



Statistical analysis of store release from a weapon bay at transonic Mach number

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ABSTRACT

Numerical analysis was conducted on the release of an air-to-air missile model from a rectangular cavity geometry, having a length-to-depth ratio of 4.5 and a width-to-depth ratio of 1. Computational Fluid Dynamics was coupled with a 6-degrees-of-freedom solver using the Stress-Blending-Eddy-Simulation turbulence model to calculate the store trajectory. The release procedure was performed at a freestream Mach number of 0.9. The study aimed to correlate cavity aero-acoustic data with missile flight, comparing flow resonant modes with store trajectory evolution. The store was released at 30 different intervals during the evolution of the flow within the cavity, to encompass the effects on trajectory dispersion due to the intrinsic unsteady nature of the flow field. Correlation analysis, based on the Hilbert-Huang transform, evidenced a direct effect of flow-field resonant modes on the weapon's roll rate and final roll angle.

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1. Introduction

Modern and future combat aircraft airframes are strongly influenced by the necessity to reduce radar signature. This is typically obtained by planform alignment (concentrating radar returns into narrow directions), minimising protuberances, avoiding corner angles and flat fuselage sides, avoiding cylindrical fuselage design, reducing/eliminating vertical and horizontal empennages, and carrying stores inside the fuselage. These aspects favoured the adoption of a weapons bay, which has become a common feature of 5th and 6th combat airframe designs (Lockheed Martin F-22, F-35, Sukhoi Su57, Su75, Chengdu J20, Shenyang J31, and Turkish Aerospace Industries MMU).

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, potentially damaging the airframe and payload. 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:

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

where 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 heat, γ , is assumed to be equal to 1.4 for air. Finally, the integer n is equal to 1 for the calculation of the first resonant mode, 2 for the second, and so on.

The intrinsic instability of the local flow inside the weapons bay poses an additional hazard during store release from the cavity, altering the trajectory of the weapon, which may cause it to collide with the launch aircraft [4–8]. Therefore, it is imperative to determine trajectory deviations during weapon release to determine the safe margin for its correct employment [4,6–14].

The numerical approach to the problem, consisting of coupling

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Nomenclature

$U_\infty/(\text{m}\cdot\text{s}^{-1})$	free stream air velocity
$\rho_\infty/(\text{kg}\cdot\text{m}^{-3})$	free stream air density
p_∞/Pa	free stream air pressure
q_∞/Pa	free stream dynamic pressure [Pa] ($= 0.5\cdot\rho_\infty\cdot U_\infty^2$)
M_∞	free stream Mach number
$\nu/(\text{m}^2\cdot\text{s}^{-1})$	kinematic viscosity
Re	Reynolds number ($= UI/\nu$)
L/m	cavity length
D/m	cavity depth
W/m	cavity width
$\vec{a}/(\text{m}\cdot\text{s}^{-2})$	rigid body acceleration vector
$\vec{\omega}/(\text{rad}\cdot\text{s}^{-1})$	rigid body angular rate vector
$\vec{I}/(\text{kg}\cdot\text{m}^2)$	inertia tensor in body axes system

f/Hz	frequency
f_s/Hz	sampling frequency
f_r/Hz	frequency resolution
RH_n	n_{th} Rossiter-Heller theory predicted mode
t_c	convective time ($= L/U_\infty$)
t_{ch}	characteristic time ($= D/U_\infty$)
δ_0	boundary layer thickness at the cavity leading edge
m/kg	mass
$\phi/(\circ)$	Euler roll angle
$\theta/(\circ)$	Euler pitch angle
$\psi/(\circ)$	Euler yaw angle
$p/(\circ\cdot\text{s}^{-1})$	roll rate, body-axes system
$q/(\circ\cdot\text{s}^{-1})$	pitch rate, body-axes system
$r/(\circ\cdot\text{s}^{-1})$	yaw rate, body-axes system

CFD with a six-degree-of-freedom (6-DOF) rigid equation solver is gaining popularity, and it has been shown to be capable of accurately predicting trajectory and attitude angles during store separation [12,13,15–19]. Kim et al. [15] computed releases from an ideal cavity at Mach 0.95. Four drops at different time instances showed trajectory variability due to changes in the store loads. The same drops, repeated with steady blowing at the leading edge of the cavity, appeared to reduce the variability. Loupy et al. [18] presented a statistical study on trajectory variability using a coupled CFD/6-DOF solver for an air-to-air missile ejected under transonic conditions. They showed that an average of 10–15 releases were necessary to predict the trajectory (with relative dispersion) with an accuracy of 5% at given conditions. It was confirmed that vertical displacement variations could be considered of second order as the movements of the store in this direction were principally governed by gravity and ejection velocity. Yan et al. [20] investigated store release in the supersonic regime. A pitch-up moment due to the missile crossing the cavity leading edge oblique shock was observed. Subsequent studies [12], still in the supersonic regime, demonstrated the beneficial effect of passive control devices (prism, wedge, and rectangle) placed at the front of the cavity in reducing store trajectory alterations. Other studies have concentrated on the repeatability analysis to determine a metric of trajectory dispersion for store release from the weapons bay [21]. Jolly et al. [22] tried to quantify the release-time dependency for a cavity-store combination. The authors proposed a predictive formulation to decide the trajectory repeatability before proceeding with the trajectory simulations. They derived a non-dimensional parameter, called the *J*-factor, which describes the ratio between the store unsteadiness and its resistance. The authors expressed the store resistance as the product of the radius of gyration and the stability margin divided by the product of the reference area and the release time squared. The unsteadiness was expressed as proportional to the square root of the product of the dominant resonating frequency and the associated spectral power. This formulation allowed the definition of a metric, considering the ejector forces as well, to express the susceptibility of the store to the unsteady conditions through the release time history. Jolly et al. argued that the greater this parameter becomes, the less repeatable and more release-time dependent the store trajectory will be. Nevertheless, no similar metric was introduced to quantify dispersion in roll, which for slender/finned bodies, like air-to-air and/or tactical ground troops' support missiles, can be the dominant factor of trajectory dispersion. Also, whilst ejector forces can

be set to reduce the dispersion of store trajectory in the longitudinal plane (vertical displacement, and pitch angle), fewer options are available to control skid and roll.

Studying store release variability is challenging, and more work is needed to explain the relationship between the fluctuations in the store loads and the observed trajectories. Moreover, a quantitative methodology capable of determining trajectory dispersion is not currently available, forcing scholars to conduct several simulations per release condition to accumulate enough trajectories for statistical convergence. Considering the quantity of data points to explore in a combat aircraft release flight envelope, 10 to 15 numerical simulations per testing condition are still too much computational effort to conduct digital flight clearance for store release certification.

For a given trajectory set and flight condition, the aim of this study was twofold. First, a procedure to determine critical trajectories within the set was developed. Second, cavity aerodynamics (flow pressure fluctuations) was correlated to roll rate and angle histories to evidence the dominant cause of the trajectory dispersion.

2. Methodology

2.1. Geometry – cavity and store

The adopted cavity model was the widely used geometry from the Arnold Engineering Development Test Centre (ADEC) during the Weapon Internal Carriage and Separation (WICS) wind-tunnel experiment [8]. This model, and the associated study of store separation, has been used in validation of numerical procedures [7,8,15].

