Numerical Investigation of Self-Excited Oscillations of a Generic Profile with CAA

M. Sabanca, J. Delfs
Deutsches Zentrum für Luft- und Raumfahrt, DLR-AS/TA, Lilienthalplatz 7, 38108 Braunschweig, Deutschland, Email: Murat.Sabanca@dlr.de

Introduction

The noise generation at a generic strut-like profile in a flow of Mach number $M = 0.1$ is studied numerically. The profile is composed of a half cylinder of diameter $d = 0.02m$ with a rearward attached wedge of different lengths l as indicated in Figure 1. Qualitatively different forms of self excited flow oscillations along with respective noise radiation are observed depending on the ratio l/d, ranging from periodic to chaotic states.

Approach

Nonlinear inviscid perturbations $\rho^{'}$, $u^{'}$, $v^{'}$, $p^{'}$ to a turbulent mean flow field ρ_0, u_0, v_0, p_0 are simulated numerically,

$$\rho = \rho_0 + \rho^{'},\ u = u_0 + u^{'},\ v = v_0 + v^{'},\ p = p_0 + p^{'}$$

where ρ, u, v, p represent density, horizontal and vertical components of velocity and pressure respectively. The steady mean flow is obtained using DLR´s RANS code FLOWER by employing the $k-\omega$ turbulence model of Wilcox at downstream of the contour kink between cylinder and wedge [5]. The perturbations are computed with the DLR´s CAA code PIANO solving the 2nd order perturbation equation [1];

$$\frac{\partial \rho^{'}}{\partial t} + (\vec{v}^{'}.\nabla)\rho_0 + ((\vec{v}_0 + \vec{v}^{'}).\nabla)\rho^{'} + \rho^{'}\nabla.(\vec{v}_0) + (\nabla.\vec{v}^{'})(\rho_0 + \rho^{'}) = 0, \qquad (1)$$

$$\frac{\partial \vec{v}^{'}}{\partial t} + (\vec{v}^{'}.\nabla)\vec{v}_0 + ((\vec{v}_0 + \vec{v}^{'}).\nabla)\vec{v}^{'} + \frac{1}{\rho_0}(1 - \frac{\rho^{'}}{\rho_o})\nabla p^{'} - \frac{\rho^{'}}{\rho_0^2}\nabla p_0 = \vec{f}, \qquad (2)$$

$$\frac{\partial p^{'}}{\partial t} + (\vec{v}^{'}.\nabla)p_0 + ((\vec{v}_0 + \vec{v}^{'}).\nabla)p^{'} + \kappa[p^{'}\nabla.\vec{v}_0 + (p_0 + p^{'})\nabla.\vec{v}^{'}] = 0. \qquad (3)$$

The quantities $(\rho, \vec{v}, p)$ are made dimensionless with reference $(\rho_\infty, a_\infty, \rho_\infty a^2{}_\infty)$, with the freestream values for density ρ_∞ and the speed of sound a_∞. These equations are discretized on structured grids by using high order accurate finite difference time domain, DRP scheme [2]. Regarding the boundary conditions, the fluctuation components should obey the same rules as fluid element on the wall for an inviscid flow, i.e. contravariant component of the velocity is set to zero on the wall. A damping term $\vec{f}$ (for 2D problems) is implemented at the nodes of the wall ∂B of the strut profile as follows;

$$\vec{f} = \begin{cases} -\alpha\vec{v}^{'} & \text{on } \partial B \\ 0 & \text{Otherwise} \end{cases}$$

(4)

in this case α is a parameter of order $O(CFL/(\Delta t)_{max})$. Moreover, radiation conditions at farfield and additional sponge layers at the outflow boundary are implemented.

Results

A parametric study on wedge length l was conducted. The flow parameters, Mach number, Reynolds number (Re=45000, based on d) and angle of attack ($\alpha = 0^o$) are taken as constant. At the beginning of each simulation the steady flow field is perturbed by an inviscid vortex disturbance in the wake region. The initial vortex is placed at $1d$ away from the trailing edge of the strut and rotates in the counter-clockwise direction. After a transient phase, the system is observed to evolve onto a self sustained flow oscillation. Depending on the slenderness l/d of the strut different oscillation phenomena are observed for the given $M = 0.1$. For all considered l/d a flow separation occurs at the contour kink between cylinder and wedge. For $\approx\ l/d < 3.75$ the mean flow separation reattaches at the trailing edge. For smaller l/d a free stagnation point occurs in the wake behind the strut (the point S shown in Figure 1), while for larger l/d the separation reattaches on the wedge contour. The simulation of $l/d = 3$ shows a periodic von-Karman-type flow oscillation with a Strouhal number, $Sr = {}^{fl}/_{U_\infty}$ of the fundamental frequency f with $Sr = 0.27$ see Figure 2. Upon increasing the slenderness to $l/d = 4$ the periodicity is lost. A chaotic state with quasi-periodic character is obtained. At again larger $l/d = 5$, for which the separation is already small, again a periodic state is observed with $Sr = 0.54$. Apparently, for sufficiently small l/d the flow oscillation is dominated by an hydrodynamic instability of the wake. In contrast, for large l/d the oscillation frequency is dictated by an acoustic feedback associated with sound waves interacting with the separation point. This can be seen by applying Rossiter´s acoustic feedback model for cavity flows to this case leading to $Sr = {}^1/_{(1/c_o + M_\infty)} \approx 0.54$ where c_0 is Rossiter´s emprical convection factor of 0.57 [4]. Figure 2 shows that this scaling is appropriate. The frequency corresponding to this acoustic feedback model can also be seen for case $l/d = 3$ although with a very small amplitude. In general, the profile becomes more silent as the wedge length increases from $l/d = 3$ to $l/d = 5$ provided that all other flow conditions are constant. This can also be seen from the spectrum in Figure 2 for different wedge lengths. The experiments conducted by Achilles et al.[3] for the profile $l/d = 2.5$ show similar frequencies to occur as simulated. Due to the compactness of the strut w.r.t. the observed frequencies, the sound radiation is dipole like in all cases (see Figure 3). Finally, the sound radiation characteristics and transition from periodic to chaotic states as well as from chaotic to periodic cases are quite sensitive to l/d.

