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Aeroacoustics Analysis of a Hybrid Control Method for the Flow-Induced Noise Generation of Transonic Cavity Flows

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Abstract: Aeroacoustics analysis of a hybrid control method applied on the M219 open cavity is conducted by means of an open-source Computational Fluid Dynamics (CFD) solver, namely OpenFOAM. The flow-induced pressure oscillations of the cavity flow are attenuated using a passive control method and an active control method. An open-loop hybrid flow control method is introduced by taking into account the advantages of both passive and active approaches, hence a potentially better performing method. The Sound Pressure Level (SPL) at a point on the cavity wall and the Overall Sound Pressure Level (OASPL) over the fluid domain is examined for each method.

Keywords: Computational Fluid Dynamics, Aeroacoustics, Open Cavity, Flow Control.

1 Introduction

The cavity flow is a fundamental type of flow in the field of Computational Fluid Dynamics. While having a rather simple geometry, cavities produces contrarily highly turbulent complex flow structures [1]. The flow has an oscillatory behavior and generates noise on par with aircraft engines at high speeds. Therefore, the control of cavity flow has been a center of interest for many scientists interested in analyzing high-speed turbulent flows.

First studies regarding cavity flows date back to 1940s and extensive research have been made hitherto [1]. Pioneering experimental studies on cavity flow begin with the analysis of pressure modes [2] and the classification of cavity flows in subsonic and transonic regimes [3]. Early experiments on cavity flows in supersonic regimes are investigated in 1980s [4].

Cavities are often encountered in modern aircraft, for instance, a retractable landing gear or an internal weapon bay are such examples. They are briefly described as indents on surfaces, which can be found in any shape and size. This work focuses on a specific type of rectangular cavity, whose shape can be defined with its height, width and length. The ratio between these parameters have a crucial importance in cavity flow characteristics along with the freestream properties [3].

For a clean cavity, empty rectangular prism with no flow control mechanism, the flow separates at the end of the upstream wall of the cavity. The separated flow then becomes a free shear layer, oscillating as it travels the through the cavity length. If the shear layer reattaches on the downstream wall, the flow is called an open cavity flow. If the flow impinges on the cavity floor, the flow is the called a closed cavity flow (Figure 1). A transitional cavity flow occurs when the flow can neither be called open nor closed.

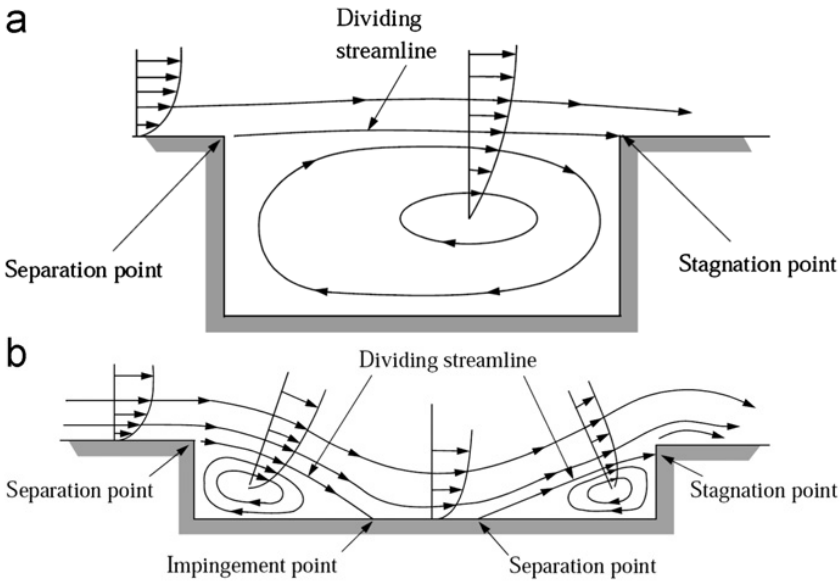

Figure 1: Open cavity flow (a) and closed cavity flow (b) at subsonic and transonic speeds [5].

