

Influence of Door-Gap on Aeroacoustics and Structural Response of a Cavity

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Numerical aero-acoustic analysis, using the SST-SAS turbulence model, was conducted on a weapon bay model based on the M219 geometry with doors incorporating radar cross section reduction features. The effect of the introduction of a gap between the doors and the cavity edge on the aero-acoustic and structural response of the cavity was analysed at Mach 0.85. The effect of introducing three degrees of sideslip was also investigated. Both mean and unsteady flow analysis was conducted. The results showed a strong palliative effect of the door gap with and without sideslip. The overall analysis of the spectral signature on the forces and moments acting on the doors indicated the possibility of fluid-acoustic coupling as all acoustic spectra showed a predominant tone located at the same frequency of the first structural mode.

Nomenclature

f	=	frequency [Hz]
f_s	=	sampling frequency [Hz]
f_r	=	frequency resolution [Hz]
γ	=	ratio of specific heats for air
ω	=	angular velocity [rad/s]
$\dot{\omega}$	=	angular acceleration [rad/s ²]
M	=	Mach number
M_n	=	n_{th} structural mode

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R_n	=	n_{th} acoustic resonant mode
RH_n	=	n_{th} Rossiter-Heller theory predicted mode
R_{CIn}	=	n_{th} acoustic mode generated by centrifugal instability
R_{TIn}	=	n_{th} acoustic mode generated by transverse instability
St	=	Strouhal number ($= f \cdot D/U$)
U	=	air speed
t_c	=	convective time ($= L/U_\infty$)
$\bar{x}$	=	Time-averaged value of the discrete-time series x_n ($\sum_{j=1}^N x_j/N$)
$\hat{X}$	=	discrete Fourier transform of the variable x
X^*	=	complex conjugate of the variable X
σ	=	root mean square
p	=	air pressure
q	=	dynamic pressure
δ_0	=	boundary layer thickness at cavity leading edge
ρ	=	air density
L	=	cavity length
W	=	cavity width
D	=	cavity dept
F_x	=	force in the x -direction [N]
F_y	=	force in the y -direction [N]
F_z	=	force in the z -direction [N]
M_x	=	moment in the x -direction [Nm]
M_y	=	moment in the y -direction [Nm]
M_z	=	moment in the z -direction [Nm]
$\vec{u}$	=	displacement vector of structure [m]
$\vec{\theta}$	=	rotation vector of structure [rad]
m	=	mass [kg]

$\vec{I}$ = inertial tensor [kgm²]

a = acceleration [m/s²]

α = angle of attack [deg]

β = angle of sideslip [deg]

Subscripts

∞ = free-stream conditions

I.Introduction

Design requirements for modern combat jets are strongly influenced by the reduction of radar signature. This implies that weapons must be carried inside the airframe, instead of suspended on the wing and fuselage. Whilst this solution also offers advantages in terms of aerodynamic drag reduction (especially at transonic and supersonic speeds), other issues are generated. During the weapon release procedure, when the bay's doors are opened and the cavity is exposed to high-speed flow, an acoustic field is developed, which has the potential to damage the airframe and the payload. Additionally, the intrinsic unsteadiness of the local flow poses a hazard for the release of the weapon. The aero-acoustic response is directly dependent on cavity geometry and freestream conditions [1]. In some cases, resonant modes are developed, further aggravating the noise produced. The frequencies at which resonance occurs are called Rossiter modes [2]. The resonating frequencies are more generally predicted using the Rossiter-Heller equation [3], which accounts for Mach number effects,

$$f_n = \frac{U_\infty}{L} \cdot \frac{n - \xi}{M_\infty \left[1 + \frac{(\gamma - 1)}{2} M_\infty^2 \right]^{-1/2} + \frac{1}{K}} \quad (1)$$

Here K is the ratio of disturbance velocity in the shear layer to the freestream velocity (generally taken as 0.57), and ξ is an empirical constant employed to account for the phase lag between the passage of an eddy, past the cavity trailing edge, and the formation of an upstream travelling disturbance. The value of ξ depends on the length-to-depth ratio (L/D) of the cavity and is evaluated as $\xi = 0.062(L/D)$ [2]. The ratio of specific heats, γ , is assumed to be equal to 1.4 for air.

As shown by Delprat [4], it is possible to express the resonating frequencies as the result of amplitude modulation of a fundamental acoustic with relative harmonics. Rossiter-Heller modes can, therefore, be expressed as:

$$f_n = (n - \xi) \cdot [f_a \pm k\Delta f] \quad (2)$$

Here, f_a is the fundamental frequency loop of the cavity (the “*carrier frequency*”), ξ is the amplitude modulation parameter, or the ratio of the amplitude modulation frequency f_b to f_a , Δf is a modulating frequency (which usually coincides with the low-frequency peaks in the spectrum), and k is an integer.

Knowing that the Rossiter-Heller equation formulation does not consider the modulating frequency Δf , it is possible to extract from a combination of equations (1) and (2) the direct dependence of f_a and f_b on the cavity geometry and freestream conditions:

$$f_a = \frac{U_\infty}{L} \cdot \frac{1}{M_\infty \left[1 + \frac{(\gamma - 1)}{2} M_\infty^2 \right]^{-1/2} + \frac{1}{K}} \quad (3)$$

$$f_b = \frac{U_\infty}{D} \cdot \frac{0.062}{M_\infty \left[1 + \frac{(\gamma - 1)}{2} M_\infty^2 \right]^{-1/2} + \frac{1}{K}} \quad (4)$$

$$\xi = \frac{f_b}{f_a} = 0.062 \left(\frac{L}{D} \right) \quad (5)$$

Subsequent studies ([5],[6],[7]) related this set of three frequencies to fluid structures inside the cavity. A typical open-type cavity, in which acoustic resonant frequencies are expected to appear, is characterised by a detached shear layer forming at the leading edge and impinging at the trailing edge. Inside the cavity a recirculation area, typically defined by one or more eddies, is present. The well-known resonance phenomenon, involving the aero-acoustic feedback loop, is usually associated with the cavity fundamental frequency f_a , and is strongly dependent on the cavity longitudinal dimension. Typically, the Strouhal numbers (based on cavity depth[‡]) are greater or equal to 0.2 in the incompressible regime, and greater or equal to 0.1 in the compressible regime.

Re-arranging Eq.(3) in terms of St_D it is possible to write:

$$St_{Da} = \frac{1}{\left(M_\infty \left[1 + \frac{(\gamma - 1)}{2} M_\infty^2 \right]^{-1/2} + \frac{1}{K} \right) \cdot \frac{L}{D}} \quad (6)$$

[‡] Unless otherwise stated, in this study the Strouhal number is calculating using cavity depth as a reference length.

We see that, for a fixed cavity geometry (i.e. fixed length-to-depth ratio) the Strouhal number for the fundamental acoustic loop frequency is only a function of the free-stream Mach number. Typical trends are shown in Fig. 1.

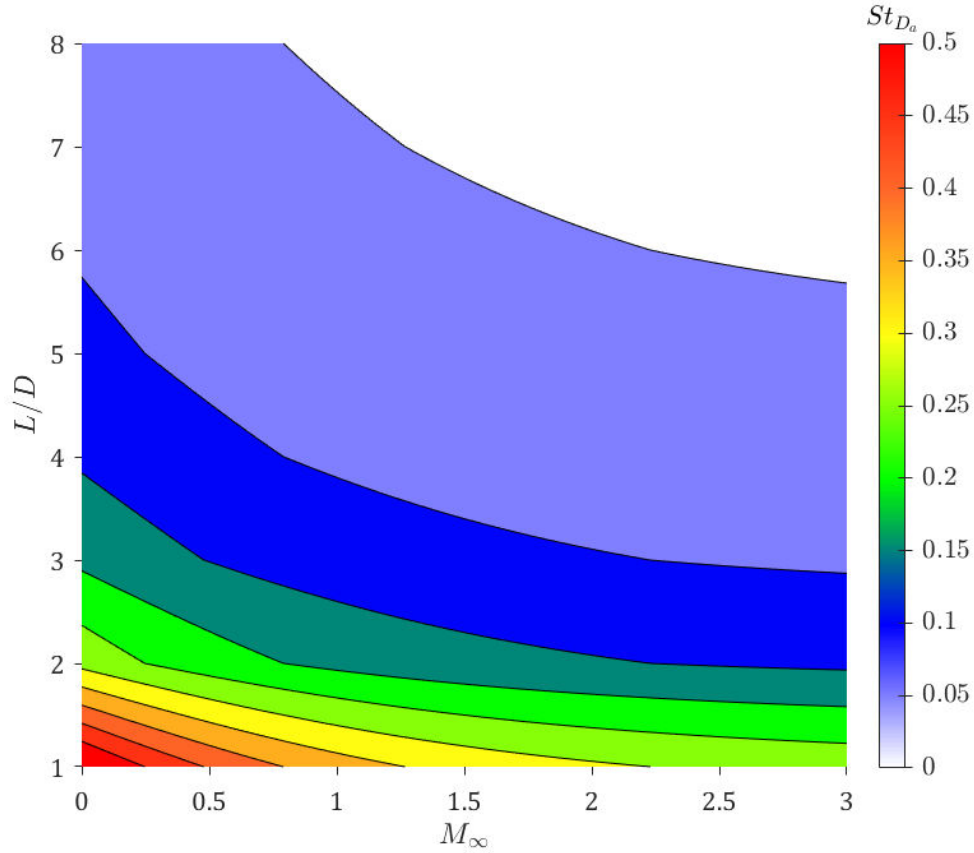


Fig. 1. Fundamental acoustic-loop Strouhal number (based on cavity depth). Variation with Mach number and length-to-depth ratio (L/D).

This frequency is typically phase-locked and is affected by non-linear saturation phenomena, that convey energy towards associated harmonics.

The low-frequency values, responsible for the frequency modulation mechanism, f_a ([4],[7]), originate from the inner flow, and more exactly from centrifugal instabilities in the recirculating eddies present in the cavity interior. Typical Strouhal numbers range from 0.005 to 0.05, depending on the source mechanism. Low Strouhal numbers are associated with velocity fluctuations in the layers of the recirculating flow inside the cavity, whereas higher ones are associated with the formation of sub-eddies inside the stratified layers of the main inner vortex. The interaction of these centrifugal instabilities with the acoustic modes of the shear layer is of a non-linear quadratic coupling, as shown in previous studies ([5],[6],[8],[9]) and is responsible for the generation of the Rossiter-Heller tones.

A third type of wave pattern can develop inside the cavity that is related to the three-dimensionality of the flow. These modes, called transverse instabilities, or spanwise induced oscillations, are the result of a non-linear interaction between the shear layer and the centrifugal oscillations and have Strouhal numbers typically between 0.1 to 0.2, for cavities with dimension of the same order of depth dimension. The associated structures are helical coils (with longitudinal axes) winding up around the inner recirculating flow [5], [6]). Table 1 summarises the observed flow structures.

Table 1 Summary of the wave pattern present on typical compressible cavity flows. Strouhal number is based on cavity depth (D).

St_D	Typology	Associated Flow Phenomenon	Nomenclature
0.005 $\rightarrow$ 0.05	Centrifugal instability	Centrifugal instabilities of the main recirculation eddy	M_{CI}, f_b
		Formation of minor-eddies inside the cavity	
0.1 $\rightarrow$ 0.2	Transverse Instability	Interaction between the shear layer and the centrifugal oscillations of the main recirculation eddy	M_{TI}
$f(M_\infty)$	Acoustic phase-locked loop	Impingement of the detached shear layer with the trailing edge and generation of aero-acoustic loop	f_a

The flow over cavities has been widely studied and the influence of geometric parameters, such as length-to-depth/width-to-depth ratios, have been consistently explored [10]. Nevertheless, the aero-acoustic response of a weapons bay can differ strongly from that seen on a standard rectangular cavity. Typical weapons bay aerodynamic and acoustic response is strongly influenced by external factors, such as interference from the aircraft fuselage, making the flow non-uniform ([11]–[13]) and/or local design solutions that alter the reference rectangular shape ([11], [14]–[20]). Dedicated studies have also studied the strong influence of bay doors on the cavity. Typically, the doors aggravate the aero-acoustic behaviour, increasing the overall acoustic signature and tonal response ([16], [21]–[23]). It is important, therefore, that attention is directed towards design details that might have a strong influence on the behaviour of the final weapons bay design.

Different combat aircraft, incorporating weapons bays, have adopted different door installation solutions. Some geometries clearly indicate the presence of a small gap between the door and the edge of the cavity (F-22 and MMU ventral bay, J20 ventral bay, F35, and B2) whereas other solutions show the absence of it, with the door directly in contact with the airframe (F-22/MMU side-bays, J20 side bays, Tu-160, B1B). Previous studies (numerical and

experimental) have adopted both geometries (gap present/not present), but a direct analysis of the associated effects has never been published. The present work seeks to explore the effect of the gap between the doors and the cavity surface. Numerical analyses, at a transonic Mach number of 0.85 were conducted on a rectangular cavity, with leading and trailing edge serrations (typical of low-RCS airframes) and 90 degree open doors installed with and without a gap at the cavity edge. The influence of the two designs have been tested at zero and 3 degree sideslip angles to explore different flow conditions. The forces and moments induced on the doors by the unsteady flow-field were recorded, and their spectrum compared with modal analysis of the doors to explore fluid/structure coupling.

