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C. R. Mecanique 331 (2003) 423–429

Comptes Rendus Mecanique

Direct noise computation of adaptive control applied to a cavity flow

Olivier Marsden [*], Xavier Gloerfelt, Christophe Bailly

LMFA, UMR CNRS 5509, École centrale de Lyon, 69134 Ecully, France

Received 17 April 2003; accepted 29 April 2003

Presented by Geneviève Comte-Bellot

Abstract

The Large Eddy Simulation of closed-loop active flow control applied to a 3D cavity excited by a compressible airflow with a Mach number of 0.6 is presented. The control actuator is an idealized synthetic jet located at the upstream cavity edge, and the control function is supplied by a feedback *LMS*-type algorithm whose input is a pressure signal measured inside the cavity. The radiated sound, provided directly by the LES simulation, was shown to decrease substantially when active control was applied. A simultaneous reduction of the vertical velocity fluctuations in the shear layer was observed. The intensity of vortical structures inside the cavity was also reduced, although the general aspect of the recirculation zone was not modified. The direct noise computation technique, which supplies the pressure field by solving the fluid mechanics equations, is shown to constitute a powerful tool for studying active aeroacoustic noise control. ***To cite this article: O. Marsden et al., C. R. Mecanique 331 (2003).***

Résumé

Simulation directe de l'atténuation par contrôle adaptatif du rayonnement d'une cavité affleurée par un écoulement. Le contrôle actif adaptatif appliqué à une cavité 3D soumise à un écoulement avec un nombre de Mach de 0,6, est mis en œuvre numériquement en réalisant une Simulation des Grandes Echelles compressible. L'actionneur de contrôle est un jet synthétique très simplifié placé au coin amont de la cavité, et le contrôle se fait par un algorithme en boucle fermée de type *LMS*, avec pour entrée un signal de pression mesuré dans la cavité. Le bruit rayonné, calculé directement par la simulation, diminue de façon notable lorsque le contrôle actif est appliqué. L'intensité des structures tourbillonnaires dans la cavité est également réduite, bien que l'allure de la recirculation soit préservée. L'intégration d'un système de contrôle au solveur du calcul direct du bruit est donc possible, et constitue un moyen efficace pour étudier le contrôle actif du bruit d'origine aéroacoustique. ***Pour citer cet article : O. Marsden et al., C. R. Mecanique 331 (2003).***

Keywords: Acoustics; Waves; Vibrations; Adaptive control; Computational aeroacoustics; Cavity noise

Mots-clés : Acoustique ; Ondes ; Vibrations ; Contrôle actif adaptatif ; Aeroacoustique numérique ; Bruit de cavité

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[*] Corresponding author.
E-mail address: olivier.marsden@ec-lyon.fr (O. Marsden).

doi:10.1016/S1631-0721(03)00096-2

Version française abrégée

Le bruit d'un écoulement affleurant une cavité est engendré par l'impact plus ou moins régulier de tourbillons sur le coin aval de celle-ci. Ce phénomène est rencontré très souvent dans l'industrie des transports terrestres et aériens, et à ce titre a fait l'objet de nombreux travaux de recherche. L'application aux cavités du contrôle actif, que cela soit avec un algorithme en boucle ouverte ou en boucle fermée [7,6] constitue un axe d'étude intéressant pour la réduction du bruit de cavité.

Ce travail présente une simulation numérique du contrôle basée sur un calcul direct du bruit par résolution des équations compressibles de Navier–Stokes. Le code de simulation utilisé est une version de ALESIA [9] consacrée aux écoulements de cavités tridimensionnelles [10]. L'objectif est de réduire le niveau de pression dans la cavité, et implicitement le niveau de bruit rayonné en champ lointain, en agissant sur le développement de la couche cisaillée.

