Active Structural Acoustical Control

This section illustrates the situation of shell structures with embedded piezoelectric actuators and sensors where they are nearly colocated. It, once again, stresses the importance of membrane components on the zeros of the frequency response function and suggests means of improving the performance when anisotropic piezoelectric material is used. The use of array sensors for modal filtering and volume velocity sensing is also considered.

ASAC plate

The *ASAC* plate[1] (Active Structural Acoustical Control) is a volume velocity control device based on the principle of the *QWSIS* sensor. The QWSIS sensor is based on the discretization of the plate sensor into narrow *strips* of width Δ (Fig.1); each strip is considered as a beam covered with piezoelectric material with quadratically shaped electrodes.

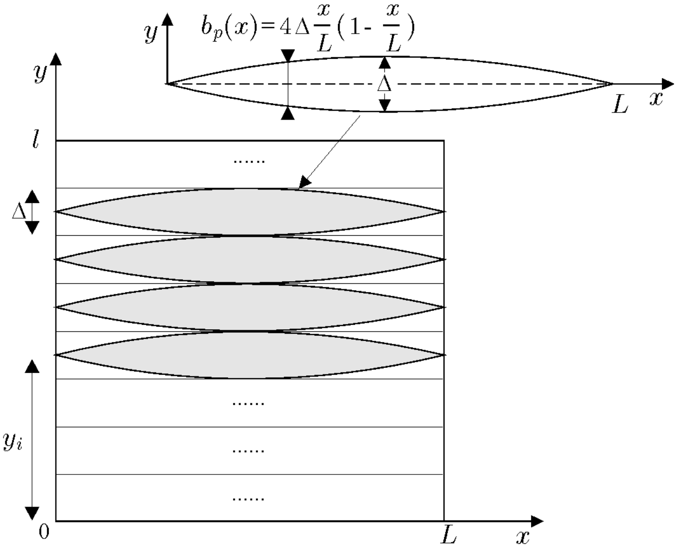
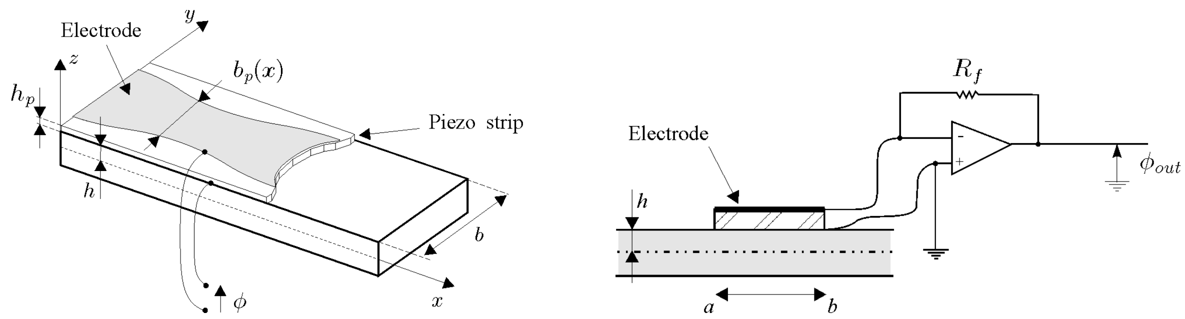


Figure 1: Discretisation of the active plate into narrow quadratic devices

The *ASAC* plate is covered on both side with piezoelectric material; the quadratic shaping of the electrodes does not only provide a volume velocity sensor, but also a uniform pressure actuator as a consequence of the duality of actuation and sensing properties of piezoelectric devices.

[1] The ASAC panel was developed and built under the Research Project *DAFNOR*



(a) Piezoelectric film on a beam structure (b) Current amplifier

Figure 2: Piezoelectric beam device

For a piezoelectric beam sensor of quadratic shape, the output signal of a current amplifier (Fig.2(b)) is proportional to the volume velocity of the beam.

$$\phi_{out}(t) = -8e_{31}R_f\frac{h}{L^2}\int_0^L \dot{w}(x)\;dx \div V_{vol}$$

Similarly, a beam actuator with an electrode of quadratic shape is equivalent to a uniform distributed load acting along the beam.

