

RANS/LES and LBM/VLES Aero-Acoustic Analysis of Weapon Bays at Transonic Mach Number

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Numerical aero-acoustic analysis was conducted on a weapon bay of a generic aircraft model using two conceptually different solvers, one based on the Navier-Stokes equations, the other based on the lattice-Boltzmann approach. The bay model was installed on a representative combat aircraft, incorporating doors and a store. The effect of angle of attack and store position on the aero-acoustic response within the weapon bay was analysed at a transonic Mach number of 0.90. It was found that both numerical approaches are capable of predicting, with good accuracy, the weapon bay's acoustic spectrum (± 10 dB) and store forces and moments ($\pm 10\%$), as compared to experimental data.

I. Nomenclature

C_p	=	pressure coefficient
$C_{x y z}$	=	store's aerodynamic force coefficient along X (or Y or Z axis) ($= F_{x y z}/q_\infty S_{\text{ref}}$)
$C_{mx my mz}$	=	store's aerodynamic moment coefficient along X (or Y or Z axis) ($= M_{x y z}/q_\infty S_{\text{ref}} l_{\text{ref}}$)
c_{avg}	=	cumulative average
D	=	store's maximum diameter (reference length), [m]
H	=	weapon bay depth, [m]
f	=	frequency, [Hz]
$F_{x y z}$	=	store's aerodynamic force along X (or Y or Z axis), [N]
L	=	weapon bay length, [m]
M_∞	=	freestream Mach number
$M_{x y z}$	=	store's aerodynamic moment along X (or Y or Z axis), [Nm]
p	=	pressure, [Pa]
p_∞	=	freestream static pressure, [Pa]
q_∞	=	freestream dynamic pressure ($= \frac{1}{2} \gamma P_\infty M_\infty^2$), [Pa]
RH_n	=	n_{th} Rossiter-Heller theory predicted mode
S_{ref}	=	store's reference area, [m ²]
t	=	time, [s]
T_∞	=	freestream static temperature, [K]
t_c	=	WB convective time unit ($= L/U_\infty$), [s]
U_∞	=	freestream velocity, [m/s]
W	=	weapon bay width, [m]
(X, Y, Z)	=	weapon bay's Cartesian coordinate system (longitudinal, transverse, vertical), [m]
(X_s, Y_s, Z_s)	=	position of the store's leading-edge in the weapon bay coordinate system, [m]
(x, y, z)	=	store's coordinate system (longitudinal, transverse, vertical), originated at its leading-edge, [m]
α	=	angle of attack of the aircraft model, [deg]
β	=	sideslip angle of the aircraft model, [deg]

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γ = ratio of specific heats for air
 ρ = air density, [kg/m³]

II. Introduction

THE design of modern combat aircraft is strongly influenced by the requirement to reduce the radar signature, implying that weapon systems must be carried inside the airframe (internally) instead of being suspended externally on the wings and fuselage. Whilst this solution offers advantages in terms of aerodynamic drag and radar cross-section reduction, other issues arise because the intrinsic instability of the local flow, when the bay's doors are opened, poses a hazard for the weapon's safe release. Additionally, an acoustic field can develop and damage the airframe and the payload electronics. Therefore, it is essential to understand the flow phenomena within internal weapons bays and the interaction of internal stores with the bay flow field.

While flight tests are expensive and limited [1–3], modern availability of high performance computing (HPC) power allows one to simulate weapon bay flows using computational fluid dynamics (CFD) solvers on a timely fashion [4–16]. However, while computational methods have demonstrated good agreement with experimental data, challenges persist for complex geometries for high Reynolds number flows and transonic/supersonic conditions.

The literature reports numerous experimental data on the flow field within cavities, with NASA making one of the first pioneering contributions with wind tunnel data on the internal flow characteristics, acoustical spectrum, and loads exerted on a slender store model placed within the cavity for a range of flow conditions [17–20]. However, while studying a generic cavity flow can provide valuable insights, it is still a simplification of the more complex flow field generated within aircraft weapon bay configurations. One of the main differences between a generic cavity and a weapons bay configuration is the presence of the bay door, which can significantly alter the flow field within the bay, resulting in higher acoustic tones [21–26]. In addition, different flight conditions of the aircraft, such as angle of attack or sideslip angle, can significantly modify the flow field into the weapon bay [21, 25, 27]. Furthermore, stores placed within the cavity are typically non-generic [5, 11, 28], featuring complex geometries with multiple fins that can fill much of the volume (particularly air-to-ground stores). Therefore, further research is required to investigate these factors in depth and to enable safe store separation with improved environmental conditions.

Several numerical modelling approaches have been proposed to address the complexity of the flow within weapon bays. Large eddy simulations (LES) still represent the most accurate modelling in terms of prediction accuracy, but the accompanying computational expense poses a limitation on its applicability to simulate complete aircraft configurations with embedded weapon bay designs. On the other hand, hybrid approaches like RANS/LES (Reynolds-averaged Navier-Stokes/large eddy simulation) or LBM/VLES (lattice-Boltzmann method/very large eddy simulation) have shown promising capabilities [8, 29, 30], as they can resolve the relevant part of the turbulence spectrum associated with the cavity flow oscillations, requiring fewer CPU hours per case. Hence, such schemes are better suited for studying complete and more realistic geometries, where the weapon bay is no longer isolated but is integrated into an airframe.

The scope of this study is to compare the accuracy of two commonly used hybrid numerical approaches, RANS/LES (ANSYS FLUENT) and LBM/VLES (SIMULIA PowerFLOW), in resolving the flow field and aero-acoustics within a weapon bay that is part of a generic aircraft model [31]. The airframe incorporated twin flanked weapons bays of rectangular shape, where a generic air-to-ground store model and two side doors were included in each bay. The generic aircraft model was tested at a transonic Mach number of 0.9 and three different angles of attack (-6, 2, and 8 degrees). Surface pressure signals were recorded in several locations inside the cavity, and time-frequency decomposition techniques were applied to discern the salient features. The possibility of analysing the response of the same system from three different points of view (an experimental case and two numerical simulations) can offer unique insights into the cavity flow phenomenon. Typically, experimental data, whilst fully representative of the physics involved, lack the resolution and depth that a numerical solution can retrieve from the flow. On the other hand, simulated solutions, whilst providing a complete knowledge of the flow dynamics, are still limited to the intrinsic accuracy of how the physics is being modelled. Hence, the approach taken in this study, in which the two different numerical models are applied to the same geometry, can further improve our understanding of the aeroacoustic response of weapons bays.

III. Methodology

A. Experimental benchmark

The study was applied to a generic aircraft model (see Fig. 1), for which wind tunnel data were available [27, 31]. The airframe incorporated twin-flanked weapons bays (WB) of rectangular shape, with a length (L) of 232 mm, width (W) of 56 mm and depth (H) of 32 mm, resulting in a length-to-depth-ratio (L/H) of 7.5 and a width-to-depth ratio (W/H) of 1.75.

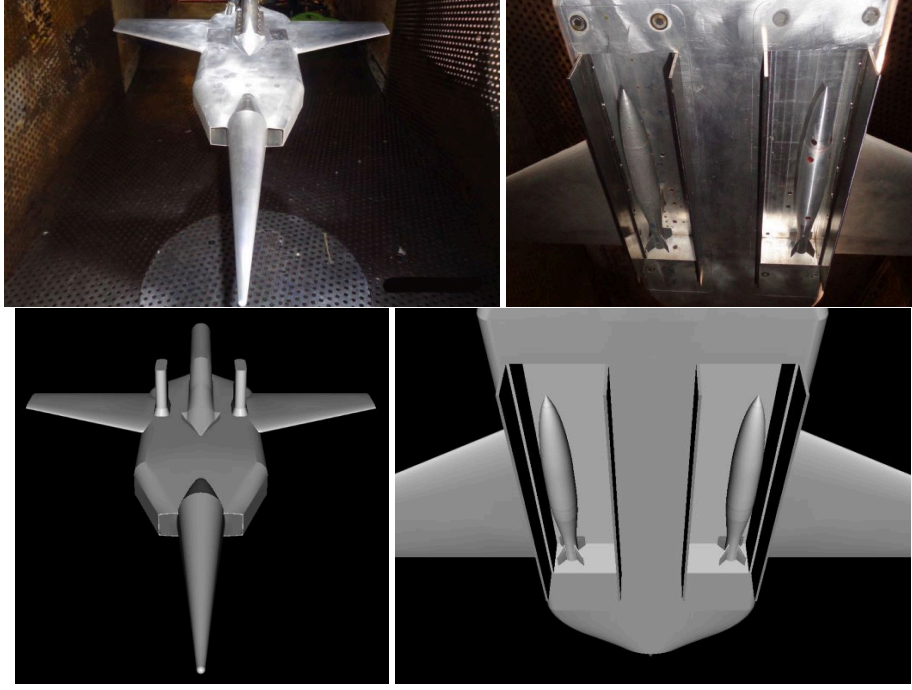


Fig. 1 Generic aircraft model. Top row: the aircraft model tested in the wind tunnel [31]; bottom row: CAD model for the numerical simulations.

