44º CONGRESO ESPAÑOL DE ACÚSTICA
ENCUENTRO IBÉRICO DE ACÚSTICA
EAA EUROPEAN SYMPOSIUM ON ENVIRONMENTAL ACOUSTICS AND NOISE MAPPING

FREQUENCY RESPONSE OF DOUBLE LEAF STRUCTURES DUE TO FLUID-STRUCTURE INTERACTION

PACS: 43.20.Tb; 43.40.+s; 43.55.+p

Chimeno Manguán, Marcos[1]; Fernández de las Heras, M.J.[2]; Roibás Millán, Elena[1]; Simón Hidalgo, Francisco[2]

[1]Escuela Técnica Superior de Ingenieros Aeronáuticos, UPM
Plz. Cardenal Cisneros 3,
28040 Madrid.
Tlf.: +34 913.366.367
emails: marcos.chimeno@upm.es; elena.roibas@upm.es;

[2]Instituto de Tecnologías Físicas y de la Información, CSIC
C. Serrano 144,
28006 Madrid.
Tlf.: +34 915.618.806
email: f.simon@csic.es

ABSTRACT

The use of thin plates stacking separated by air gaps is an ordinary technique to make building elements or isolating structures in almost every engineering branch. In this kind of configuration the air gap acts as a rigid element that connects the plates and presents a well-known resonance. This resonance usually shows up very clearly on the dynamical response of the system to a transmitted field. When the resonance is close to the first modes of the plates, they couple together an as a consequence the dynamic response changes. In this work, this coupling is studied, its behaviour as a function of the properties of the air gap and plates is presented, and its effect on the low frequency sound transmission outlined.

INTRODUCTION

At the present, the use of multilayer partitions to solve sound insulation problems is a standard in building acoustics. It allows obtaining insulation values comparable or even higher to those obtained by using single-leaf walls with less mass and –sometimes– less width, what results in higher acoustics performances together with lower cost and technical demands. Among all the multilayer partitions the wider extended one is the double one (double walls) for, apart from being the simplest possible, it offers acoustic performances enough to be used in dwellings and office construction.

From the theoretical point of view sound transmission through one of these elements is modelled as the wave propagation through two plates (or planes) connected by a stiff element (the air) that may have some dissipation as well.

Physical models usually assume that the plates behave as uniform, non-flexible plane elements supported within the medium by elastic suspensions with mechanical losses. From the propagation equations of a wave through the double layer configuration the equation of the transmission coefficient can be obtained as (for instance, see [1]):

$$\tau = \frac{\left|2\, j z_o^2 / kd\right|^2}{\left|\left(z_1 + z_o - j z_o/kd\right)\left(z_2 + z_o - j z_o/kd\right) + j z_o/kd\right|^2} \tag{1}$$

where:

z_o: air impedance ($\rho_o c_o$),
k: wavenumber of the propagating sound field,
d: cavity width,
z_1: mechanical impedance of plate 1,
z_2: mechanical iompedance of plate 2,
j: $\sqrt{-1}$.

Mechanical impedances of the plates can be expressed as:

$$z_i = m_i\left(j\omega + \eta_i\omega_i - j\frac{\omega_i^2}{\omega}\right) \tag{2}$$

where

m_i: mass per unit area of plate i,
ω: angular frequency,
ω_i: *in-vacuo* natural frequency of plate i,
η_i: mechanical loss factor of plate i,
K_i: mechanical stiffness of plate i.

Each one of the parenthesis in the denominator of eq. (1) contains a term related with the impedance of the plates and two additional terms related with the load due to the air: there exists a radiation loss (z_o) and a stiffness term (z_o/kd). On the other hand, stiffness term of the plate corresponds to the last term in eq. (2). For the usual building elements the dominant stiffness is that of the air, what leads to a maximum in the sound transmission in the frequency:

$$\omega_c^2 = \frac{z_o c_o}{d}\left(\frac{1}{m_1} + \frac{1}{m_2}\right) \tag{3}$$

This equation is the well-known cavity resonance or *mass-air-mass-resonance*. Assuming that air stiffness dominates the propagation means that $\omega_i << \omega_c$ and as a consequence mutual interaction can be neglected. The frequency range of interest in building acoustics helps to back this assumption. What is more, an increase in the transmission through the first plate in the neighbourhood of ω_i will be obstructed by the presence of the cavity, so that the air plays an outstanding role in the dynamic response of this kind of element.