II. Numerical Method - CFD

A. Cavity Geometry

The adopted cavity model was derived from the well-known M219 geometry, with a length-to-depth ratio of five and a width-to-depth ratio of one. The new geometry, shown in Fig. 2 introduced a double chevron step of 5 mm depth at the front and rear walls. The angle of the indentations was set equal to 45 degrees, typical of the value present in military aircraft with radar signature suppression/control design philosophies. The step height was chosen assuming the hypothesis that enough room would have been available to accommodate the bay doors in a closed position ([24], [25]). The cavity was complemented by a set of two doors, opened at 90 degrees. The doors could be directly attached to the cavity side surface (no-gap configuration), or separated from it, with a constant gap of 1 mm (gapped configuration). The cavity was chosen to incorporate the most prominent features of weapon bays installed in modern, low-observable, combat aircraft. The specific aim of this study was to explore the gap effects on a representative weapon bay, as current airframes may, or may not, incorporate this detail. In most studies [16], [21]–[23]), the doors are attached to the surface surrounding the edge of the cavity.

The reference axis system for the cavity (X_c, Y_c, Z_c) had the origin coincident with the leading edge, with the xz -plane coincident with the bay symmetry plane (see Fig. 2). On the other hand, the door axis system, in which force and moments were computed, was centred at door centre of gravity as shown in Fig. 2.

Three rakes, each consisting of 19 pressure probes were placed on the cavity floor, to monitor pressure signals. The naming convention and coordinates are shown in Table 2.

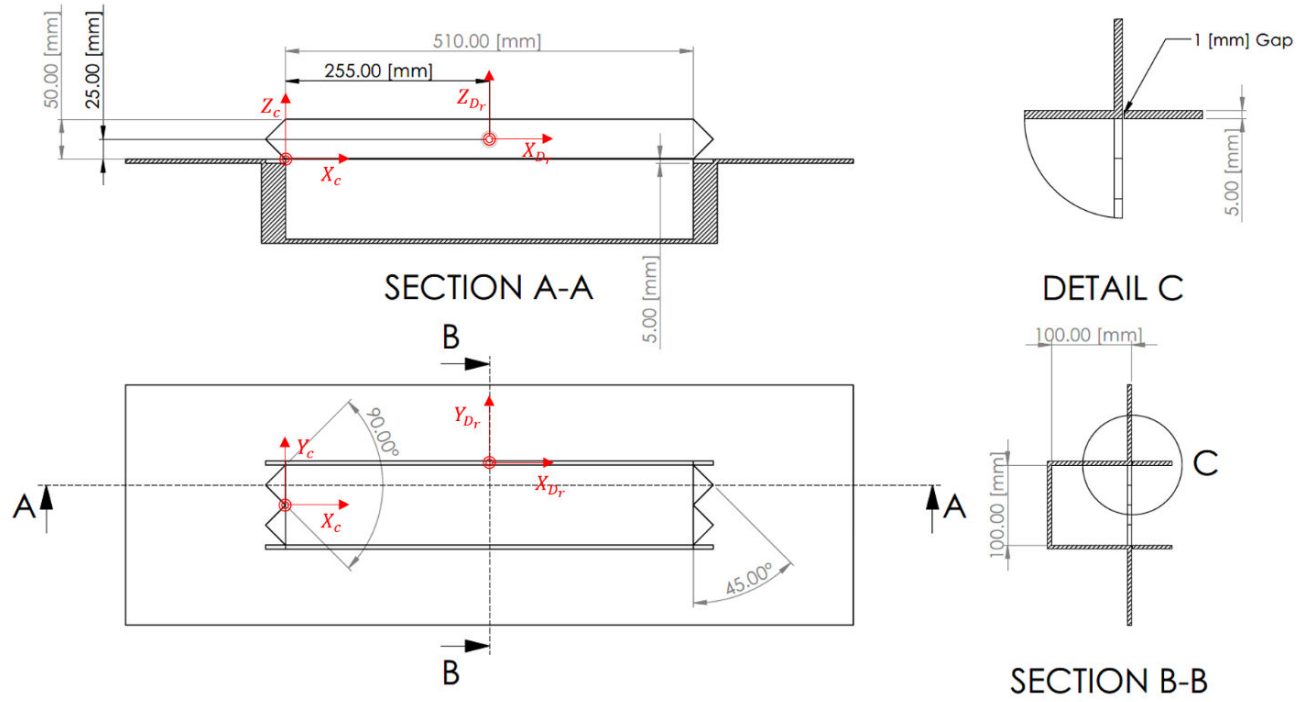


Fig. 2. General layout of the cavity geometry showing the coordinate system and origins .

Table 2 Pressure rake naming and coordinates.

<i>Rake Name</i>	$x_c[m]$	$y_c[m]$	$z_c[m]$	x/L	$2y/W$	z/D
<i>Rake R</i>	0.0255	+0.05	-0.1	0.05	+0.5	1.0
	0.0510			0.10		
	0.0765			0.15		
	0.1020			0.20		
	0.1275			0.25		
	0.1530			0.30		
	0.1785			0.35		
	0.2040			0.40		
<i>Rake C</i>	0.2295	+0.00	-0.1	0.45	+0.0	1.0
	0.2550			0.50		
	0.2850			0.55		
	0.3060			0.60		
	0.3315			0.65		
	0.3570			0.70		
	0.3825			0.75		
	0.4080			0.80		
<i>Rake L</i>	0.4335	-0.05	-0.1	0.85	-0.5	1.0
	0.4590			0.90		
	0.4845			0.95		

B. Numerical Simulation

The simulations in this study were performed using the SST-SAS turbulence model within the ANSYS Fluent 2021R2 CFD code. The capability of this code and the turbulence model, to properly address transonic cavity flow has been previously demonstrated by Egorov, et al. [26] .

An unstructured polyhedral-type mesh was used, with a prism layer wrapped around the viscous surfaces, for accurate boundary layer resolution, with a y^+ value of 1 or less. For accurate vortex structure modelling with Scale Resolving Simulations (SRS), the detached shear layer was resolved using a spacing equal to 0.05 times its minimum thickness (i.e., at the cavity leading edge), as suggested by Menter [27]. All solid walls were specified as adiabatic surfaces where the no-slip velocity condition was applied. The computational outer boundary was specified as a far-field, using the modified Riemann invariants condition. The computational domain (Fig. 3) consisted of a cavity placed flush on a planar surface, extending $1.5L$ fore and aft of the cavity leading and trailing edges respectively. The solid wall was then surrounded by a symmetry-type boundary (no-friction) extending a further two cavity lengths. The overall domain extended for $8L$ in the longitudinal direction, $29D$ in the transverse direction, and $5L$ in the vertical direction. The computational domain dimensions adopted here were validated in a previous study [28], hence no domain sensitivity analysis was conducted for this case.

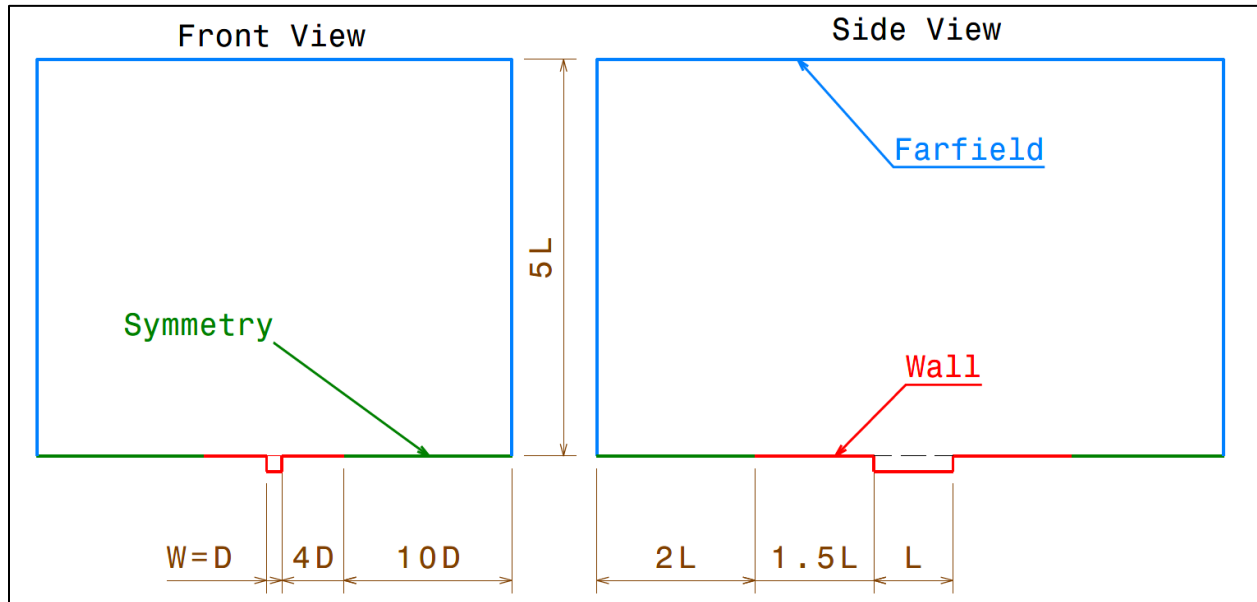


Fig. 3. Boundary conditions and computational domain dimensions.

The air was treated as an ideal compressible gas using Sutherland's law for viscosity modelling. Due to the compressible nature of the problem a pressure-based coupled (in momentum and continuity) solver was used. For the

momentum equation, the pressure interpolation used the standard second order central differencing scheme. For the continuity equation the non-viscid fluxes were calculated using the Rhie and Chow technique [29]. Density and energy interpolation were performed using a second-order upwind scheme [30], whilst for momentum, the bounded central differencing scheme was adopted [31]. Finally, viscous fluxes were interpolated using the second-order upwind scheme [30]. These settings were in line with previous studies on similar applications and already validated for strongly separated flows and acoustics [26, 27]. Viscous fluxes were resolved using a second-order upwind scheme [30] as per previous studies on similar flows [26] and gradients were evaluated using the least squares method. The time marching scheme was an implicit second-order dual-time formulation. Temporal discretisation used the standard bounded second-order scheme. Five inner sub-iterations were found to be adequate, which is consistent with the recommendation of Menter [27] and the approaches of Chaplin [29] and Bacci [32]

As advised by Menter [27], the time step was chosen to ensure a CFL number approximately equal to unity in the LES part of the domain. Unsteady simulations were initiated from a converged RANS solution to reduce the start-up time. To resolve accurately all the main features, the simulation was run for a total of 250 convective times (t_c), discarding the initial $100 \cdot t_c$ seconds to clear the solution from the start up transient. This allowed data samples with a temporal duration greater than 30 cycles of the lowest frequency mode of interest (1st Rossiter-Heller Mode) as in accordance with the values suggested by Menter [27].

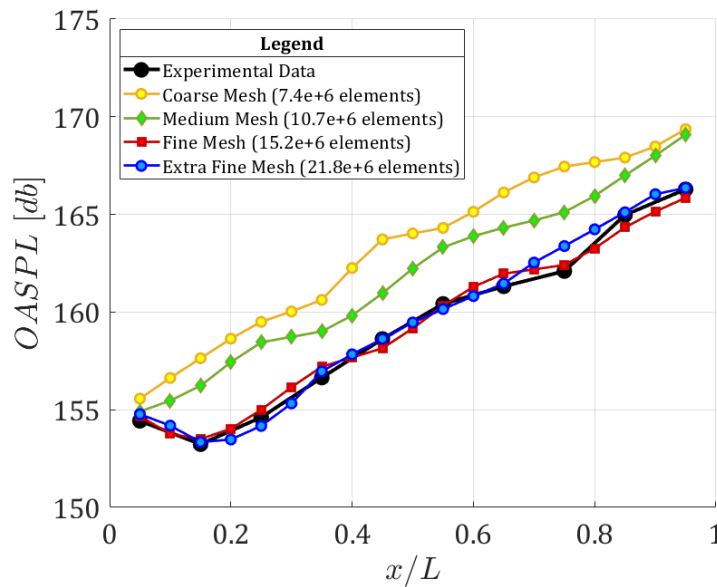


Fig. 4. CFD Grid convergence on OASPL, and comparison with experimental data.

To validate the computational settings and mesh convergence, data were used from wind tunnel studies of the M219 cavity [30] and compared against a computational model of the same geometry. Four meshes were developed (coarse, medium, fine, extra fine), and the results were compared to the experimental data (see Fig. 4). The comparison was done using pressure recordings on the cavity floor, in terms of OASPL, defined as:

$$OASPL = 20 \log_{10} \left(\frac{\sigma_p}{p_{reference}} \right) \quad (7)$$

where p_{ref} is the minimum audible pressure, defined as the threshold of human hearing, and equal to 2×10^{-5} Pa.