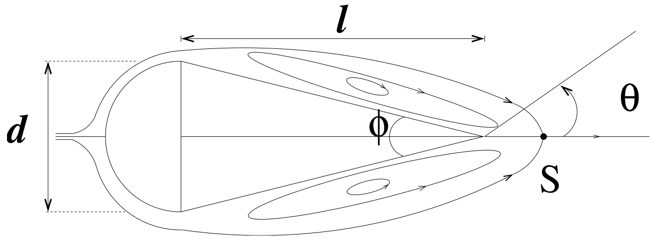

Figure 1: (a) Sketch of geometry with a possible stagnation point of flow.

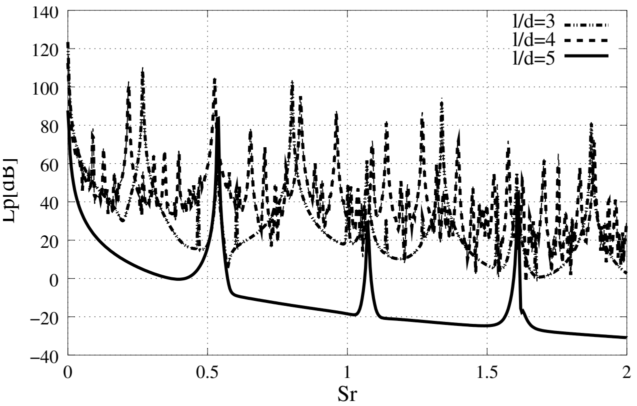

Figure 2: Narrowband spectrum for $l/d = 3, 4, 5$ at $\theta = \pi/2$, $\Delta f = 1.3\ Hz$ and $r = 0.33m$.

Acknowledgements

Das diesem Bericht zugrunde liegende Vorhaben wurde mit Mitteln des Bundesministeriums für Bildung und Forschung unter dem Förderkennzeichen 19 U 1074C gefördert. Die Verantwortung für den Inhalt dieser Veröffentlichung liegt beim Autor.

References

[1] M. Lummer, T. Lauke, J. Delfs, *"Simulation von Hinterkantengeräusch mit dem Störungsverfahren PIANO des DLR"*, DAGA'03, (2003), 798-799.

[2] C. K. W. Tam and J. C. Webb, *"Dispersion Relation Preserving Finite Difference Schemes for Computational Acoustics"* J. Comp. Phys., **107**, (1993), 262–281.

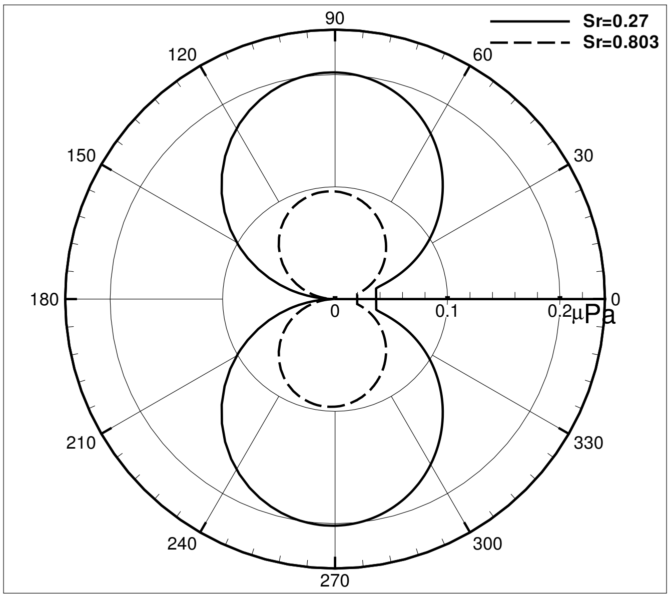

Figure 3: Directivity pattern for different harmonic and subharmonic frequencies for $l/d = 3$ at a distance of $r = 0.33m$.

[3] S. Achilles, A. Zeibig, A. Wilde, *"Aeroakustische Validierungen am Beispiel einer generischen Fahrzeugstruktur"* DAGA '05.

[4] J. E. Rossiter, *"Wind-Tunnel experiments on the flow over rectangular cavities at subsonic and transonic speeds"*, A. R. C., R. & M. (1966), No **3438**.

[5] "FLOWer Installation and Handbook", Release 116, 2002.