If the building element is made up by light or very stiff plates, the resonances involved in the transmission process (ω_i *y* ω_c) may have close values so that the response of the whole system is influenced by the interaction among them [2, 3]. In the usual building acoustic case this situation does not happen, nevertheless, nowadays, the interest of extend the working frequency range to the low frequencies and the ever increasing use of technically advance materials have caused that today cases as the ones described turn up, so that interaction among the different resonant processes have to be taken into account.

In this work it is assessed to what extent this resonance interaction may arise in the sound transmission of double walls, taking as a starting point current usual building elements and making their characteristics change. In addition, as the walls are not non-flexible elements actually, extra vibration modes are included in the analysis. To ease the analysis, this is carried out by simplified modal models of the walls. At the end, a case that poses the presence of more than one mode in the cavity is studied, as well.

As we are interested on the range of maximum transmission a simplified modal analysis is carried out where the first modes of each plate are taken into account only. When it is needed the number of modes taken into account it is increased.

FUNDAMENTAL EIGENFREQUENCY IN COUPLED SYSTEMS

The response of a complex system can be analysed in terms of the modal response of the coupled system, and therefore, the determination of the coupled eigenfrequencies and eigenvectors are of main interest. The determination of the first eigenfrequency is critical as it drives the response of the system at the low frequency range.

The first eigenfrequency of double leaf structures as the stated above is function of the properties of the structural elements (and therefore of their first eigenfrequencies) and of the junction provided by the air between them. This section presents an analysis of the resulting behaviour of the system depending on the stiffness of the structural elements and the thickness of the air layer between them.

To study qualitatively the behaviour of these systems, a simple model based on inertia and stiffness elements is considered. The structural elements are simulated by two degrees of freedom systems and the air layer is considered only in terms of stiffness as depicted in Figure 1. The values of the inertia and stiffness elements are defined by the mass and first eigenfrequency of the structural elements. The acoustic stiffness of the air layer is the value deducted in the previous section through the *mass-air-mass* resonance.

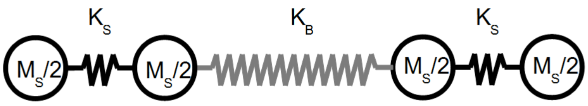

Figure 1. Inertia and stiffness elements model for a double leaf structure

The coupled eigenfrequencies of the compound system are computed solving the corresponding eigenvalue problem for the model in Figure 1. Four different double leaf structures are considered, with successive decreasing thickness of the leaf for a typical hollow brick wall (with the transmission in the double-cavity direction) of 4.3 x 3 metres separated in 0.050 metres. The evolution of the first three eigenfrequencies of the system with the decreasing mass is plotted in Figure 2 along with the *mass-air-mass* resonance predicted analytically for normally incident waves.

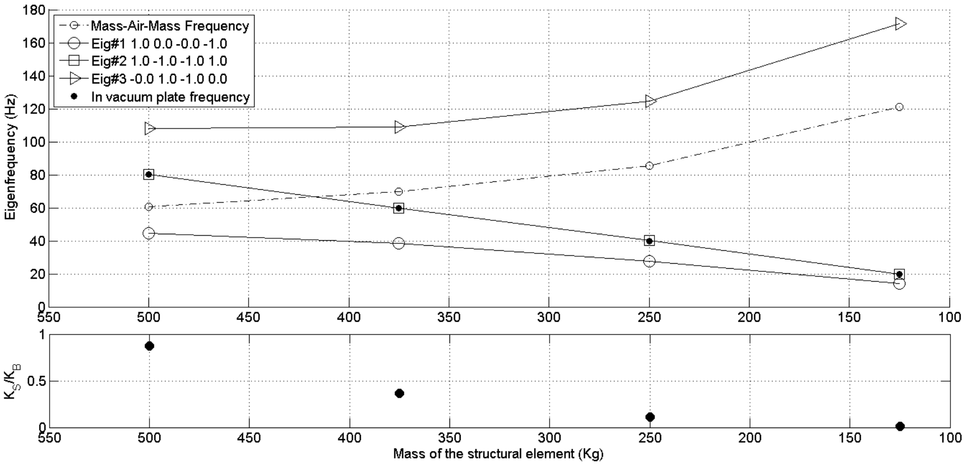

Figure 2. Top: Eigenfrequencies corresponding to model in Figure 1 for several cases of mass and in vacuum eigenfrequencies for the structural elements; in vacuum structural fundamental frequency and ideally predicted *mass-air-mass* resonance. Bottom: ratio between structural and fluid stiffness.

