o^2}+\frac{A_{12}}{4}\left(\frac{p_2^2}{p_o^2}-\frac{p_1^2}{p_o^2}\right), \tag{7}$$

yet, there is no sound generation inside room 2 ($W_2=0$), resulting in Eq. (8), as follows.

$$\frac{A_2}{4}\frac{p_2^2}{p_o^2}=\frac{A_{12}}{4}\left(\frac{p_1^2}{p_o^2}-\frac{p_2^2}{p_o^2}\right) \tag{8}$$

Physically analyzing Eq. (8), it shows that the dissipated power in room 2, due to the interaction between acoustical waves and the absorbent surfaces of the room, is numerically equal to the power transmitted from subsystem 1 to subsystem 2.

Figure 2 shows a block diagram representing the power flow between the subsystems.

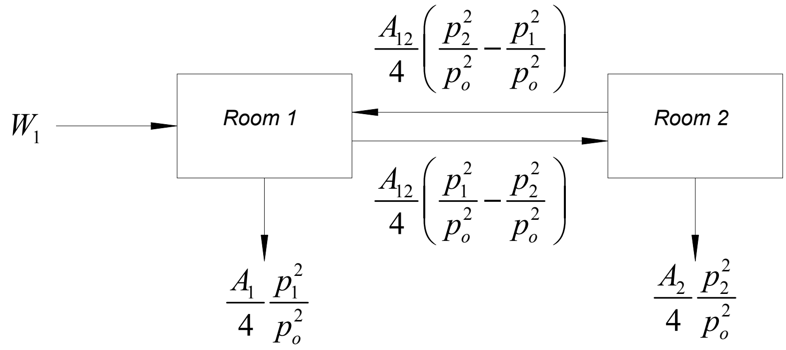

Figure 2: Diagram of the energy flow in the system composed of two rooms.

2.2. General formulation

From the equations herein presented, it is possible to generalize the formulation for any system composed of s subsystems (or rooms) interacting with each other through a common opening of area A_{sk}. The generalized formula is given by Eq. (9).

$$\boxed{\frac{W_s}{W_0}=\frac{A_s}{4}\frac{p_s^2}{p_0^2}+\sum_k \frac{A_{sk}}{4}\left(\frac{p_s^2}{p_0^2}-\frac{p_k^2}{p_0^2}\right)}, \quad (9)$$

where:

$$A_s=\left(\sum_i S_i^s\,\bar{\alpha}_i^s\right)-\sum_k A_{sk} \quad (10)$$

2.3. Analogy with the SEA

The developed formulation for the proposed method (Eq. (9)) has many similarities with the SEA formulation. Considering systems s and k as rectangular rooms, whose total number of existent modes can be approximated by the cubic term, the SEA equation becomes Eq. (11). (Craik, 1996)

$$W_s=\eta_{sd}\frac{f\,\mathrm{V}_s}{\rho c^2}p_s^2+\sum_k \eta_{sk}\frac{f\,\mathrm{V}_s}{\rho c^2}\left(p_s^2-p_k^2\right) \qquad \underline{\text{SEA}} \quad (11)$$

Directly comparing the terms of Eq. (9) and (11), a correspondence between the pairs (A_s and η_{sd}) and (A_{sk} and η_{sk}) becomes notably clear. Furthermore, expressions for the coupling loss and internal loss factors may be written as a function of the opening area and the total absorption area of the room's walls:

$$\eta_{sd}=\frac{\rho c^2 W_0}{4p_0^2 f\,\mathrm{V}_s}A_s \text{ and } \eta_{sk}=\frac{\rho c^2 W_0}{4p_0^2 f\,\mathrm{V}_s}A_{sk}\,. \quad (12)$$

The above relations constitute one of the most significant contributions brought in by the present work. By using them, it is possible to calculate, in a very simple manner, the acoustical phenomena of transmission and absorption to which systems composed of multiple subsystems are submitted.

By these means, the analogy between the SEA methodology and the energetic method proposed in this work is met. Once the peculiar hypotheses are adopted, any complex system composed by innumerous subsystems, which exchange energy by various ways, can be simplified into subsystems and its energetic balance realized. Therefore, the resultant noise pressure levels can be calculated and a sensibility study can be carried out for optimizing the characteristics of the confined space under interest.

3. CONSIDERATIONS AND DISCUSSIONS

The formulation generalized by Eq. (9) was developed under the energetic analysis approach, taking the equations from the Room Acoustics as a basis. As premises for the development of the formulation, some hypotheses and considerations were adopted, which are herein outlined for a better and clearer understanding of the method, of its usage and of its limitations. The hypotheses are:

1. The acoustical field inside the rooms is perfectly diffuse;
2. The acoustical field is in the steady-state;
3. The rooms' walls have high transmission loss, so that all energy transmission between rooms occurs strictly through the open areas;
4. The mean absorption coefficients $\bar{\alpha}$ of the rooms are small, and the room constant R can be approximated by Eq. (13).

$$R \approx \sum_i S_i \alpha_i \tag{13}$$

If hypothesis nr. 3 is not true and there is energy transmission through the interface of the rooms, it is possible to include such influence in the power balance of Eq. (9). The absorption coefficient α of the surfaces can be separated into a parcel of absorption by dissipation α_D and another by transmission between the materials α_T :

$$\alpha = \alpha_D + \alpha_T \tag{14}$$

The α_T coefficient derives from the relation between transmitted and incident energy. From such coefficient, the transmission loss of a material is defined. This means that, if the transmission loss coefficient of the material is known, its α_T coefficient may be attained by means of Eq. (15).

$$\alpha_T = 10^{-\frac{PT}{10}} \tag{15}$$

Actually, by Eq. (14), any transmission between subsystems can be assimilated as an opening between them. Hence, hypothesis nr. 3 does not represent a limitation to the model; it was only adopted for simplification purposes.

