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EXPERIENCE OF USING A CFD CODE FOR ESTIMATING THE NOISE GENERATED BY GUSTS ALONG THE SUN-ROOF OF A CAR

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Abstract

The problem to be examined here is the fluctuating pressure distribution along the open cavity of the sun-roof at the top of a car compartment due to gusts passing over the sun-roof. The aim of this test is to investigate the capability of a typical commercial CFD package, PHOENICS, in recognizing pressure fluctuations occurring in an important automotive industrial problem. In particular to examine the accuracy of transporting pulsatory gusts traveling along the main flow through the use of finite volume methods with higher order schemes in the numerical solutions of the unsteady compressible Navier-Stokes equations. The Helmholtz equation is used to solve the sound distribution inside the car compartment, resulting from the externally induced fluctuations.

INTRODUCTION

In the automotive industry cavities with different geometrical configurations occur in many instances such as; the car door gap, gear gap, open sun-roof and wheel wells. It has been observed experimentally [1-3] that the cavity flowfield is complex with intense pressure oscillation. Such cavity flows become one of the main aerodynamic noise sources. The intense fluctuating pressure distribution can cause discomfort to the driver's and passengers' ears, and result in an increase of drag. On the other hand, the flow-induced aerodynamic noise contributes to environmental noise pollution. The flowfield characteristics are strongly dependent on the length-to-depth ratio (L/D) of the cavity, free stream conditions, the upstream boundary layer, etc.

This paper examines a hypothetical car configuration with an open sun-roof with part of the compartment forming the resulting cavity. The car is travelling at a cruising speed with induced flow fluctuation due to the open sun-roof. The pressure along the sun-roof is computed by solving the unsteady compressible Navier-Stokes equations using a typical commercial finite-volume CFD package, PHOENICS, and the pressure fluctuation due to the sun-roof is extracted and analysed. Various numerical schemes are used to provide a better understanding of their advantages and disadvantages for this application. In order to study the acoustic response inside the car compartment, the acoustic pressure distribution is calculated by solving the Helmholtz equation.

THE PROBLEM DESCRIPTION

Previous experience of an open cavity with a lip shows induced oscillatory fluctuation of pressure [4] caused by shear layer separation at the upstream end. This leads to further interests in related problems such as a hypothetical car with an open sun-roof as depicted in Figure 1. The length of the sun-roof is 0.6m and the effective depth of the opening lip is 0.05m. The free stream velocity is 25 m/s (90 km/h). An artificial sinusoidal vertical-velocity disturbance, as shown in Figure 1, is used to represent a vortex generated by a vehicle travelling at upstream of this car. The vortex strength is given by $W = W_0 \sin(2\pi a t)$, where W_0 = -1.2 m/s and a is a parameter chosen as a constant independent of time. Different frequencies of this upstream vertical-velocity disturbance are applied to generate different the acoustic responses at the top of the sun-roof.

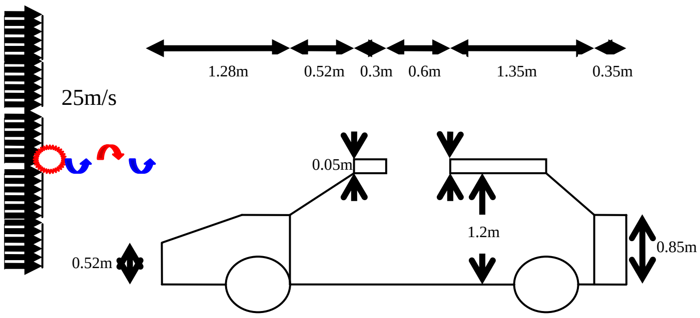


Figure 1 – A hypothetical car with a sun-roof

THE NUMERICAL PROCEDURE

This section gives a brief description of the numerical algorithm for the solution of unsteady flow problems, the pressure fluctuations due to the cavity opening and the sinusoidal disturbance, and the analysis of acoustic responses.

Solutions of unsteady Navier-Stokes Equations

In the present paper, a structured finite-volume based software package, PHOENICS, is used to compute time-accurate unsteady flow fields. The package may be used in the computations of compressible and incompressible flows.

The Navier-Stokes equations and continuity equation for a compressible fluid based on a Cartesian coordinate system, ignoring body forces, may be written as

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{u}) = 0, \tag{1}$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla(\rho \vec{u} \otimes \vec{u}) = -\nabla p(\rho) + \rho \nu \nabla^2 \vec{u}, \tag{2}$$

where ν is kinematic viscosity, velocity $\vec{u} = [u_1(t,x), u_2(t,x), u_3(t,x)]^T$ are functions of the time, $t \in (0,T]$, and the spatial coordinate $x \in \Omega$, where $\Omega \subset \Re^3$ is a domain exterior to the compact obstacle, $p(\rho)$ is the pressure and ρ is the fluid density.