Upon refining the mesh from coarse to medium a considerable change was observed at all stations. The same was true for the change from medium to fine mesh. However, the second refinement did not produce appreciable changes in the predicted OASPL, indicating that the level of agreement between the medium and fine grids was sufficient to consider that the fine grid produced a grid-converged solution. The differences between fine grid and the experimental data was within the error band of the latter (± 1 dB) and, according to similar transonic cavity flow studies ([18],[24]), was considered adequate for the aero-acoustic analysis.

The computational domains for all the other geometries were constructed following the same resolution of fine-mesh case.

C. Test Matrix

The cavity geometry with doors in the two different configurations (Gap, and No-Gap), were tested at a representative transonic Mach number of 0.85. The effect of side-slip was explored as well. In all cases, the angle of attack was fixed at zero. Table 3 shows the test matrix with the boundary conditions:

Table 3 Test Matrix & Boundary Conditions

<i>Geometry</i>	M_∞	p_∞ [Pa]	T_∞ [K]	α [deg]	β [deg]				
No Gap	0.85	63177	266	0.0	0.0				
					3.0				
Gap					0.0				
					3.0				

III. Numerical Method – Modal Analysis

A structural modal analysis was conducted for the door geometry, as it was considered the element subjected to the greatest deformation in this configuration, and the component for which loads would have been more affected by the presence of the gap and sideslip angle.

A. Geometry

The door geometry with a gap introduced five rectangular-bodies representing hinges, which in the simulation had the function of anchor points for the body (see Fig. 5). These cube-shaped additional parts, of 5 mm side, and equally spaced along the door length were generated by comparing the various weapons bay doors of existing combat aircraft. The idea was not to re-create an exact hinge model but to introduce an equivalent constraint in the geometry deformation to have a representative model of a bay door's eigenmodes.

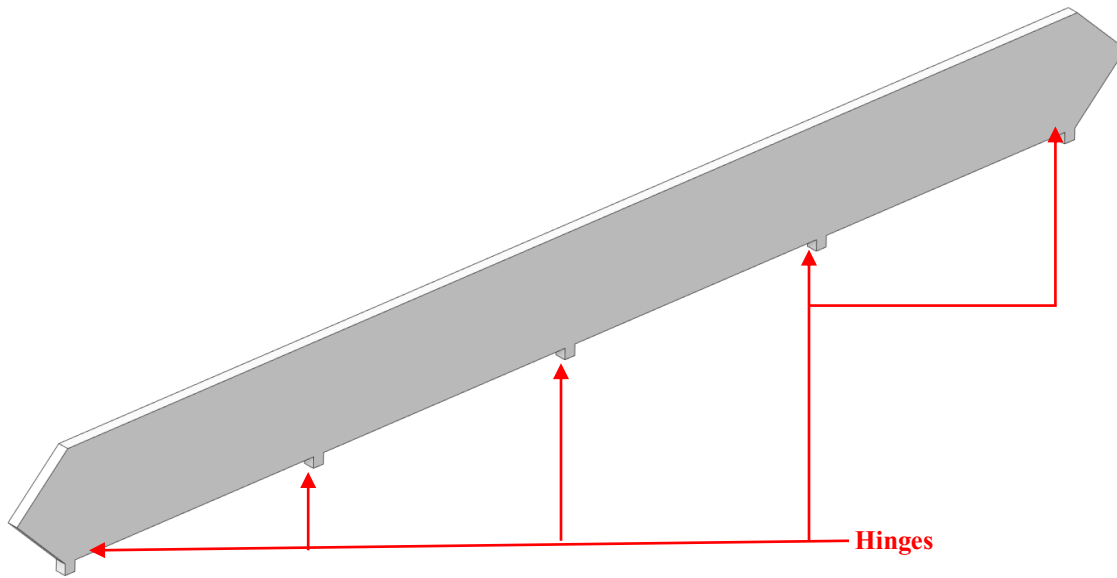


Fig. 5. Door model used in the structural modal analysis

The mass and inertia properties of the door are listed in Table 4.

Table 4 Door Mass and Inertia Properties

<i>Property</i>	<i>Value</i>	<i>Units</i>
m	0.3736	[kg]
I_{xx}	7.77e-5	[kgm ²]
I_{yy}	9.02e-3	[kgm ²]
I_{zz}	8.94e-3	[kgm ²]

B. Numerical Simulation

Modal analysis was conducted using ANSYS Mechanical ADPL 2021R2 code. The door body was discretised using hexahedral elements, imposing a minimum mesh size of 1 mm. This resulted in a total of 99000 elements, with the door's thickness discretised with at least 6 nodes. A rigid contact boundary condition was placed at each of the lower faces of the hinges. The mode extraction method used the undamped approach. The material selected for this study was 2024 aluminium alloy. The number of modes extracted was iteratively increased until the cumulative effective mass fraction reached the value one for all 6 motion components $(u_x, u_y, u_z, \theta_x, \theta_y, \theta_z)$ [34]. This corresponded to an extraction of 20 modes. The accuracy of the simulation was considered of first order, but it was in the scope of this study, that aimed to extract proper frequency modes, with an accuracy of ± 20 [Hz], and hence comparable with the pressure fluctuation spectral resolution. The same computational model was used for the determination of the deformation of the doors subjected to aerodynamic loads.

IV. Data Analysis Procedure

A. Flow Analysis

The mean flow analysis consisted in the study of the mean pressure coefficient $\overline{C_p}$ and the Overall Sound Pressure Level (OASPL) trends, quantities respectively defined as:

$$\overline{C_p} = \left\langle \frac{2}{\gamma_{air} \cdot M_\infty} \cdot \left[\frac{p}{p_\infty} - 1 \right] \right\rangle \quad (8)$$

Here, the overbar indicates that the quantity has been time-averaged.

The non-stationary flow analysis involved both frequency and time-frequency domains analysis. For the frequency domain analysis, the Sound Pressure Level of the fluctuating part of the pressure signals was calculated as:

$$SPL(f) = 10 \log_{10} \left(\frac{PSD(f)}{p_{reference}^2} \right) \quad (9)$$

In this study the PSD (Power Spectral Density) was obtained using the Welch method [35], with the division of the original signal into smaller blocks of 50% overlap and with the number of samples equal to the closest power of 2 of the ratio of f_s/f_r §.

§ The frequency resolution was posed equal to 20 Hz.

To analyse the pressure signals in the time-frequency domain, the procedure (based on the Hilbert-Huang spectral analysis [36]) already used by Bacci [32] was adopted.

Given a signal $x(t)$, of temporal length T , with the implicit mode functions extracted using one of the above methods, it is possible to write the following:

$$x(t) = \sum_{i=1}^n IMF_i(t) + r_n(t) \quad (10)$$

Here, $r_n(t)$ is the residual after the decomposition in n modes. The number of modes extracted can vary according to the complexity of the signal. Typically, the extraction is stopped when the energy ratio (ER_i) for the i^{th} extraction reaches a value of 20 dB [36] :

$$ER_i = 10 \log_{10} \left(\frac{\|x(t)\|_2}{\|r_i(t)\|_2} \right) \quad (11)$$

The successive step is to apply the Hilbert transform to each IMF, and derive the analytical signal $z(t)$ of $x(t)$:

$$z(t) = \sum_{i=1}^n IMF_i(t) + jH \left\langle \sum_{i=1}^n IMF_i(t) \right\rangle = \sum_{i=1}^n a_i(t) e^{j\theta_i(t)} \quad (12)$$

$$H\langle x(t) \rangle = \frac{1}{\pi} P \int_{-\infty}^{+\infty} \frac{x(t')}{t - t'} dt' \quad (13)$$

Equation (13) is the definition of the Hilbert transform, where P is the Cauchy principal value. From Eq.(12) it is possible to express each IMF in terms of instantaneous amplitude ($a_i(t)$) and instantaneous phase ($\theta_i(t)$), from which the instantaneous frequency ($f_i(t)$) definition follows:

$$f_i(t) = \frac{\omega_i(t)}{2\pi} = \frac{1}{2\pi} \cdot \frac{\partial \theta_i(t)}{\partial t} \quad (14)$$

The Hilbert spectrum is then defined as:

$$H(\omega, t) = \sum_{i=1}^n H_i(\omega, t) \quad (15)$$

and:

$$H_i(\omega, t) = \begin{cases} |a_i(t)|, & \omega = \omega_i(t) \\ 0, & \text{otherwise} \end{cases} \quad (16)$$

This definition enables the representation of the amplitude and the instantaneous frequency as a function of time in a 3D plot, in which the amplitude can be contoured in the frequency-time plane. This frequency-time distribution of the amplitude is defined as the Hilbert spectrum $H(\omega, t)$, with the associated Hilbert spectral energy $H_e(\omega, t) = H^2(\omega, t)$. It is possible to see that each IMF represents an intrinsic feature of the signal and, if properly calculated, describes a physical phenomenon [36].

From the Hilbert spectrum it is possible to define the Hilbert marginal spectrum $h(\omega)$:

$$h(\omega) = \int_0^T H(\omega, t) dt \quad (17)$$

This quantity represents the cumulated amplitude over the entire data span in a probabilistic sense. In the Hilbert spectrum, the presence of a peak at a frequency bin, has a different meaning from the Fourier spectral analysis. In the Fourier representation, the existence of energy at a frequency, indicates that a component of a sine or a cosine wave persisted through the period of the data. In the Hilbert marginal spectrum, the existence of energy at the frequency indicates that, in the whole timespan of the data, there is a higher likelihood for such a wave to have appeared locally.

B. Bay Door Load Analysis

The door mean and unsteady behaviour, generated by flow unsteadiness, were reported in terms of acceleration and angular acceleration in the door axis reference system (see Fig. 2). The relative spectra $a(f)$ and $\dot{\omega}(f)$ were calculated as follows:

$$a(f) = \frac{2|\hat{a}|}{N} \quad (18)$$

$$\dot{\omega}(f) = \frac{2|\hat{\dot{\omega}}|}{N} \quad (19)$$

Here $\hat{a}$ and $\hat{\dot{\omega}}$ are the one-sided FFT of the acceleration and angular acceleration signals, whilst N is the number of samples of the time-series. This approach allowed the spectra to be expressed respectively in units of $\frac{m}{s^2}/Hz^{1/2}$ and $\frac{rad}{s^2}/Hz^{1/2}$.

V.Results

A. Aero-Acoustic Analysis

1. Mean Flow Analysis

Mean flow analysis of the reference geometry** indicated that the longitudinal mean pressure gradient on the cavity floor, was in line with an open-type behaviour [10]. In the front part of the bay, up to x/L 0.25, the pressure was approximately constant, with negative values. Beyond this point a sharp positive gradient was observed, with the mean pressure coefficient increasing to a value of 0.22 at the rear of the cavity (Fig. 6 – Upper). Changes in geometry, represented by the introduction of the gap, made the positive part of the curve flatter. The inflection point, where the gradient changed from positive to negative was shifted rearwards to x/L 0.30. This changed the pressure gradients as well, with the front negative one being slightly steeper with respect to the reference case, whilst the rear positive one was slightly flatter with a maximum $\overline{C}_p$ value, at the rear of the cavity of 0.18. On the other hand, the appearance of sideslip, in both geometries, made the curve flatter in the front part and displaced the inflection point upstream by 0.1 x/L . The positive-gradient was influenced as well, becoming steeper, and reaching a maximum $\overline{C}_p$ value, at the rear of the cavity of 0.26 for the no-gap case, and 0.22 for the gap-case.