Les notations utilisées sont présentées sur la Fig. 1. La cavité est décrite par un maillage 3-D, avec pour paramètres géométriques $L/D = 1$ et $L/W = 1{,}28$, où $L = 2$ mm. Le nombre de Mach de la couche limite laminaire amont est de 0,6, et le rapport $L/\delta_\theta = 57$. Le nombre de Reynolds est de $\mathrm{Re}_D = 28720$. Le point de mesure P est situé à une distance de $3D$ depuis le coin aval, dans la direction principale de rayonnement. Le développement des structures tourbillonnaires dans la couche cisaillée est contrôlé par un système composé d'un jet synthétique agissant sur une zone située immédiatement derrière le coin amont, et d'un algorithme qui fournit le signal de contrôle à partir de la pression mesurée sur la paroi aval de la cavité.

La complexité de la rétroaction aéroacoustique dans la cavité rend difficile la modélisation du chemin secondaire *actionneur-capteur d'erreur* par un filtre linéaire. Nous avons choisi une approche de contrôle en boucle fermée, basée sur l'algorithme récursif *RLMS* avec un filtre à réponse impulsionnelle infinie *IIR*. L'actualisation des coefficients du filtre se fait avec un fort taux de *fuite*, ceci pour limiter automatiquement le taux d'atténuation des perturbations à l'amont de la cavité et ainsi assurer la stabilité du contrôle.

Les champs de pression de la Fig. 2 montrent la diminution du champ acoustique rayonné par la cavité. La réduction dans le champ sonore rayonné, mesurée point P, est de 12 dB. La Fig. 3 montre l'effet du contrôle sur le signal de pression au même point. On montre que cette atténuation du niveau de la pression est associée à la diminution des fluctuations de vitesse verticale des tourbillons dans la couche cisaillée tracées sur la Fig. 4. Leur impact contre la paroi est aussi moins régulier. On observe que la fréquence principale du rayonnement acoustique n'est pas modifiée, traduisant le fait que le couplage aéroacoustique n'est pas détruit. Cette fréquence correspondant à un nombre de Strouhal $\mathrm{St} = 0{,}74$ est associée à la présence en moyenne de deux tourbillons dans la couche cisaillée. Ce point est confirmé par les spectres du signal de pression au point P, reportés sur la Fig. 5. Les spectres indiquent aussi une forte réduction des principaux pics et une atténuation globale sur une large bande de fréquences.

L'utilisation d'un contrôle actif adaptatif de la couche cisaillée a permis de réduire le niveau de pression à la fois dans la cavité et dans le champ acoustique rayonné. Le système de contrôle a pu être intégré dans un code de résolution des équations de la mécanique de fluides. Cette simulation met aussi en évidence l'intérêt du calcul direct du bruit pour l'étude des systèmes de contrôle de phénomènes aéroacoustiques.

1. Introduction

Cavity noise, which occurs when a cavity is placed in a grazing flow, is of increasing concern to both the transport and the military industry, and as such has been extensively studied over the past few decades, both experimentally and numerically.

Active control techniques have been investigated as a possible means of reducing noise generation. Numerous studies have examined the effects of open-loop control via fixed-frequency forcing techniques. Among the extensive experimental literature regarding closed-loop cavity control, one can mention the use of loud-speakers [1], piezo and mechanical devices [2,3], and pulsed jets [4–6].

Past simulations of subsonic-flow cavity noise include hybrid simulations, where unsteady CFD results are used as source terms for a wave equation, and direct computations, in which the compressible Navier–Stokes equations are solved with highly precise numerical schemes in order to capture the acoustic pressure field. Actively controlled aeroacoustic resonances have also been simulated with low-order numerical schemes [7,8]. Direct aeroacoustic 3D simulations of cavity flows are very recent.

The simulation code used in the present study is an extension to the 3D compressible Navier–Stokes equations solver ALESIA [9], developped by Gloerfelt et al. for cavity flows. A description of the numerical algorithm, boundary conditions as well as a physical analysis of cavity flow dynamics, is to be found in Gloerfelt et al. [10,11].