The complexity of the cavity flow is driven by the unsteady behaviour of the shear layer and the aeroacoustic effects when it interacts with the cavity walls (Figure 2). The cavity flow generates acoustic waves that propagate in the fluid domain inside and around the cavity. Scientists have been working on ways to attenuate the flow-induced noise in cavity flow by either using passive and active methods. This work examines possible ways to combine advantages of both approaches by means of Computational Fluid Dynamics (CFD).

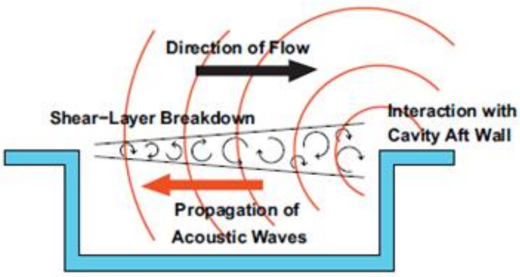

Figure 2: Schematic of a cavity flow problem [1].

2 Problem Statement

A flow control method is categorized either as passive or active depending on its working principles. Passive control devices do not require an energy input in order to work and remain stationary during the entire flight. In the case of a cavity on an aircraft, this could adversely affect the overall flight performance when the flow control is not necessary. On the other hand, active control mechanisms can be controlled by the pilot or operated autonomously as closed-loop systems. However, active devices require an energy input which adds the cost of the flight by increasing fuel consumption. Considering both approaches, a compromise can be achieved by exploiting the advantages of each approach and come up with a hybrid type of flow control method.
This work takes the M219 study [6] as a reference for the baseline cavity geometry. The M219 experiment is conducted in a transonic wind tunnel operating with a speed of 0.85 Ma. A clean cavity with a length-to-depth ratio of 5 and a width-to-depth ratio of 1 is firstly analyzed and a series of passive

control devices are tested on this geometry for noise suppression (Figure 3).

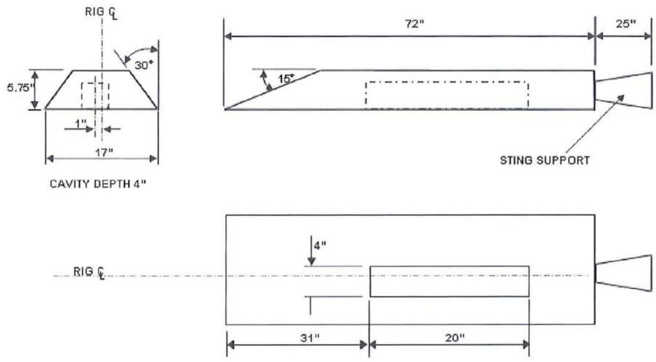

Figure 3: Geometry of wind tunnel rig for the M219 experiments [7].

Passive spoilers on the upstream wall of the cavity have been proven to be very effective in noise suppression in cavity flows [1]. They are easy to produce and integrate on cavity surfaces, but they cannot be removed when not needed. As for active control methods, mass injection from the cavity walls have been analyzed both experimentally and numerically [7, 8]. However, implementation of this method into an actual aircraft can be problematic as a steady and constant mass flow has to be injected into to cavity fluid domain.

In this work, a hybrid injection (HI) method is envisioned by merging the forwardly inclined spoiler (IS) and the front wall mass injection (MI) methods. This method incorporates a hinged spoiler and a channel connecting the upstream wall and the cavity front wall as presented in Figure 2. Compared to its stationary counterpart, the spoiler is hinged for retraction when flow control is not needed. Hence, the hinged spoiler can be deployed concurrently with the cavity doors, which would guide the freestream into the cavity, acting as the source of mass injection.