In the present simulation, the computational domain is taken as 17.6m by 8.8m with 176 by 88 mesh points distributed across it. Fine sub-grid regions with up to 16 times finer mesh are applied in certain parts of the computational domain, e.g. around the sun-roof, to obtain an accurate solution. To satisfy both the mass and momentum conservation laws, the velocity and pressure field are solved iteratively by using the SIMPLE pressure-correction algorithm proposed by Patankar and Spalding [5]. In using PHOENICS, standard boundary conditions are used for inflow, solid wall, symmetry, and far-field boundaries. Five different discretisation schemes have been tested in this paper in order to provide a better understanding of their advantages and disadvantages for the present study. In order to resolve the acoustic disturbance correctly a minimum of 20 temporal integration steps were chosen to represent each oscillation cycle at the highest frequency of interest. For this reason the time step length, δt, chosen for the temporal integration is 1ms resulting in a maximum resolved frequency of 50Hz.

Extracting Pressure Fluctuations

Two factors contributed to the pressure fluctuation above the sun-roof. First the incoming flow over certain vehicle. Second the artificial disturbance introduced upstream of the configuration. For the present study the artificial disturbance requires a time equal to $528\delta t$ to reach downstream of the sun-roof. It is possible to use the pressure obtained from the CFD calculation to examine the frequency response inside the car compartment. The pressure fluctuation along the upper surface of the car configuration and at the sun-roof opening is given by $P_f(x,t) = P(x,t) - \overline{P}(x,t)$, where P is the instantaneous pressure distribution along the upper surface obtained by using the CFD calculation and $\overline{P}$ is the background pressure distribution along the upper surface due to the upstream velocity and the car configuration.

Numerical Schemes for convection discretisation

In all finite-volume CFD codes for which cell-centre values of variables are stored, as in the schematic diagram below, values of the variable ϕ are known for the cell centres W, P and E; but the values of ϕ at face w, which travels from cell W to cell P, or from P to W, may be calculated by using a number of numerical schemes.

```
-------------------------------------------
|             |             |             |
|     W      w|      P      |      E      |
|        -------->          |             |
|             |             |             |
-------------------------------------------
```

The numerical scheme influences the balance equations for both cell W and cell P. To ensure fairly good solution one can choose $\phi_w = \phi_W$ when the flow is from W to P, but $\phi_w = \phi_P$ when the flow is from P to W. This, or rather the so-called "hybrid" variant of it, is used as the default numerical scheme, together with other schemes, in PHOENICS. In this paper, five different numerical schemes, three linear and two non-linear schemes as listed below, are being tested and each of them has a different approach to calculate the cell face value ϕ_w.

- UDS Upwind-differencing scheme: $\phi_w = \phi_W$
- CDS Central-differencing scheme: $\phi_w = \frac{\phi_P + \phi_W}{2}$
- QUICK Quadratic upwind scheme: $\phi_w = \frac{3}{8}\phi_P + \frac{3}{4}\phi_W - \frac{1}{8}\phi_{WW}$
- SMART Bounded QUICK: $\phi_w = \phi_W + 0.5B\left(\phi_W - \phi_{WW}\right)$
- HQUICK Harmonic QUICK: $\begin{cases} if \;\; r \le 0, & \phi_w = \phi_W \\ if \;\; r > 0, & \phi_w = \phi_W + \dfrac{2\left(\phi_P - \phi_W\right)\left(\phi_W - \phi_{WW}\right)}{\phi_P + 2\phi_W - 3\phi_{WW}} \end{cases}$

Here $B = \max\left(0, \min\left(2r, \frac{3r+1}{4}, 4\right)\right)$, $r = \frac{\phi_P - \phi_W}{\phi_W - \phi_{WW}}$, and ϕ_{WW} is the cell-centre further upstream.