The cavity has a length-to-depth ratio of 4.5 and a width-to-depth ratio of 1. The reference axis system for the cavity, labelled "Construction Axes" (X_c, Y_c, Z_c) or CNST, has the origin coincident with the cavity leading edge, with the x - z plane coincident with the bay symmetry plane (see Fig. 1). A single rake, consisting of 19 pressure probes was placed on the cavity floor (in the symmetry plane) to monitor pressure signals. The probe positions range from $x/L = 0.05$ to $x/L = 0.95$ and were evenly spaced (Fig. 1 dashed/dotted line).

The store model was an AIM9-L Sidewinder, following the WICS experiment [7]. The missile, representative of an air-to-air loadout, had a length of 2.817 m and a body diameter of 127 mm. The reference axis system for the store, labelled "Body Axes" (x_b, y_b, z_b)

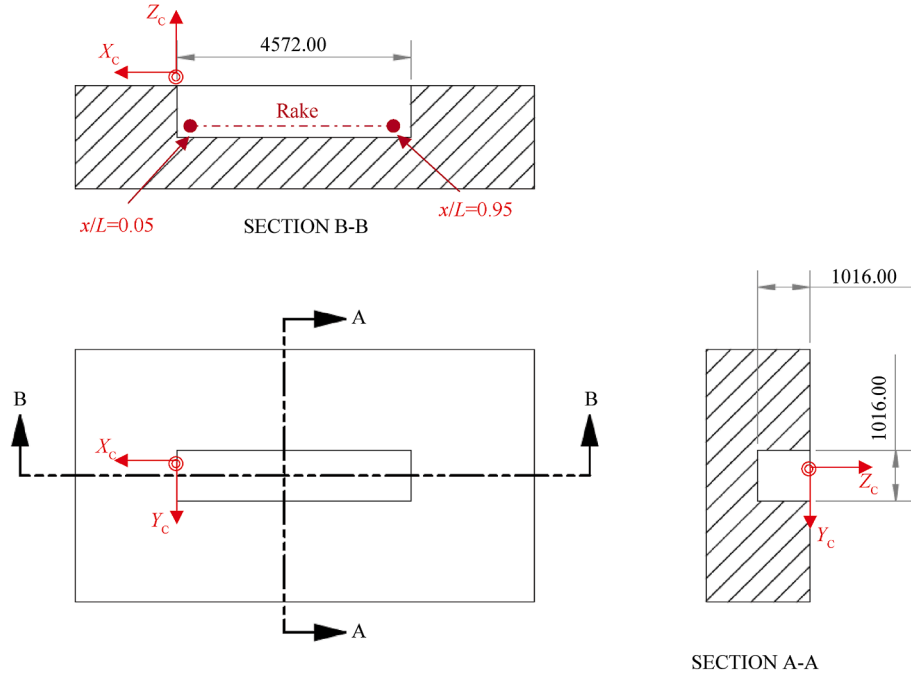


Fig. 1. Cavity geometry and construction axes definition. Dimensions are in millimetres (full-scale geometry).

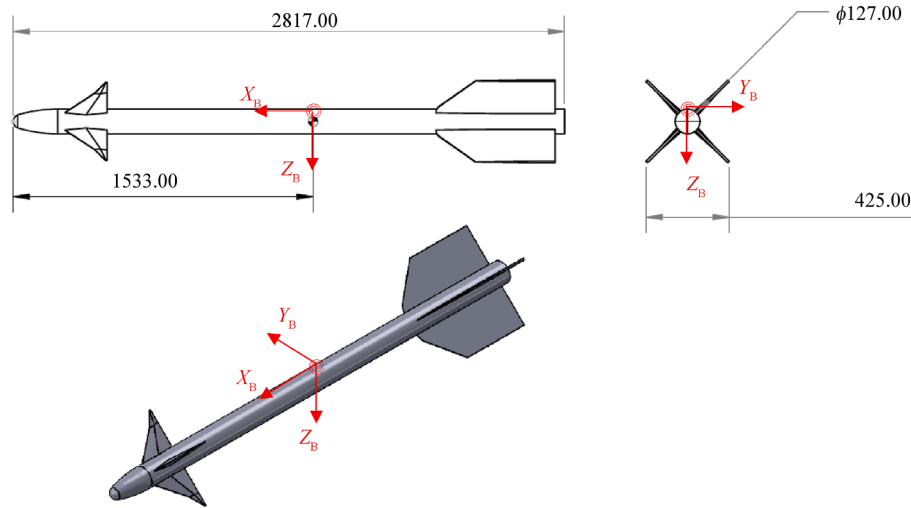


Fig. 2. Store geometry and body axes definition. Dimensions are in millimetres (full-scale geometry).

or BODY has the origin at the missile's centre of gravity as shown in Fig. 2.

The store mass and inertia properties are summarised in Table 1.

2.2. Numerical simulation

2.2.1. Computational fluid dynamics

The simulations were performed using ANSYS Fluent 2023R2 CFD code, adopting the hybrid RANS/LES Stress Blending Eddy Simulation (SBES) [23]. The RANS part of the SBES turbulence model is part of the hybrid RANS/LES category and is directly derived from the standard SDES (Shield Detached Eddy Simulation) formulation, which is an upgraded variant of the well-known DDES model (Delayed Detached Eddy Simulation).

Table 1
Store mass and inertia properties.

Parameter	Units	Value
m	kg	88.500
I_{xx}	kg.m ²	0.678
I_{yy}		61.771
I_{zz}		61.771
I_{xy}		0.000
I_{xz}		0.000
I_{yz}		0.000

Within the DDES/ $k\omega$ SST models, the k -equation is formulated as (a detailed description of the , including the constant values, can be found in Ref. [24]):

$$\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i k) = P_k - E_{DDES} + \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] \quad (2)$$

$$E_{DDES} = \rho \frac{k^2}{L_t} \max \left[1, \frac{L_t}{0.61 \Delta} (1 - F_{DDES}) \right] \quad (3)$$

$$L_t = \frac{\sqrt{k}}{(0.09)^{0.25} \omega} \quad (4)$$

The function F_{DDES} is designed in such a way as to return a value of 1 inside the wall boundary layer and 0 away from the wall. The definition of this involves a balance between proper shielding and not suppressing the formation of resolved turbulence as the flow separates from the wall. As the function F_{DDES} blends over to the LES formulation near the edge of the boundary layer, no perfect shielding can be achieved. In the SDES model, the dissipation term E_{DDES} is re-formulated as E_{SDES} which is calculated as:

$$E_{SDES} = -0.09 \rho k \omega F_{SDES} \quad (5)$$

$$F_{SDES} = \max \left[1, \frac{L_t}{0.4 \Delta_{SDES}} (1 - f_{SHIELD}) \right] - 1 \quad (6)$$

$$\Delta_{SDES} = \max \left((V)^{\frac{1}{3}}, 0.2 \Delta_{\max} \right) \quad (7)$$

where V is the cell volume, whilst $\Delta_{\max}$ is the maximum dimension of the cell and ensures a limit for very high aspect ratio elements. On the other hand, f_{SHIELD} is the "shield function" (varying from 0 to 1), designed to protect attached boundary layers from the switch to the LES regime.