** Unless otherwise stated, the reference geometry was the no-gap configuration at zero sideslip.

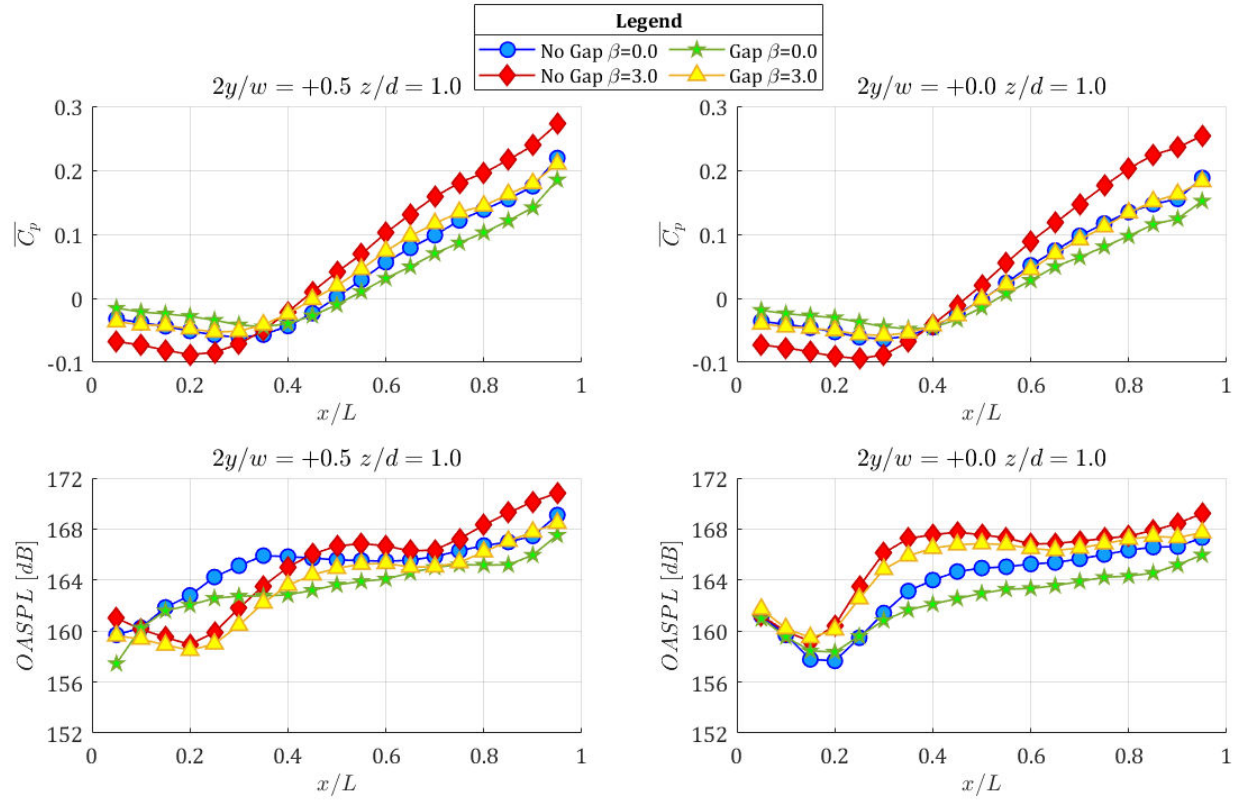


Fig. 6. Mean pressure coefficient and OASPL comparison. Data refers to *Rake C* (right column) and *Rake R* (left column).

The influence of geometry and sideslip were observed in the rms pressure trend as well. The reference geometry experienced OASPL levels ranging from 158dB at the front, up to 167dB at the rear. Noticeably, acoustic levels were higher towards the side of the cavity than the central portion (Fig. 6 – Lower). The introduction of sideslip increased OASPL in the centre of the cavity, up to 4dB, whilst towards the sidewall, this effect was less pronounced (+2dB) and in the front sector of the bay, OASPL was reduced by up to 4dB compared with the zero sideslip case. The introduction of the gap improved the situation reducing the acoustic footprint whether in presence of sideslip or not. The average reduction in OASPL with respect to the no-gap geometry was 2dB.

Flow inspection, using the mean-velocity vector field line-integral-convolution (LIC) technique, indicated the presence of three vortices inside the cavity (ω_1 , ω_2 , ω_3 labels in Fig. 7). The main eddy was responsible for the overall recirculation, typical of an open-type cavity, its structure being predominant in the bay. Its core was in the front part of the cavity, at x/L of 0.20. As shown in Fig. 7 its position was not affected by the door gap or sideslip. This main vortex was accompanied by two smaller ones, located on the front floor (ω_3) and rear floor (ω_2). Again, these fluid structures did not change with geometry and/or sideslip introduction, appearing in similar positions, indicating that

the eddies system inside the cavities is more influenced by changes in parameters typical of the longitudinal plane of symmetry as L/D ratio or angle of attack [25], rather than secondary changes in the flow and/or geometry in the transverse direction (in the same location for all four cases analysed in this study.

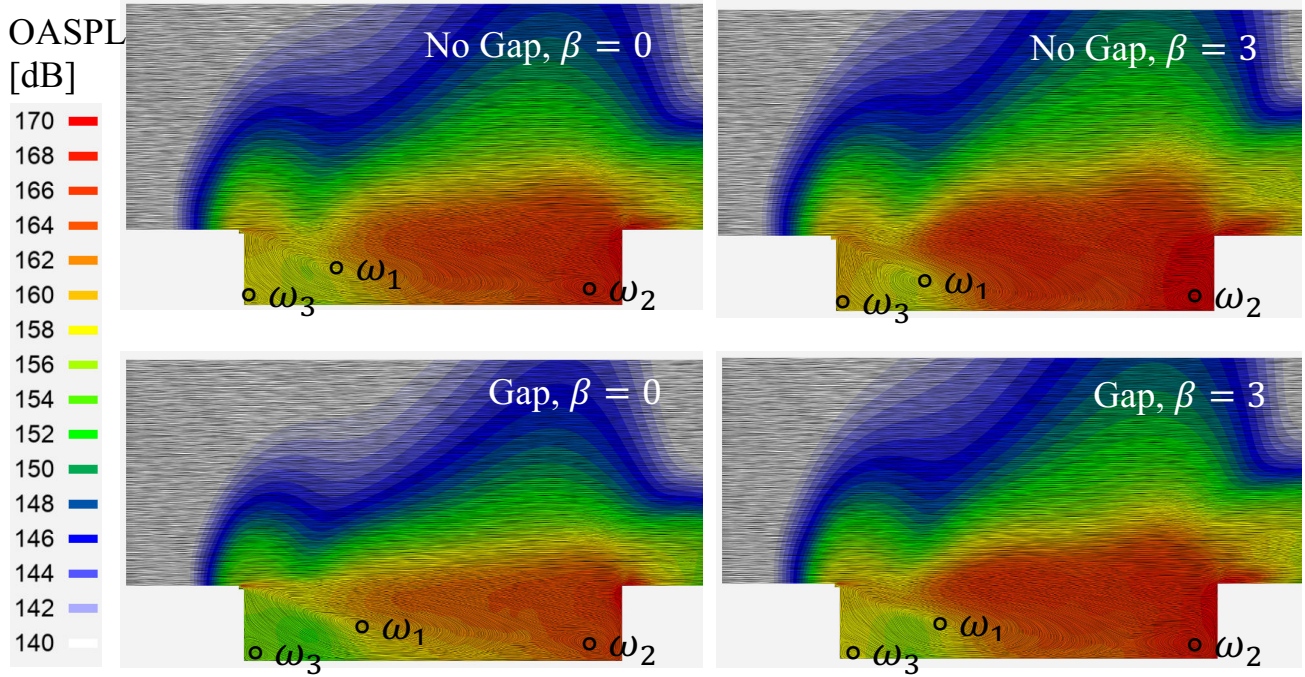


Fig. 7. Comparison of mean flow velocity LIC coloured by OASPL. Slice at $2y/W = 0$. Flow from left to right.

Conversely, OASPL contour levels were strongly influenced either by gap or sideslip appearance. As already observed in the data of Fig. 6, introduction of sideslip increased the acoustic radiation inside and outside the cavity. Flow visualisation indicated that β introduced an enlargement of the area outside the cavity where OASPL levels reached values of more than 164dB. Again, the gap acted as palliative, reducing both the extension, and the overall intensity, of the acoustic footprint. Flow analysis in a plane placed 5 mm above the cavity exit (Fig. 8), allowed quantification of the extent of sideslip effect across the cavity span. Here it was possible to observe that the windward side of the cavity experienced a consistent increase in OASPL levels when sideslip was introduced, especially in the front part, which was influenced by flow separation from the windward door. The area outside the cavity was influenced as well. In the reference case (Fig. 8 – Upper), an extended, green-coloured, area (representing OASPL levels between 150dB to 156dB), was present outside the confined space created by the doors, in the rear half.

Relative effects of introducing a gap and/or placing the cavity in zero/positive sideslip with respect to the freestream flow are summarised in Fig. 10.

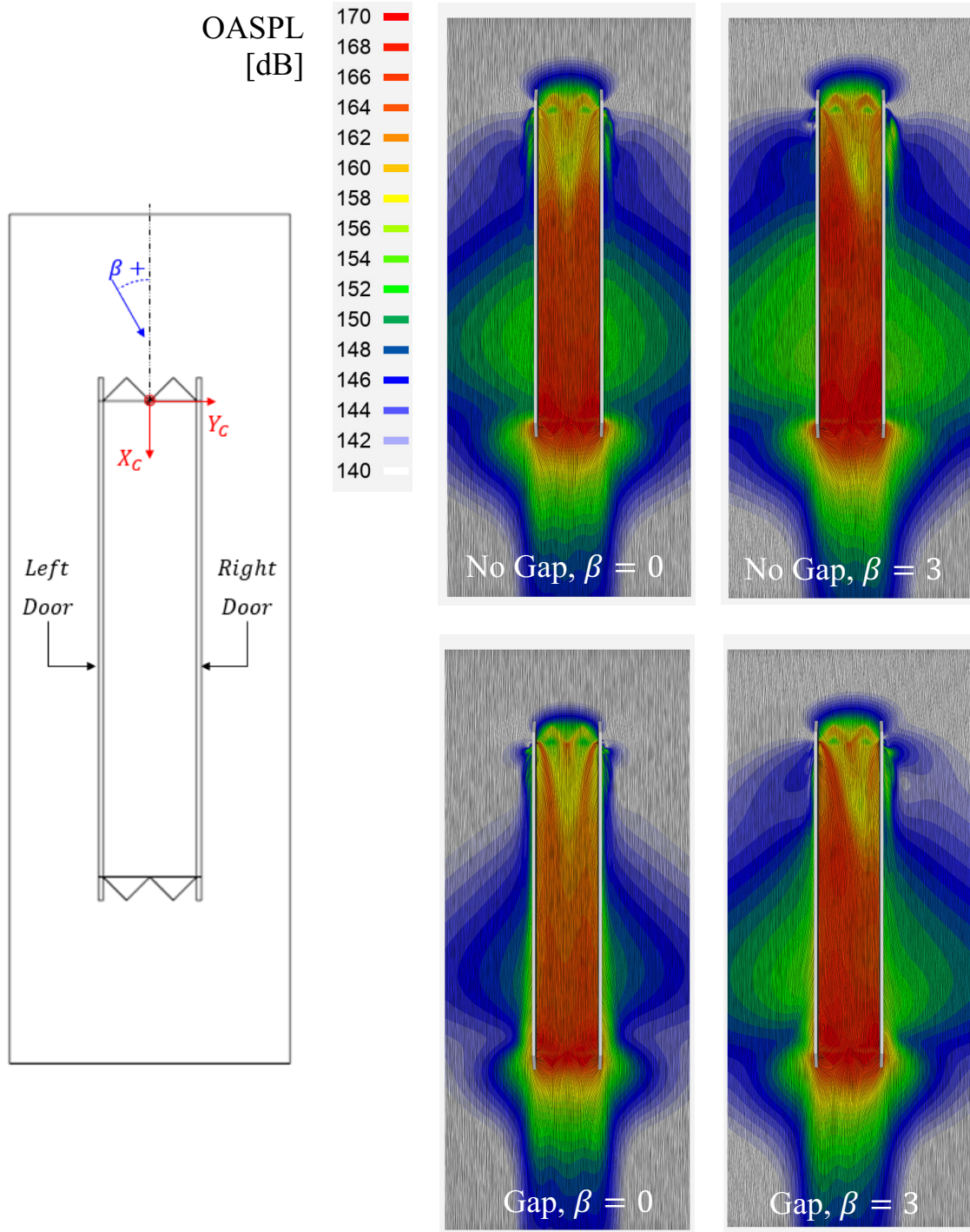


Fig. 8. Comparison of mean flow velocity LIC coloured by OASPL. Slice at $z/D = 0$. Flow from left to right.

This area expanded with sideslip on both the windward and leeward side, extending upstream as well. As expected, the windward side experienced a higher increase than the leeward. Introducing a door gap lowered the OASPL levels, reducing the green-coloured area both with and without sideslip.

The overall geometry/sideslip effects are shown in Fig. 9, where a perspective view of the cavity is shown. In this case, OASPL contours were calculated on the cavity and door walls together with the surrounding boundary. LIC visualisation was calculated using the mean-wall-shear vector field. Again, the higher acoustic load of the geometry without gap was visible.