Figure 2 shows nine observation points marked with their node numbers, along y = 1.6m, i.e. just one-cell above the sun roof. The time history of the pressure fluctuations at these observation points are shown in column 2 of Table 1. A zoom-in to the neighbourhood of the sun-roof with seven other observation points and their pressure fluctuations are shown in column 3 of Table 1. It can easily be seen that first order accurate Hybrid / Upwind and HQUICK schemes are too dissipative and therefore not suitable for this type of example. As a result, the magnitude of pressure fluctuations observed on top of the sun-roof is very small. CDS even failed to converge because the cell Peclet number is not guaranteed to be less than 2. However, SMART and QUICK scheme show interesting results. The pressure fluctuations on top of the sun-roof gradually grow in magnitude in a sinusoidal form. The

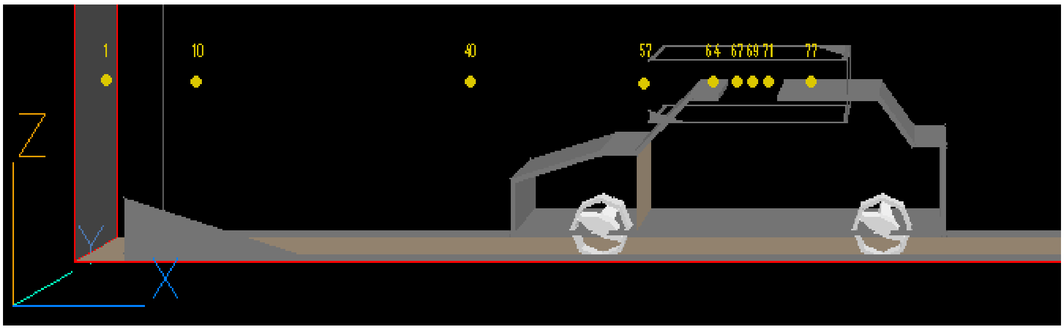
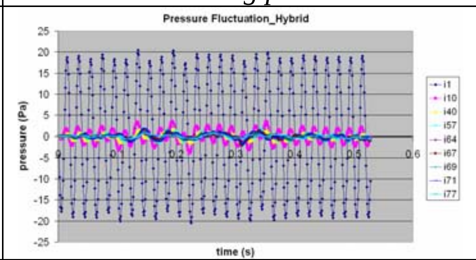
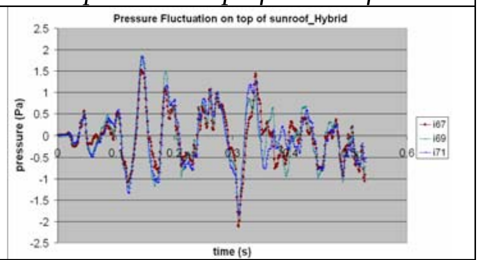
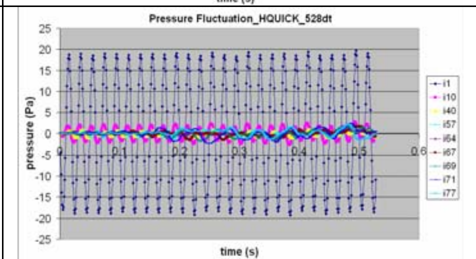
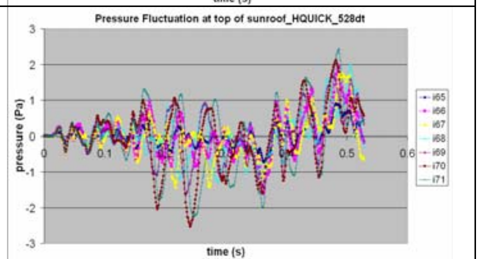
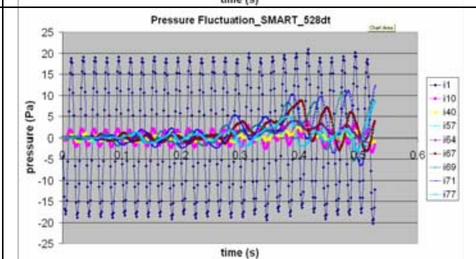
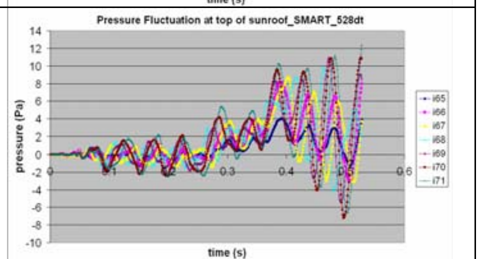
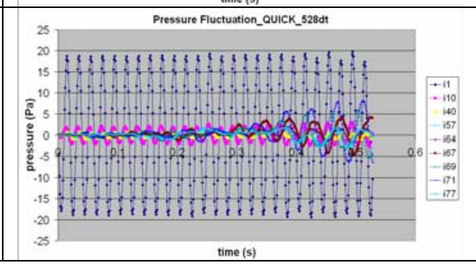
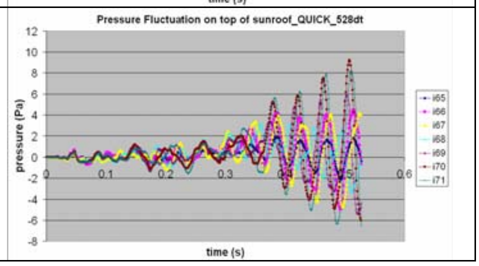