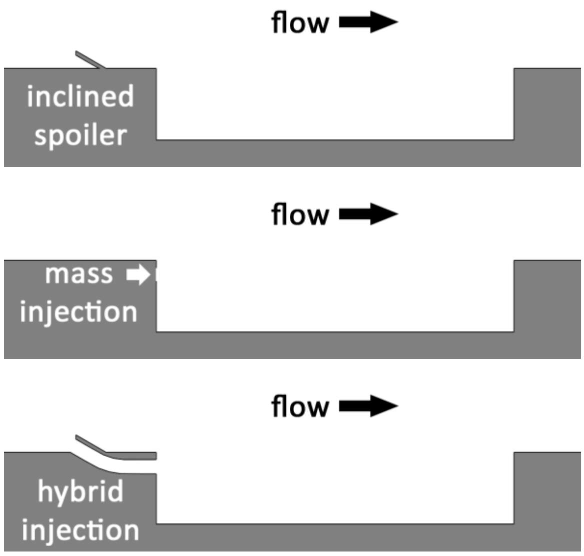

Figure 4: Representation of different cavity flow control methods.

3 Methodology

Using Computer Aided Design (CAD) tools, the top surfaces and the cavity walls of the wind tunnel rig in Figure 3 are modelled as boundaries of a fluid domain. The overall numerical domain is described with the patch names shown in Figure 5.

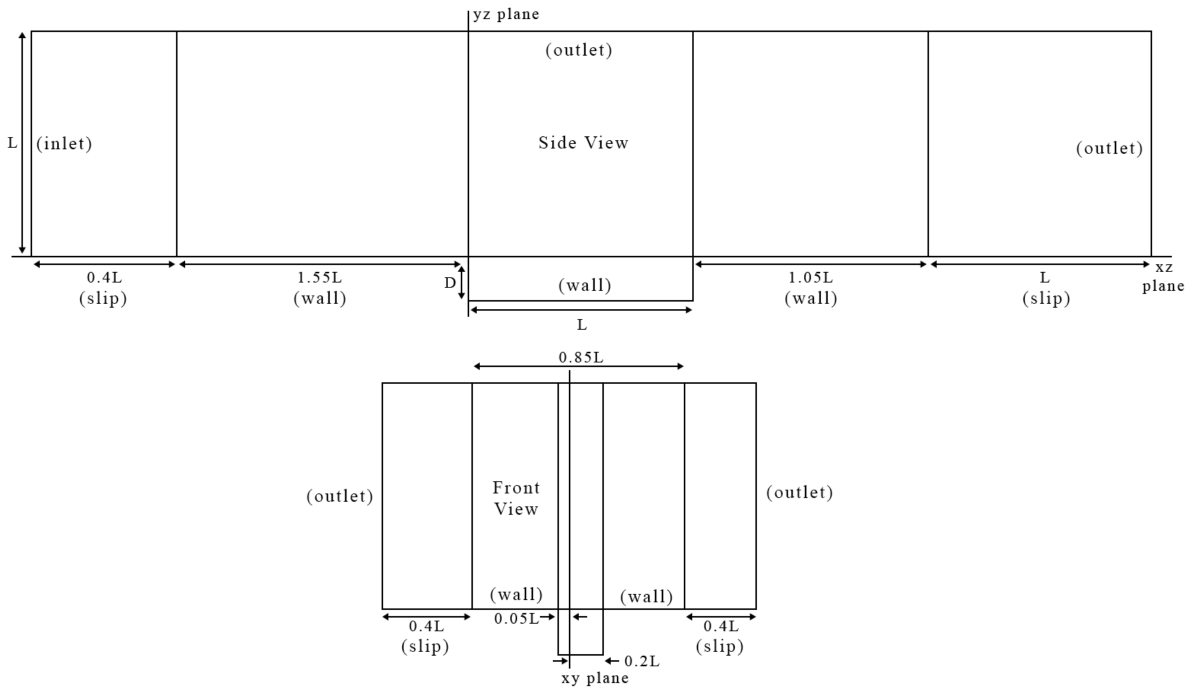

Figure 5: Numerical domain (not-to-scale).