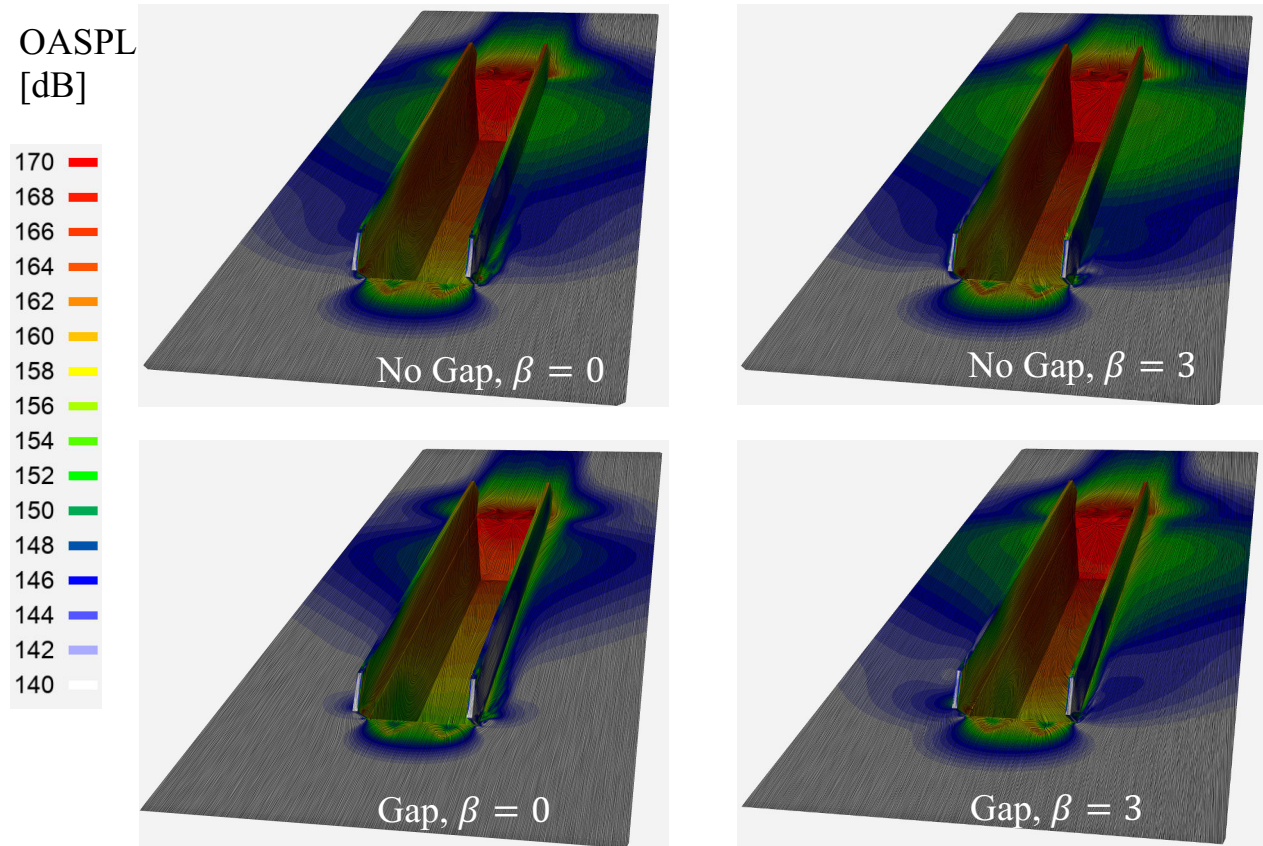


Fig. 9. Comparison of mean wall-shear LIC coloured by OASPL.

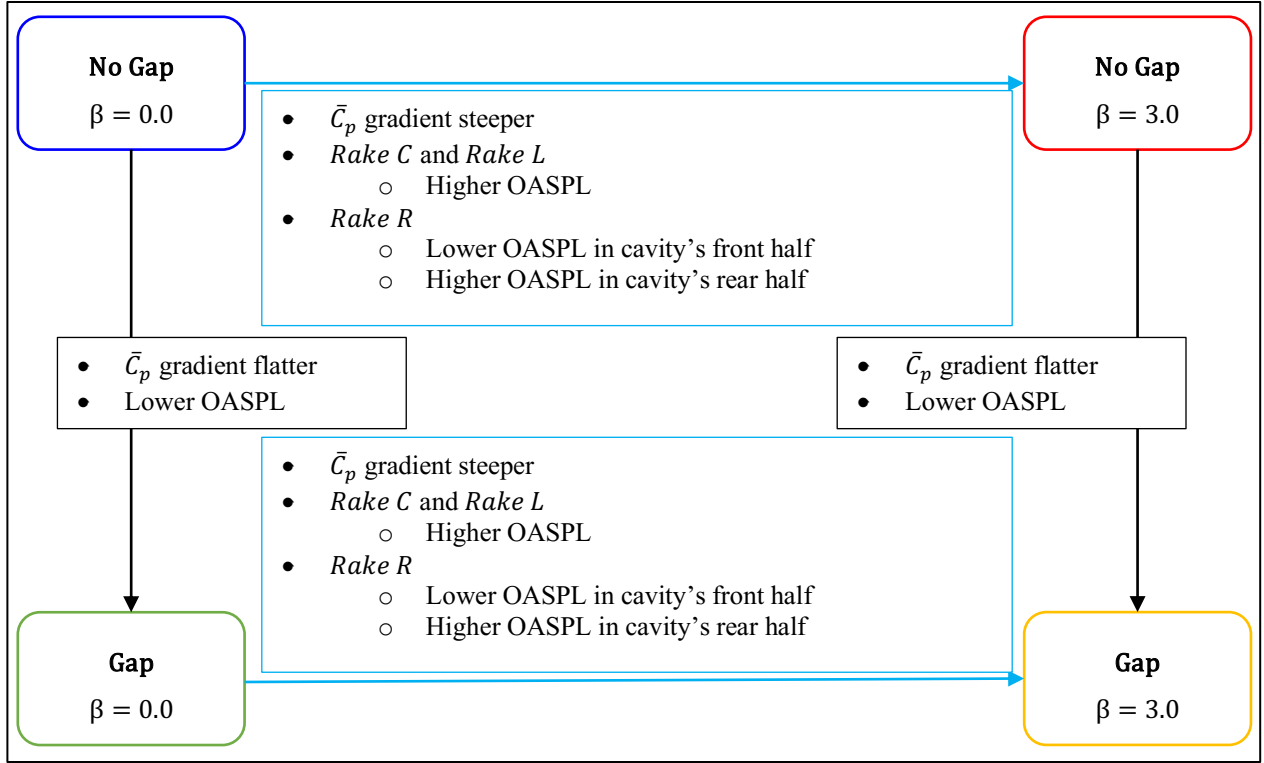


Fig. 10. Summary of mean flow qualitative changes ($\bar{C}_p$ and OASPL).

2. Unsteady Flow Analysis

The spectral analysis of pressure signals on the cavity floor showed the presence of three resonant modes corresponding to the 2nd, 3rd, and 4th Rossiter-Heller theory predicted values. As show in Fig. 11, for the reference case the probe at $x/L=0.95$ showed a main resonant mode, R_2 at 390 Hz/143.8 dB, close to the theory-predicted value of 365 Hz. This mode was accompanied by R_3 , 586 Hz/136.4 dB, and R_4 , 840 Hz/129.8 dB (here, by comparison, theory predicted RH_3 at 577 Hz and RH_4 at 789 Hz). No appreciable difference was observed between the central rake and the side rake, confirming the global nature of the acoustic phenomenon. In accordance with previous studies and experiments of rectangular cavity flows ([1], [3], [10], [37]), probes placed at $x/L=0.50$ were characterised by a spectrum having only R_2 and R_4 modes (R_3 being buried in the background noise), whilst a 3-peak spectrum was again present within pressure signals recorded at $x/L=0.05$. Finally, in accordance with the OASPL analysis, whilst the frequency of the resonant modes did not change with longitudinal position, spectral power increased in the rear of the bay compared to the front.

The introduction of a transverse component of the flow affected the main mode R_2 , increasing its SPL value to 146.7 dB and lowering its frequency to 371 Hz. On the other hand, R_4 remained unchanged, whilst R_3 maintained a

SPL value of 136.4 dB but changed frequency, from the previous value of 586 Hz to 547 Hz. Similar trends were observed at different locations, again suggesting a global change affecting the overall cavity acoustic response, rather than local differences induced by sideslip angle. Inspection of the flow features, using the Iso-Q criterion (Fig. 12-Upper), showed how eddies detaching from the cavity leading edge increased in size and overall velocity magnitude upon sideslip introduction. This result was directly correlated to the increased acoustic power.

The introduction of the door gap again acted as a palliative to the aero-acoustic response. With symmetric flow conditions the pressure spectra had the same qualitative characteristics as the no-gap case (three main resonant modes located at the same frequencies) but experienced a lower SPL value. At all longitudinal stations, tones and broadband noise SPL was reduced by 3% with the introduction of the gap. The same was true in the presence of sideslip where, on average, SPL values of both broadband and tonal noise were reduced by 2% with respect to the no-gap case.

Again, the inspection of flow features (Fig. 12) indicated that, whilst gap introduction did not change the qualitative aspect of vortex structures dominating the domain, it reduced their intensity.

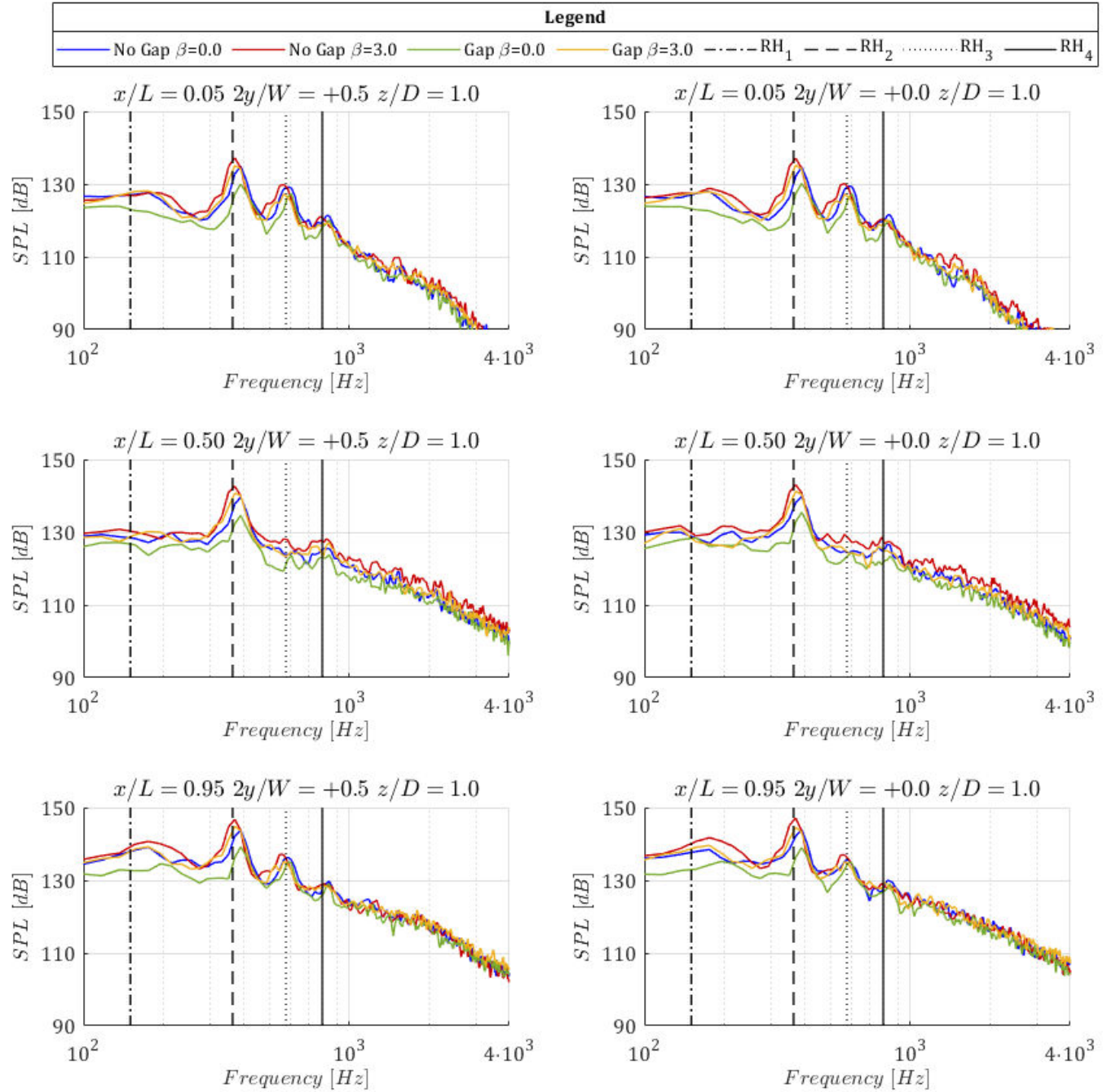


Fig. 11. SPL comparison at 6 probe locations. Black-coloured vertical lines represent Rossiter-Heller theory-predicted modes.

Further details of the pressure-signal characteristics were extracted using the Hilbert-Huang spectral analysis. In this case only probes placed at $x/L=0.95$ in the central rake were analysed. Time spectral analysis (Fig. 13 – upper left) indicated the intermittent nature of the signal, showing amplitude and frequency modulation (AM/FM) phenomena as well. The dominant mode R_2 , in the reference case, whilst having only mild FM behaviour, was

characterised by strong variations in amplitude. Similarly, R_3 and R_4 , were not continuous features in time and frequency. Rather, they experienced strong variations both in amplitude and frequency during the temporal evolution of the signal.