Figure 2 – Nine observation points in the computational domain

Table 1 – Comparison of pressure fluctuations using different numerical schemes

Numerical Scheme	*Pressure Fluctuation at nine observing points*	*Pressure Fluctuation at all seven points on top of sun-roof*
Hybrid / Upwind		
HQUICK		
SMART		
QUICK		

fluctuations obtained by using QUICK scheme lead to a more stable and regular sinusoidal shape. At this stage, this seems to be the best schemes to use in this application.

Analysis of Acoustic Response

Frequency components of the pressure fluctuations are then examined by producing an acoustic power spectrum of the time history at all seven points on the sun-roof via sampling a 512-point Fast Fourier Transform. The spectrum is depicted in Figure 3 and shows the dominant frequency at all observation points on the sun-roof occurs roughly at around 13Hz.

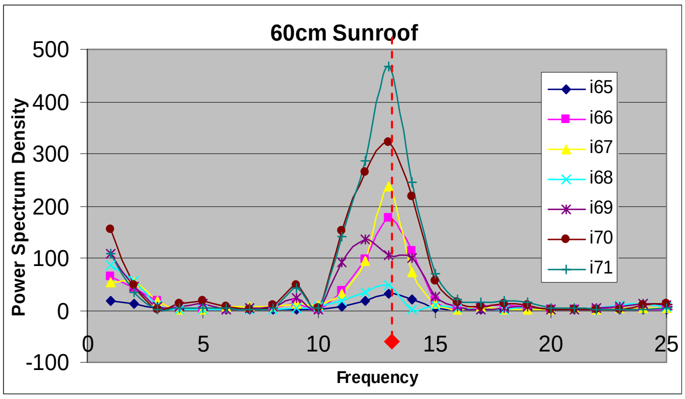


Figure 3 – power spectrum density of the time history via a 512-point FFT

To study the acoustic response along the sun-roof, different frequencies of the upstream disturbance are applied. Numerical tests as a function of input disturbance are performed to verify the hypothesis that the lower the frequency of disturbance, the lower the frequency of acoustic response obtained. In this study, 25Hz and 10Hz disturbance frequencies are compared with the maximum resolvable frequency of 50Hz (see Table 2). The power spectra show that for incoming disturbance at a frequency higher than 25Hz the dominant mode of the noise generated due to the sun-roof occurs at roughly 13 Hz which is the resonant frequency. On the other hand for incoming disturbance at lower frequency, say 10 Hz, seems to excite a half harmonic at around 6Hz while maintaining the harmonic of 13Hz at a weaker strength.

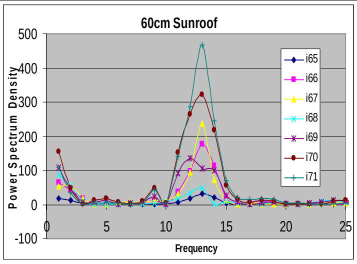
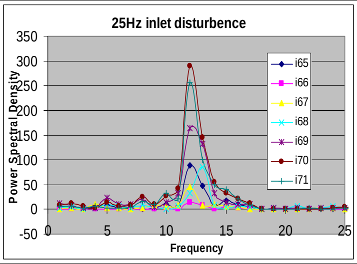
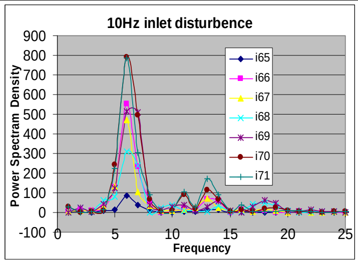
Sound distribution inside the car component

To compute the sound distribution inside the car compartment, one needs to solve the Helmholtz equation, i.e.

$$-\omega^2\psi - c^2\nabla^2\psi = 0\text{, where } \psi = \int_{-\infty}^{\infty} pe^{i\omega t}dt \tag{4}$$