A structured grid with quadrilateral elements is generated by preprocessing the two-dimensional model of the fluid domain. The grid is generated such that the maximum dimensionless wall distance (y^+) parameter for the upstream wall is less than 150. The resulting 2D mesh (Figure 6) for the clean cavity has a total of 12600 cells with a maximum aspect ratio of 250 and an average of less than 10.

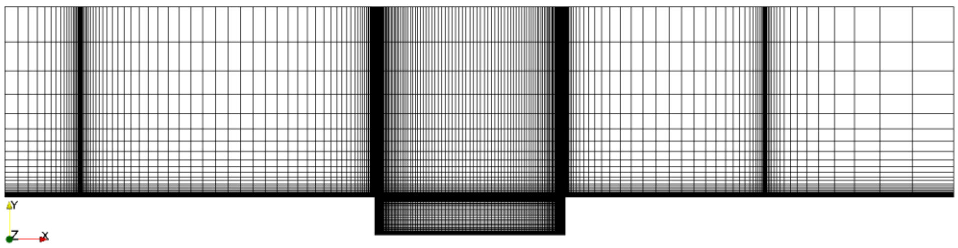

Figure 6: Structured grid for the 2D clean cavity.

For the 3D analyses, the characteristics of the generated grids are kept similar with the 2D grids, while the third dimension is added to the model. The resulting 3D grid for the clean cavity is obtained as follows.

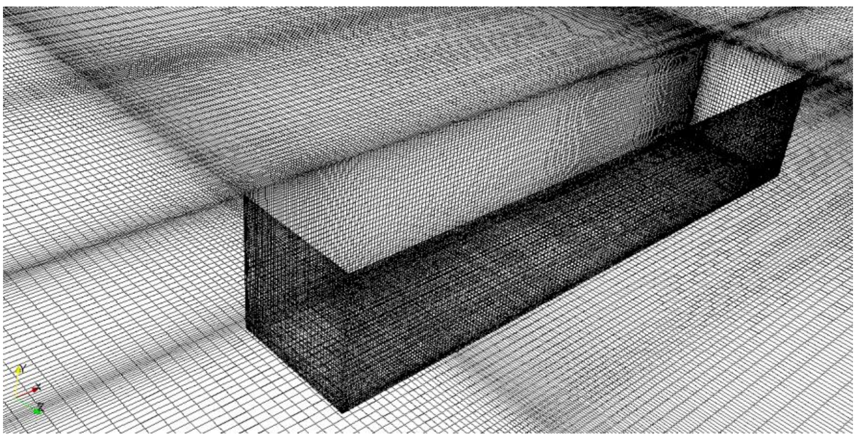

Figure 7: Close-up on the structured grid generated around the 3D clean cavity.

The 3D grid generated for the clean cavity has a total of 3136000 hexahedral cells with a maximum aspect ratio of 50 and an average of around 7. The y^+ value on the upstream wall is increased to about 300 in order to reduce the total number of cells for the 3D grids.

On the clean cavity model, the previously described flow control mechanisms are modelled in coherence with the baseline grid (Figure 8).