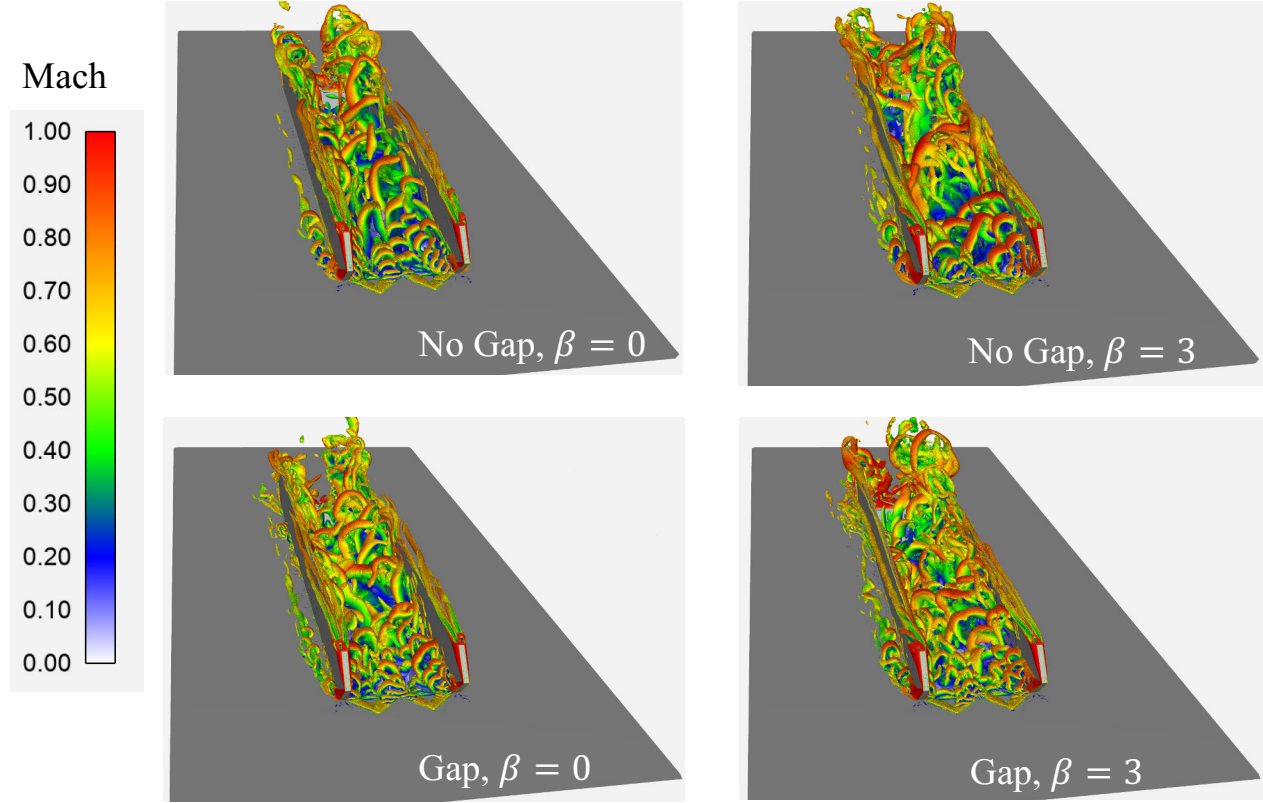


Fig. 12. Comparison of Iso-Q surface coloured by Mach number.

The introduction of the gap (Fig. 13 – lower left) did not change the signal’s feature but considerably reduced the excursions in amplitude, indicating an inferior acoustic power with respect to the no-gap geometry. Sideslip (Fig. 13 – right) increased the temporal consistency of R_2 together with the acoustic power. On the other hand, R_3 and R_4 still increased the acoustic power but, at the same time showed a spreading in frequency leading to stronger FM behaviour.

The marginal Hilbert spectrum allowed further insight into the characteristics of the acoustic response of the flow. For the reference case, 5 distinct peaks were observed, as shown in Fig. 14 at 84 Hz ($M_{CI} \equiv f_b$), 200 Hz (f_a), 368 Hz (R_2), 568 Hz (R_3) and 900 Hz (R_4) respectively. According to the classification of Table 1, and using Delprat’s decomposition rule, tones at 368 Hz, 568 Hz, and 900 Hz were indeed associated with the Rossiter-Heller modes, which in turn were the direct consequence of the non-linear interaction and energy transfer between two fundamental frequencies, f_a , which in this case was associated with the peak at 200 Hz, and f_b , the peak at 86 Hz. Given their

frequency, whilst the former was associated with the acoustic phase-locked loop, the latter was a characteristic of centrifugal instabilities, originating in the main recirculation eddy and caused by the minor vortices present inside the cavity, as shown in Fig. 7.

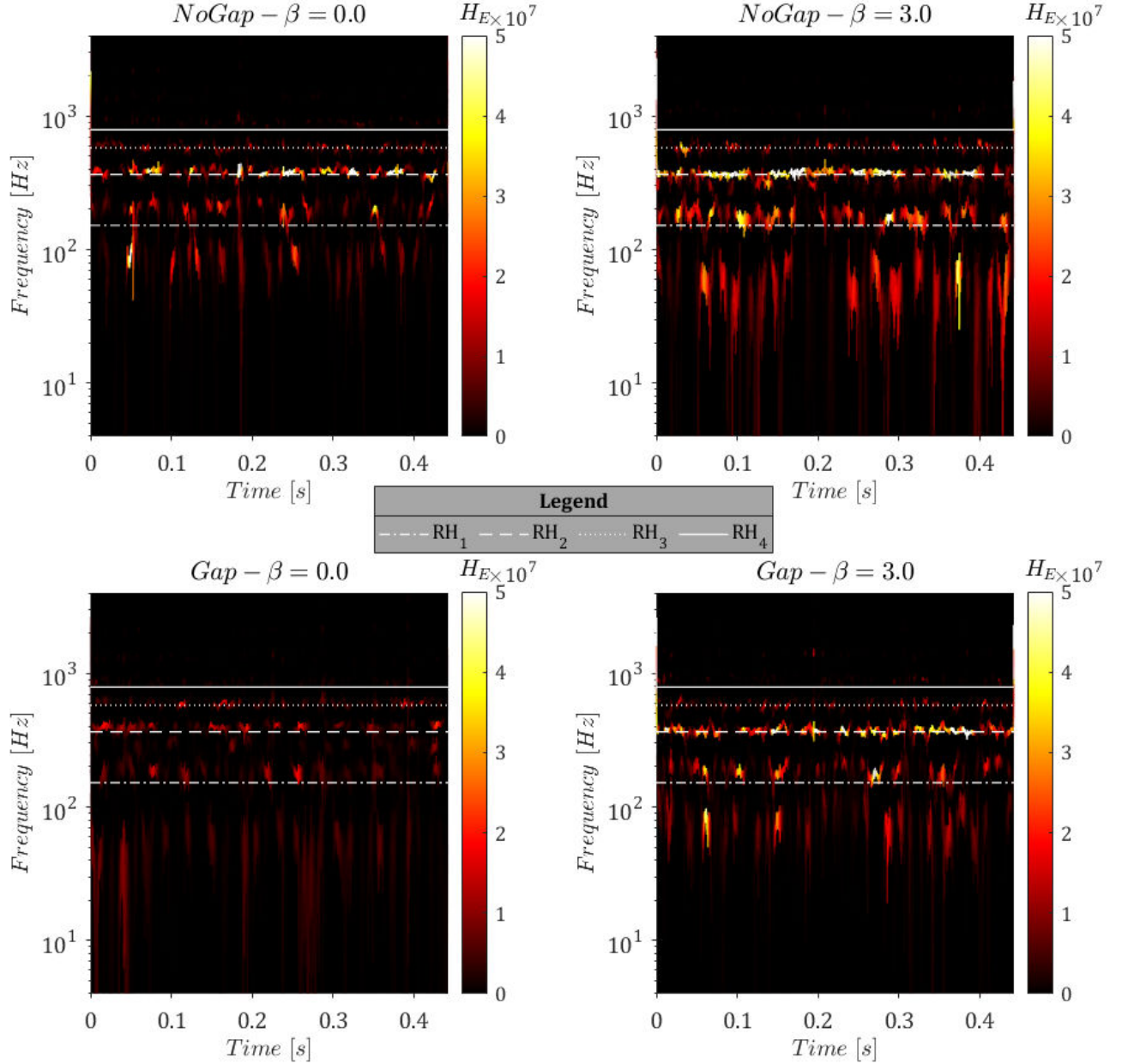


Fig. 13. Comparison of Hilbert Spectrum of pressure signal at x/L 0.95, $2y/W$ 0.0, z/D 1.0.

Sideslip minimally affected R_2 and R_3 , whilst moving the relative peak of R_4 to higher frequencies, increasing the associated band as well (i.e. the amplitude of the peak's base, which in turn corresponded to a stronger FM behaviour, as observed in Fig. 13). By comparison, f_a was moved to 180 Hz and f_b to 48 Hz, with the latter having a considerably

flatter peak. This phenomenon could have been correlated to the influence of local flow variations, induced by sideslip, on the secondary eddies inside the cavity and the centrifugal instabilities as well. A flatter peak typically corresponds to higher dispersion of energy across multiple bands, which in turn reflects as a strong FM behaviour. From this it was deduced that whilst the globally associated phenomenon was still present, its nature assumed a less coherent aspect.

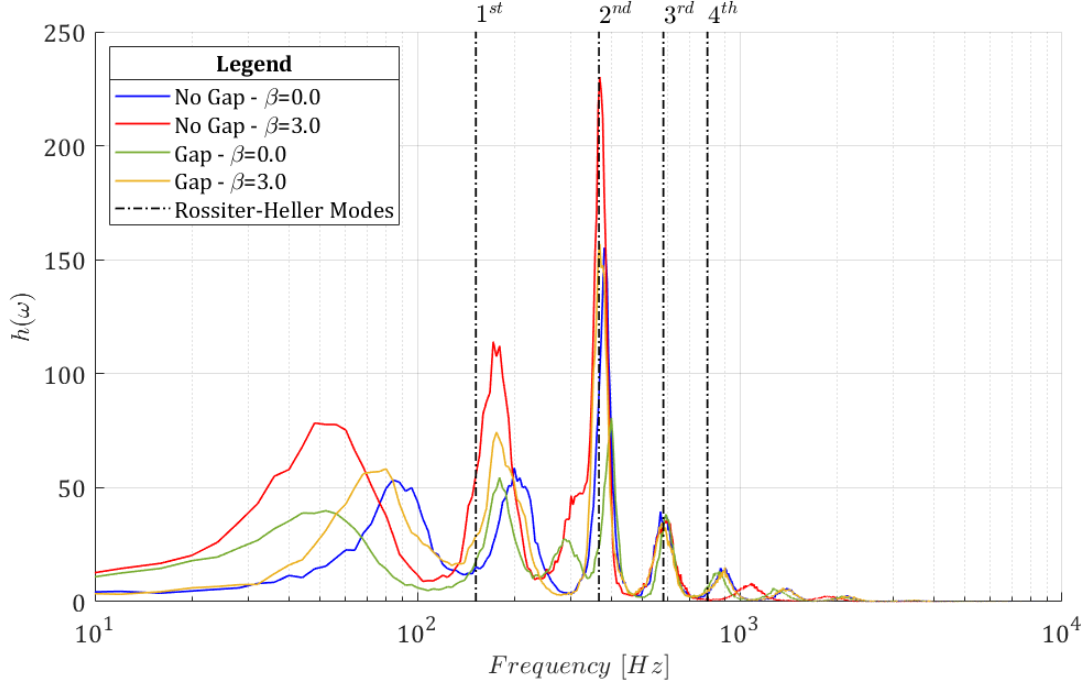


Fig. 14. Comparison of Marginal Hilbert Spectra of pressure signal at x/L 0.95, $2y/W$ 0.0, z/D 1.0.

Whilst again not changing the placement in frequency of R_2 , R_3 , and R_4 , the gap decreased the energy content of f_a and f_b , with the latter's peak again spread over a wider band with respect to the equivalent no gap case. According to the Hilbert spectrum, the major effect of the gap introduction was to spread f_a and f_b energy in a wider band hence reducing not only their associated energy but also those as a direct consequence of their non-linear coupling, i.e. the Rossiter-Heller tones. This finding confirmed the results of the spectral analysis where gap-geometry acoustic power was always less than the corresponding no-gap case. Notably, the gap geometry in sideslip presented an additional tone at 290 Hz, which was identified as a transverse mode excited by the flow spilling in the transverse direction across the gap, entangling with the shear layer.

B. Modal Analysis

A total of 20 modes were extracted during the structural analysis. Nevertheless, just 4 were considered fundamental, as they accounted for more than 75% of the effective total mass in all principal directions of deformation.

These were M_1 (385 Hz), M_2 (487 Hz), M_9 (1840 Hz), M_{15} (3885 Hz). The associated displacements are shown in Fig.

15.

Table 5 Summary of Principal Modes Characteristics for the hinged door.

