ACOUSTIQUE. — *Contrôle actif des oscillations dans les cavités excitées par un écoulement.* Note, à langue dominante anglaise, de **Michel Sunyach** et **John. E. Ffowcs Williams,** présentée par Robert Dautray.

Cette étude concerne la suppression par contrôle actif des oscillations résultant de l'interaction entre un écoulement et une cavité. On propose tout d'abord un schéma théorique du système. On montre ensuite dans une expérience que le concept d'absorption acoustique active est effectivement applicable à ce type de problème. Le bruit émis à fréquence pure est complètement éliminé et il est possible d'obtenir une atténuation à large bande à l'intérieur de la cavité.

ACOUSTICS. — The active suppression of oscillation in flow-excited cavities (mostly in English Language).

The paper outlines a simple theory for suppressing flow-excited cavity oscillations by active means. Early experiments confirm the validity of the concept that techniques of antisound are applicable to this class of problem. The tonal response was completely cancelled and some wide-band attenuation also demonstrated.

Les phénomènes instationnaires liés à l'interaction entre un écoulement et une cavité affleurante jouent un rôle fondamental en aéroacoustique. Cette interaction s'effectue par l'intermédiaire de la couche de cisaillement qui sépare la cavité de l'écoulement (fig. 1). *Le mécanisme de base est la stimulation mutuelle entre les modes acoustiques de la cavité et les instabilités à large bande de la couche de cisaillement.*

Pour modéliser le contrôle actif des oscillations produites, le point de départ est le calcul classique du résonateur d'Helmholtz dans lequel on introduit outre le débit du haut-parleur de contrôle, des termes complémentaires liés à la présence de l'écoulement. Un modèle élaboré de la différence de pression S *q qui se développe de part et d'autre de l'ouverture peut être utilisé* [3]. *On obtient alors l'expression* (4) *qui relie la pression p_i à l'intérieur de la cavité à la pression turbulente p_t au-dessus de l'ouverture. Cette expression permet de mettre en évidence l'effet destabilisant de l'écoulement en raison des valeurs prises par la fonction* S [*modification du dénominateur de* (4)]. *Par opposition, certaines valeurs de la fonction de transfert* Z *du contrôleur ont un effet stabilisant et il existe une solution simple et causale pour laquelle la pression interne p_i est égale à la pression turbulente p_t ce qui annule l'effet de la cavité.*

Les résultats de l'expérience schématisée sur la figure 1, *confirment l'analyse effectuée. On a examiné successivement les deux cas pour lesquels le microphone de référence est placé à l'extérieur de la cavité* (fig. 2), *puis à l'intérieur de celle-ci* (fig. 3). *Dans les deux cas, un simple retard généré par le contrôleur suffit à éliminer les composantes à fréquences pures, et donne* 25 *dB d'atténuation pour le fondamental* (140 *Hz*). *Pour le cas du bruit à l'intérieur de la cavité* (fig. 3), *on peut remarquer que la fonction de transfert utilisée n'est pas suffisamment élaborée pour obtenir une réduction du bruit sur toute la bande de fréquences. Cependant un effet important est déjà obtenu au voisinage du troisième harmonique.*

La conclusion générale de l'étude est que les méthodes d'absorption acoustique active fournissent un moyen efficace pour contrôler les interactions entre les ondes acoustiques et les écoulements.

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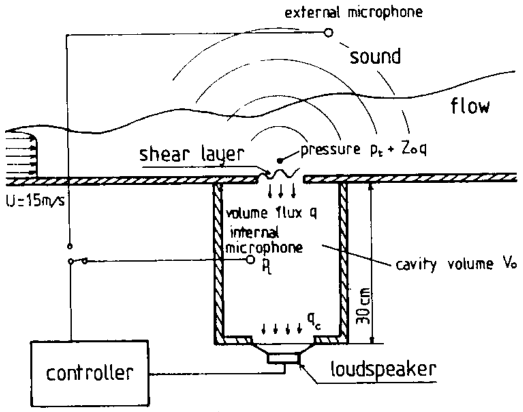