In applying this equation, it is assumed that the flow inside the car compartment is negligible. For the present study the analysis of sound distribution for the dominant frequency of f = 13Hz due to an incoming disturbance of 50 Hz is examined. The power spectrum density along the sun-roof is used as Dirichlet boundary conditions for the Helmholtz equation, which gives the acoustic pressure distribution inside the car compartment. Figure 4 shows the acoustic pressure distribution along several horizontal lines and vertical lines below the sun-roof inside the car compartment. It shows that the highest acoustic pressure is experienced at x = 7.1m. On the other hand along the horizontal line just below the sun-roof the pressure shows an oscillatory behaviour resulting from the pressure fluctuation above the sun-roof. This oscillatory behaviour gradually becomes weaken as one moves deeper into the car compartment. The acoustic pressure distribution along all vertical lines seems to show the corresponding behaviour in such a way that oscillatory effects deep inside the car compartment disappear. This shows that the solution obtained is reliable. The acoustic pressure tends to be more stable at the bottom of the car compartment.

Table 2 – Comparison of peak frequencies obtained via a 512-point FFT due to different incoming disturbances of 50, 25 and 10Hz

<table>
<tr><th>50Hz</th><th>25Hz</th><th>10Hz</th></tr>
<tr><td>
</td><td>
</td><td>
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<tr><td>Obtained f = 13Hz</td><td>Obtained f = 12Hz</td><td>Obtained f = 6Hz</td></tr>
</table>

CONCLUSION

Sound distribution inside a car compartment due to incoming disturbance over the sun-roof is studied. The car compartment excites a particular frequency of oscillation at 13 Hz. Input disturbance has an influence on the particular harmonic excites. Lower frequency input excites a half harmonic at roughly 6 Hz. Higher order schemes are necessary to extract such pressure fluctuations. The Helmholtz equation has been used to describe the acoustic pressure distribution inside the car cavity.

ACKNOWLEDGEMENT

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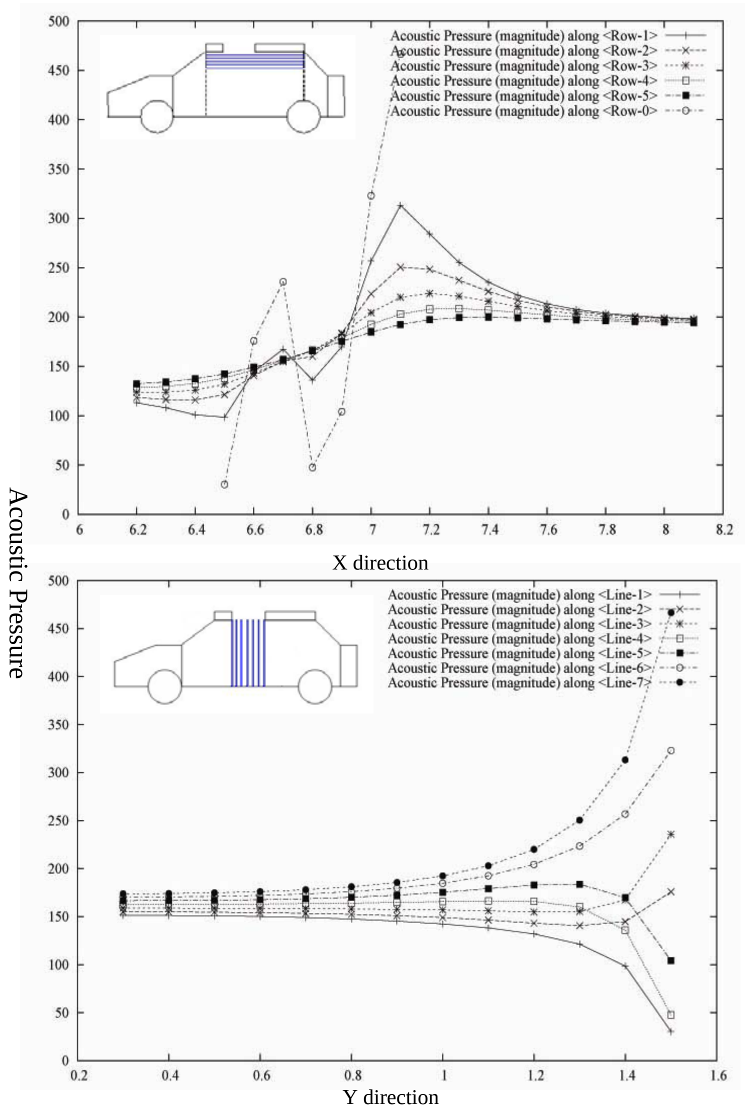

Figure 4 – Acoustic pressure inside the car component along several horizontal and vertical lines