Each WB was characterised with a right-handed Cartesian coordinate system (X, Y, Z), as depicted in Fig. 2. The origin was set to mid-width at the upstream edge of the bay. The positive X -axis was in the streamwise direction, the positive Z -axis was normal to the bay ceiling and outward from it, and the Y -axis was in the cavity lateral direction, positive outboard. Several low-frequency (static) and high-frequency (dynamic) pressure transducers were installed on the surface of the right-side WB (PXXX and PDXX, as shown in Fig. 2). In the experiments, the static and dynamic pressure data were sampled simultaneously at 220 Hz and 21 kHz, respectively. For the aero-acoustic analysis in this study, only the dynamic pressure recordings of PD02 and PD17 were used; where PD02 was placed at $(X, Y, Z) = (0, 0, -0.5D)$, and PD17 was placed at $(X, Y, Z) = (0.905L, 0, -D)$.

A generic air-to-ground store model (based on a modified Mk84 JDAM geometry) and two side doors were installed in each WB. The store had a length of 182 mm, a maximum diameter of $D = 21.5$ mm, and a corresponding maximum cross-section area of $S_{\text{ref}} = 362.7 \text{ mm}^2$. The location of the store within the WB was evaluated by the position of its pointed leading edge, denoted by (X_s, Y_s, Z_s) , in the right-handed Cartesian coordinate system of the WB (see Fig. 3). For all configurations investigated herein, the streamwise and lateral positions of the store's leading edge were fixed at an X_s of 25 mm and Y_s of 9 mm (outwards from the plane's centreline), respectively. On the other hand, the store was positioned along the Z_s axis at three different stations, st1 ($Z_s/D = -0.75$), st2 ($Z_s/D = 0.00$), and st3 ($Z_s/D = 1.00$).

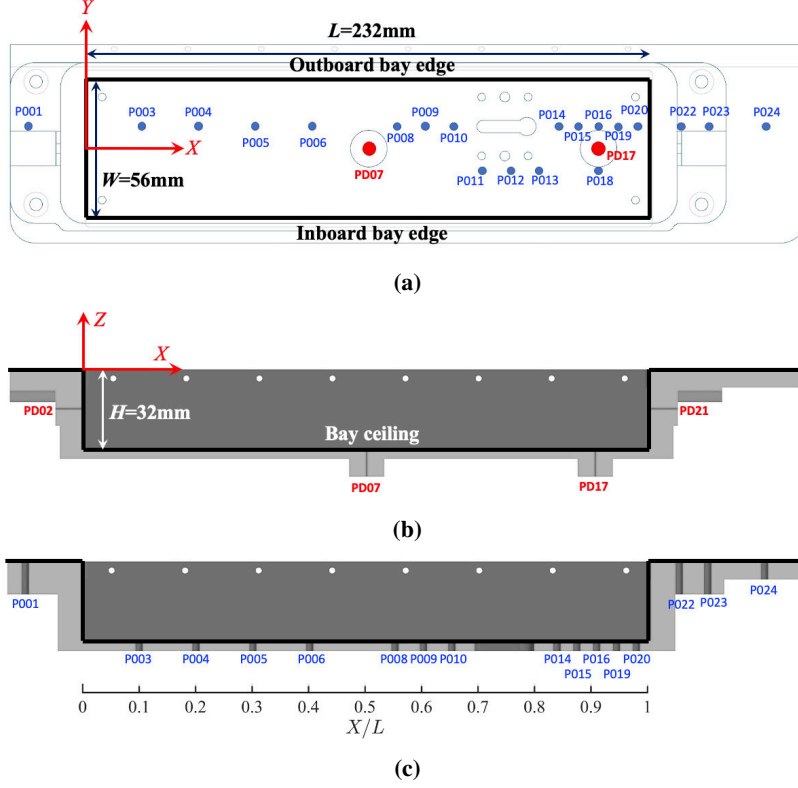


Fig. 2 Pressure transducer layout within the right-side weapons bay [31]. The static and dynamic pressure transducers are marked in blue and red, respectively. (a) Top view; (b) Side view at $Y/W = 0$; (c) Side view at $Y/W = 0.16$.

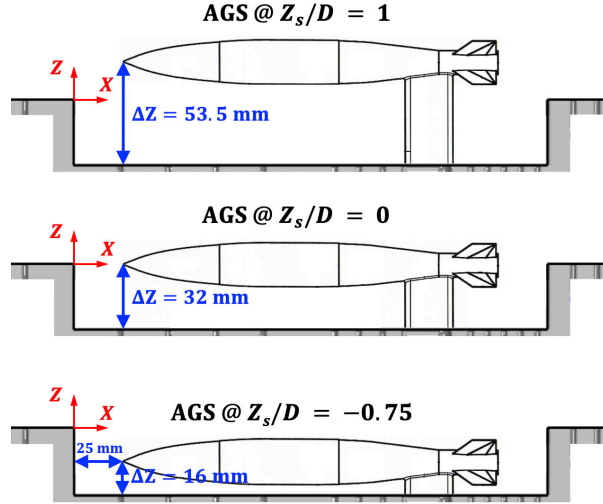


Fig. 3 Vertical locations of the store with respect to the weapon bay [31]: $Z_s/D = 1$ (top), 0 (mid), and -0.75 (bottom).

The store's side and normal force coefficients were denoted by C_y and C_z , respectively, and the pitching and yawing moment coefficients were denoted by C_{m_y} and C_{m_z} , respectively. The store's coordinate system (x, y, z) for the measurements of the aerodynamic coefficients is depicted in Fig. 4. Here, a positive normal force accounts for a vertical motion of the store into the WB ceiling, while a positive side force corresponds to a lateral motion of the store towards

the aircraft centreline. In addition, a positive pitching moment results in a pitch-up motion of the store into the WB ceiling, while a positive yawing moment reflects the movement of the store nose toward the aircraft centreline. The reference values for computing the store's aerodynamic coefficients are listed in Table 1.

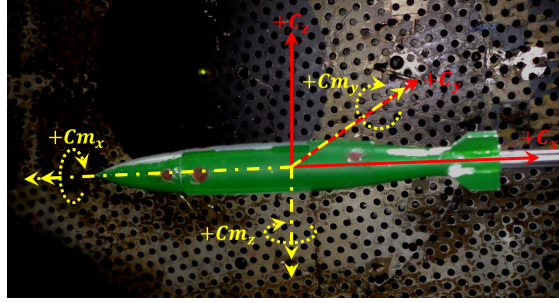


Fig. 4 Store's coordinate system for aerodynamic coefficients measurement.

Table 1 Store's reference values for aerodynamics coefficient calculations.

Name	Value	Units	Comment
S_{ref}	362.7	[mm ²]	reference area
D	21.5	[mm]	reference length
x_{ref}	75.0	[mm]	from store's leading edge
y_{ref}	0.0	[mm]	
z_{ref}	0.0	[mm]	

B. Numerical setup

In this study, two different numerical approaches were used to compute the flow around the aircraft: a Navier-Stokes equations-based approach and a lattice-Boltzmann method (LBM) approach. The Navier-Stokes simulations were performed using ANSYS FLUENT (Release 2024R2) with the improved delayed detached eddy simulation (IDDES) model and a $k-\omega$ SST turbulence model [32, 33]. The mesh utilised a mix of polyhedral and hexahedral-type cells, with prism cells having a growth ratio of 1.2 and wrapping the viscous surfaces, resulting in a y^+ value below 5 on the lower surface of the model. All solid walls were specified as being adiabatic, with a no-slip velocity condition applied. The computational outer boundary was specified as a far-field, using the modified Riemann invariants condition. Due to the compressible nature of the problem, a density-based solver was used. The inviscid flux vector was evaluated using the Roe-FDS upwind, flux-difference splitting scheme [34]. Inviscid fluxes were resolved using a third-order MUSCL scheme [35]. Viscous fluxes were resolved using a second-order upwind scheme; gradients were evaluated using the least squares method with the Minmod multi-dimensional cell-to-face limiter [36]. To march the solution in time, an implicit dual-time formulation was used (second-order Euler backwards in physical time and implicit pseudo-time marching for inner iterations) with a maximum of 10 inner iterations and a time step of $\Delta t = 2.5 \cdot 10^{-6}$ s. This value is well below the WB convective time unit ($t_c = L/U_\infty$) for the cases studied herein, and specifically $\Delta t < 0.05t_c$, which is consistent with the recommendation of Menter [37] and the approach of Chaplin and Birch [38]; thus resulting in CFL values of unity or less inside the WB. Unsteady simulations were initiated from a converged steady solution to reduce the start-up time.