Results show that the first eigenfrequency of this type of structure is close to the *mass-air-mass* resonance only for heavy and stiff structures. For lighter structures (lower ratio of structural to fluid stiffness) the coupling of the structural and fluid elements leads to a much lower first eigenfrequency than the one predicted studying the propagation of normal waves within the air cavity.

The influence of the thickness of the air cavity between the structural elements is also a main issue in the resulting system's response. Figure 3 depicts the same results shown above, the first eigenfrequencies of a double leaf HB structures (4.3 x 3 metres HB panels with 0.110 and 0.055 metres thickness and mass of 500 and 250 Kg respectively) for several values of the air cavity thickness.

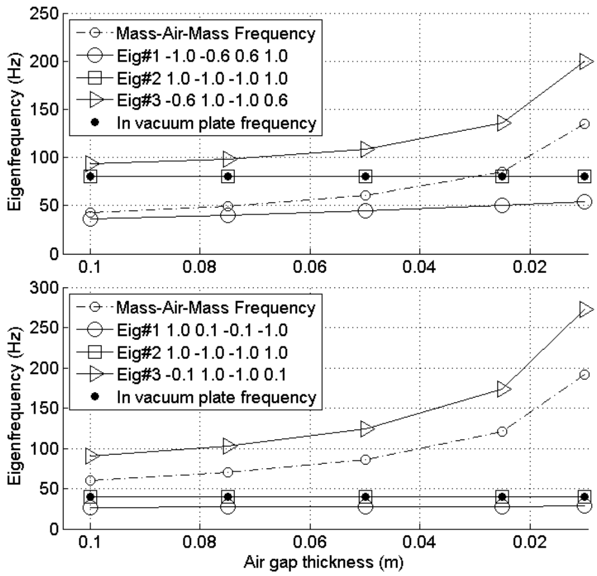

Figure 3. First eigenfrequencies predicted by model in Figure 1 for a double leaf HB structure considering two panels' thickness, providing structural masses of 500 (top) and 250 (bottom) Kg, for different thicknesses of the air gap between the panels.

Results confirm that in general the fundamental frequency does not correspond with the mass-air-mass resonance, but it is the results of the coupling between the structural and fluid resonances. Even for heavier and stiffer structures the mass-air-mass resonance is not the fundamental frequency for small distance between leafs.

AIR GAP MODELS

This section presents a study on different models for the air layer within these systems. All the models presented are based in inertia and stiffness elements in order to provide a useful set of qualitative models to study the influence of the different parameters of the system as the mass of the structure or the thickness of the air layer.

To simulate the response of the structural elements two and three degrees of freedom systems are considered in combination with several models for the air between them. In order to model the air layer, increasing complexity models are considered: massless stiffness element; distributed mass stiffness element, single degree of freedom system and two degrees of freedom system.

The properties of the inertia elements involved in each model are derived from the mass of air contained in the region between leafs. The magnitude of the stiffness are derived, accordingly to the inertia ones, from the air resonance in the air cavity between leafs.

In order to establish the effect of the stiffness of the structural elements, two 4.3 per 3 metres double leaf walls are considered: one with its first eigenfrequency above the mass-air-mass resonance (80 Hz and a mass density of 30 Kg/m^2) and one with its first eigenfrequency below it (40 Hz and a mass density of 15 Kg/m^2).

The two simpler models consider each panel as a two degree of freedom system while the air is modelled through a massless stiffness element or as a distributed mass stiffness element. Difference in the results for both models is negligible and the evolution of the eigenfrequencies with the distance between leafs is shown in Figure 4.

