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HIGH FREQUENCY PLATE RADIATION BY POWER FLOW ANALYSIS WITH EXPERIMENTAL VALIDATION

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ABSTRACT
This paper deals with high frequency analysis of point excited fluid loaded plates. Acoustic and structural energy densities are calculated by a power flow approach. Coupling between subsystems is characterized by local power exchanges. Three radiation mechanisms are involved in these exchanges: radiation of supersonic waves, radiation from edges and direct radiation from the excitation point. These radiation processes induce local energy losses for the panel. They correspond to power sources for the acoustic. Using an integral power flow approach, energy fields are derived and compared to frequency averaged experimental results.

1 - INTRODUCTION
Radiation of structures is a crucial matter in the industry because of the increasing importance of the acoustic comfort. Nevertheless, the audible frequency range often lies above the classical approaches possibilities. Statistical Energy Analysis [1] was developed as an alternative method for high frequencies, and was extensively applied to vibroacoustic problems. Working with energy variables, this approach matches well with averaged measured datas when fields are diffuse enough. Exterior space radiation is a problem of practical importance where acoustical fields are not diffuse.
The power flow analysis describing energy and power flow densities inside the subsystems does not need the diffuse field assumption, since a local description is achieved. Starting with the local power balance, energy kernels for structures and acoustics are determined and used in a boundary integral formulation [2]. The coupling between plates and acoustical media is characterized by local power exchanges, depending on the frequency: when structural waves are subsonic (i.e. below the so-called critical frequency), radiation is located on structural discontinuities. Diffraction phenomena give rise to boundary acoustical power sources (edges and excitation points are reported in this paper). Discontinuities act as dissipative elements for the structural energy. In the supersonic frequency range the radiation of the whole surface of the plate should also be considered. Boundary power sources are thus located on the whole surface and structural energy losses are taken into account by a continuous damping factor.
Section 1 deals with the calculation of power exchanges involved in radiation process. Realistic directivities of the power being radiated are determined, allowing an accurate description of the acoustical energy field. The energetic calculation is detailed in Section 2. In Section 3 an experimental validation is performed with an unbaffled free plate.

2 - POWER BALANCE FOR RADIATION
Using the locality principle valid for high frequencies, we assume that radiation phenomena may be characterized with isolated parts of the system and then introduced in the whole system resolution. Edge, excitation and propagative waves radiations are successively calculated. The fluid density is ρ and the fluid wavenumber k. The fluid loaded plate propagative wavenumber is noted k_s, and the plate stiffness D. The pulsation is ω.

2.1 - Edge radiation
Consider a structural wave impinging the edge of a plate with an incidence θ_s. Reflection process produces sound radiation. The phenomenon depends strongly on the boundary conditions of the plate and the

acoustical medium. The fully coupled calculation requires the use of the Wiener-Hopf technique [3]. We propose here a simplified approach valid under the light fluid assumption. The calculation is performed using Fourier transform U of the in vacuo displacement field due to the impinging and reflected waves on the normal to the edge [4]. We note θ and φ the spherical angles around the edge line. The diffracted pressure corresponds to the branch cut contribution of the pressure Fourier integral and may be evaluated by the saddle method. The specific intensity in (θ, φ) direction is expressed in terms of the impinging structural flux I_s:

$$P_{rad}\left(\theta,\varphi\right)=\Sigma_{edge}\left(\theta_s,\theta\right)\delta\left(\varphi-\varphi_{rad}\left(\theta_s\right)\right)I_s \qquad \text{with} \qquad k\text{cos}\varphi_{rad}=k_s\text{sin}\theta_s \tag{1}$$

and the edge radiation efficiency:

$$\Sigma_{edge}\left(\theta_s,\theta\right)=\frac{4\pi\rho\omega^2}{k}\frac{\left|U\left(K\text{sin}\theta\right)\right|^2}{\Re\left(D\left(k_s^3+k_s^2k_s^*\right)\right)}$$