The lattice-Boltzmann simulations were performed using SIMULIA PowerFLOW (Release 6-2025R1), which utilises a 39-state LBM model that enables solving flows up to a Mach number of 2.0. Recently, the solver was reported to yield good accuracy in resolving transonic cavity flows [7, 29]. A Cartesian mesh was utilised for the LBM simulations, consisting of variable resolution regions that locally refine the grid size by successive factors of 2. Bounce-back boundary conditions for no-slip walls and the specular reflection for frictionless walls were ensured thanks to a generalised volumetric formulation for the intersection of arbitrary-oriented surface elements and the volume elements [39]. Finally, a wall model accounting for pressure gradients was used to model boundary layer behaviours at high Reynolds numbers [40]. The current setup had the finest cell size of 0.29 mm, corresponding to a y^+ value of 110

on the lower surface of the model. The solver marched explicitly in time ($\Delta t = 4.5 \cdot 10^{-7}$ s), ensuring a CFL value below unity in the whole domain. In both solvers, the air was treated as an ideal compressible gas using Sutherland's law for viscosity modelling. Regarding the mesh size, the total number of elements was 26 million for FLUENT, whilst for PowerFLOW it was 79 million.

C. Data analysis

Considering the partially random and partially ordered oscillatory behaviour of cavity flows, data averaging (time-wise) had to be conducted using a defined procedure to avoid errors. Such a setup had two objectives: to clear the solution from the unphysical start-up transient, typical of scale-resolving simulations, and to properly compare the results obtained from the two solvers. Considering the critical importance of the store's forces and moments to the safe store separation, attention was naturally directed towards monitoring the temporal histories of these quantities throughout the solution; in particular, the evolution of the temporal mean values. For such analysis, the cumulative average ($c_{\text{avg}}(n)$) of the time-varying store's force and moment coefficients signals was computed, as follows:

$$c_{\text{avg}_{y|z|my|mz}}(n) = \frac{1}{n} \sum_{i=1}^n C_{y|z|my|mz}, \quad (1)$$

where n is the number of iterations considered and $C_{y|z|my|mz}$ is the history of the force/moment coefficient under consideration from 1 to the n^{th} element. As shown in Fig. 5, for both solvers, a time of 0.1 s could be considered as the threshold after which all coefficient histories reached convergence in a statistical sense. Hence, in all simulations, the initial 0.1 s of time history were discarded and the time-averaged values were computed using the subsequent 0.3 s of data. These samples consisted of a total of 380 convective times ($t_c = L/U_\infty$). This allowed data sample lengths with a temporal duration greater than 30 cycles of the lowest frequency mode of interest (1st Rossiter-Heller mode) following the values suggested by Menter [37].

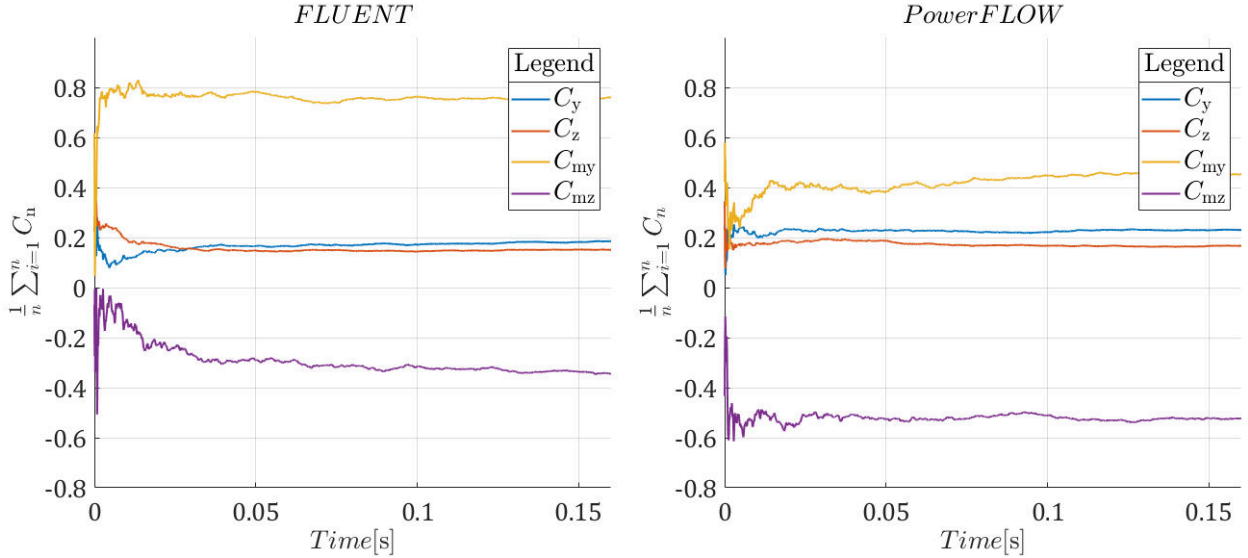


Fig. 5 Store's coefficient cumulative mean trends vs time. Data refers to a generic aircraft model at an angle of attack of 2 degrees and a store positioned at st2.

The non-stationary flow analysis was based on a study of the sound pressure level (SPL) of the fluctuating part of the pressure signals, defined as:

$$SPL(f) = 10 \log_{10} \left(\frac{PSD(f) \Delta f}{p_{\text{ref}}^2} \right) \text{ [dB]}, \quad (2)$$

where p_{ref} is the minimum audible pressure, equal to $20 \mu\text{Pa}$, which is defined as the threshold of human hearing. The PSD (power spectral density) was obtained using Welch's method [41], with the division of the original signal into

segments of 2^{13} samples with a 75% overlap. To compare the capacity of each solver to predict resonating tone with accuracy, the band-integrated sound pressure level was computed (in the mean sense), defined as:

$$BISPL(f) = 10 \log_{10} \left[\frac{1}{p_{\text{ref}}^2(f_2 - f_1)} \int_{f_1}^{f_2} PSD(f) \Delta f df \right] \quad (3)$$

Here, the limits of integration for the n_{th} Rossiter-Heller mode are defined as:

$$f_1 = RH_n - f_b \quad (4)$$

$$f_2 = RH_n + f_b, \quad (5)$$

where RH_n denotes the n_{th} Rossiter-Heller mode, computed accordingly:

$$RH_n = \frac{U_{\infty}}{L} \cdot \frac{n - 0.062(L/H)}{M_{\infty} \left[1 + \frac{\gamma-1}{2} M_{\infty}^2 \right]^{-1/2} + \frac{1}{0.57}}, \quad (6)$$

whilst f_b is the modulating frequency according to Delprat's decomposition [26, 42]:

$$f_b = \frac{U_{\infty}}{H} \cdot \frac{0.062}{M_{\infty} \left[1 + \frac{\gamma-1}{2} M_{\infty}^2 \right]^{-1/2} + \frac{1}{0.57}} \quad (7)$$

D. Simulation matrix

The geometry was simulated at a Mach number of 0.9, varying angle of attack (3 cases) and store position (3 cases). This resulted in a matrix of 9 simulations. To directly compare numerical results with experimental data, each case boundary condition (freestream pressure and temperature) was set equal to the wind tunnel value recorded in the previous experimental campaign [31]. The following table summarises the test conditions for the runs simulated. It must be specified that during all the tests, only the position of the store in the left weapon bay was changed, whilst the store in the right WB was kept fixed at $Z_s/D = 0$.

Table 2 Test conditions for the simulated runs (from experiments [31]).

M_{∞}	st	Z_s/D	α [deg]	β [deg]	p_{∞} [Pa]	T_{∞} [K]	U_{∞} [m/s]	q_{∞} [Pa]
0.9	1	-0.75	-6	0	97,369	266	294	55,208
			+2		99,159	267	295	56,223
			+8		99,434	268	295	56,379
	2	0	-6		99,422	266	294	56,372
			+2		99,043	269	296	56,157
			+8		99,974	268	295	56,685
	3	1.00	-6		96,733	261	292	54,848
			+2		98,319	265	294	55,747
			+8		97,767	265	294	55,434

IV. Results

A. Store forces and moments analysis

Fig. 6-8 show a comparison of the simulated and measured store's time-averaged force and moment coefficients for st1, st2, and st3. Experimental runs showed a strong and non-linear variation of the aerodynamic coefficients with the aircraft's angle of attack, regardless of store position. The large positive pitching moment (up to 2.25 in the worst case) and yawing moment (up to 1 in worst case) exerted on the store at negative α values were considered extremely detrimental, causing store rotations towards the interior of the weapons bay, with the possibility of unsafe separation

(store impacting on airframe walls). Generally, the store's normal and side force coefficients varied non-linearly with the store's station, as a linear correlation with store position change and force variation could be identified. On the other hand, a more linear trend was observed for pitching and yawing moments, with the store experiencing larger pitch-up and yaw-right moments when placed closer to the cavity ceiling. C_{my} varied from 2.25 at st1 to 1.5 at st3 (still considering the worst case scenario corresponding to $\alpha = 8^\circ$). Similarly, C_{mz} varied from 1.2 at st1 to -0.22 at st3. Contrary to this, the effect of the store's vertical position was secondary when compared with variations in angle of attack, which dominated the loads induced by the flow on the store.