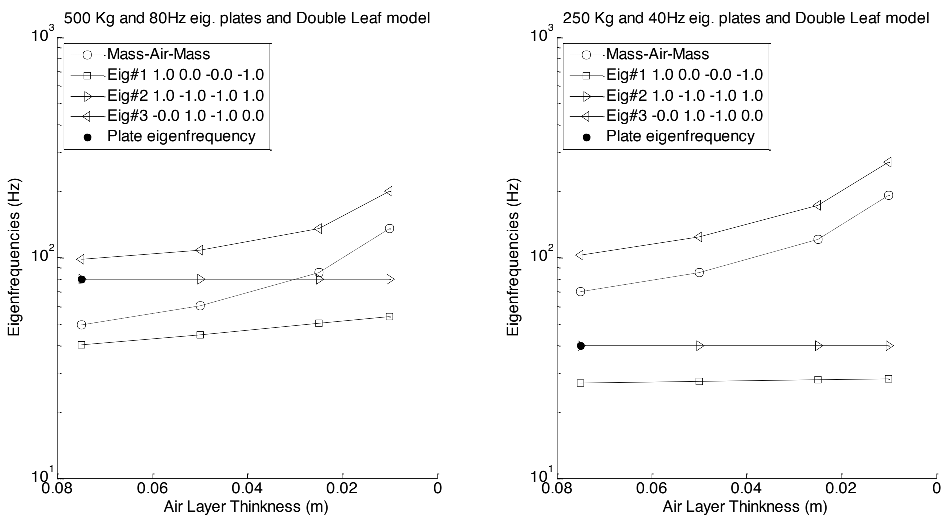

Figure 4. Eigenfrequencies of double leaf structures through a model considering each panel as two degrees of freedom systems and the air both as a massless and distributed mass stiffness element for two structures: structural panels with 80 Hz (left) and 40 Hz (right) as fundamental frequency.

The conclusion stated in the previous section on the fundamental frequency of the systems is observed for both cases although the level of accuracy of the model is low due to the few degrees of freedom considered, especially as the air is not considered as a degree of freedom itself. Including the air contained between the panels as an additional degree of freedom provides more information in the system's response but in the high frequency as the resulting new eigenfrequecy is higher than the previously detected as Figure 5 shows.

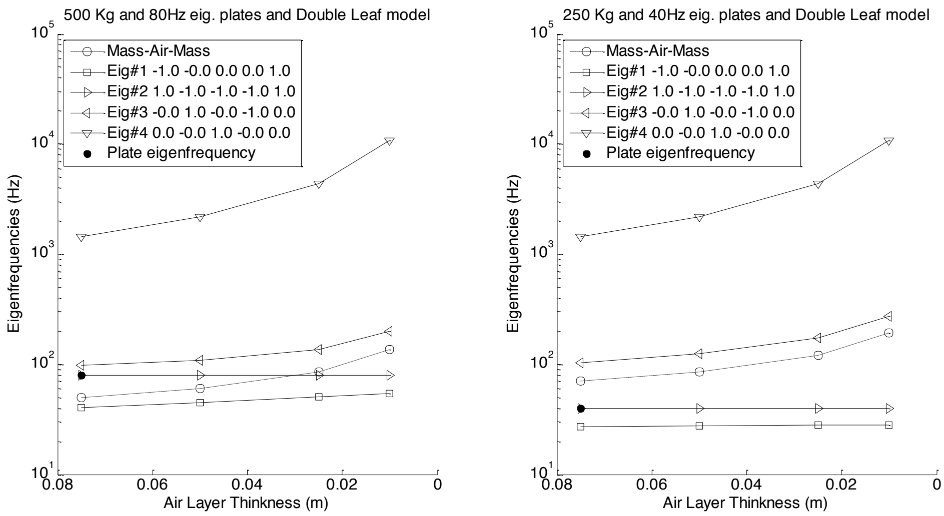

Figure 5. Eigenfrequencies of double leaf structures through a model considering each panel as two degrees of freedom systems and the air as a single degree of freedom system for two structures: structural panels with 80 Hz (left) and 40 Hz (right) as fundamental frequency.

As shown in previous results, the level of information obtained is not improved and higher complexity models are required for both structural and fluid domains. In a first step, the model for the air is improved including a second degree of freedom. The predicted response of the system for these six degrees of freedom is shown in Figure 6.