The SBES model uses the same shielding function as the SDES formulation (f_{SHIELD}), though in the SBES case, the shielding function is extended to achieve a blending of the stress levels between the RANS and LES formulations:

$$\mu_t^{SBES} = f_{SHIELD} \mu_t^{RANS} + (1 - f_{SHIELD}) \mu_t^{LES} \quad (8)$$

For this study the RANS eddy viscosity (μ_t^{RANS}) was formulated using the SST- $k\omega$ generalised turbulence model (GEKO [25]), which accounted for a curvature correction term to address common challenges with $k\omega$ turbulence models in dealing with strong swirling flows [26]. LES eddy viscosity (μ_t^{LES}) was computed using the WALE (Wall-Adapting Local-Eddy) viscosity model [27].

The mesh (38.2 million elements) utilised unstructured tetrahedral-type cells, with prism cells having a growth ratio of 1.2 and wrapping the viscous surfaces, resulting in a y^+ value below 3. 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.

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 density-based solver was used. The inviscid fluxes vector was evaluated using the AUSM+ scheme. Inviscid equations were discretised using a bounded central differencing scheme [28], whilst viscous ones adopted a second-order upwind scheme. Gradients were evaluated using the Green-Gauss node-based method with the Minmod multi-dimensional cell-to-node limiter [29]. To march the solution in time, an implicit dual-time formulation was used (second-order Euler backward in physical time and implicit pseudo-time marching for inner iterations) with a maximum of 10 inner iterations and time step of 0.2 ms. This corresponded to values below $0.05 t_{char}$ consistent with the

recommendation of Menter [30] and the approach of Chaplin and Birch [31], resulting in a CFL number below two in the domain and unity inside the cavity.

2.2.2. Six-degree-of-freedom method

The store motion during the release procedure was modelled using the Six-Degree-of-Freedom method (6-DOF) coupled with the CFD solver. The governing equation for the translational motion of the centre of gravity is solved in the inertial coordinate system, which for this case was coincident with the CNST axes:

$$\vec{a}_{CNST} = \frac{\vec{F}_{CNST}}{m} + \vec{g}_{CNST} \quad (9)$$

where $\vec{F}_{CNST}$ is the sum of the external forces acting on the store (aerodynamics + ejector when active) and $\vec{g}_{CNST}$ the contribution due to gravity, which in construction axes had components [0, 0, 9.81] m/s².

On the other hand, the solver computes the angular accelerations in the body axes:

$$\vec{\omega}_{BODY} = \vec{I}^{-1} \left(\vec{M}_{BODY} - \vec{\omega}_{BODY} \times \vec{I} \cdot \vec{\omega}_{BODY} \right) \quad (10)$$

where $\vec{M}_{BODY}$ is the sum of external moments acting on the store centre of gravity. The orientation of the store is tracked using a standard 321 Euler rotation sequence (ϕ, θ, ψ). The moments are therefore transformed from construction to body coordinates using the following expression:

$$\vec{M}_{BODY} = DCM_{C2B} \cdot \vec{M}_{CNST} \quad (11)$$

$$DCM_{C2B} = \begin{bmatrix} C_\phi C_\psi & C_\phi S_\psi & -S_\phi \\ S_\phi C_\psi - C_\phi S_\psi & S_\phi S_\psi + C_\phi C_\psi & S_\phi C_\phi \\ C_\phi S_\psi + S_\phi C_\psi & C_\phi C_\psi - S_\phi S_\psi & C_\phi C_\phi \end{bmatrix} \quad (12)$$

where, in generic terms $C_\alpha = \cos \alpha$ and $S_\alpha = \sin \alpha$.

Once the translational and angular accelerations are computed from Eqs. (9) and (10) the rates ($\vec{V}_{CNST}$ and $\vec{\omega}_{BODY}$) are determined by numerically integrating using a fourth-order Adams-Moulton formulation [32]:

$$\chi^{k+1} = \chi^k + \frac{\Delta t}{24} \left(9\dot{\chi}^{k+1} + 19\dot{\chi}^k - 5\dot{\chi}^{k-1} + \dot{\chi}^{k-2} \right) \quad (13)$$

where χ represents either $\vec{V}_{CNST}$ or $\vec{\omega}_{BODY}$ and Δt is the integration time step. The overset mesh algorithm takes as input the translational and angular velocity rates of the store and updates the position of the associated mesh accordingly.

2.2.3. Computational domain

The computational domain (Fig. 3) placed the cavity on a flat plate. The domain extended $2L$ on each side of the cavity. The overall length was equal to 9 cavity lengths in the streamwise direction, and extended $3L$ upstream, and $5L$ downstream from the cavity leading and trailing edges respectively. Finally, the overall length in the vertical direction was equal to 5 cavity lengths. The flat plate where the cavity laid flush extended $1.5L$ ahead and aft of the cavity and was followed by symmetry boundary conditions about the z -axis. As this setup has already been used in previous studies [33], no domain sensitivity study was conducted.

2.2.4. Store release procedure validation

The 6-DOF simulation was validated using the ADEC data obtained during the WICS wind-tunnel experiment [8]. In these

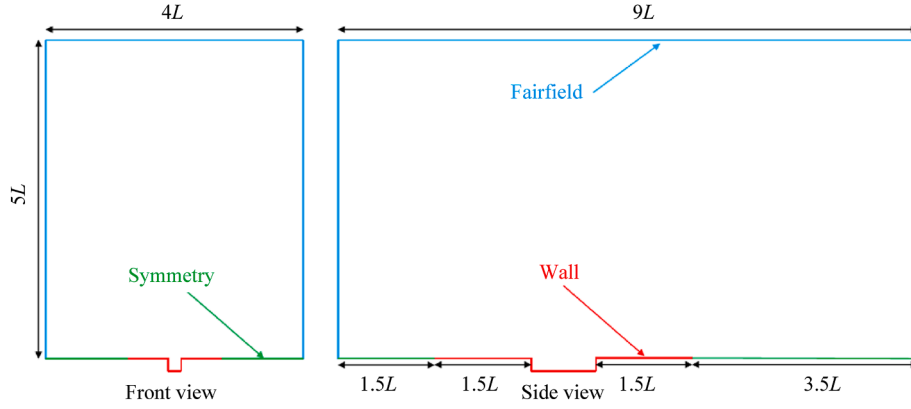


Fig. 3. Computational domain.

experiments, a Captive Trajectory System (CTS) was used. The store had five degrees of freedom with rolling disabled, and the centre of gravity (CG) was placed at half cavity depth. The ejector stroke had a length of 0.2 m and imposed a final velocity of 9.14 m/s and a final pitch-down rate of 1 rad/s on the store.

A total of 4 releases were performed at different times spaced by $10t_{ch}$. As shown in Fig. 4, the displacements were in good agreement with a maximum difference, between experiments and numerical simulations, of ± 10 mm. Pitch and yaw angles (roll was fixed during wind tunnel experiments) showed maximum deviations from experimental data of the order of $\pm 1.5^\circ$. The deviations observed were in line with previous studies conducted on the same geometry [15,19], demonstrating the capability of the

numerical procedure to compute the store trajectory.