The numerical results presented in Fig. 6-8 include vertical bars representing rms values. Overall, the numerical predictions of the time-averaged forces were in good agreement with experiments for all simulations, although particular differences were observed. In addition, CFD, independently of the solver considered, underpredicted the largest pitching moment value at $\alpha = 8^\circ$ by nearly 50%. Underprediction of positive pitching moment values leads to underprediction of the safety margin for store separation from the WB (positive C_{my} values represent the store pitching up towards the cavity ceiling). Nevertheless, if the rms value boundaries are included in the comparison, the prediction accuracy increases considerably, reducing the error below 5%. It must be noted that compared to experimental runs, where data was gathered for 2-3 seconds, the length of the time series of the numerical runs was 0.3 s, which is an order of magnitude lower. In such a situation, the rms value played a major role from a statistical point of view and should be considered when comparing the offset between numerical and experimental data. Hence, it is the rms boundaries that should be considered for the statistical determination of the safety margin during store release analysis with numerical methods. For the st1 case, considering the rms boundaries, numerical predictions were in line with experimental data, especially in terms of moment coefficients (Fig. 6). In this case, the accuracies of both PowerFLOW and FLUENT were the same.

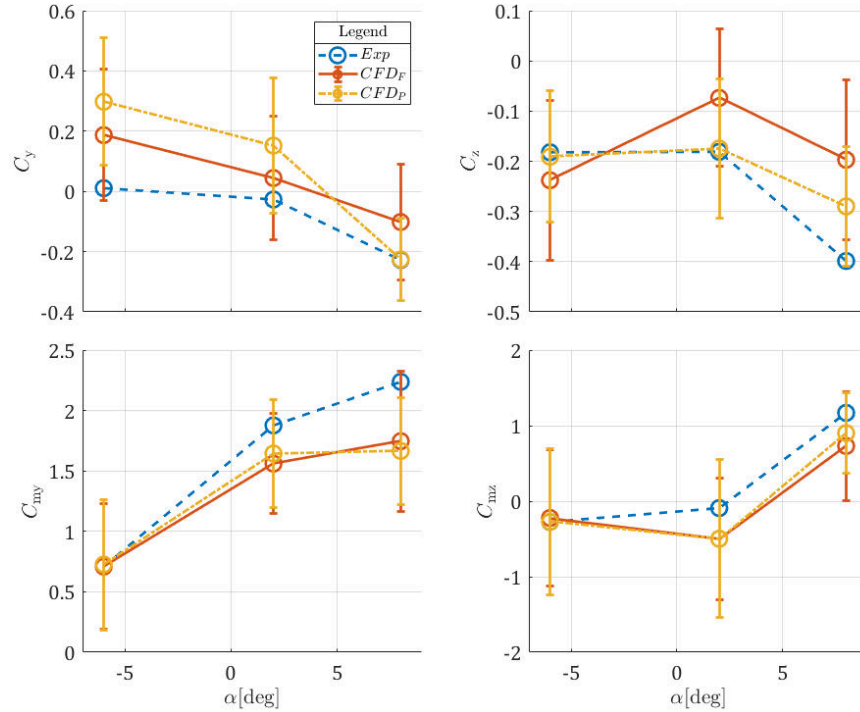


Fig. 6 Comparison of simulated and measured store's time-averaged force and moment coefficients at st1. F.=FLUENT, P.=PowerFLOW. Bars represent rms values.

A similar trend was observed for st2 (see Fig. 7). Again, the predictions of both solvers were in good agreement with experimental data. In such cases, apart from C_{my} , all other coefficients were predicted with an average error below 10%, considering just the mean value and not the rms boundaries. For the case of the store placed outside the cavity at st3 (see Fig. 8), the biggest offset in numerical prediction was still observed for the pitching moment coefficient. In this case, mean errors were above 50%, although the rms upper boundary recovered the offset. Again, both solvers had similar accuracies. Minor differences were observed only in C_{my} mean value prediction at st2 and st3. Here, PowerFLOW had better accuracy than FLUENT at negative α , whilst the opposite was true at $\alpha = 2^\circ$ and $\alpha = 8^\circ$.

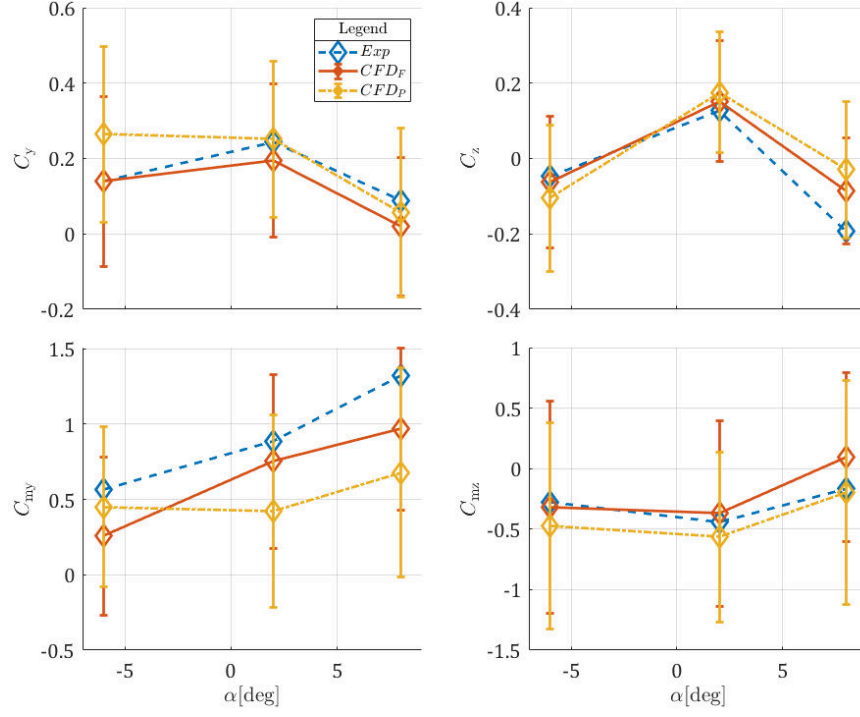


Fig. 7 Comparison of simulated and measured store's time-averaged force and moment coefficients at st2. F.=FLUENT, P.=PowerFLOW. Bars represent rms values.

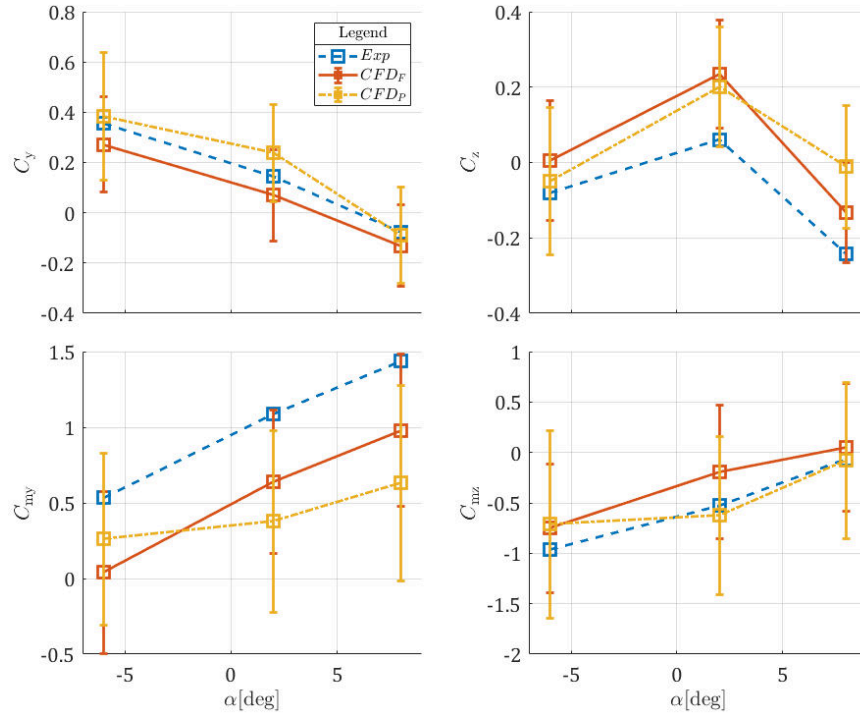


Fig. 8 Comparison of simulated and measured store's time-averaged force and moment coefficients at st3. F.=FLUENT, P.=PowerFLOW. Bars represent rms values.