Mode	f [Hz]	Ratio of Effective Mass to Total Mass %					
		u_x	u_y	u_z	θ_x	θ_y	θ_z
M_1	385	-	75.05	-	99.11	-	54.86
M_2	487	-	-	-	-	-	20.25
M_9	1840	-	10.62	-	-	-	-
M_{15}	3885	98.87	-	-	-	-	-
Total		98.87	85.67	-	99.11	-	75.11

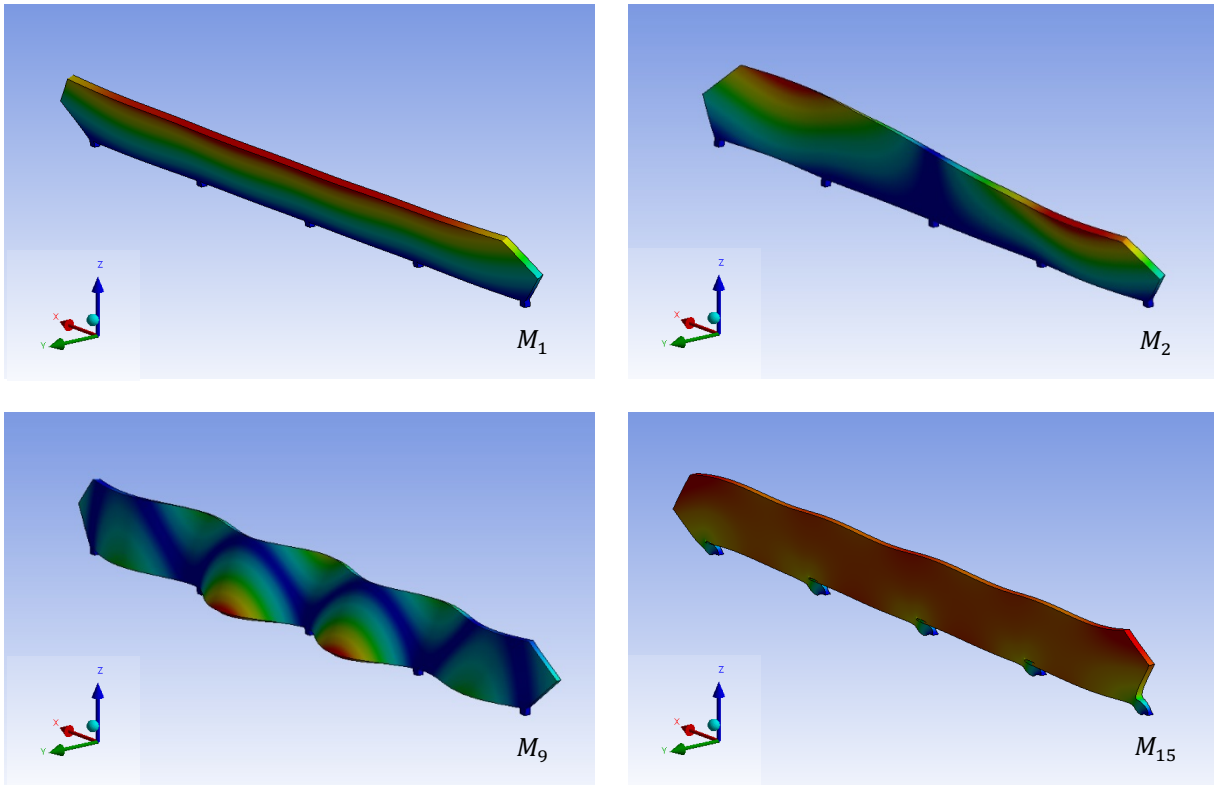


Fig. 15. Principal structural modes visual identification.

M_1 consisted of a coupled flexural response along the door's y-axis coupled with a torsional deformation along the x-axis and z-axis. M_2 was related to the torsional deformation of the structure in the z-axis direction. The difference between M_1 , regarding the deformation around the z-axis was that M_2 had a nodal point whilst M_1 did not. M_9 , still

involving flexural response along the y-axis, differed from M_1 . In the former there were multiple nodal points, coincident with the hinges. Finally, M_{15} represented shear deformation along the x-axis. Table 5 summarises these principal modes with their relative contribution to the total mass for each direction. It is worth noting that no appreciable contribution was observed for u_z and θ_y . This outcome was, nevertheless, as expected since these deformation directions were directly blocked by the no displacement constraint imposed on the hinge base.

C. Doors Load Analysis

Door displacement was reported in terms of linear and angular accelerations. The analysis of mean and rms values allowed the determination of the general picture regarding the different effects induced either by sideslip or gap. At zero sideslip and no gap (see Table 6), the mean values indicated that the structure was mainly by a force in the y-direction and a torque in the x and z-direction. By comparison, the torque in the y-direction was 2 orders of magnitude smaller, whilst forces in the x and z-direction were respectively 50% and 75% less than the y-component. Elastic analysis of door deformations caused by aerodynamic loads indicated that, in these symmetric flow conditions, fluid forces acted to push doors away from the centre of the cavity, whilst the torques tended to further increase the opening, as shown in Fig. 16-upper. The elastic deformation of the door panels increased by a factor of 8000 to ease visualisation. The results were calculated using the Static Structural analysis sub-routine of ANSYS Mechanical ADPL 2021R2.

Table 6 Summary of doors angular and linear accelerations mean values

<i>Geometry</i>	β [deg]	<i>Door Id</i>	<i>Linear Accelerations</i> $\left[\frac{m}{s^2}\right]$			<i>Angular Accelerations</i> $\left[\frac{rad}{s^2}\right]$		
			a_x	a_y	a_z	$\dot{\omega}_x$	$\dot{\omega}_y$	$\dot{\omega}_z$
<i>No Gap</i>	0.0	<i>Left</i>	29.07	-43.34	12.92	-862.68	1.58	-200.72
		<i>Right</i>	29.18	43.03	13.01	978.77	6.25	203.62
	3.0	<i>Left</i>	29.12	32.34	14.88	-1908.57	16.83	-586.02
		<i>Right</i>	32.45	125.02	16.36	219.20	-7.30	211.11
<i>Gap</i>	0.0	<i>Left</i>	28.20	-45.18	1.52	-876.53	-5.05	-192.02
		<i>Right</i>	28.25	44.86	1.67	830.33	-6.69	196.07
	3.0	<i>Left</i>	28.39	22.03	2.66	-1493.26	-5.50	-482.13
		<i>Right</i>	32.07	115.06	2.36	31.58	-7.80	65.99

The addition of sideslip introduced asymmetry in the load on the doors. The lateral flow component introduced a force along the y-axis that acted in the same direction as the original zero sideslip case for the leeward door, whilst in

the opposite direction for the windward one. For the windward door, a_y changed sign becoming positive, whilst for the leeward door, the sign was still positive, but the modulus increased by a factor of 300%. Similar behaviour was observed for the dominant angular accelerations $\dot{\omega}_x$ and $\dot{\omega}_z$. The windward structure experienced an increase in magnitude of the associated moments, whilst the leeward door had lower ones. The overall effect on the structural deformation (Fig. 16-lower) was that the door shear in the xy-plane was greater on the side exposed to the lateral flow component.

The geometry with the gap underwent similar behaviour but, due to the gap, the increase in magnitudes experienced by the windward door was reduced, by 10% for a_y and by 20% for $\dot{\omega}_x$ and $\dot{\omega}_z$ respectively.

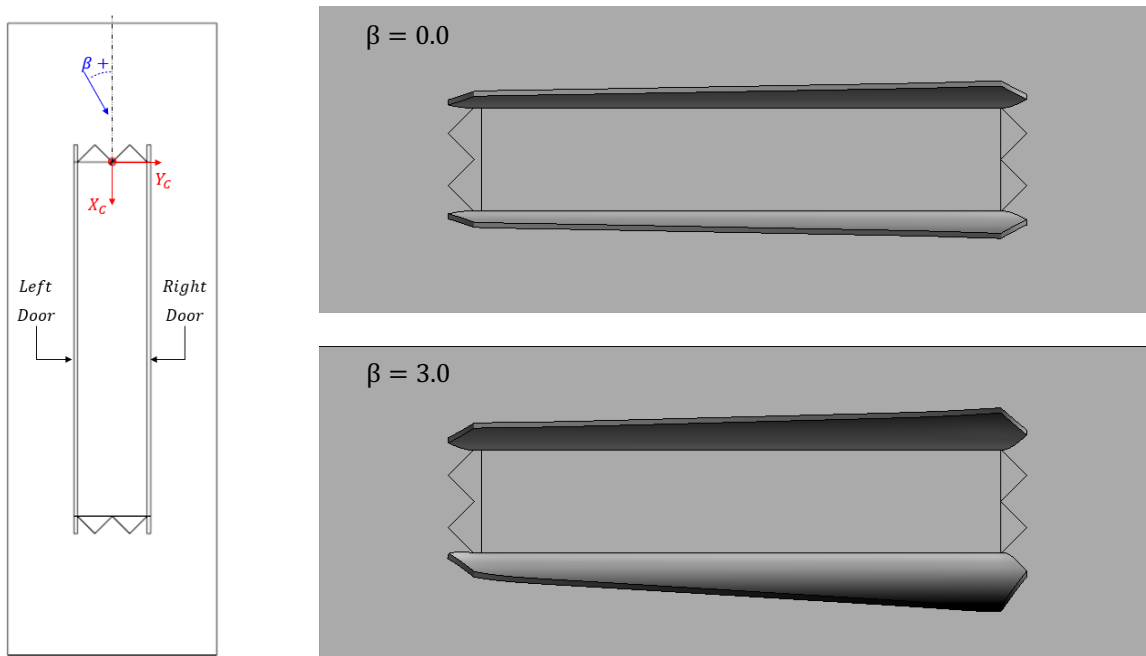


Fig. 16. Qualitative comparison of doors elastic deformation with and without sideslip. No-Gap geometry. Displacement scale factor 8000.

The rms values of the accelerations were prevalent in the y-direction (linear) and x and z-direction (angular), in accordance with the mean value analysis. Under symmetric flow conditions the introduction of the gap again reduced the magnitude of the effect with respect to the no gap case, with a -40% for a_y , -30% for $\dot{\omega}_x$ and -35% for $\dot{\omega}_z$. These findings indicated that the gap not only alleviated time-averaged loads, but also the time-varying ones associated with the cavity's unsteady flow.

With the introduction of sideslip, in the no-gap case, whilst the rms value of lateral acceleration increased by 30% for both doors, an asymmetry was observed in the rms values of $\dot{\omega}_x$ and $\dot{\omega}_z$. The x-component of the angular

acceleration increased by 50% on the windward door, whilst on the leeward one, the rms value was augmented only by 10%. Conversely, the z-direction rms angular acceleration was increased by 30% in the leeward side, whilst it was practically unchanged on the windward side. These effects were correlated to the coupling of the cavity shear layer vortex system with the unsteady detachment of eddies at the door edges, induced by the transverse flow component, as shown in Fig. 12. The addition of the gap induced unsteady load alleviation levels like the one observed in the zero-sideslip case.

Spectral analysis of the linear accelerations for the reference case (see Fig. 17 and Table 7) indicated that the spectrum of both doors was dominated by a peak located at 385 Hz, which corresponded to the value of M_1 calculated in the modal analysis, indicating potential fluid-structure resonance. The absolute value of the peak, present in all components of acceleration, varied accordingly with a_y being the strongest one, with a value of $3.44 \text{ ms}^{-2}/\text{Hz}^{1/2}$. By comparison, the relevant peak magnitude for a_z was $0.26 \text{ ms}^{-2}/\text{Hz}^{1/2}$, and $0.07 \text{ ms}^{-2}/\text{Hz}^{1/2}$ for a_x .

Table 7 Summary of doors angular and linear accelerations rms values

<i>Geometry</i>	β [deg]	<i>Door Id</i>	<i>Linear Accelerations</i> $\left[\frac{\text{m}}{\text{s}^2}\right]$			<i>Angular Accelerations</i> $\left[\frac{\text{rad}}{\text{s}^2}\right]$		
			a_x	a_y	a_z	$\dot{\omega}_x$	$\dot{\omega}_y$	$\dot{\omega}_z$
<i>No Gap</i>	0	<i>Left</i>	1.85	37.41	3.64	994.38	25.32	425.76
		<i>Right</i>	1.89	36.44	3.73	1043.12	24.05	413.83
	3.0	<i>Left</i>	1.99	44.58	4.99	1470.95	33.09	471.22
		<i>Right</i>	2.14	43.64	3.69	1121.49	25.85	543.28
<i>Gap</i>	0.0	<i>Left</i>	1.38	22.87	2.45	694.84	19.14	282.06
		<i>Right</i>	1.36	24.78	2.48	691.98	20.63	292.17
	3.0	<i>Left</i>	1.81	35.94	3.34	1203.85	26.75	427.42
		<i>Right</i>	1.92	32.75	2.76	907.12	21.51	433.29

Moving to higher frequencies, both a_y and a_z were characterised by broadband noise. On the other hand, an additional peak, centred at 570 Hz occurred in the a_x spectrum, but this value was sufficiently separated from M_2 (487 Hz) to not be of concern for possible aero-elastic resonance.