2.2.5. Test matrix

The store release process can be divided into 3 phases:

- Carriage. In this case, the weapon is fixed, and the flow is allowed to develop. For this study, all releases begin with the store CG coordinates, in construction axes (see Fig. 1), $[-2.266, 0.0, -0.508]$ m. All releases were conducted in a flow-developed condition of the cavity.
- Stroke. In this phase, the store is pushed towards the cavity opening. During this phase, a vertical velocity of 9.14 m/s and a pitch-down velocity of 1 rad/s was imposed. All releases lasted

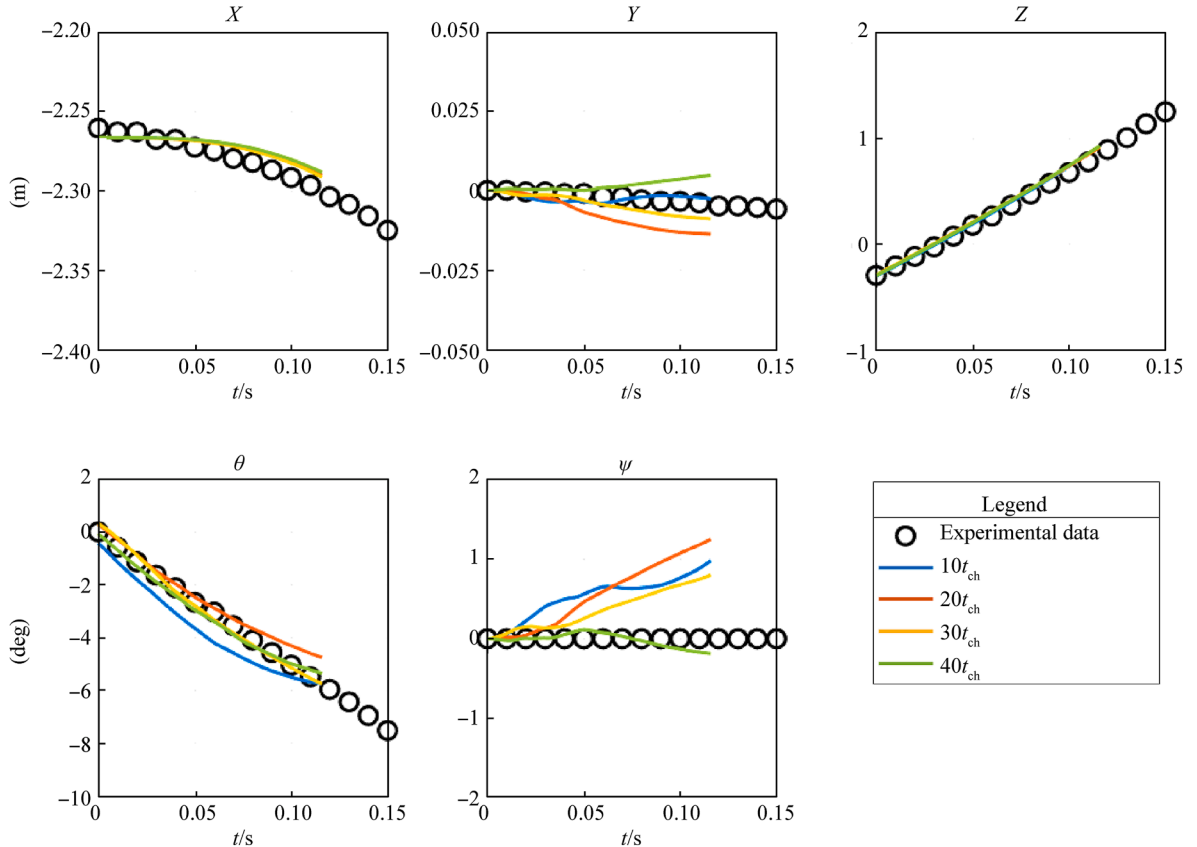


Fig. 4. Store position during release for validation.

for 0.044 s, though each release was started at different times to explore statistical dispersion. As shown in Table 2, in this study, a total of 30 different releases were conducted, starting from $30t_{ch}$ up to $175t_{ch}$ spaced by $5t_{ch}$.

- Free Flight. In this phase, the store is completely detached from the carriage, and its trajectory is subjected only to gravity and aerodynamic forces. All simulations run up to 0.16 s. After this time, the weapon separation from the cavity was considered complete, and its trajectory evolution was no longer dependent on the cavity's unsteady flow field.

Table 2 summarises the test matrix adopted in this study.

3. Data analysis procedure

3.1. Trajectory metrics

The comparison of store trajectories is a critical part of the release process. A store-release study would likely include comparing several trajectories for closeness and similarity. It is then necessary to define a metric capable of quantifying the "similarity" between each store path in space. Fréchet distance is a type of metric already used in store-release analysis [21,22,34] and was selected to quantify the difference between the computed trajectories. Given 2 different curves in space, P and Q , with their associated parametrisation, so that:

$$\begin{cases} P(\alpha)_{\alpha[0,1] \rightarrow [0,N]} \\ Q(\beta)_{\beta[0,1] \rightarrow [0,M]} \end{cases} \quad (14)$$

It is possible to write these curves in terms of the parameter $\tau \in [0, 1]$. The Fréchet distance $\delta_F(P, Q)$ is mathematically defined as:

$$\delta_F(P, Q) = \min\{\max[d(P(\alpha(\tau)), Q(\beta(\tau)))]\} \quad (15)$$

This equation indicates that for every possible function $\alpha(\tau)$ and $\beta(\tau)$, the largest distance between the two curves, as they evolve along their respective path, is calculated. Then among these maximum distances, the smallest value is selected. From this definition also comes the dependency of the Fréchet distance on the difference function $d(P, Q)$ used to measure the "effective" distance between P and Q . Euclidean distance is the most common metric difference function, and, in this study, it was used to determine the maximum spatial separation between two different trajectories. For this metric, the difference function is defined as:

$$d(P_i, Q_j)_{ij} = \|P_i - Q_j\|_2 \quad (16)$$

Nevertheless, in the analysis of different store trajectories, the orientations of the relative Euler angles are required to quantify the different evolution of store body axis system orientation. To do so, the rotation history must be used instead of a location history. In this case, the rotation metric was derived such that at each discrete point in the history, a rotation matrix was formed using the trajectories of Euler angles. The procedure adopted in this study involved the Euler-Rodriguez vector to compute the L_2 norm of the Euler angles:

$$\vec{a}_i = E2R(\varphi_{P_i}, \theta_{P_i}, \psi_{P_i}) \quad (17)$$

$$\vec{b}_j = E2R(\varphi_{Q_j}, \theta_{Q_j}, \psi_{Q_j}) \quad (18)$$

$$d(P_i, Q_j)_{ij} = \|R2E(\vec{a}_i - \vec{b}_j)\|_2 \quad (19)$$

Table 2

Test matrix for the store release study.

M_∞	p_∞ / Pa	T_∞ /K	Release t_0 /ms ^a	Release t_0/t_{ch}	Stroke length/m	Stroke final velocity/(m·s ⁻¹)	Stroke final pitch rate/(rad·s ⁻¹)
0.90	59909	284	100.50	30	0.2	9.14	-1.0
			103.85	35			
			107.20	40			
			110.55	45			
			113.90	50			
			117.25	55			
			120.60	60			
			123.95	65			
			127.30	70			
			130.65	75			
			134.00	80			
			137.35	85			
			140.70	90			
			144.05	95			
			147.40	100			
			150.75	105			
			154.10	110			
			157.45	115			
			160.80	120			
			164.15	125			
			167.50	130			
			170.85	135			
			174.20	140			
			177.55	145			
			180.90	150			
			184.25	155			
			187.60	160			
			190.95	165			
			194.30	170			
			197.65	175			

Note. ^aThis value indicates the absolute time, in the cavity unsteady simulation evolution, at which the release procedure begun. This indicated that each release started in a different cavity flow pattern arrangement.

where, $E2R$ and $R2E$ are the operators that allow the calculation of the Rodriguez vector from the Euler angle and the Euler angles from the Rodriguez vector (see Ref. [35]).