$$F_0 = e_{31}\phi\, b_p''(x)\, h$$

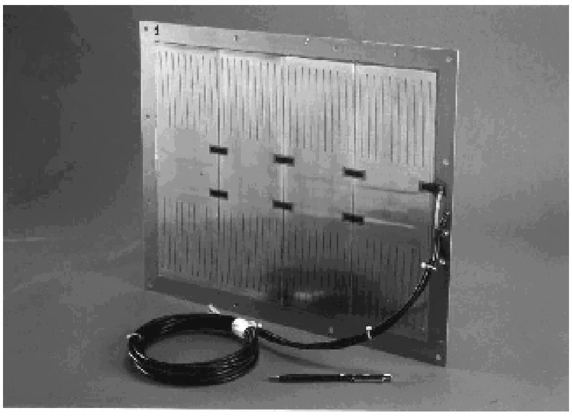


Figure 3: *ASAC* experimental setup

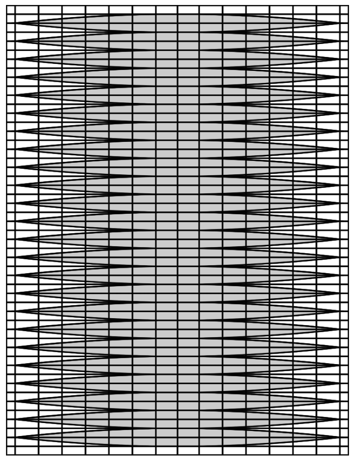


Figure 4: *FE* mesh

The main idea behind the *ASAC* panel is to realize a perfectly colocated actuator/sensor pair to control the volume velocity. The control system consists in a clamped 1 mm thick plate of aluminium (420 mm×320 mm) covered on both sides with 0.5 mm thick piezoelectric *PVDF* films (400 mm×300 mm). For the actual laboratory model (Fig.3) the actuation and sensing layer electrodes consist of 24 strips. The material properties are summarized in Table 1. The direction of smaller piezoelectric coupling coefficient (e_{32}) is perpendicular to the strips. The finite element mesh is shown on Fig.4.

Aluminium		
Y	71	(GPa)
ν	0.3	
ρ	2800	(kg/m^3)
PVDF		
Y	2.7	(GPa)
ν	0.29	
ρ	1800	(kg/m^3)
d_{31}	1.8 10^{-11}	(Cb/N)
d_{32}	0.3 10^{-11}	(Cb/N)
ε_r	2600	

Table 1: Material properties

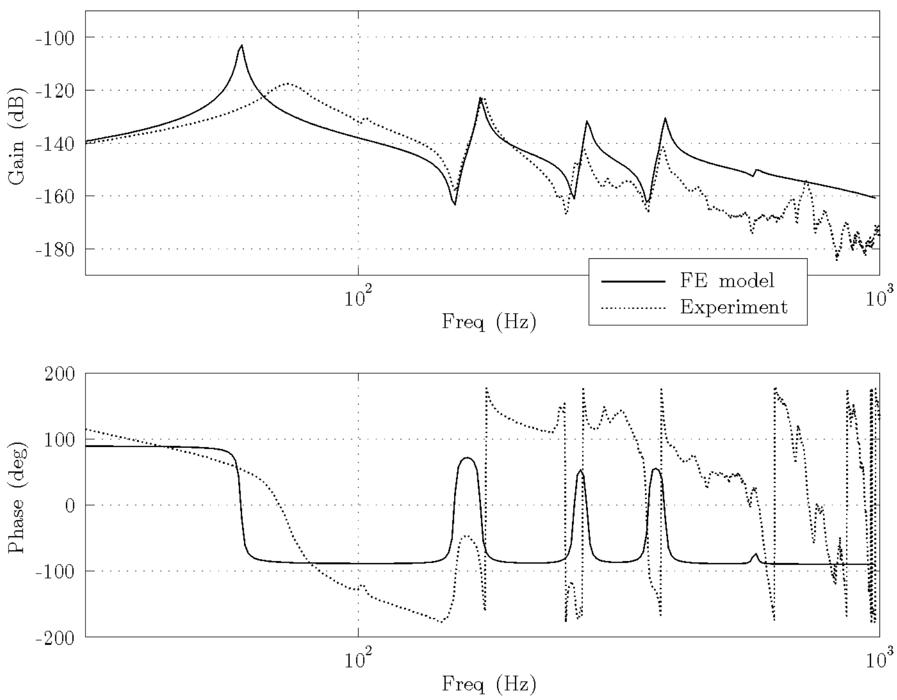


Figure 5: *ASAC* plate: Sensing

Figure 5 shows the comparison between the experiment[2] and the *FE* analysis for the plate used as a volume velocity sensor; the frequency response function between an incident sound pressure (provided by a loudspeaker in the experiment and assumed to be a uniform pressure in the *FE* analysis) and the volume velocity sensor signal is represented.