B. Aero-acoustic analysis within the WB

The nominal weapon bay spectrum at the upstream WB wall (PD02, see Fig. 2) was characterised by two main resonant modes corresponding to the 2nd and 3rd Rossiter-Heller (RH) tones (Fig. 9). The 1st RH tone had a large bandwidth, and it was difficult to distinguish it from the broadband component. Store position and angle of attack quantitatively influenced the spectral response of the pressure fluctuations, but in general, the qualitative trend remained unaffected. Experimental data indicated that the weakest case (in terms of tone power) was for st1 and $\alpha = -6^\circ$, whilst the strongest peaks were observed for st2 and $\alpha = 2^\circ$. Here, the second and third RH modes achieved 147.8 dB and 134.4 dB, respectively. Both solvers agreed well with the experiments with regard to the spectral dynamics, tone frequencies and amplitude for most of the modes, although PowerFLOW performed better in comparison to FLUENT for almost all conditions in terms of predicting the SPL value of the Rossiter-Heller tones. In terms of resonant tone frequency determination, both solvers could predict the experimental data with good accuracy, with maximum deviations in the order of $\pm 0.5 f_b$. On the other hand, for the determination of SPL values, PowerFLOW performed better than FLUENT in almost all cases. This trend was confirmed as well from the BISPL plots (see Fig. 10). For RH_1 , the average error (in terms of BISPL) was -8.5 dB for FLUENT, and 1.4 dB for PowerFLOW. For the dominant tone, RH_2 , the average error for PowerFLOW was worse, with a mean overprediction of 5.4 dB, whilst FLUENT performance remained unchanged, still achieving an average underprediction of -8.4 dB. Finally, for RH_3 , PowerFLOW still tended to overpredict the tone power, with an average error of 2.5 dB, whilst the mean error for FLUENT was -6.2 dB. Regarding the broadband spectral power (>2000 Hz), both solvers were similar, with an average error of -2 dB. A table summarising the experimental RH tones (frequency and SPL) observed, and comparing with numerical predictions, is reported in Appendix A.

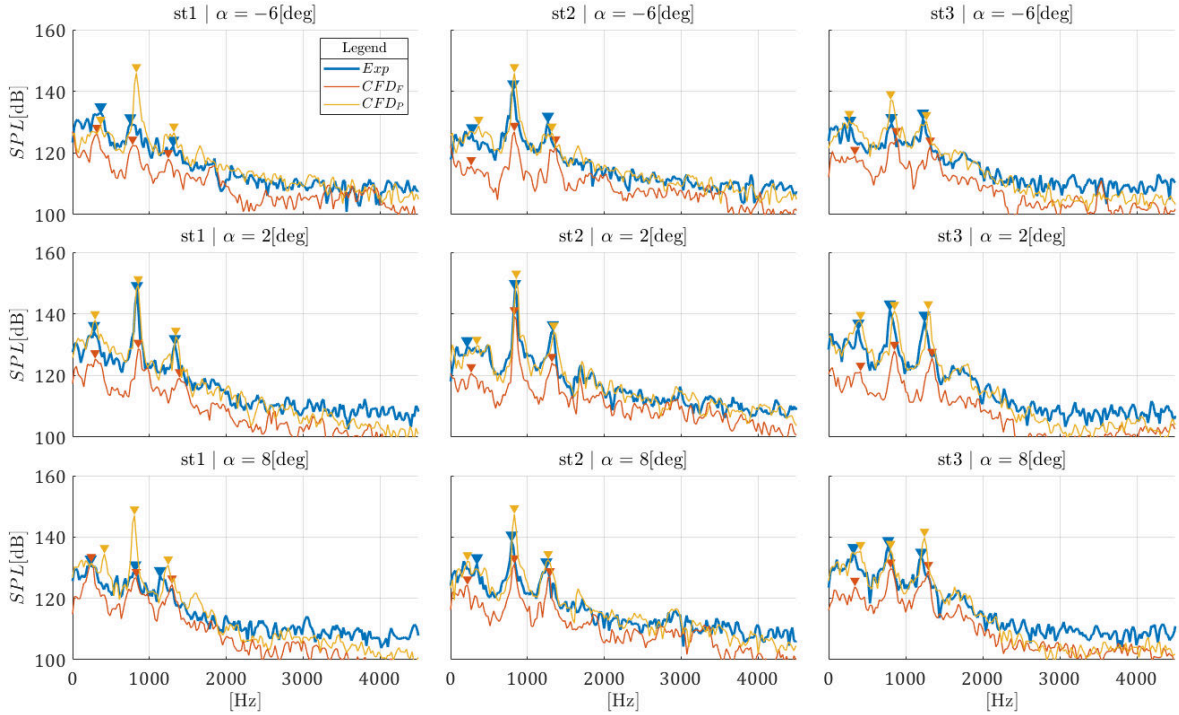


Fig. 9 Comparison of simulated and measured acoustic pressure spectra at the upstream WB wall (probe PD02, see Fig. 2). F.=FLUENT, P.=PowerFLOW. Markers indicate major Rossiter-Heller tones.

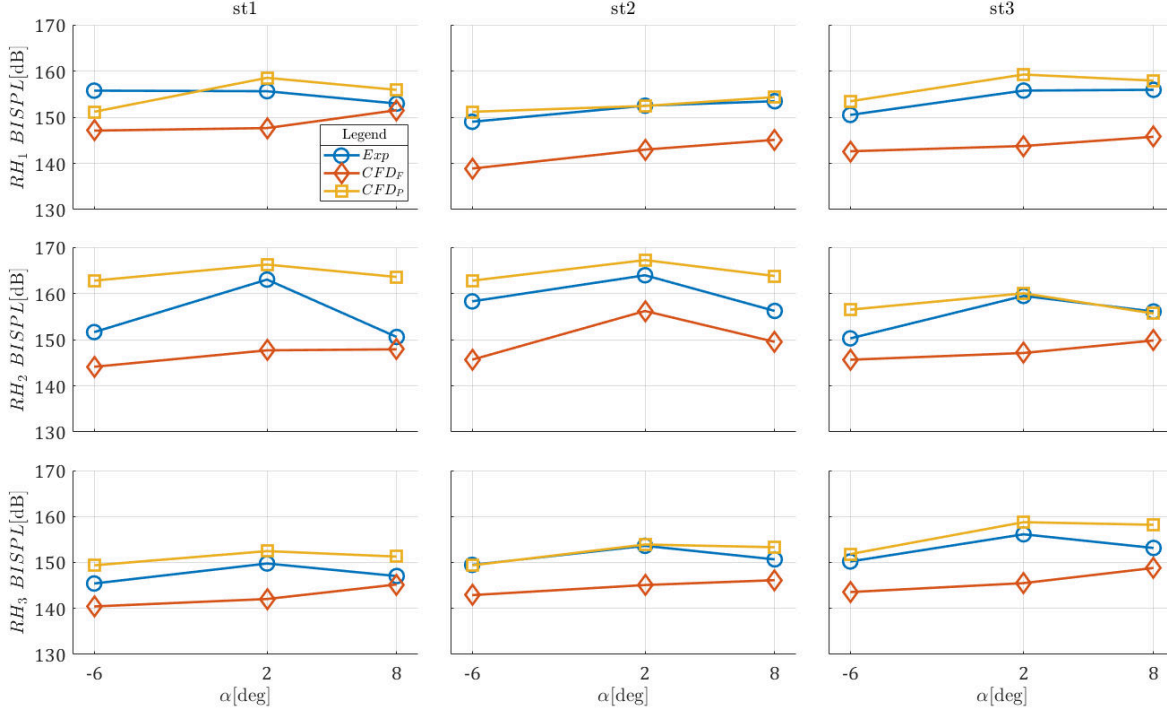


Fig. 10 Comparison of simulated and measured BISPL values (for RH 1, 2, and 3) at the upstream WB wall (probe PD02, see Fig. 2). F.=FLUENT, P.=PowerFLOW.

A different picture was observed for the probe placed on the WB ceiling, close to the downstream wall (PD17 – see Fig. 2). In this case, both solvers overestimated the level of pressure fluctuations (see Fig. 11), although the major resonating tone frequencies were in good agreement with experimental data, as shown in Fig. 12. For this probe, it was FLUENT, which in general achieved better predictions, with average errors on the three dominant resonant tones of ~ 8 dB. On the other hand, the average error on SPL for PowerFLOW was ~ 11 dB. Finally, in terms of broadband noise, both solvers overpredicted it by an average of 5 dB. As shown by the numbers, the prediction of cavity acoustic at this position was worse. This can be explained by the interference of the store, which makes it more difficult to capture the proper physics of the flow. On the other hand, the probe placed at the upstream WB wall was free from interference and well positioned to capture the feedback loop acoustic waves.

C. Flow visualisation

Flow visualisation allowed for a detailed comparison of the fluid dynamics predicted by both solvers. Fig. 13 shows the instantaneous pressure coefficient. The upper row compares the results of FLUENT (left) and PowerFLOW (right) for the store at st1 and an angle of attack of $\alpha = -6^\circ$. The lower row instead compares the solvers' prediction for the case with store at st2 and $\alpha = 2^\circ$. The global picture was similar, especially on the flat surface in front of the WB, where the footprint of a vortex system generated by the upstream geometry was visible. On the other hand, minor differences could be observed locally, especially on the store's surface, which explains the variation in force/moment coefficients.

The three-dimensional flow structures in the vicinity of the WB were visualised using iso-surfaces of the Q -criterion [43], colored by the velocity magnitude (see Fig. 14). Although local differences were observed, the overall flow patterns are similar when comparing the solvers' solutions. For the st1 case (Fig. 14 - upper row), both solvers evidenced the coupling between the vortex formations detached from the airframe forebody and air intake, and the WB downstream. Of particular relevance was the ingestion inside the weapon bay shear layer of the trailing vortices generated by the air intake. This underlined the importance of studying installation effects on weapon bay aero-acoustic. On the other hand, for the st2 case (Fig. 14 - lower row), PowerFLOW still predicted a small vortex system coming from the air intakes, whilst FLUENT did not. Generally, PowerFLOW's solution shows finer vortex structures than those resolved by FLUENT, which is mainly because the former is based on a mesoscale modelling approach rather than the commonly used macroscale Navier-Stokes approach.