Hence, using these two metrics, it was possible to quantify the maximum spatial distance, and the maximum angular deviations between two different trajectories.

3.2. Trajectory analysis

Once a metric to quantify the differences between several trajectories has been defined, the next step is the clustering process; that is, the grouping of a set of trajectories, such as objects in the same group (called a cluster) that are similar. This operation not only reduces the size of the dataset to process but also allows the identification of the conditions responsible for trajectory differences. Of particular interest for this study was the analysis of outliers that in a real store release scenario typically determine the most dangerous situation, where the store has a greater chance of impact on the surrounding environment. So far, at least in the open literature, clustering has been performed using agglomerative hierarchical clustering (AGC) [22,34], or visual identification of maximum offsets from the overall mean [18]. A major drawback of hierarchical clustering is that the shape and structure of clusters largely depends on the linkage criteria that must be selected before the dataset analysis, which can strongly affect the final shape of the cluster. Additionally, this approach is not capable of handling eventual noise, that is the presence of outliers that might not be possible to agglomerate in any cluster. Other authors [36] used Dynamic Time Warping combined with k-medoids to generate clusters. This method is well-suited to compare misaligned data series in time and has a similar conceptual basis to the Fréchet distance approach. However, an approach based on k-medoids assumes an "a priori" knowledge of the number of clusters. Again, this approach has pitfalls as it is dependent on initial conditions and struggles with clustering an arbitrarily shaped group of objects.

Since, for this study, the analysis of outliers was considered of high importance, it was decided to analyse store release trajectories represented by the density-based algorithm DBSCAN (Density Based SCANNing) [37]. DBSCAN is a clustering algorithm that segregates data points into high-density regions separated by regions of low density. Its better performance in analysing store-release trajectory dispersion can be justified considering the following points:

- DBSCAN is well-suited to determine outliers. For store release, an outlier is defined as a release event leading to a trajectory variation, such that it cannot be considered part of the overall average. Hence, the outliers could represent peculiar conditions to explore, as might be the case where the store trajectory evolved unpredictably. This in turn helps to isolate potentially dangerous conditions far away from the expected behaviour during a release.
- Considering that no prior knowledge is available for trajectory dispersion, an algorithm like DBSCAN is capable of processing datasets of any shape. Its density-based nature allows it to adapt to the structure of the data, forming clusters that might be intertwined or elongated.
- Spatial datasets align well with DBSCAN's capabilities. Its foundation on spatial density makes it an appropriate choice when working with spatially coherent data.

3.3. Signal analysis

For this study, the time-frequency approach, based on the Hilbert-Huang transform [38] was used. This approach was necessary given the short temporal duration of the store release sequence compared to the required simulation length to achieve a statistical convergence of frequency-based characteristics.

Signals $x(t)$, of temporal length were decomposed in implicit mode functions (IMF) using the procedure already adopted for cavity flows by Bacci et al. [39]. Given a history $x(t)$, of m samples, the decomposition procedure can be expressed as:

$$x(t) = \sum_{i=1}^n IMF_i(t) + r_n(t) \quad (20)$$

where $r_n(t)$ is the residual after the decomposition in n modes. The number of modes extracted can vary according to the complexity of the signal. Once the IMFs are extracted, the successive step is to apply the Hilbert transform to each IMF, and derive the analytical signal $z(t)$ of $x(t)$:

$$z(t) = \sum_{i=1}^n IMF_i(t) + jH\left(\sum_{i=1}^n IMF_i(t)\right) = \sum_{i=1}^n a_i(t)e^{j\theta_i(t)} \quad (21)$$

$$H\langle x(t) \rangle = \frac{1}{\pi} P \int_{-\infty}^{+\infty} \frac{x(t')}{t-t'} dt' \quad (22)$$

This last equation is the definition of the Hilbert transform, where P is the Cauchy principal value. From here 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:

$$f_i(t) = \frac{\omega_i(t)}{2\pi} = \frac{1}{2\pi} \frac{\partial \theta_i(t)}{\partial t} \quad (23)$$

The Hilbert spectrum is then defined as:

$$H(\omega, t) = \sum_{i=1}^n H_i(\omega, t) \quad (24)$$

$$H_i(\omega, t) = \begin{cases} |a_i(t)| & \omega = \omega_i(t) \\ 0 & \text{otherwise} \end{cases} \quad (25)$$

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 $H_e(\omega, t) = (H(\omega, t))^2$. It is possible to see that each IMF represents an intrinsic feature of the signal and, if properly calculated, describes a physical phenomenon [38].

Using the definition of the analytical signal, it is possible to define the cross-analytic function between two signals, $x(t)$ and $y(t)$:

$$z_{xy}(t) = z_x^*(t) \cdot z_y(t) \quad (26)$$

where $z_x^*(t)$ is the complex conjugate of the analytic function of $x(t)$, whilst $z_y(t)$ is the analytic function of $y(t)$.

It is then possible to introduce an instantaneous transfer function with associated magnitude ($H_{md}(t)$) and phase ($H_{ph}(t)$).

$$H_{md}(t) = 10 \cdot \log_{10} \left| \frac{Z_{xy}(t)}{Z_{xx}(t)} \right| \quad (27)$$

$$H_{ph}(t) = \frac{re[Z_{xy}(t)]}{|Z_{xy}(t)|} \quad (28)$$

Like canonical transfer functions, these quantities express the correlation between an "input" and an "output". For this study, such an approach was used to express the correlation between pressure fluctuations ($x(t)$) and resulting body kinematics. Decomposing and representing correlations in this fashion allows a true time-localized instantaneous measure revealing subtle properties in the data and inconspicuous relations to other data sets using analytic components [40].

3.4. Store trajectory/flow-field coupling analysis

Previous studies [18,22,41–44] showed that store trajectories are strongly influenced by the cavity oscillatory behaviour. The resulting resonant modes were found to relate directly to the forces applied to the store and cavity structures [45,46], generating frequency spectra directly correlated with the pressure fluctuations.

Although CFD simulations can give additional insight into the flow, especially how the spatial structures associated with the resonant mode can influence the store's motion, this study aimed to develop an analysis procedure that could be used for experimental data and in future flight activity. Hence, it was decided to analyse the correlation between pressure signals (recorded inside the cavity) and the store's trajectory variability.

4. Results

The data analysis workflow is summarised in Fig. 5.

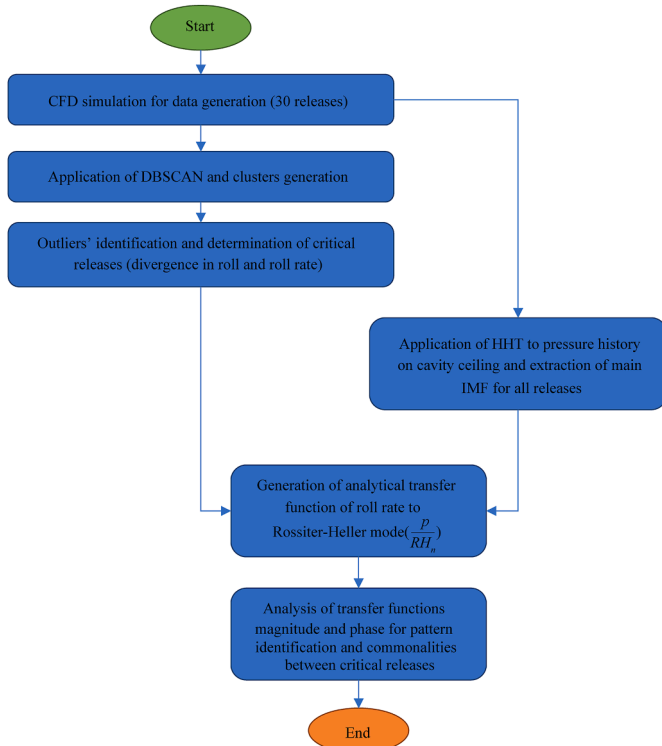


Fig. 5. Data analysis workflow.