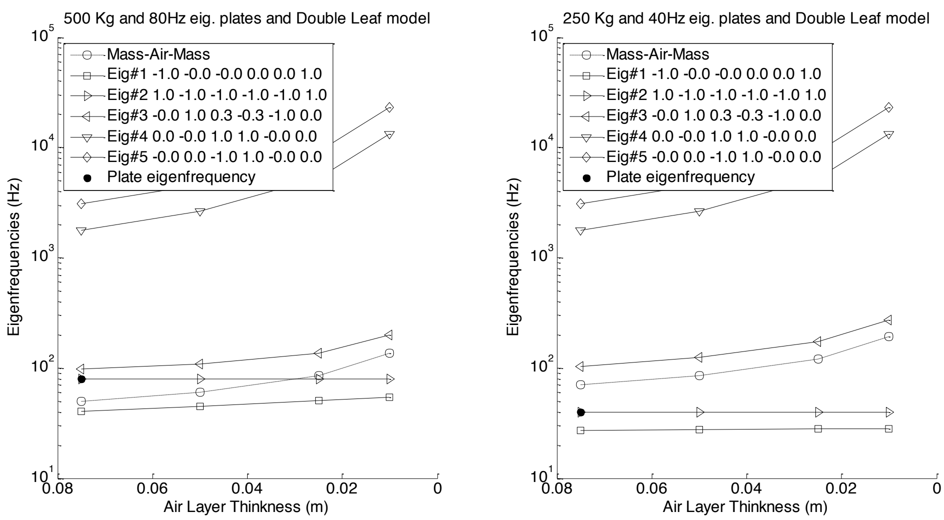

Figure 6. Eigenfrequencies of double leaf structures through a model considering each panel as two degree of freedom systems and the air as a two degrees of freedom system for two structures: structural panels with 80 Hz (left) and 40 Hz (right) as fundamental frequency.

Still, the frequency content of the response is not according to the reality and the same information on the low frequencies is achieved. To include complex response due to the structure a higher order model is simulated: each structural panel is considered a three degrees of freedom system together with a two degrees of freedom system for the air resulting in a nine degrees of freedom for the whole system.

As consequence of considering a higher frequency content in the leaf model, the frequency content of the whole structure is also increased at low frequencies. As in the previous models, the predicted fundamental frequency of the system is lower than the mass air mass resonance far from the highest and stiffest limit, but in this model, the coupling between both structural elements leads to additional resonances in the low frequency range, as the one between the two *in vacuum* ones as depicted in Figure 7, that is according to the measured response in such systems.

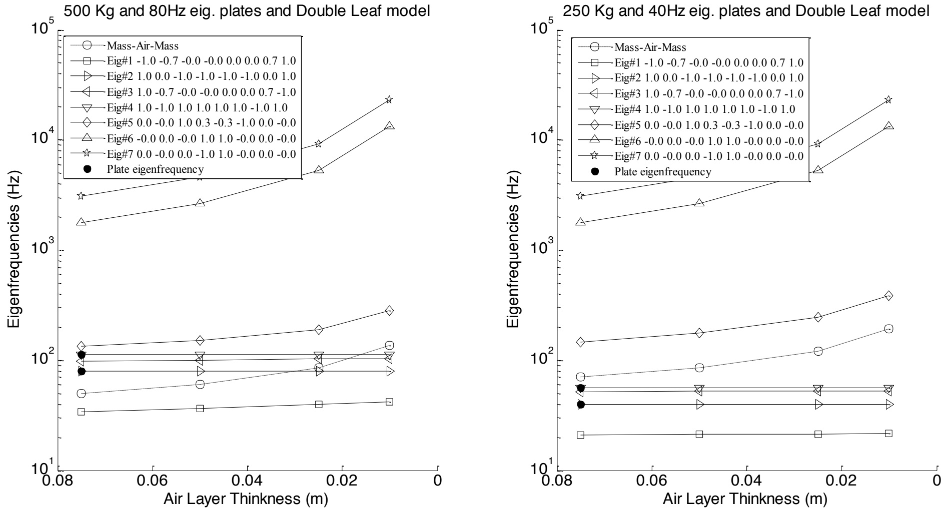

Figure 7. Eigenfrequencies of double leaf structures through a model considering each panel as three degrees of freedom systems and the air as a two degrees of freedom system for two structures: structural panels with 80 Hz (left) and 40 Hz (right) as fundamental frequency.