This work is intended to show the pertinence of direct noise simulations in studying active flow control and its effects on radiated noise. It should be noted that this simulation delivers information not only on the control effects inside the cavity, which is of interest in military applications, but also information about far-field noise reduction which is more generally of concern to civil transport applications.

2. Active control system

The reduction of cavity noise with open-loop active control systems has been extensively investigated, and the limitations of such non-adaptive systems are well-known. Fixed-frequency forcing techniques tend to increase sound levels at the forcing frequency and are as such unsuitable in cases where flow conditions are likely to change. Adaptive or closed-loop control systems do not suffer from this drawback and are therefore inherently more versatile over a wide range of operating conditions as well as potentially more effective at any given frequency. A simple form of pulsed injection is used as the control actuator. It relies on adding a control term to momentum equation on ρv where v is the vertical velocity, inside the time integration. This term is added on a zone whose envelope is Gaussian in the x and y directions and of half-width $L/50$ in both directions. The injection zone, spanning the entire width of the cavity, is placed immediately after the upstream corner, as shown in Fig. 1. The

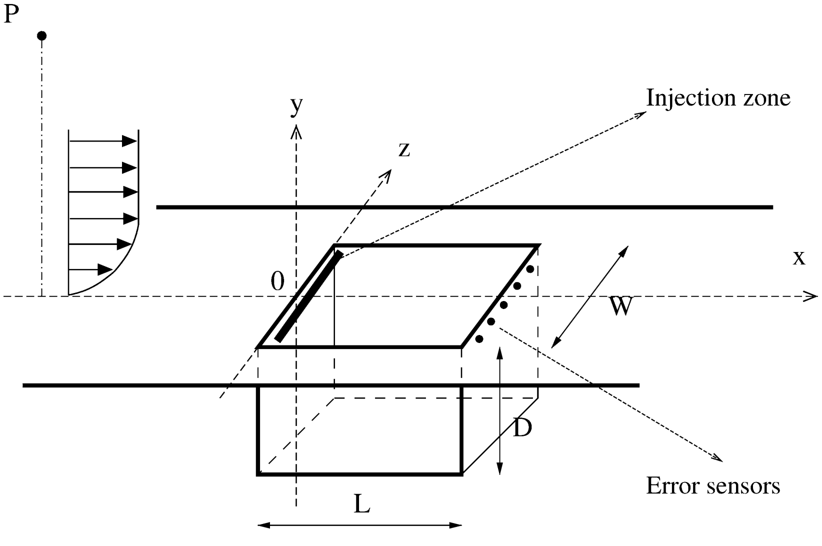

Fig. 1. Simulated cavity layout. The injection zone is Gaussian in the (x, y) plane, with a half-width of 2Δ ($\Delta = L/100$), and is centered around $x = 2\Delta$, $y = 0$. The injection envelope in the z direction is given by a symmetrical Gaussian window.

Fig. 1. Cavité simulée. La zone d'injection est de forme gaussienne dans le plan (x, y), de demi-largeur 2Δ ($\Delta = L/100$), et centrée sur $x = 2\Delta$, $y = 0$. Dans la direction z, la forme de l'envelope est donnée par une fenêtre gaussienne symétrique.

error signal supplied to the control algorithm is the pressure perturbation $p - p_0$ measured slightly underneath the impact zone on the downstream cavity wall and averaged over five sensors in the spanwise direction.

The noise generation process in cavity flow problems is complex and nonlinear. Instabilities are shed by the upstream cavity corner and are simultaneously convected and amplified by the shear layer until they impact the downstream cavity wall, thus generating noise. Pressure waves induced by the impact can create a feedback loop by synchronising the upstream shear layer oscillations, resulting in very high pressure fluctuation levels. The application of feedback algorithms designed for linear control situations is therefore not straightforward.