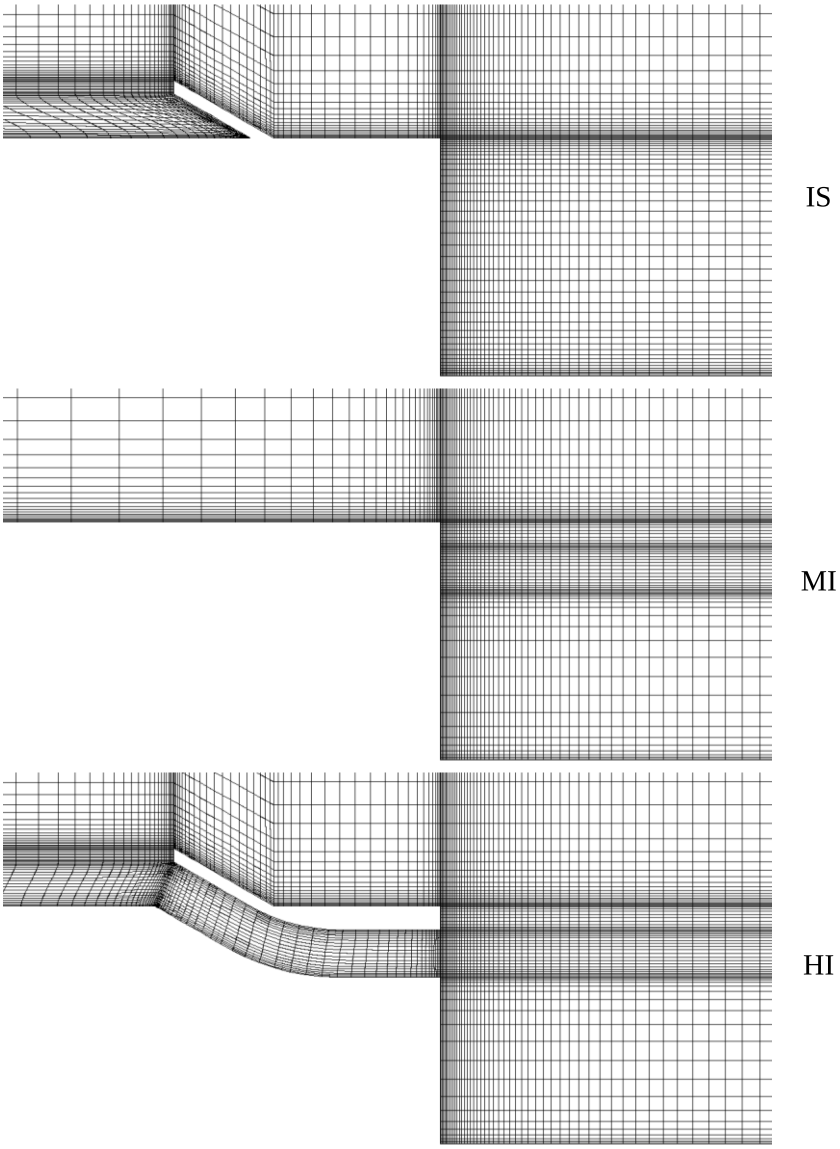

Figure 8: Close-up of the section cut on the grids generated for the flow control analyses.

Two-dimensional preliminary analyses are conducted on the defined numerical domain by taking into account the section cut that coincides with the xy-plane of the domain. The analyses are conducted using the sonicFoam solver of OpenFOAM 4.1 with the $k - \omega\, SST$ turbulence model [9]. Three-dimensional analyses are conducted as Detached Eddy Simulations with, again, the $k - \omega\, SST$ turbulence model. The following boundary conditions are entered into the “0” file.

Table 1: Boundary conditions for the clean cavity.

	inlet	outlet	slip	wall
alphat	calculated	zeroGradient	symmetry	compressible::alphatWallFunction
k	fixedValue	zeroGradient	symmetry	kqRWallFunction
nut	calculated	zeroGradient	symmetry	nutkWallFunction
omega	fixedValue	zeroGradient	symmetry	omegaWallFunction
p	waveTransmissive	waveTransmissive	symmetry	zeroGradient
T	fixedValue	zeroGradient	symmetry	zeroGradient
U	fixedValue	zeroGradient	symmetry	noSlip

For IS and HI control methods, the boundary conditions are kept the same with the clean cavity case, since they do not introduce any new boundaries to define. However, for the MI case, a mass flow rate boundary condition had to be defined. In OpenFOAM 4.1, this can be handled by making use of the flowRateInletVelocity boundary condition. This boundary condition is written for velocity and keeps the mass flow rate on a boundary at a desired constant value with the following input:

- type flowRateInletVelocity
- massFlowRate 0.3659 $\mathrm{kg/s}$

The mass flow rate is calculated from the blowing coefficient equation, a commonly defined parameter for mass injection problems. This parameter is briefly, the ratio between the mass flow rate of the injection and the mass flow rate of the freestream entering the cavity. The area considered for the freestream term is the roof area of the cavity:

$$B_c = \frac{\dot{m}_i}{\dot{m}_\infty} = \frac{\dot{m}_i}{\rho_\infty L W V_\infty}$$

where L is the cavity length and W is the cavity width. A blowing coefficient of 20‰ is applied for the mass injection analyses.