Fig. 1

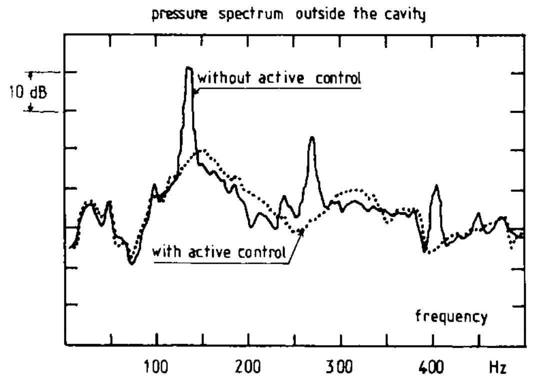

Fig. 2

The unsteady flow in and near cavity-type geometries forms an intricate variety of aero-acoustic phenomena, some pleasantly musical and others an irritating nuisance. The various forms of whistles and woodwind instruments are in this class, as are the buffeting oscillations inside a car with an open roof. The screeches that sometimes occur when flow moves at high speed over the open wheel bays of an aircraft or through a slotted wall wind tunnel are technologically significant examples of this familiar problem.

The distinctive feature of these oscillations is that the broad-band instability of the mean flow's vortex layer is preferentially stimulated by the modal cavity response which in turn is energized by the excited instability. When there is more energy transferred into the mode from the shear layer than is lost by damping, the response amplitude grows, exponentially according to linear theory, eventually settling down into a limit cycle of period close to that of the natural cavity oscillation. Turbulence is also generated which additionally excites the cavity with a broadband disturbance to induce a response whose frequency distribution also reflects the cavity's modal structure. Some of the modal damping is the acoustic field which radiates away a sound that reflects the higher response levels of weakly damped cavity modes.

The detailed modelling of these shear-layer-excited cavity oscillations is an extremely complicated matter, too complicated in fact to be feasible in anything other than the most idealized conditions. Both the turbulence and the non-linear wave diffraction aspects of the problem are classically difficult problems of mechanics. None-the-less, great strides have been made, both theoretically and experimentally [1], with model problems which have helped characterize the essential qualitative elements of the problem; the parameters governing the boundaries of the various behavioural regimes are well known, but it is still not easy to arrange flows near cavities in such a way that makes them immune from cavity resonances.

The fact that small amplitude unsteady cavity responses are an essential ingredient of the oscillation, and the knowledge that weak disturbances could alternatively be generated artificially by other means, made us wonder about the possibility of neutralizing the natural response by the controlled stimulation of its phase-inverted opposite number. This is the technique of noise control by anti-sound [2]. Can these techniques be applied to stabilize the flow excited system and to maintain quiescent conditions within the cavity? Our theoretical modelling indicates a clearly positive answer and our initial experiments confirm that conclusion. We give a brief outline of both in this short note.

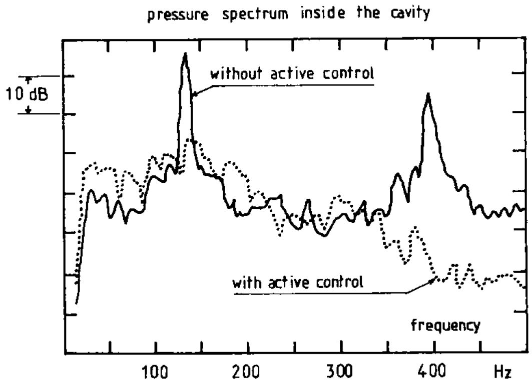

Fig. 3

The cavity-area averaged pressure in the stream outside the cavity is a superposition of turbulent and cavity —induced components, p_t and $Z_0 q$ respectively, q being the volume flux through the cavity opening (*Fig.* 1). The bottom of the cavity is fitted with a loudspeaker which induces there a volume flux q_c linearly related to the assumed uniform pressure p_i inside the cavity. The controller transfer function p_i to q_c is Z, a general complex function of frequency. Our design task is to select Z so as to enhance the stability of the system and minimize noise within (and also outside) the cavity.