The introduction of sideslip did not change the qualitative form of the spectra but caused an increase in the peak value of the dominant tone. In this case, a value of $4.28 \text{ ms}^{-2}/\text{Hz}^{1/2}$ was recorded. Additionally, the peak did not occur at 390 Hz but at the lower frequency of 360 Hz.

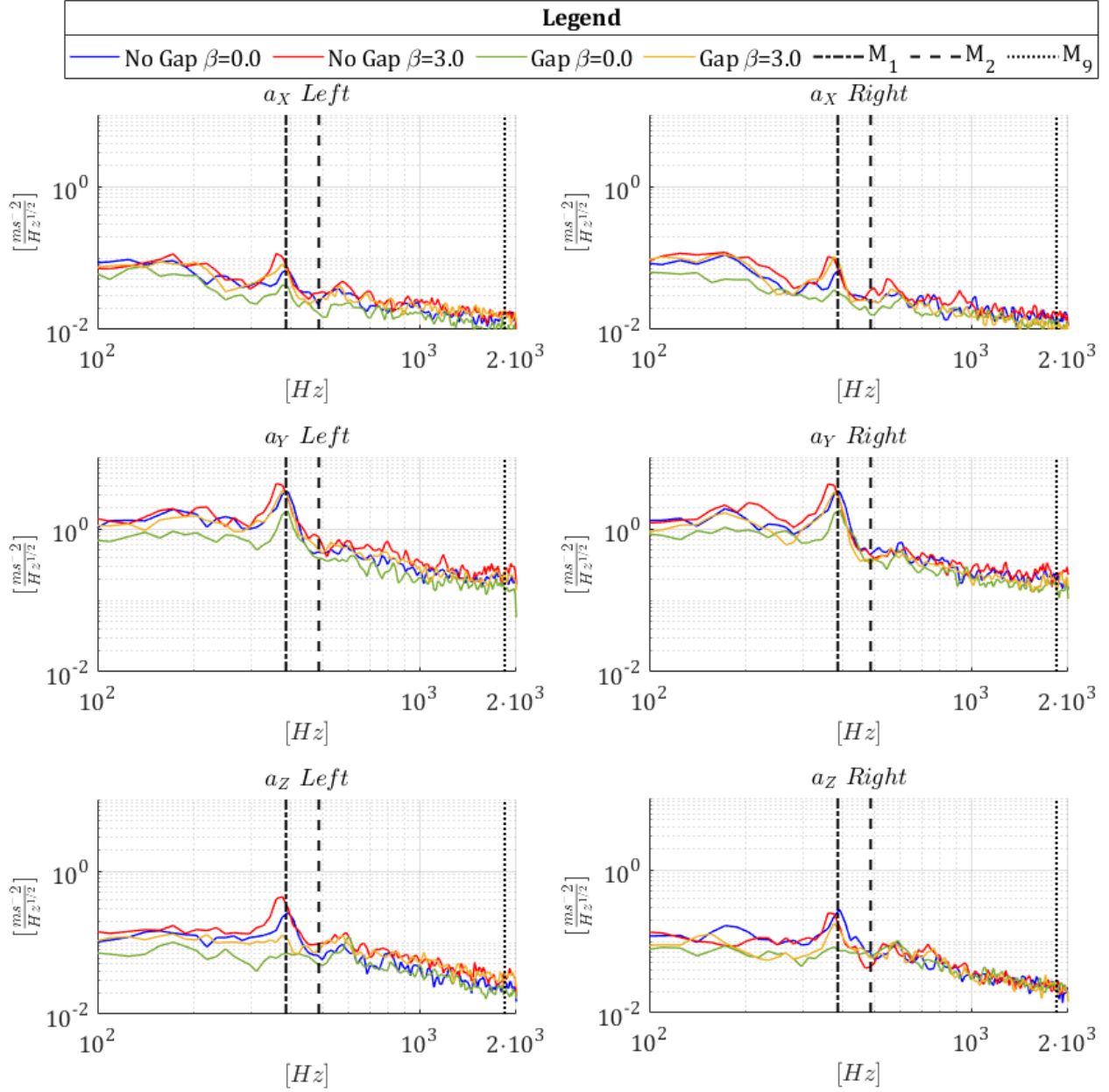


Fig. 17. Doors' linear acceleration spectrum comparison. For non-null sideslip, left door is on the windward side, the right door on the leeward.

The presence of the gap attenuated the magnitude of peaks and broadband noise, with an average reduction of $2 \text{ ms}^{-2}/\text{Hz}^{1/2}$ in both sideslip and no-sideslip cases. Interestingly, for the null-sideslip case, the a_x and a_z spectra did not present a resonant peak. Only the y-component acceleration showed a resonant mode, though still smaller in magnitude with respect to the no-gap case.

Spectral analysis of the angular accelerations, in accordance with the rms results, indicated that $\dot{\omega}_x$ and $\dot{\omega}_z$ were one order of magnitude higher than $\dot{\omega}_y$ as shown in Fig. 18.

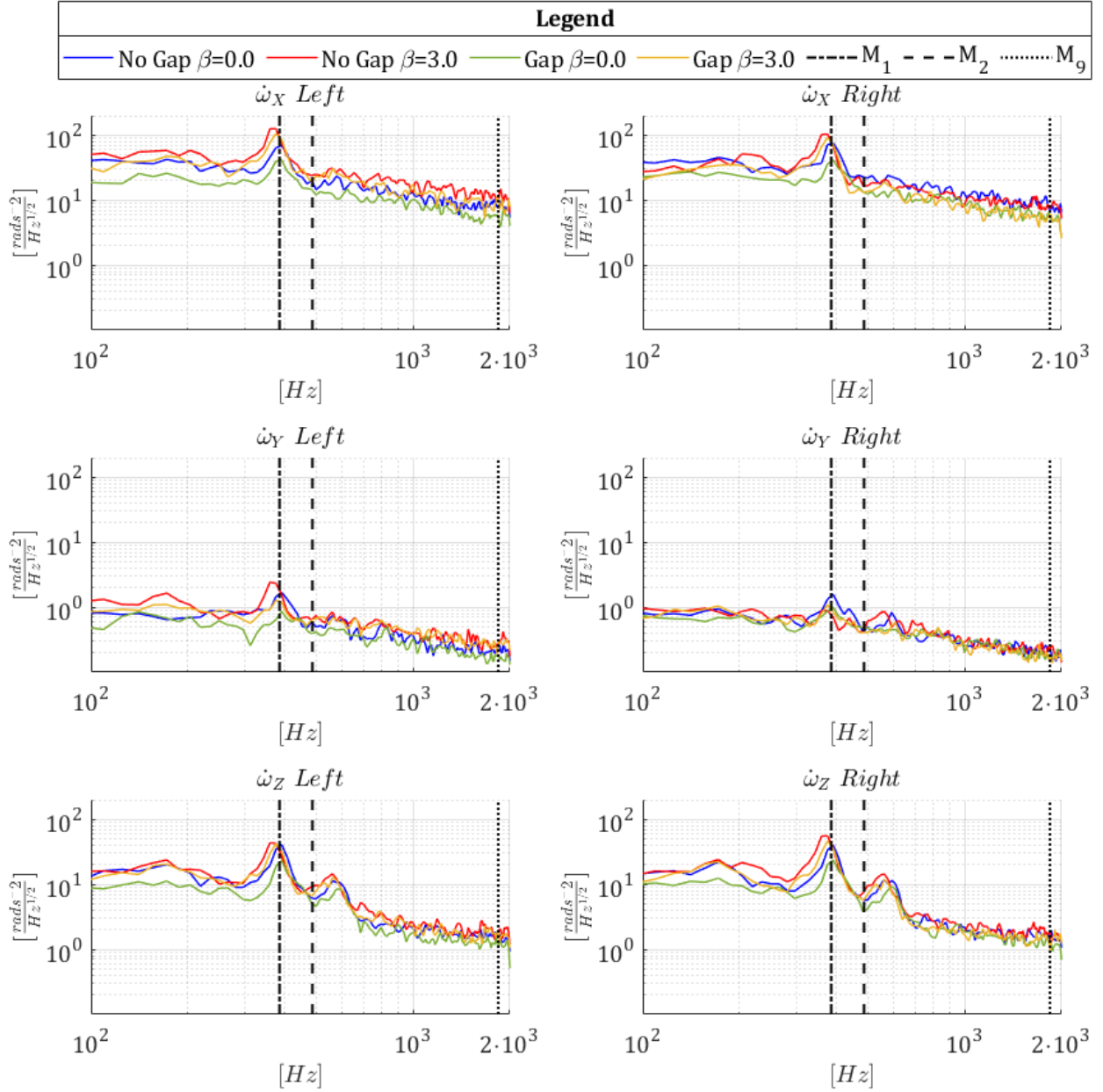


Fig. 18. Doors' angular acceleration spectrum comparison. For non-null sideslip, left door is on the windward side, right door on the leeward.

All components had a spectrum characterised by broadband noise, slowly decaying at higher frequencies, with a predominant peak corresponding with the first modal tone (385 Hz). In the reference case the peaks, equal for both the left and right door, attained values of 69.2, 1.7, and 41.2 $\text{rads}^{-2}/\text{Hz}^{1/2}$ for the x, y, and z-component respectively. Similar to the linear acceleration case of a_x , only the $\dot{\omega}_z$ spectrum showed a second peak, centred at 570 Hz with a value of 11.7 $\text{rads}^{-2}/\text{Hz}^{1/2}$. The introduction of sideslip had different effects between the left and right door. The left door (windward side) angular acceleration spectrum values increased for all components, +54% for $\dot{\omega}_x$, +35% for $\dot{\omega}_y$,

and +5% for $\dot{\omega}_z$. Additionally, for all components, the main peak location changed from the no-sideslip value of 385 Hz to a new value of 360 Hz.

On the other hand, the right door (leeward side) showed a different response. Here the relative changes, with respect to the no-sideslip case, were +48% for $\dot{\omega}_x$, -50% for $\dot{\omega}_y$, and +33% for $\dot{\omega}_z$. Again, where present, peak resonant frequency was lowered to 360 Hz from the previous 385 Hz value. These findings showed that the loads underwent local and global changes with the addition of a lateral velocity component. From a global point of view, the main resonant frequency was lowered to 360 Hz, slightly decoupling the associated moments from the door characteristic M_1 value. Regarding the gap-case geometry, whilst the qualitative changes introduced by sideslip were like the no-gap case, the overall angular acceleration levels were typically 50% smaller.

The overall analysis of the spectral signature on the forces and moments acting on the doors indicated that the possibility of fluid-acoustic coupling was likely to occur as all spectra showed a predominant tone located at the same frequency of the first structural mode M_1 . As shown in Table 5, this mode was characterised by having almost the entire structure effective mass associated with displacements along the y-direction, and rotation around the x and z-axes. As the linear acceleration was dominated by the a_y component and angular acceleration by the $\dot{\omega}_x$ and $\dot{\omega}_z$ components, aerodynamic-induced structural resonance was likely to occur.

VI. Conclusion

The study confirmed the influence of a small gap, located between the door and cavity edge, in the acoustic response and induced forces related to a representative model of a low-RCS weapon bay (cavity). The numerical computations indicated that a gap, located at the door connection within the cavity, acted as a palliative, reducing overall the OASPL value by 2 dB and SPL spectrum by 2%. The influence of sideslip angle was also explored. In general, it worsened the acoustic tones both inside the cavity and in the area outside it. Hilbert-Huang spectral analysis confirmed the existence of Delprat base frequencies, the fundamental acoustic feedback loop, correlated with the shear layer detachment at the cavity lip and impact on the rear wall, and the main modulating frequency, associated with centrifugal instabilities of the main recirculatory eddy, dominating the cavity volume. Mean flow analysis indicated that such instabilities were correlated with the presence of two subsidiary eddies located at the rear and the front of the cavity. The Hilbert marginal spectrum confirmed that with sideslip, the main Delprat tones increased their energy content, hence increasing the power expressed by their non-linear generated modes, i.e. the Rossiter-Heller tones.

Again, the palliative effect of the introduction of a gap was confirmed, which acted to make the fundamental modes diffused in frequency, spreading the energy across a wider band, hence reducing the associated acoustic load.

Analysis of the effects on the doors indicated that in symmetrical flow conditions, the major contribution was correlated with a force in the y-direction, acting as to push the doors away from the centre of the cavity, and torques in x and z-direction acting to increase the door opening angle. Sideslip increased accelerations (both linear and angular) on the windward side, whilst it reduced them on the leeward side. On the other hand, the gap reduced forces and moments in both the symmetric flow condition and in presence of sideslip.

Finally, the modal analysis indicated that a potential fluid-structure resonance was possible, as the main door mode coincided with the strongest peak in acceleration spectra.

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