4 Results

To validate the adopted numerical tool, the clean cavity is analyzed in 2D and 3D. The resulting Overall Sound Pressure Level (OASPL) along the cavity walls (Figure 9) are computed using Paraview.

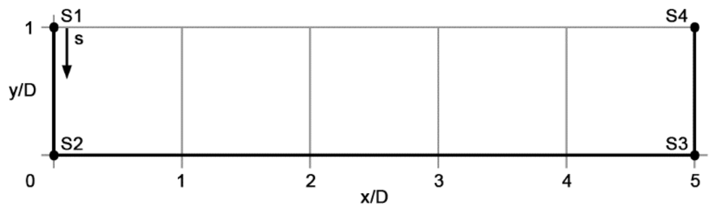

Figure 9: Station definitions along cavity walls.

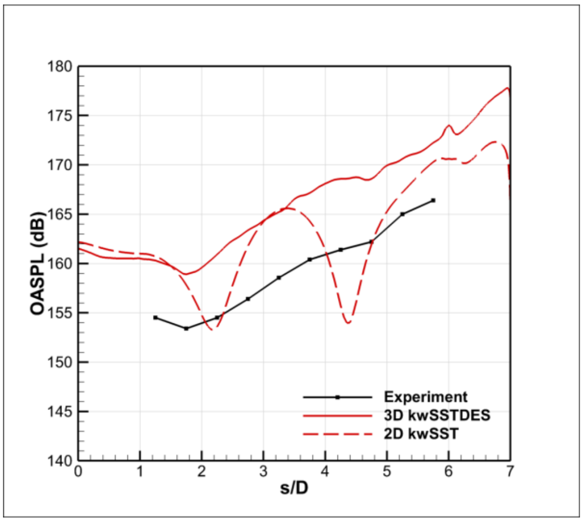

Figure 10: OASPL output from the validation analyses.

The OASPL distribution for both URANS (2D) and DES (3D) simulations are plotted in Figure 10. Results for a total of 7 depth lengths are plotted since the depth-to-length (L/D) ratio for M219-CC is 5 (0-1: front wall, 1-6: floor, 6-7: aft wall).
Because of the overprediction, the results obtained from 2D or 3D analyses are compared with the baseline clean cavity numerical results (Figure 11).