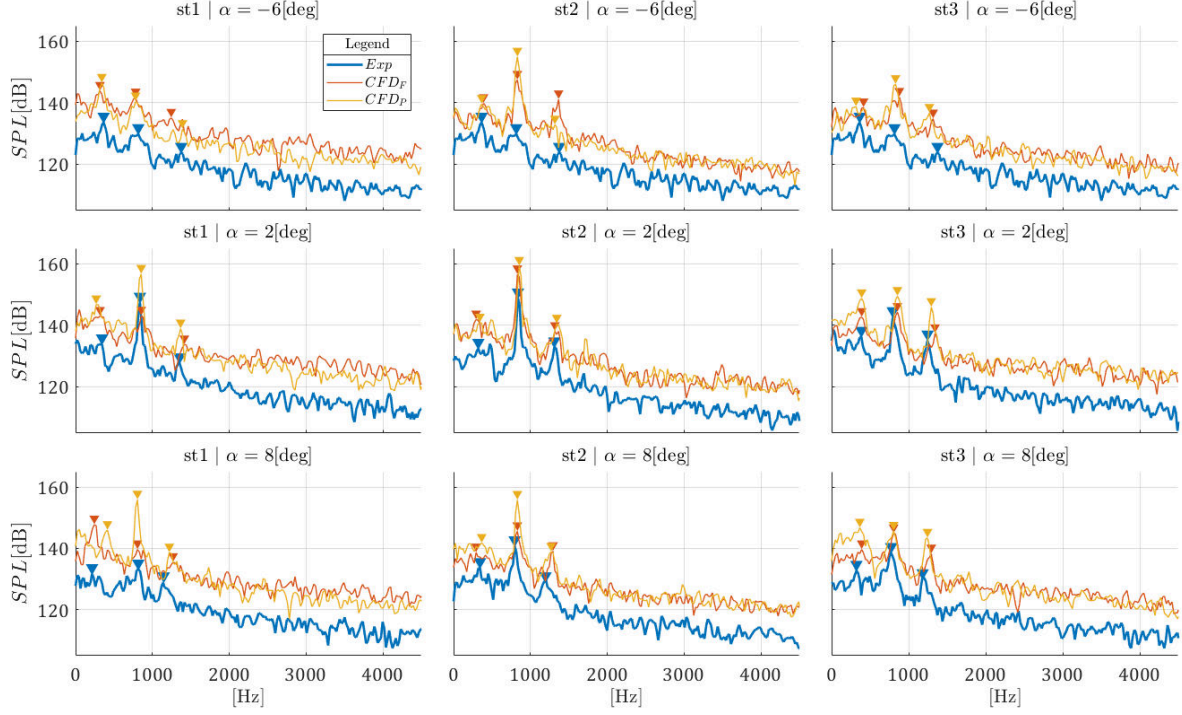


Fig. 11 Comparison of simulated and measured acoustic pressure spectra at the upstream WB wall (probe PD17, see Fig. 2). F.=FLUENT, P.=PowerFLOW. Markers indicate major Rossiter-Heller tones.

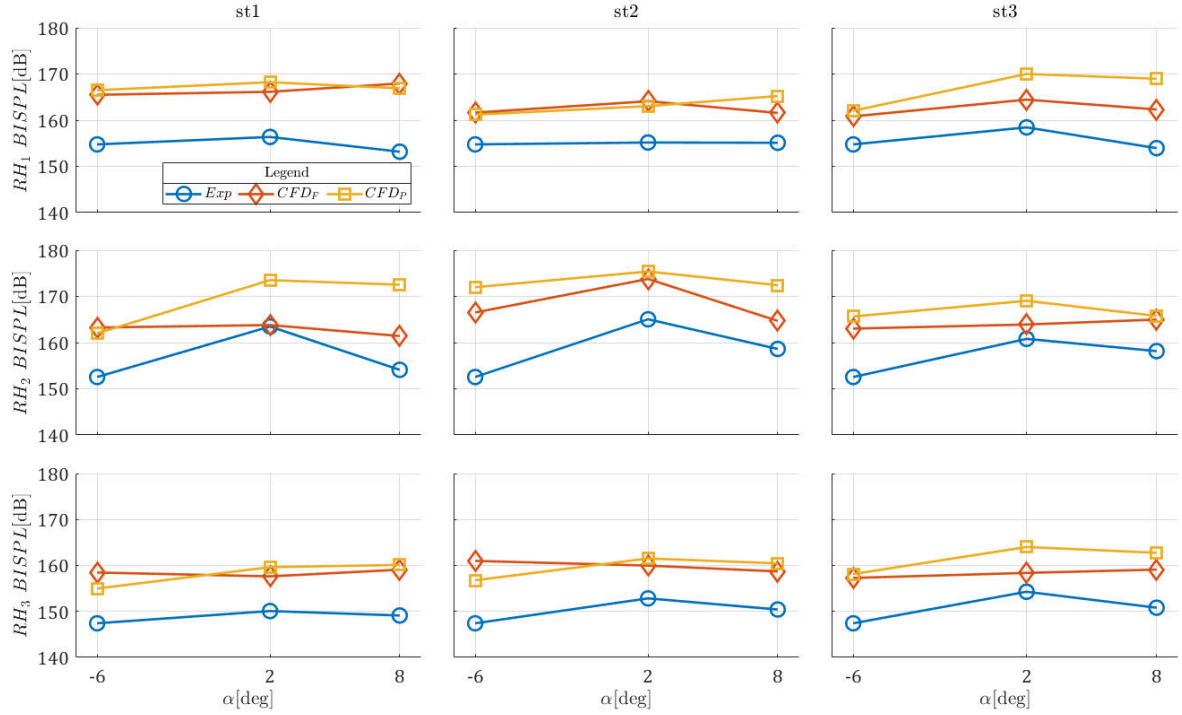


Fig. 12 Comparison of simulated and measured BISPL values (for RH 1, 2, and 3) at the upstream WB wall (probe PD17, see Fig. 2). F.=FLUENT, P.=PowerFLOW.

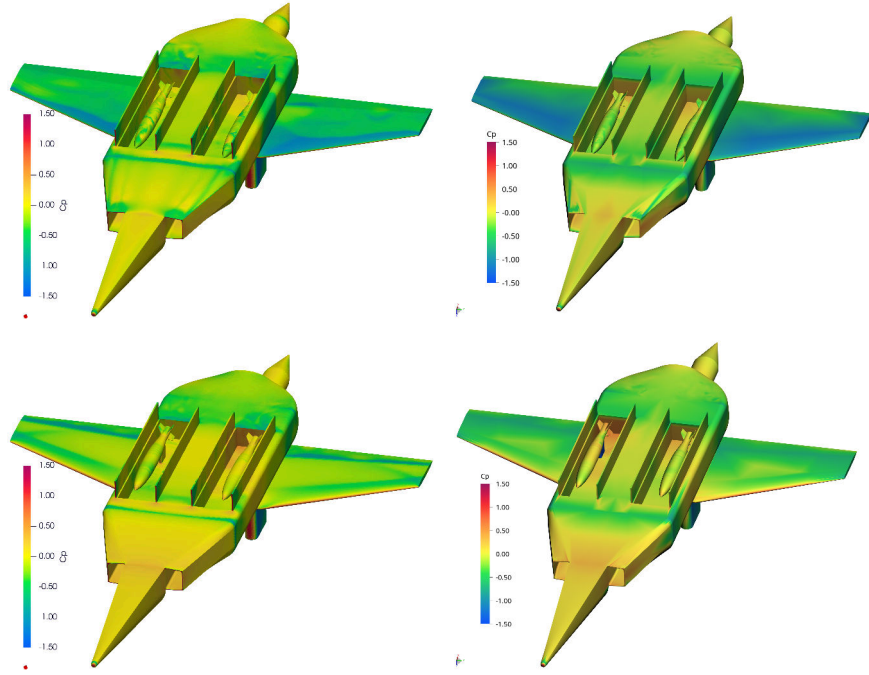


Fig. 13 FLUENT (left column) to PowerFLOW (right column) comparison of the instantaneous pressure coefficient C_p on the aircraft surface. Upper row: st1 and $\alpha = -6^\circ$; lower row: st2 and $\alpha = 2^\circ$.