In case of hypothesis nr. 4 not being verified for a certain space (*i.e.* its mean absorption coefficient $\bar{\alpha}$ is not small and thus not despicable), the general expression would assume the following form:

$$\frac{W_s}{W_0} = \frac{A_s}{4}\frac{\tilde{p}_s^2}{p_0^2} + \sum_k \frac{A_{sk}}{4}\left(\frac{\tilde{p}_s^2}{p_0^2} - \frac{\tilde{p}_k^2}{p_0^2}\right), \tag{16}$$

where:

$$\tilde{p}_s^2 = \frac{p_s^2}{\left(1-\bar{\alpha}^s\right)} \text{ and } \tilde{p}_k^2 = \frac{p_k^2}{\left(1-\bar{\alpha}^k\right)} \tag{17}$$

In this case, the effect of term $-10\log\left(1-\bar{\alpha}^s\right)$ of Eq. (1) results in the amplification of the partial power of rooms s and k by the factors $1/\left(1-\bar{\alpha}^s\right)$ and $1/\left(1-\bar{\alpha}^k\right)$, respectively.

4. CONCLUSIONS

Based on some hypotheses and considerations, this work introduced an energetic approach for the estimation of the acoustical characteristics of a system. The formulation proposed the division of a complex system into subsystems, which allowed the modeling of acoustical energy flows between them. Such type of approach is very similar to the Statistical Energy Analysis formulation, which is a prominent and popular method for predicting diffuse sound fields. The new method, however, is notable, in comparison to the other existent methods, for having easy usage and for providing fast results in acoustical predictions.

The main limitation of the energetic approach for the proposed study of the sound is, as a matter of fact, being only applicable to the diffuse reverberant field existent at a room. As sound absorptive surfaces are introduced in an ambient, its field will trend to be less diffuse and the formulation will no longer be valid. Nevertheless, the unquestionable advantage of the method is given by the simplification of complex systems and by the fast results on the estimation of the ambient's conditions. (Muller, 2006)

It is important to raise the discussion about the direct relation established between acoustical comfort and electrical energy consumption. A building subjected to high external noise levels will require the treatment, or even the total obstruction, of the openings of its façade. This would imply in the need of using artificial cooling systems so that minimal conditions of human thermal comfort are achieved. Mechanical ventilation requires electricity, occasioning a raise in the energetic consumption of the building. Thus, there is a higher demand on the generation of electric energy and a higher load on the energy transmission network.

By using combustible sources – such as coal, gas and petroleum – for energy attainment, the process of electric energy generation in the last 50 years became the main responsible agent for emissions of pollutant gases into the atmosphere. The increase of the concentration of carbon dioxide (CO2) plays the leading role on the greenhouse effect – phenomenon responsible for the global warming. As a result, the artificial cooling system suffers a greater demand. Thus, a closed cycle is established, demanding higher and higher energy generation.

The transport of electric energy constitutes another weak point of the energetic system, for it may become inefficient in distributing all the capacity of the generated energy. This is a common problem in many Brazilian cities, whose transmission network does not support the energy demand and they suffer from blackouts sporadically.

As far as the Kyoto protocol is concerned, developed and developing countries committed to reduce and to restrict the emissions of CO2, aiming the preservation and the quality of the environment. The countries that fail to meet its Kyoto obligation are penalized. For a sustainable development, any measure that directs the economy into the reduction of combustible energy consumption, or into its substitution by energy proceeding from other renewable sources, shall be encouraged. Renewable sources of energy, such as wind or solar generation, that do not produce any kind of pollution, are the new technological tendencies and deserve conspicuousness today.

The knowledge brought by the present article intends to prepare professionals from other areas related to civil projects onto the understanding of the physical phenomenon of sound, of its undesired infiltration and its consequences. As a further work, a more detailed and generalized energetic method is suggested, as well as the implementation of calculation of variables – such as pressure differentials, air temperature, air flow – that allow the quantitative evaluation of the environmental air condition and its implication on people's thermal comfort.

At last, it shall be highlighted that the best way to solve acoustical problems is by avoiding them, yet not correcting them. At the project phase, high noise related problems can usually be avoided with a bit of thought and with a different arrangement of the same construction materials. Modifying the project of a constructed space imposes relatively high costs; but, yet, its cost can be considered small when compared to the benefits associated with the health of those that are exposed to inadequate and overwhelming sound pressure levels on a daily basis.

5. ACKNOWLEDGEMENTS

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