The pressure difference across the cavity opening will be a linear function of the flux. We denote that function by Sq, S being a complex function of frequency equal to $\rho_0 i\omega/l$ in the absence of flow, l being the representative dimension of the opening.

$$(1) \qquad p_t + Z_0 q - p_i = S q.$$

The internal pressure rises in the cavity at a rate equal to $\rho_0 c^2/V_0$ times the entering volume flux, $q - q_c$,

$$(2) \qquad i\omega p_i = \frac{\rho_0 c^2}{V_0}(q - q_c).$$

The control law

$$(3) \qquad p_i = Z q_c$$

completes the information needed to relate p_i to p_t.

$$(4) \qquad p_i = \frac{p_t}{\{1 + [(S - Z_0)/Z] + (S - Z_0)(i\omega V_0/\rho_0 c^2)\}}.$$

The (no-flow) Helmholtz resonator result is found when $Z = \infty$, Z_0 is negligible and $S = \rho_0 i\omega/l$; unforced ($p_t = 0$) internal pressure fluctuation can only occur at frequencies such that the denominator vanishes i.e. $\omega^2 = lc^2/V_0$. The small real part of Z_0 will provide the modal damping which ensures the finiteness of the internal pressure induced by turbulent forcing.

The effect of flow is to change the form (*cf.* [3]) of S, in particular giving it a real part that can be the opposite of that in Z_0 which is the natural damping element in the system. As flow increases the real part of $(S - Z_0)$ eventually changes sign and the uncontrolled ($Z = \infty$) system become unstable. But the instabilities can be avoided with control and there is considerable freedom in the choice of control strategy. If for example Z were arranged to be $-\rho_0 c^2/i\omega V_0$ then $p_i = p_t$ and $q = 0$. This constitutes a totally stable system diffracting none of the turbulence sound; that controller is also causal.

The denominator in 4 describes the system performance. The greater its magnitude at the real frequencies, the smaller will be the cavity noise. The zeros of the denominator control the system stability and the zeros of Z determine the realizability of the control system. Stability and causality requires that those zeros all lie in the upper half of the complex plane. i. e. $\omega=\omega_i+i\omega_i$ with $\omega_i>0$. Natural cavity oscillations correspond to cases where the $(Z^{-1}=0)$ value of the denominator in (4) has zeros with $\omega_i<0$. It is easy to choose Z to avoid this possibility, simply turn up the gain (make $|Z^{-1}|$ large) so that the second term in the denominator of (4) is dominant, and vary the phase; so moving the zeros around the complex ω plane. In this way it will be possible to stabilize any particular mode. Other modes may of course be destabilized in that process but our experiments confirm our view that this is not inevitable. The high gain that ensures $|(S-Z_0)/Z|$ is much greater than $|1+(i\omega V_0/\rho_0 c^2)|$ also ensures a broad band attenuation of cavity noise, again a feature we found in our experiments.

Our experimental arrangement is illustrated in Figure 2; the flow-excited cavity resonance was the dominant sound in the laboratory. We experimented with two microphone and control arrangements, the first corresponding to the foregoing theory and the second taking signals from an external microphone. The results of these experiments are shown in Figures 2 and 3. The main points demonstrated in these experiments were:

1. Flow-excited cavity resonances can be suppressed by controlled loudspeaker movements.
2. Stabilization can be achieved over a wide range of phase and amplitude settings.
3. Broad-band suppression of the noise interior to the cavity is also possible.
4. Minimizing the interior cavity noise is a different constraint from minimizing exterior noise; both are achievable.

Our conclusions are therefore that anti-sound techniques definitely provide an interesting and versatile means for modifying flow-induced cavity resonances and their associated noise, both periodic and broad band. It is probable that these techniques will allow their more controlled study in future and may lead to technologically significant schemes for suppressing their deliterious effects. The consistency between our theoretical model and experiment, though both are still extremely rudimentary and tentative, leads us to expect that significant benefits will come from their careful and systematic development.

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REFERENCES

[1] D. ROCKWELL and E. NAUDASCHER, Review—Self sustaining oscillations of flow past cavities, *Transactions of the A.S.M.E.*, 100, 1978, pp. 152-165.

[2] J. E. FFOWCS WILLIAMS and C. F. ROSS, *Anti-Sound*, Oxford University Press, 1986 (in preparation).

[3] M. S. HOWE, The influence of mean shear on unsteady aperture flow, with application to acoustical diffraction and self-sustained cavity oscillations, *J. Fluid Mech.*, 109, 1981, pp. 125-146.

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