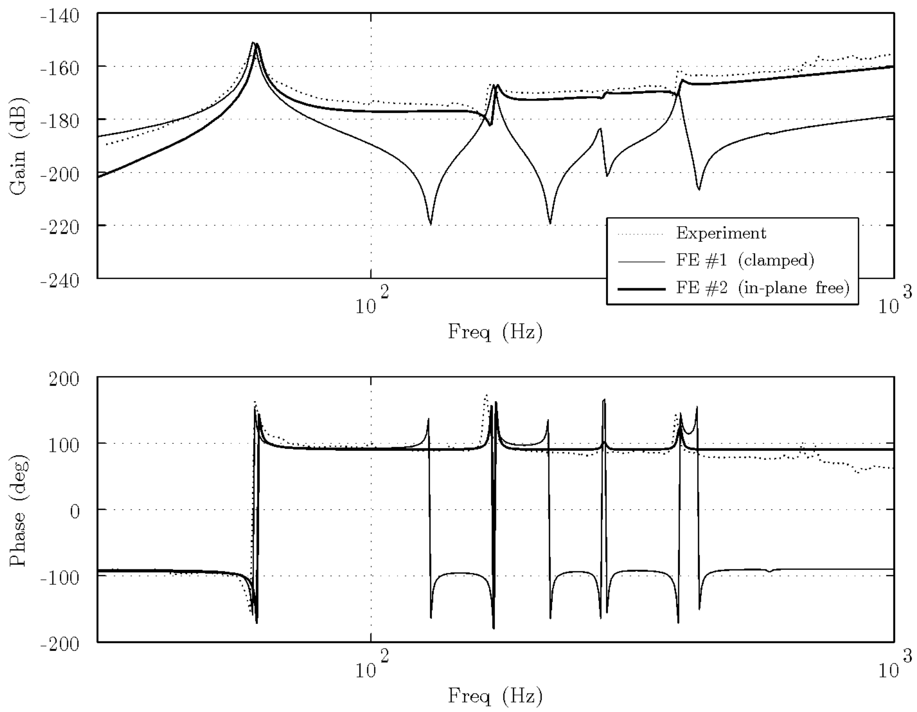


Figure 6: Open loop frequency response functions of the *ASAC* plate

The panel was next considered as a control device; the open-loop frequency response function between actuator and sensor was determined experimentally[2] and is shown on Fig.6 (dotted lines). Since the performance of the control system is to a large extend related to the distance between the poles and the zeros of the open-loop frequency response function, these results were considered as disappointing, contrary to simplified analytical predictions which indicated far better performances (Gardonio et al., 1999). At first, this lack of performance was attributed to imperfect alignment of top and bottom layers (non colocated actuator/sensor pair) or to an electrical coupling due to the wiring.

In fact, the finite element based simulations have shown that this lack of controllability is actually due to local membrane effects (Piefort & Henrioulle, 2000), neglected in the first analytical models together with the static contribution of the unmodelled high frequency modes (also called *residual mode*).

In a first attempt to model the open-loop frequency response function of the *ASAC* panel

[2]Experimental datas kindly provided by Kris Henrioulle (KUL-PMA)

using finite elements, the agreement of results with the experiment was rather unsatisfactory (Fig.6, FE #1). It appeared soon that the boundary conditions were not those of a clamped plate: in the actual experiment, the plate was almost free to move in its plane. The in-plane movement of the plate results in an even stronger influence of the membrane components and, therefore, in a stronger in-plane mechanical coupling between actuator and sensor. This induces an important *feedthrough* term in the frequency response function: a substantial part of the strain induced by the actuator induces directly membrane strain in the sensor, without contributing to the transverse displacement which produces the volume velocity (useful control). The frequency response function of (Fig.6, FE #2) was obtained by freeing the in-plane movement of the plate in the finite element model; it shows a very good agreement with the experimental result.