The initial step in the analysis of the results was the classification of the simulated trajectories. For all releases (named t_{ch} 030, t_{ch} 035, t_{ch} 040 ... t_{ch} 175), Fréchet mutual distances (spatial and angular) were calculated. This resulted in 435 combinations, which were analysed using the DBSCAN algorithm. To do so, it was necessary to define a threshold to identify self-similarity between trajectories. Hence, for both space and angular Fréchet distances representative values were chosen. For the space distance (Δs), the following formula was used:

$$\Delta s = \frac{D_{body}}{2} = 63.5 \text{ [mm]} \quad (29)$$

where D_{body} is the missile body diameter. The factor 1/2 was introduced considering that, since the flow physics of weapons bays is oscillatory in nature, a better approach to capture the time scale of the phenomenon was to consider the Nyquist frequency instead of the period of a complete oscillation.

On the other hand, the angular distance threshold ($\Delta \gamma$) could not be directly correlated to ejector and cavity time characteristics. An equivalent angular delta had to be calculated using cavity/store metrics (characteristic length). Nevertheless, angular deviations from optimal trajectories are considered extremely dangerous during the separation phase, as they can quickly generate divergence from the prescribed path. In this case, the representative scale was selected as:

$$\Delta \gamma = \text{asin} \left(\frac{D_{body}}{2 \cdot l_{x_{cg}}} \right) \cong 2.4 \text{ [deg]} \quad (30)$$

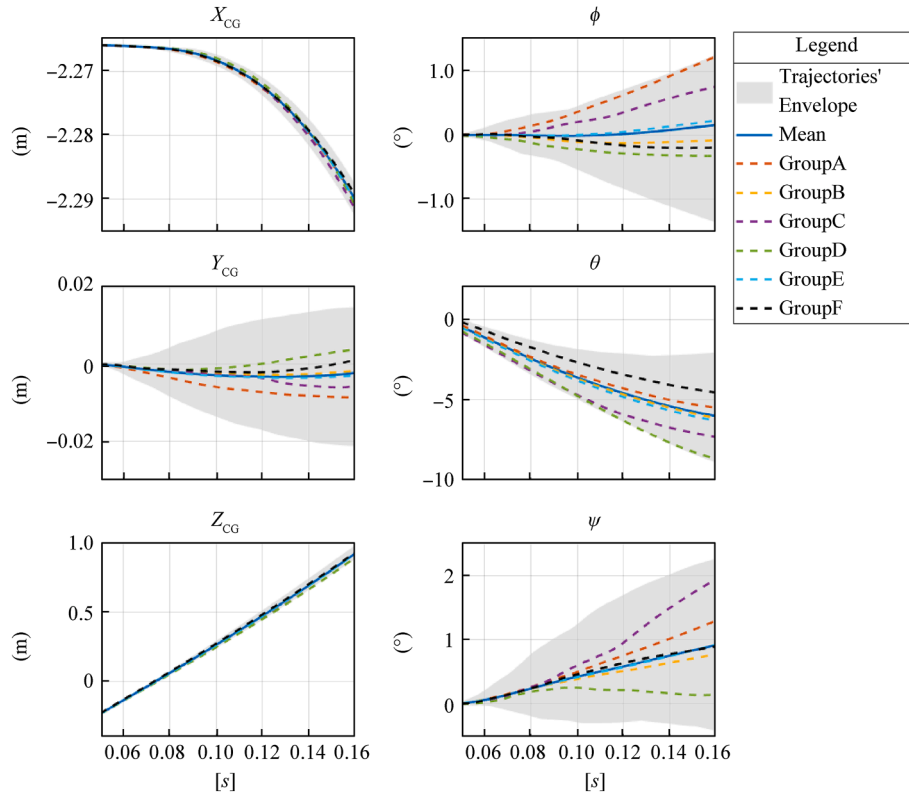
where $l_{x_{cg}}$ is the distance from the nose to the centre of gravity (see Fig. 2). The formula determines the angular rotation, around the missile CG, necessary to produce a displacement at the nose (the farthest point of the body from the centre of rotation) equal to the body's radius.

Using these values, the DBSCAN algorithm was applied to the trajectory set. For space and angular distances, a value of -1 was used to classify outliers, whilst positive integers identified the relative clustering. The results are shown in Table 3. All trajectories were members of the same cluster when considering the space distance metric (Eq. (16)). Such an outcome indicated that all releases did not differ from each other more than the missile's body radius. The result confirmed that gravity and the ejector's force could contain trajectory dispersion in space. On the other hand, clustering using the angular distance metric (Eq. (19)) resulted in the identification of 4 groups, labelled A, B, C, and D. In each group, all the members did not differ, in terms of body rotation, more than $\Delta \gamma$. Again, this outcome was expected as store release from a cavity, with a low-inertia weapon, is typically more susceptible to angular fluctuation rather than spatial.

The DBSCAN algorithm also identified 5 outliers (group F) that could not be agglomerated to any cluster. Analysing the mean trend for the whole dataset and each single group, it was observed that removing the outliers from the mean trajectory calculation did not affect the result considerably (see Fig. 6 – group E). On the other hand, the mean values obtained by considering member trajectories of other groups, including the outliers (group F) did vary from the overall dataset average. The logical explanation was that each group, although aggregating similar trajectories, brought together events resulting in a deviation from the expected statistical value. Further insight into each group was obtained by analysing the trajectory dispersion, as shown in Fig. 7. Here, error bars

Table 3
Clustering results.

Group name	Group size	Cluster index space	Cluster index angle	Trajectory (t_{ch})
A	5	1	1	035 045 095 110 140
B	16	1	2	040 050 055 060 065 070 075 080 085 100 115 130 135 145 150 160
C	2	1	3	105 170
D	2	1	4	165 175
Derived groups				
E (No Outliers)	25	1	[1–4]	035 040 045 050 055 060 065 070 075 080 085 095 100 105 110 115 130 135 140 145 150 160 165 170 175
F (Outliers)	5	1	–1	030 090 120 125 155

**Fig. 6.** Mean trajectory evolution and dispersion. Dash lines represent the mean evolution for each Group. Centre of gravity coordinates are reported in CNST axes. The left side of the plots marks the ejector stroke end phase ($t = 0.044$ s).

define the maximum positive and negative deviation from the mean value of the group¹. The "x" marker defines the group mean value delta from the reference zero, which was the whole dataset's expected value. For example, the reading for group F for X_{CG} (black error bar, Fig. 7-upper left) was that the mean of this group deviated from the overall mean (grey-coloured error bar) by +0.74 mm, whilst the upper bound (still relative to the overall mean) was +1.24 mm and the lower bound -1.5 mm.