The energetic structural reflection coefficient must take into account the part of power being diffracted:

$$R\left(\theta_s\right)=1-\int_{-\pi/2}^{\pi/2}\Sigma_{edge}\left(\theta_s,\theta\right)d\theta \tag{2}$$

2.2 - Excitation radiation

The plate is excited by a point force or moment. The same analysis as in the previous calculation is performed using the point drive impedance Y (instead of U) to describe the response of the fluid loaded infinite plate [5]. The diffracted specific intensity deriving from the saddle point contribution is expressed in spherical coordinates in terms of the injected power P_{inj}:

$$P_{rad}\left(\theta\right)=\Sigma_{exci}\left(\theta\right)P_{inj}$$

with excitation radiation efficiency:

$$\Sigma_{exci}\left(\theta\right)=\frac{\rho\omega k}{4\pi^2P_{inj}}\left|Y\left(k\text{sin}\theta\right)\right|^2 \tag{3}$$

The power being supplied to the fluid loaded plate system is the sum of the diffracted power and the power injected in the plate: P_{inj}=P_{struc}+P_{rad}. The term P_{struc} is calculated by expressing the structural flux carried by the propagative travelling waves. Writing the residue contribution of the propagative pole k_s in the displacement integral and using asymptotic expressions of the Hankel function, the power supplied to the plate is obtained:

$$P_{struc}=\frac{\omega\left(\left|F\right|^2+\left|k_sM\right|^2\right)}{16Dk_s}\left|1-j\frac{\rho\omega^2}{4D}k_s^{-2}\left(k^2-k_s^2\right)^{-3/2}\right|^{-2} \tag{4}$$

2.3 - Supersonic waves radiation

The power radiated by a supersonic travelling wave is derived in equation (5). Substituting the propagative forms of displacement and pressure in the fluid loaded infinite plate equations, the directional specific intensity may be expressed in terms of structural power flow carried by the travelling wave. φ denotes the spherical angle with the normal to the plate.

$$P_{rad}\left(\varphi\right)=\Sigma_{surf}\delta\left(\varphi-\varphi_{rad}\right)I_s \qquad \text{with} \qquad \text{sin}\varphi_{rad}=k_s/k \tag{5}$$

and with the surface radiation efficiency

$$\Sigma_{surf}=\frac{\rho\omega^2\Re\left(\left(k^2-k_s^2\right)^{1/2}\right)}{\left(k^2-k_s^2\right)\Re\left(D\left(k_s^3+k_s^2k_s^*\right)\right)}$$

This proportionality relation shows that continuous radiation is a loss of structural energy corresponding to a damping factor: $\eta_{rad}=c_s\Sigma_{surf}/\omega$ (6), c_s being the group velocity.

3 - DERIVATION OF ENERGY MODEL

Energy calculation is derived using a power flow integral approach. This method is an alternative to the EFEM [6] and was successfully developed for 1D, 2D and 3D systems, and for coupling between systems of the same dimension [2]. It is here devoted to vibroacoustic coupling. Energy and power flow kernels (noted G and $\boldsymbol{H}$) are used to describe the fields inside the subsystems: assuming that propagative fields are uncorrelated, the linear superposition principle is applied on energy variables. Energy and power flow densities are the sum of direct contributions emanating from sources ρ inside the system, and diffraction contributions coming from source σ located on the boundaries:

$$W(M) = \int_{\Omega} \rho(S)\, G(S,M)\, dS + \int_{\delta\Omega} \sigma(P)\, G(P,M)\, dP \qquad \text{with} \qquad G(r) = \frac{e^{-mr}}{c\gamma_0 r^{n-1}}$$

Kernel expressions depend on the dimension n of the systems. m is the attenuation factor, c is the group velocity and γ_0 is the solid angle of space. Kernels are solution of the local power balance for point excited infinite systems.
Structures are first solved taking into account the dissipation phenomena due to radiation (eq. 2,4,6) and corresponding to the previous local problems. Then acoustical media are calculated using the expressions of the determined directional radiated intensities (eq. 1,3,5).