Moreover, the time step of the numerical simulation is more than two orders of magnitude smaller than the time scale governing the shear layer instabilities that are to be controlled. Numerical stability issues can therefore arise if careful filtering of the control signal is not undertaken.

Regarding acoustic active feedback control, most recent algorithm developments, such as the *Filtered-X LMS* or *FXLMS* family of algorithms, have been aimed at avoiding positive feedback instabilities that can occur in the *secondary path* between the control signal and the error signal. Additional digital filters are used to take into account the control actuator's contribution to the measured error signal. In the case of the cavity, the secondary path as well as being complex, involves different physical quantities (i.e., velocity and pressure), and seems therefore to be less prone to the aforementioned instabilities. A basic *Least Mean Squares* or *LMS* algorithm was consequently chosen as the basis of the control. After testing both finite and infinite impulse-response (*FIR* and *IIR*) digital filters, an *IIR* filter was chosen. *IIR* filters are intrinsically better suited to capturing nonlinear behaviour, which means that much shorter filters can be used. A 16 point filter was adopted, with 10 points in the numerator and 6 in the denominator. The LMS coefficient-updating algorithm was correspondingly modified to deal with the feedback or denominator part of the filter; a modified version of the *Recursive Least Mean Squares* (*RLMS*) algorithm [12] was used.

An additional advantage of the *LMS* algorithm as compared to the *FXLMS* one is the elimination of the secondary path identification phase. This phase, during which a digital filter representation of the secondary path behaviour is calculated, is difficult to perform when the secondary path is strongly non-linear. What is more it has to be undertaken *offline* prior to the control phase since *online* identification relies heavily on secondary path linearity. The elimination of this phase saves both effort and computation time.

3. Control results

The simulated cavity is shown on Fig. 1. The cavity is 2 mm long, with $L/D = 1$ and $L/W = 1.28$. The upstream flow has a Mach number of $M = 0.6$ and a Reynolds number based on the cavity depth of $\mathrm{Re}_D = 28720$. The upstream boundary layer is laminar, with $L/\delta_\theta = 57$. The measurement point P is located at a distance of $3D$ from the downstream corner, in the direction of the main acoustic radiation. The simulation domain extends from $-2L$ to $3L$ in the streamwise direction, from $-L$ to $2L$ in the vertical direction and from $-W$ to W in the spanwise direction. The domain is bounded laterally by non-reflecting boundary conditions, and downstream by an outflow condition.

The pressure fields on Fig. 2 clearly show the effect of the control system on the radiated cavity noise. The directivity is unchanged but the radiated levels are substantially reduced. Fig. 3 illustrates the reduction in the pressure signal at the point P, when the control system is started.

The first vortex in the shear layer, corresponding to the first (blue) negative pressure zone, is clearly smaller and less intense. This reduction can more generally be seen both in the amplitude of the vertical velocity oscillations in the shear layer, whose time signal is shown on Fig. 4, and in the average intensity of the instabilities convected by the shear layer. The pressure spectra on Fig. 5 show tonal reduction as well as reduced broadband levels. This stems from the smaller size of the convected structures impacting the downstream cavity wall which are responsible for the broadband as well as the tonal emissions. The prevailing cavity mode, corresponding to the average number of vortices in the shear layer at any one time, is not modified by the control: the mode 2 oscillations corresponding to