Considering the whole dataset (grey-coloured error bars), the dispersion was small for translational motion, especially in the longitudinal plane (X-Z). Minor deviations were observed in the lateral/directional plane, although the threshold Δs (see Eq. (29)) was never exceeded. Notably, the maximum linear CG deviation was observed along the z-axis (CNST reference frame) with values of -39.2/+61.1 mm.

For rotational motion, higher values were observed in the roll

channel. Here, the dispersion bound was -15.2/+10.9°. On the other hand, pitch and yaw dispersion (-2.9°/+3.9° and -1.3°/+1.3°, respectively) was in the order of $\Delta\gamma$ (see Eq. (30)) and could be considered of secondary importance. The asymmetry of the dispersion boundaries indicated that the sample was not big enough to consider it statistically converged. Such a finding was remarkable as upper/lower bounds, especially for angles, differed more than 20% (for Z_{CG} , ϕ and θ), indicating that, for such a complex phenomenon as store release from a cavity, statistical convergence requires more than the previous studies finding of 10–15 releases [18,19].

The analysis of groups derived from clustering indicated that group F (the outliers) included those releases responsible for positive and negative maximum dispersion for Y_{CG} , Z_{CG} , the upper bound for pitch, and the lower bound for roll (see also Table 4). On the other hand, it was group A that incorporated the releases responsible for the upper bound in roll. This group was also characterised by only positive roll values, with minimal dispersion (i.e., 5 similar roll angle histories). Finally, groups B and E had the

¹ Hence, the bars are a quantitative representation of the "dispersion".

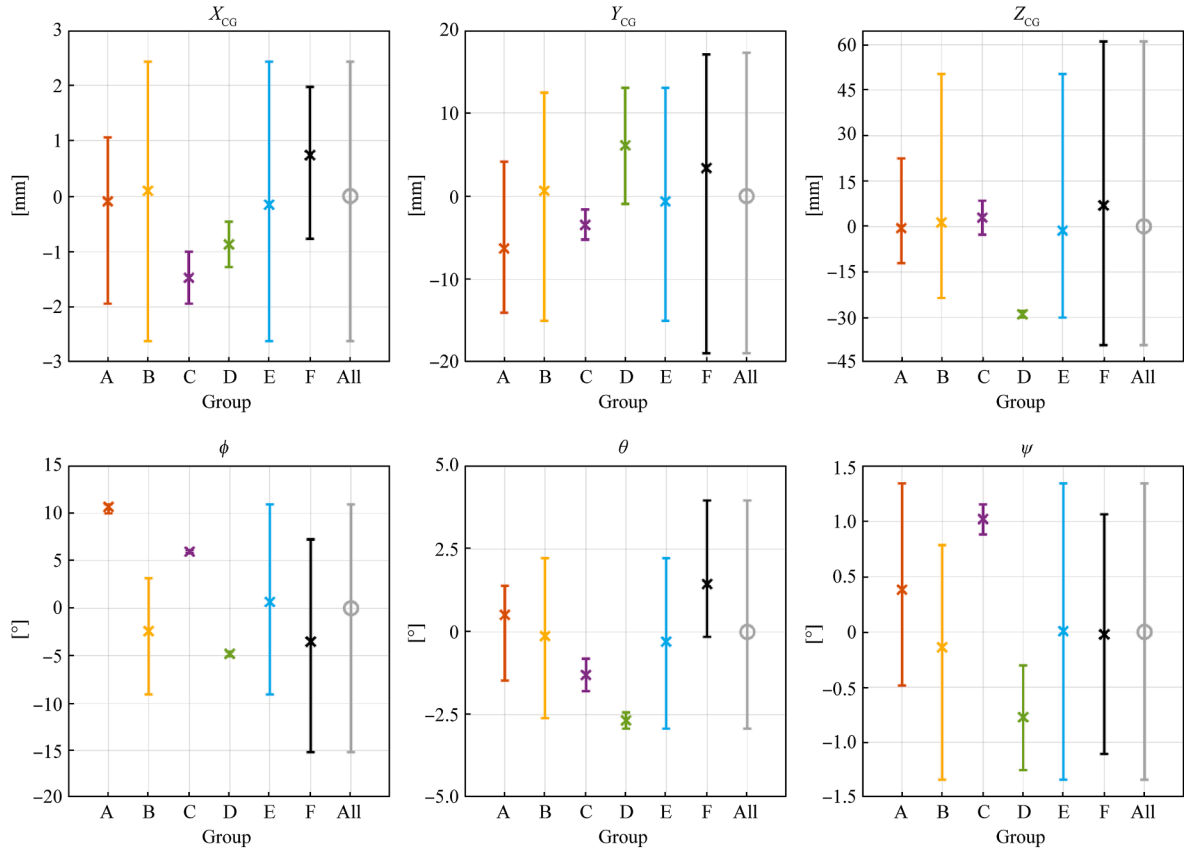


Fig. 7. Trajectories dispersion for each group of Table 3. The bar represents the upper and lower bounds from the mean for each Group. The cross marker indicates the deviation of the Group mean value from the overall mean.

Table 4
Trajectory dispersion summary and identification of “worst-case” release^a.

Type	X_{CG}/mm		Y_{CG}/mm		Z_{CG}/mm		$\phi/^\circ$		$\theta/^\circ$		$\psi/^\circ$	
	Lwr	Upp	Lwr	Upp	Lwr	Upp	Lwr	Upp	Lwr	Upp	Lwr	Upp
Trajectory (t_{ch})	100	160	030	090	155	030	120	140	175	030	115	045
Max Δ from mean	-2.6	2.4	-18.9	17.2	-39.2	61.1	-15.2	10.9	-2.9	3.9	-1.3	1.3
Group membership	B	B	F	F	F	F	F	A	D	F	B	A

Note. ^a“Lwr” = lower bound, “Upp” = upper bound.

widest dispersion in terms of pitch, with a difference between upper and lower bounds of $\sim 5^\circ$.

For trajectory variance, roll angle was the crucial parameter affecting the results and accounting entirely for the dissimilarities between different release histories. This was a critical aspect, as store-induced roll motions are considered the most difficult to control and can lead to potential danger (airframe impact and/or lost lock). The analysis also showed that group A and group F collected those releases with the biggest roll motions. It was then decided to focus attention on a subgroup of these, where releases had in common a final roll angle of $\pm 8^\circ$ and achieved, during the ejection, roll rates above $\pm 100^\circ/\text{s}$. The trajectories of this subgroup are shown in Fig. 8. Here, the “solid line” represents the flight phase in which the store CG was inside the cavity, whilst the “dashed” part showed when it was outside. The plot shows that whilst still inside the cavity the store roll angle was never more than $\pm 3^\circ$, although in four cases roll rate went beyond $100^\circ/\text{s}$ (t_{ch} 035, 045, 120, and 140). When the store cleared the cavity, in all cases of Fig. 8 the roll angle began to build up quickly, and a steady roll rate above $100^\circ/\text{s}$ was achieved once passing $t = 0.1$, which, for

every case corresponded to the missile completely clearing the shear layer (considering not just the CG but the entire geometry).