4 - EXPERIMENTAL VALIDATION

An experiment was performed in an anechoic chamber (Fig. 1). The plate is 1m large and long, 1.5mm thick, in aluminum. Its critical frequency in air is 4kHz. It is excited by a shaker with an impedance head in order to measure the power being injected in the structure. Energy acquisitions are performed on several points of the plate by a laser velocimeter. Three microphones were used to measure acoustical energy. Acquisitions are performed in sweep sine starting at 3.2kHz and covering 2 octaves (up to 12.8kHz). Two series of acoustical measures are performed, corresponding to microphones lying parallel or normal to the plate (Fig. 1).

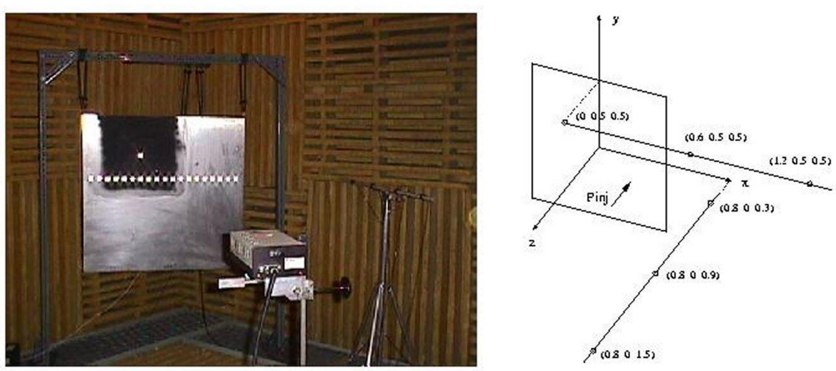

Figure 1: Experimental device.

Measured datas are averaged over several acquisitions and by 1/9 octave band (Fig. 2).

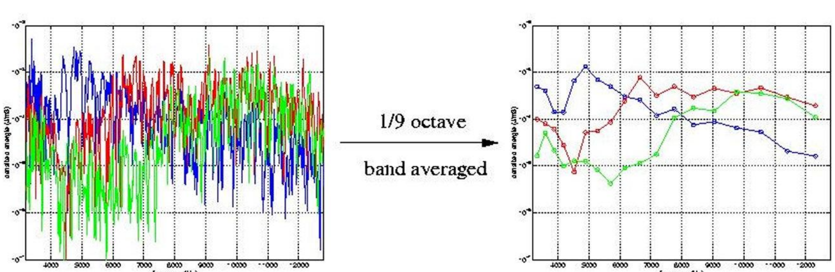

Figure 2: Experimental datas exploitation.

For both microphone positions, power flow calculations are compared to experimental datas and display a very good correlation (Fig. 3). It is remarkable that variations of acoustical energies strongly depend on the location of the microphones and that this dependence is well predicted by the model. Spatial repartition is thus well described by the power flow analysis.

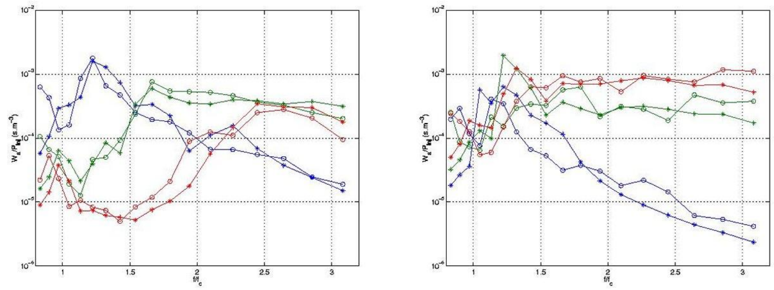

Figure 3: Frequency variations of acoustical energies for the 3 microphones of both antenna positions; -o- experimental; -*- calculated.

5 - CONCLUSION

Efficient description of non diffuse radiated acoustical energy fields is obtained by integral power flow method, using different kinds of realistic boundary power sources.

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