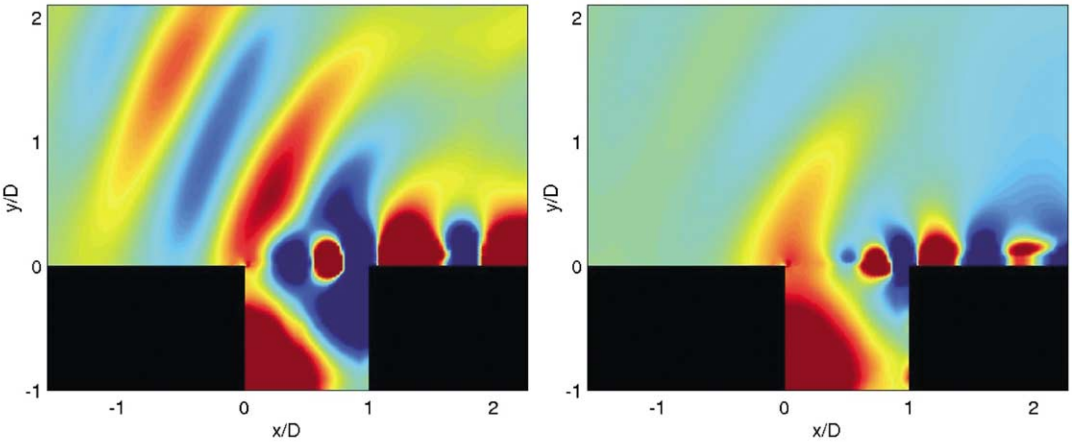

Fig. 2. Phase-synchronized instantaneous fluctuating pressure snapshots in the (x, y) plane, taken before and during control phase. Colour scale is between -200 and 200 Pa.

Fig. 2. Champs de pression dans le plan (x, y) avant et pendant le contrôle. Images prises à un temps équivalent dans le cycle. Échelle de couleurs entre -200 et 200 Pa.

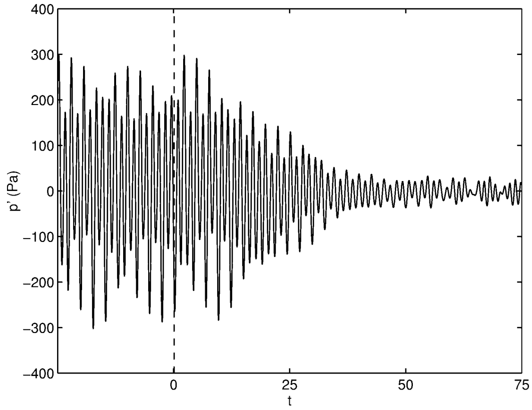

Fig. 3. Radiated pressure signal at point P as a function of non-dimensional time. Control phase starts at $t = 0$.

Fig. 3. Evolution en temps adimensionalisé de la pression rayonnée au point P. Le contrôle démarre à $t = 0$.

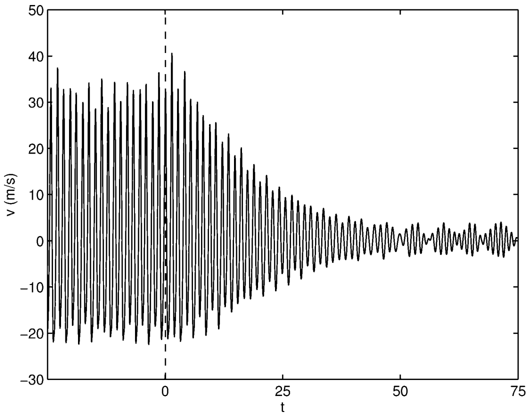

Fig. 4. Downstream vertical velocity signal measured in the (x, z) plane as a function of non-dimensional time. Measurement at a distance of $L/15$ from the downstream corner. Control phase starts at $t = 0$.

Fig. 4. Évolution en temps adimensionalisé de la vitesse verticale à l'aval, dans le plan (x, z). Le point de mesure se trouve à une distance de $L/15$ du coin aval. Le contrôle démarre à $t = 0$.

a Strouhal number of $\mathrm{St} = 0.74$ remain dominant both in the far field and inside the cavity. The first main peak in the pressure spectra at a Strouhal of $\mathrm{St} = 0.34$ corresponds to the low frequency modulation that is clearly visible at the beginning of the temporal pressure signal. This modulation becomes less regular when control is applied, due to the greater instability of the smaller upstream shear layer perturbations.