The influence of the residual mode on the open-loop frequency response function is illustrated on Fig.7 for the two considered boundary conditions above (*perfect clamp* and *in-plane free*). The first twenty eigenmodes were extracted from the dynamic analysis and taken into account for the state space representation. The influence of the residual mode is independent of the frequency and introduces an important feedthrough component in the frequency response function. By not taking it into account, the in-plane coupling is almost completely washed out (because in-plane vibration modes are quite higher in frequency, outside the bandwidth, and therefore unmodelled) leading to an incorrect prediction of the control system performances.

Note that, in the current design, the in-plane coupling is particularly strong because the direction of higher piezoelectric effect ($e_{31} \gg e_{32}$) for the sensor and the actuator are parallel; the most important strain is induced in a direction parallel to the direction of the strips and the sensor has the highest sensitivity to the strain in the direction of the strips. The actuation and sensing strips being layed in the same direction for the $ASAC$ plate, it is in the worst possible configuration. However, for the actuator and the sensor taken separately, the direction of the strips has no influence on their characteristics. From this observation, the idea raised that the feedthrough component could be substantially reduced by using sensor and actuator strips perpendicular to each other.

Alternative *cross-ply* design of the $ASAC$ plate

In the current design, the in-plane strain induced by a voltage ϕ in the direction of the highest sensitivity of the sensor (e_{31}) is directly related to $e_{31}\phi$ while the in-plane strain induced in the direction of the lowest sensitivity of the sensor (e_{32}) is directly related to $e_{32}\phi$; neglecting the *Poisson* effect, we have a feedthrough factor related to $e_{31}^2 + e_{32}^2$. In a *cross-ply* design, this feedthrough factor would be related to $2e_{31}e_{32}$; assuming a piezoelectric anisotropy ratio χ ($e_{32} = \chi e_{31}$), an in-plane feedthrough term reduction of about $2\chi/(1+\chi^2)$ can be expected, which may be substantial for small χ ($\chi = 0.2$ is a common typical value).

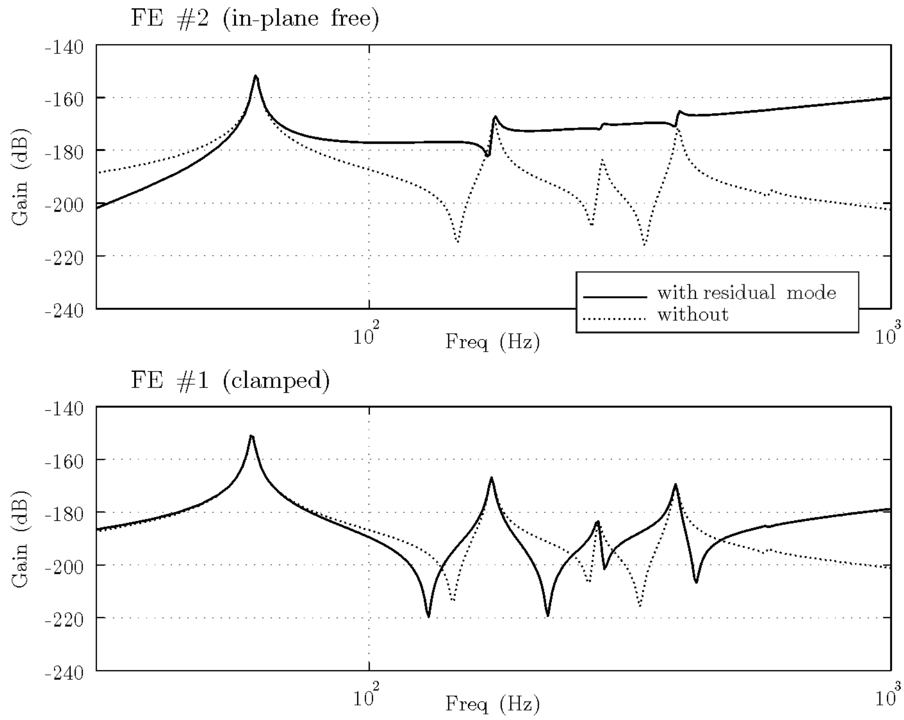


Figure 7: Effect of the residual mode (in addition to the 20 modelled modes) on the predicted open-loop frequency response functions