As Figure 7 shows, the complexity of the response of the system is highly driven by the level of complexity considered in the structural model. The analysis of a model considering the three degrees of freedom model for the leafs and a simpler model for the air between them (one degree of freedom) is shown in Figure 8

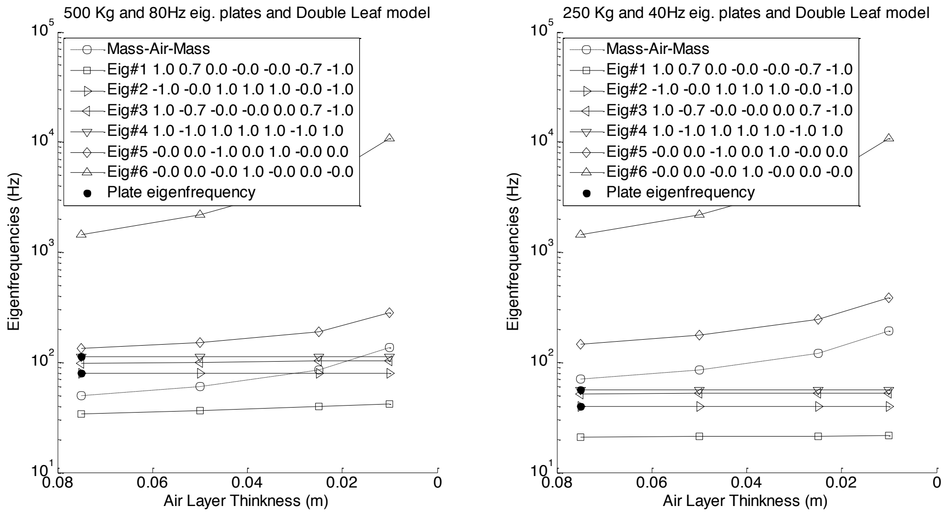

Figure 8. Eigenfrequencies of double leaf structures through a model considering each panel as three degrees of freedom systems and the air as a single degree of freedom system for two structures: structural panels with 80 Hz (left) and 40 Hz (right) as fundamental frequency.

The results in the low frequency range is equivalent to the same model considering more complexity in the air modelling, showing that the parameter in the models is the complexity on the structural domain. Further analysis can be performed considering a two dimensional model for the panels through FE in order to deep in the behaviour of the system although it is beyond the scope of this work.

CONCLUSIONS

The analysis of double leaf structures use to assume a high stiffness of the structural elements leading to the appearance of the so called mass-air-mass resonance. This work shows that even considering this resonance to define the behaviour of the air between the wall-leafs the fundamental frequency of the system is not, in general, equal to this value. The present industrial trend to lighten up the structures leads to a scenario in which the fundamental frequency, as has been shown, falls quite below the assumed value.

To study qualitatively the response of these systems, a set of discrete models have been presented showing the effects of the model complexity in the scope of the results obtained. Analysing two structures of different stiffness and mass the general influence of the distance between leafs has been identified: although for heavy structures the fundamental frequency increases as the distance decreases for lighter structures it is quite less sensitive to the air layer thickness.

The comparative analysis of the simulated response predicted by the several models (3/2/3 dof model versus a 3/1/3 dof one) has allowed identifying the complexity of the structural model to be the critical parameter in order to provide a complex response of the system. From this it follows that a higher complexity model for the structure (as a FE two-dimensional model) would provide significant insight in the behaviour of the system.

It should be stated that, if the frequency range is to be extended to lower frequencies, the first resonance (or mode) that will likely appear will be the cavity resonance, but if the lower limit goes down to 50 Hz appearance of other modes that will increase the transmission in its vicinity should turn up as well so that the traditional method to estimate sound transmission loss of this kind of elements should be modified accordingly.

REFERENCES

1. Fahy, F.; Gardonio, P. "Sound and Structural Vibration. Radiation, Transmission and Response". 2ª ed. Oxford, UK. Academic Press. 2007
2. Chimeno-Manguán, M.; Martínez-Calvo, B.; Roibás-Millán, E.; Fajardo, P.; Simón, F.; López-Díez, J. "Comparison of numerical models for vibro-acoustic analysis of structural panels in low modal density range engaging air layers". Proc. '12th European Conference on Space Structures, Materials & Environmental Testing' Noordwijk, Holanda. 2012.
3. López-Díez, J.; Simón, F.; Chimeno-Manguán, M.; Wijker, J.J. "Influence of gap thickness on the vibroacoustic response of satellite solar panels". internoise 2010. Lisboa, Portugal. 2010.