The stability of the controlled cavity is one of the more delicate aspects of the simulation. It was found that the total elimination of upstream instabilities, although possible for a short time, must be avoided in order to obtain a stable state. Indeed if the upstream instabilities become too small, they can very easily be perturbed and end up in phase with the injected control signal, leading to positive feedback and rapid divergence. The control algorithm

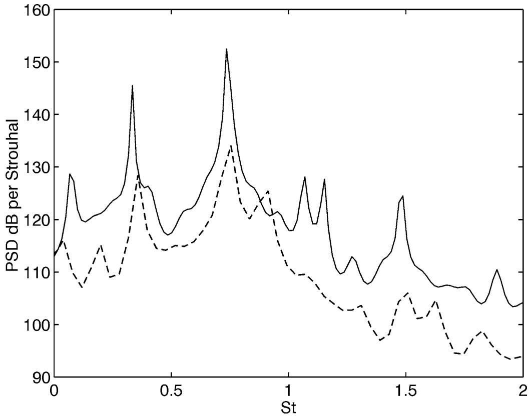

Fig. 5. Radiated pressure fluctuations spectra: —: without active control, - - -: with active control. Spectra calculated with autoregressive method.

Fig. 5. Spectres des fluctuations de pression : — : sans contrôle, - - - : avec contrôle. Spectres calculés par la méthode autorégressive.

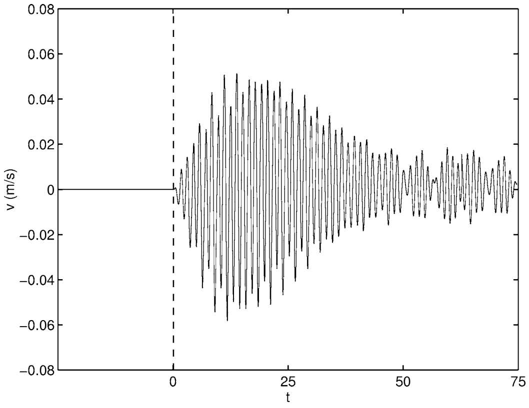

Fig. 6. Injection velocity signal as a function of non-dimensional time. Control phase starts at $t = 0$.

Fig. 6. Évolution en temps adimensionalisé de la vitesse injectée. Le contrôle démarre à $t = 0$.

should therefore not converge to an error value of zero, since this state is unstable. Rather than impose a non-zero sinusoidal error toward which to converge, a *Leaky LMS* approach with a strong leakage factor was used, to avoid the error signal becoming too small. This method both avoids having to establish a priori a target error signal to obtain, and also increases the algorithm's response speed to phase and frequency changes in the error signal. The injected velocity signal on Fig. 6 shows that the response time of the control system is of the order of 4 instability periods.

Control stability is also greatly affected by the filtering of the error signal. A low-pass four point *IIR* filter was implemented, with a cut-off frequency slightly higher than that of the dominant mode 2 oscillations, and thus well under the critical Shannon frequency. Without this filter, the gain of the control system had to be diminished for a stable state to be obtained.

The overall noise reduction obtained in the simulations reached 12 dB, with a 20 dB reduction at the main oscillation frequency. These results are encouraging, but have as yet to be achieved on cavity flows where the upstream boundary layer is substantially more turbulent.

4. Conclusions

A direct noise calculation is performed on a cavity excited by a $M = 0.6$ grazing flow, in which the shear layer dynamics are controlled by an active flow control system. Direct numerical simulation is shown to be well suited to examining the behaviour of active flow control systems. Radiated pressure levels, as well as the size of the instabilities that develop in the shear layer, are lowered by the control algorithm. It is shown that a modified *LMS* style algorithm is capable of handling the complex cavity behaviour.

Acknowledgements

The authors wish to thank Marie-Annick Galand for helpful comments, especially regarding the subject of active control.

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