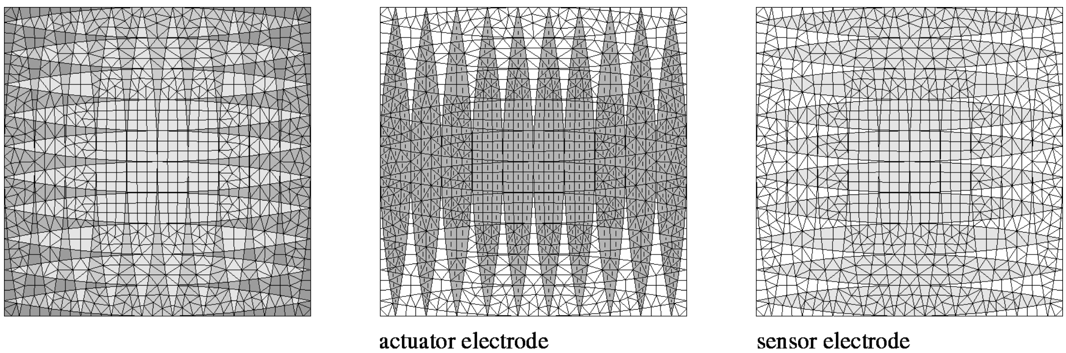


Figure 8: *FE* mesh

By using sensor strips perpendicular to the actuator strips, the control device would then exhibit a *cross-ply* actuator/sensor architecture and the in-plane feedthrough term would be greatly reduced. The *FE*-based tools allow to modelize such architectures quite easily and to extract the corresponding frequency response functions to verify if this alternative is any better. The mesh used is represented on Fig.8; the sensor electrode forms a right

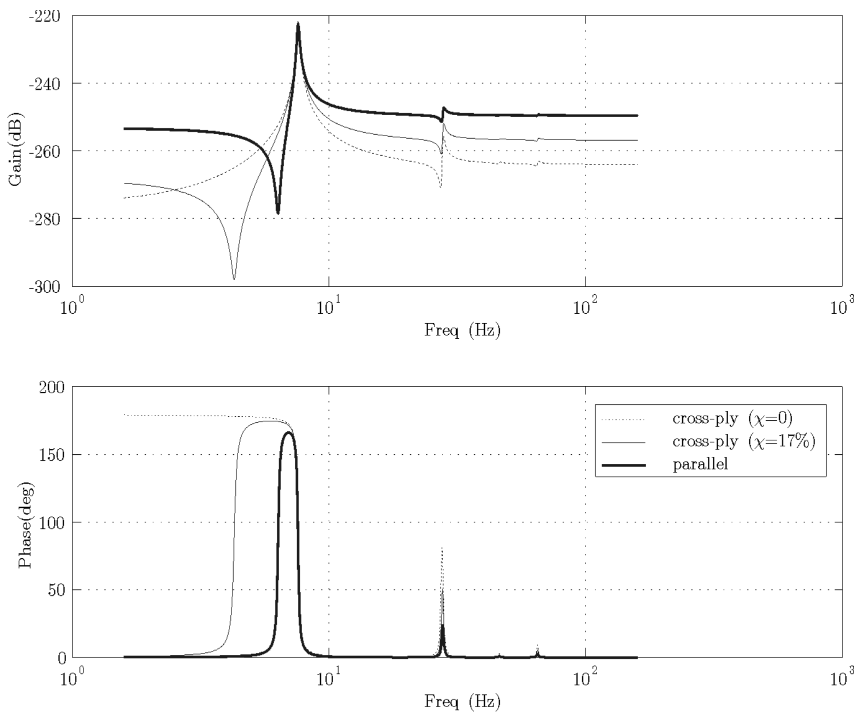


Figure 9: Open-loop frequency response functions

angle with the actuator electrode. The comparison of the frequency response functions between the voltage applied to the actuator layer and the charge measured on the sensor layer for the *parallel* and *cross-ply* architectures for two piezoelectric anisotropy ratios are represented on Fig.9.

Indeed, the distance between the poles and zeros of the frequency response function is much larger for the cross-ply configuration, as compared to the parallel configuration, and the distance increases when the piezoelectric anisotropy ratio χ of the material decreases. As a result, improved closed-loop performances may be expected from the cross-ply design.

References

Gardonio, P., Lee, Y., Elliott, S. & Debost, S., 1999, 'Active control of sound transmission through a panel with a matched PVDF sensor and actuator pair', Active 99, Fort Lauderdale, Florida, USA.

Piefort, V. & Henrioulle, K., 2000, 'Modelling of smart structures with colocated piezoelectric Actuator/Sensor pairs: Influence of the in-plane components', 5th International Conference on Computational Structures Technology, Leuven, Belgium.