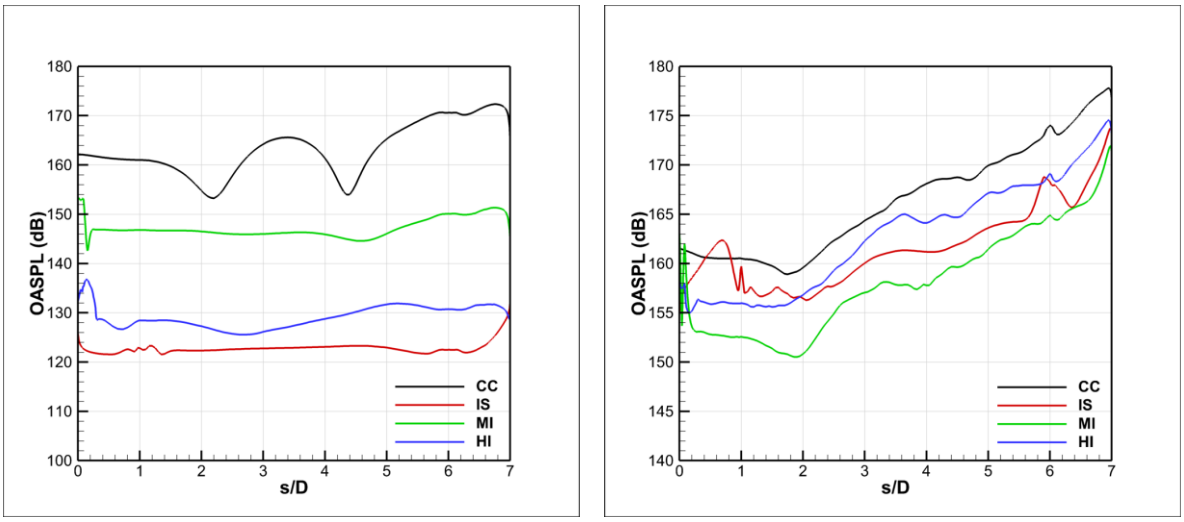

Figure 11: OASPL results from 2D (left) and 3D (right) analyses.

Additionally, the Sound Pressure Levels (SPL) at a certain point on the cavity walls is examined via a pressure probe located on 95% of the cavity floor when cutting with the xy plane.

5 Conclusion

The OASPL computed from the 2D analyses give two distinct drops on the cavity floor. When compared with the M219 experiment results, these drops are not physical, but numerical errors. On the other hand, the sound pressure levels are overpredicted. However, if they are ignored, the gradual increase in OASPL is well captured even in 2D analyses. The 3D DES results are in good agreement with the experimental results with an overprediction of about 5-6 dB.
Regarding URANS results, there is a significant decrease in sound levels by the adopted control methods. HI method is seen to superior to MI method. As compared to the IS method, HI method

produces less noise near the centre of the cavity. However, DES simulations reveal MI as the most efficient noise suppression method with IS and HI having a similar effect.

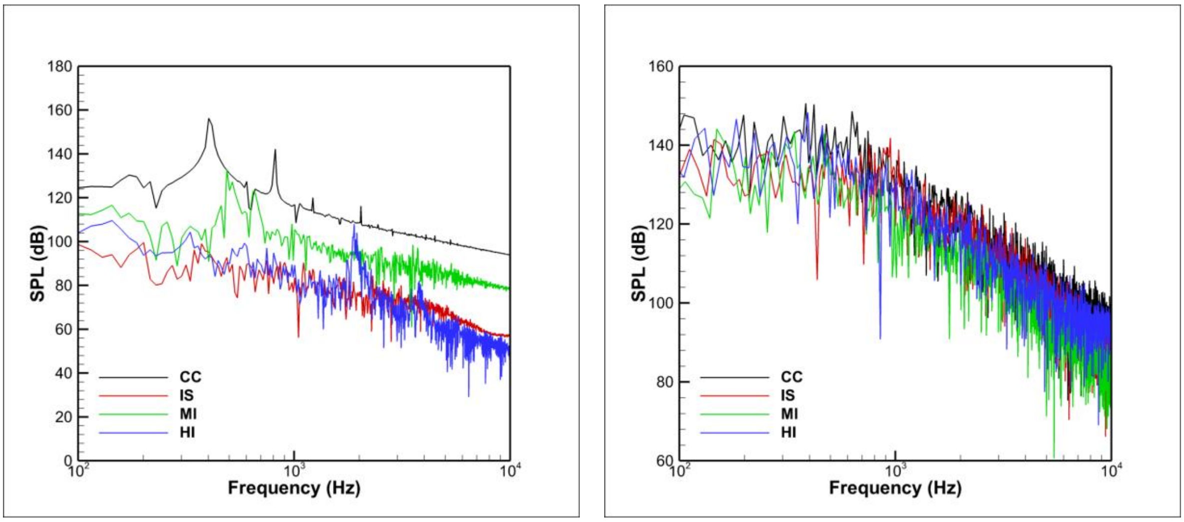

Figure 12: SPL results from 2D (left) and 3D (right) analyses.

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