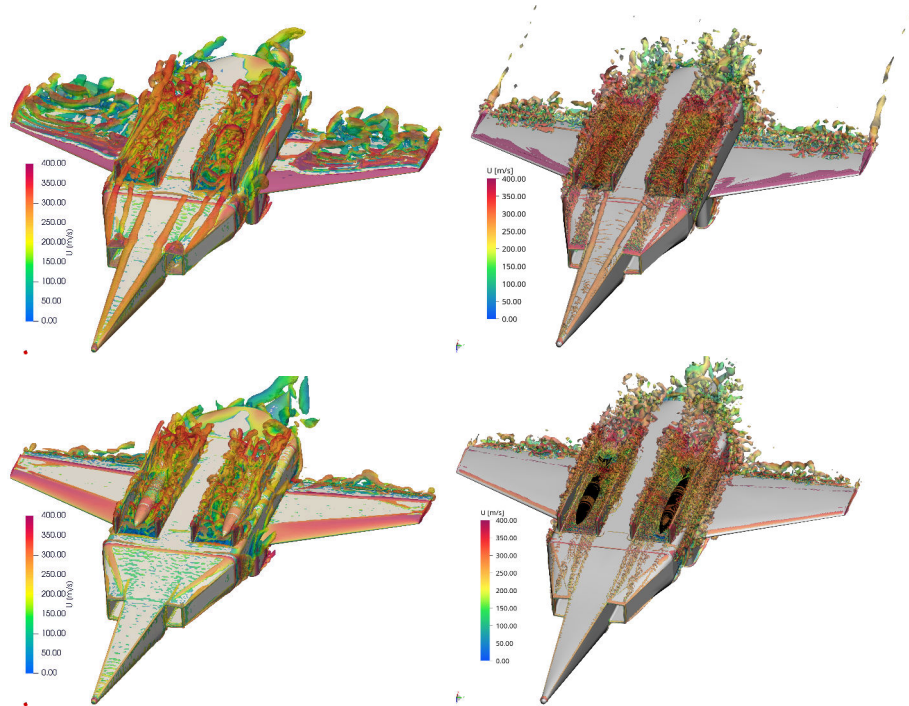


Fig. 14 FLUENT (left column) to PowerFLOW (right column) comparison of instantaneous iso-surfaces of the Q -criterion ($Q = 5 \cdot 10^7 \text{ [s}^{-2}\text{]}$), colored by the velocity magnitude. Upper row: st1 and $\alpha = -6^\circ$; lower row: st2 and $\alpha = 2^\circ$.

V. Conclusions

This study compared the prediction capabilities of two different numerical approaches in the resolution of the flow around a generic aircraft with two rectangular weapons bays incorporating a generic air-to-ground store. The solvers were based on two different approaches, as FLUENT resolved, using a finite-volume approach, the standard Navier-Stokes equations, whilst PowerFLOW adopted the Lattice-Boltzmann formulation. To compare prediction accuracies, both the aero-acoustic field inside the WB and the forces/moments exerted on the store were analysed and compared with experimental data. The generic aircraft geometry was simulated at three angles of attack and three store positions, for a total of nine different cases. Results showed that both numerical approaches could predict store position and angle of attack effects with respect to the pressure spectra and resonant modes inside the WB. In this situation, in general, the PowerFLOW solver achieved a better accuracy in comparison to FLUENT at the upstream WB wall, whilst the opposite was true close to the rear WB wall. It was also noted that the average error using FLUENT was constant and in the order of 8 dB, whereas PowerFLOW accuracy varied according to the probe/store position and angle of attack. The observed error for the LBM solver ranged from 2 dB to values as high as 11 dB. In terms of the store's time-averaged aerodynamic forces and moments, the two numerical approaches were able to capture the experimental data sign and trend, with both solvers achieving similar accuracy, except for some differences observed mainly at negative angles of attack. In this case, in general, it was FLUENT that achieved better predictions, especially when the store was outside the cavity (at st3). It was found that the biggest error was on the prediction of store pitching moment, with both solvers typically estimating lower values when compared to experimental data. Therefore, whenever using simulations for store release safety margin determination, the mean values should be increased by the rms component to define a more realistic boundary for worst-case scenarios.

Appendix A

Comparison of calculated main RH tones with experimental data for PD02

st	α [deg]	Mode	Experiment		FLUENT		PowerFLOW		RH-Theory
			[Hz]	SPL [dB]	[Hz]	SPL [dB]	[Hz]	SPL [dB]	[Hz]
1	-6	RH_1	365	132.9	342	125.4	366	128.8	288
		RH_2	752	129.4	781	122.4	830	145.9	811
		RH_3	1311	122.1	1245	118.0	1318	126.6	1334
	+2	RH_1	279	134.2	293	125.3	292	137.9	288
		RH_2	838	147.1	854	128.6	854	149.8	811
		RH_3	1332	129.9	1391	119.1	1342	132.6	1334
	+8	RH_1	236	130.7	244	131.5	415	134.4	288
		RH_2	816	128.9	830	126.6	805	147.0	811
		RH_3	1138	127.0	1293	124.5	1245	130.7	1334
	-6	RH_1	279	126.1	268	115.7	366	128.8	288
		RH_2	816	140.3	830	126.6	830	145.9	811
		RH_3	1267	129.9	1367	122.5	1318	126.6	1334
2	+2	RH_1	215	129.3	268	120.7	341	129.6	288
		RH_2	837	147.8	830	139.2	854	151.1	811
		RH_3	1332	134.4	1318	124.1	1343	134.3	1334
	+8	RH_1	344	131.2	219	124.2	220	132.1	288
		RH_2	795	138.6	830	131.1	830	147.4	811
		RH_3	1246	129.9	1294	126.9	1269	132.5	1334
	-6	RH_1	279	128.5	342	119.0	268	130.7	288
		RH_2	816	129.4	879	125.2	805	137.1	811
		RH_3	1224	130.9	1318	122.0	1269	130.3	1334
	+2	RH_1	387	134.9	415	121.2	415	137.7	288
		RH_2	795	141.2	854	128.0	854	140.9	811
		RH_3	1246	137.5	1342	125.7	1294	141.2	1334
3	+8	RH_1	322	134.6	342	123.8	415	135.5	288
		RH_2	733	136.8	806	129.7	806	135.8	811
		RH_3	1203	133.3	1294	129.3	1245	129.8	1334

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Correction: RANS/LES and LBM/VLES Aero-Acoustic Analysis of Weapon Bays at Transonic Mach Number

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<https://doi.org/10.2514/6.2025-3850>

Correction Notice

Figure 6 should be replaced with the following one:

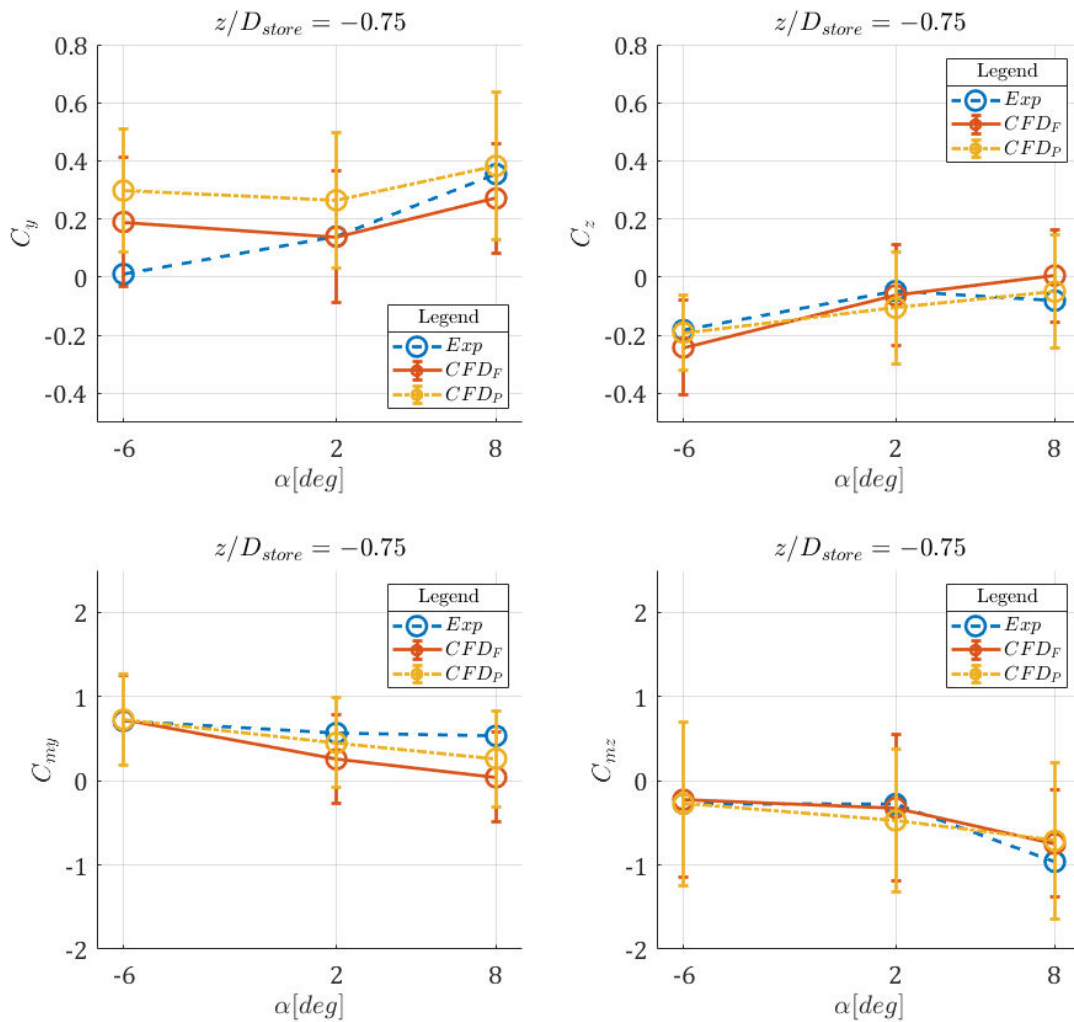


Figure 7 should be replaced with the following one:

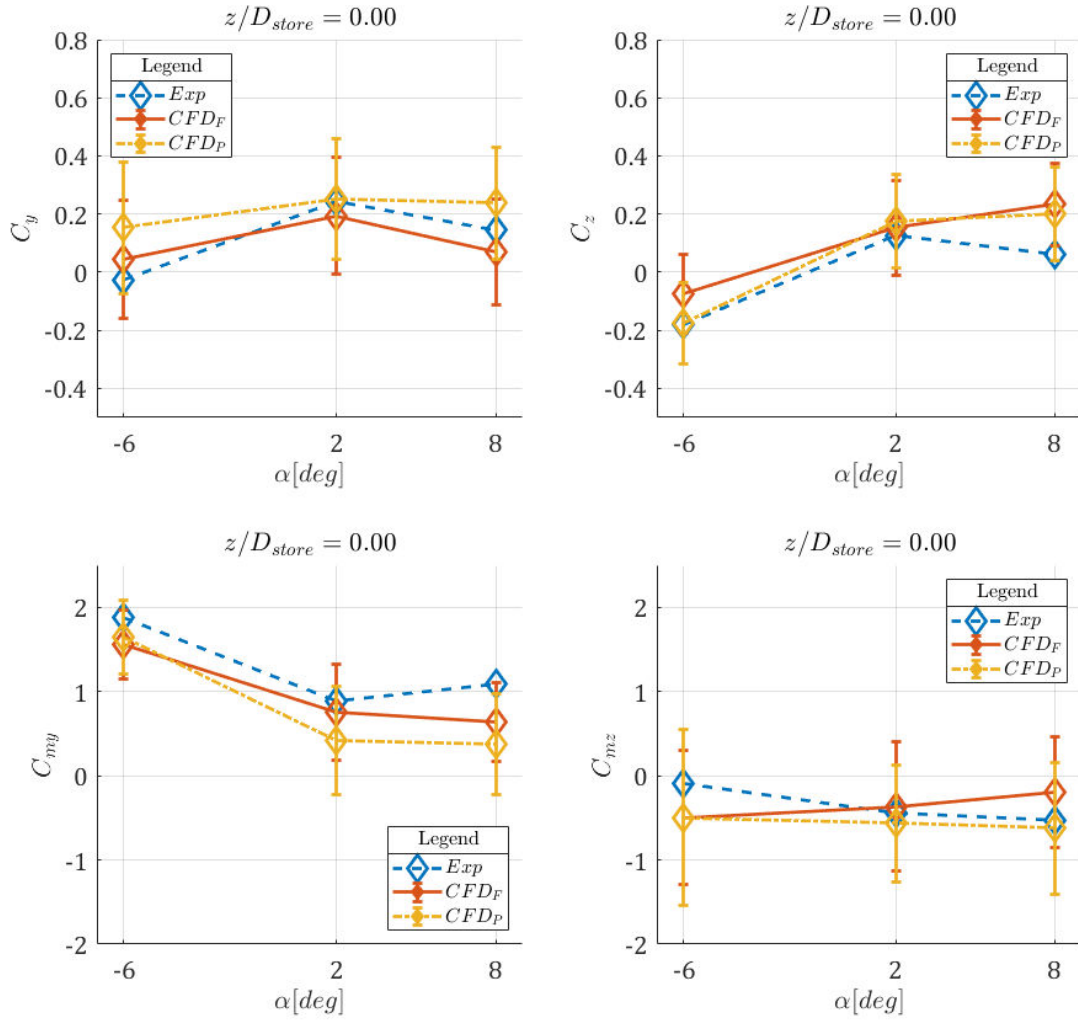
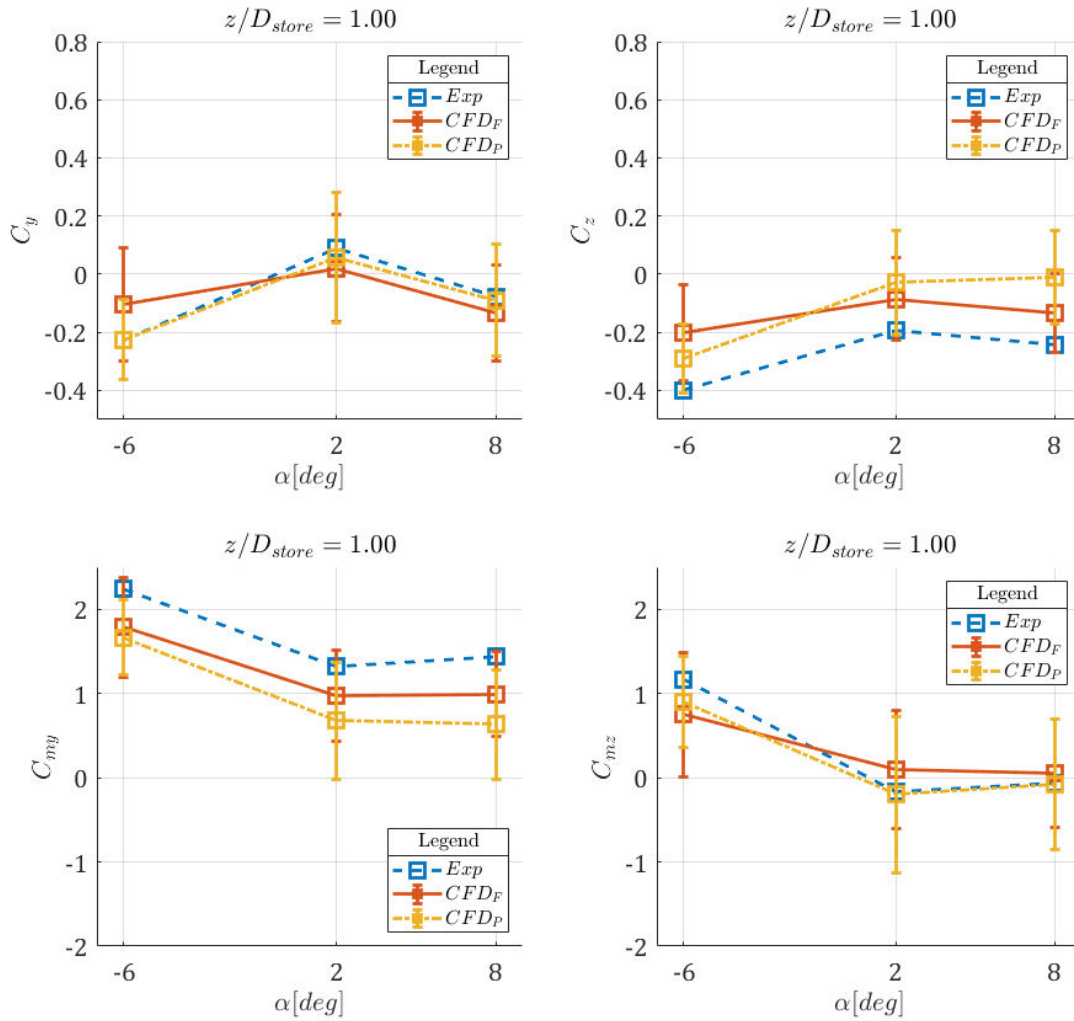


Figure 8 should be replaced with the following one:



The following paragraph on page 8

“In this case, mean errors were above 50%, although the rms upper boundary recovered the offset. Again, both solvers had similar accuracies. Minor differences were observed only in C_{my} mean value prediction at st2 and st3. Here, PowerFLOW had better accuracy than FLUENT at negative α , whilst the opposite was true at $\alpha = 2^\circ$ and $\alpha = 8^\circ$ ”

should be replaced with this one:

“In general, although both solvers had similar accuracy in predicting forces and moments, FLUENT values were closer to the experimental data compared to PowerFLOW.”



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RANS/LES and LBM/VLES aero-acoustic analysis of weapon bays at transonic Mach number

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2025-07-29

American Institute of Aeronautics and Astronautics (AIAA)

<https://doi.org/10.2514/6.2025-3850>

Bacci D, Saddington AJ, Ben-Gida H. (2025) RANS/LES and LBM/VLES aero-acoustic analysis of weapon bays at transonic Mach number. In: AIAA Aviation Forum and Ascend 2025, 21-25 July 2025, Las Vegas, USA. Paper number AIAA 2025-3850