To explore the correlation between the trajectory evolution and the cavity aerodynamics, pressure signals were recorded at the rear ceiling of the cavity in the symmetry plane ($x/L = 0.95$ – see Fig. 1), along with roll rate time histories. Subsequently, both signals were decomposed using the Hilbert-Huang Transform (HHT). The characteristic of a Hilbert-Huang time-frequency map is shown in Fig. 9. Aside from minor differences, the pressure signals were dominated by an IMF corresponding to the 2nd Rossiter-Heller mode (RH_2 , 43 Hz from Eq. (1)) and the 3rd Rossiter-Heller mode (RH_3 , 68 Hz from Eq. (1)). The first mode, RH_1 (19 Hz from Eq. (1)), was not present as the short duration of the simulation compared to the time scale of this mode made its contribution to the system dynamics irrelevant. On the other hand, the major contribution of roll rate came from two IMFs located in the band from 10 Hz to 50 Hz.

Once the HHT transform was applied to both the roll rate and pressure signal of all releases, the next step of the data analysis procedure was the construction of the transfer function (TF_{m_n})

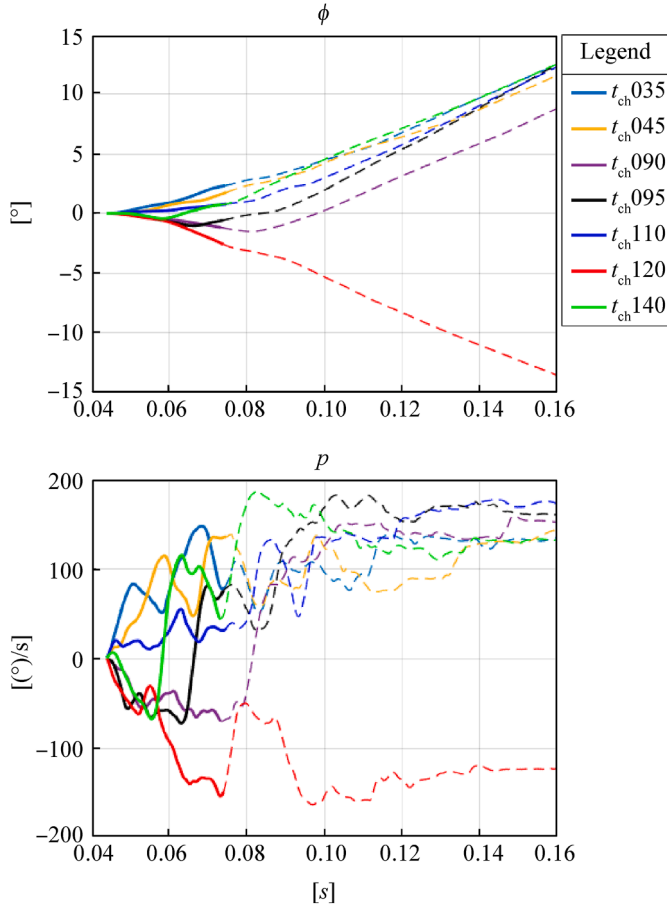


Fig. 8. Roll angle and rate temporal evolution for the most "critical" releases. The dashed part of the curve indicates the flight phase where the store CG was outside the cavity.

between the roll rate and the Rossiter-Heller mode. Using Eq. (26), the transfer function was defined as:

$$\begin{cases} TF_{m_n} = z_{xy}(t) = z_{x_n}^*(t) \cdot z_{y_m}(t) \\ z_{y_m}(t) \rightarrow \text{analytic function of } p_m \\ z_{x_n}(t) \rightarrow \text{analytic function of the IMF associated with the } n^{\text{th}} \text{ RH mode} \end{cases} \quad (31)$$

where p_m indicates the roll rate history during the m^{th} release, while the subscript n indicates the n^{th} RH mode extracted from the pressure history recorded at $x/L = 0.95$ (see Fig. 1) during the m^{th} release. Then, for each TF_{m_n} magnitude and phases were computed using Eqs. (27) and (28).

This procedure was applied to the trajectories of Fig. 8 and the trajectories of group D. The latter was considered significant, as it represented a group having a small value of the final roll angle. The outcome of the two worst² trajectories, t_{ch} 120 and t_{ch} 140, are shown in Fig. 10. The lower row compares the magnitude and the

² Meaning trajectories with the largest value of roll angle at the end of the simulation.

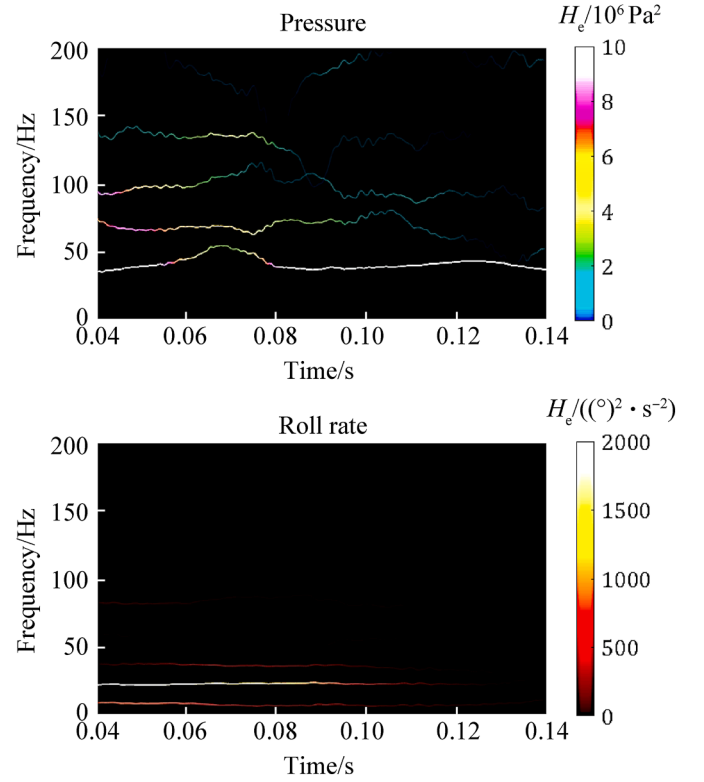


Fig. 9. HHT of pressure signal at cavity ceiling (upper plot - $x/L = 0.95, y/W = 0.0, z/D = 1.0$), and roll rate (lower plot) for release t_{ch} 120.

phase of the RH_2 to the roll rate transfer function, whilst the upper row shows the temporal evolution of the roll rate and the IMF associated with the 2nd Rossiter-Heller tone.

From the figure, it was possible to see how an increase of H_{md} was associated with roll rate acceleration. In both releases the maximum roll rate ($-162^\circ/s$ for t_{ch} 120 and $187^\circ/s$ t_{ch} 140), was achieved with transfer function modulus values above -15 dB. Additionally, when high H_{md} values (> -15 dB) occurred together

with H_{ph} values of ± 1 the roll rate increased rapidly in time. By comparison, when the store was not subjected to such high values of roll rate during release, like the case for t_{ch} 165 and t_{ch} 175, the time interval with a transfer function magnitude above -15 dB was considerably inferior. As shown in Fig. 11, both releases were characterised by lower maximum roll rate values ($-70^\circ/s$ for t_{ch} 165 and $-90^\circ/s$ t_{ch} 175). These local maxima were achieved at the highest value of transfer function modulus, though the exposure time was not enough to induce high rolling moments.

New formulation for critical release identification.

Preliminary analysis indicated that a correlation existed between roll angle and roll rate divergence and TF_{m_n} values, although in the previous example, the analysis was conducted on just 4 handpicked trajectories, the two worst ones, and the two best ones. To test the validity and robustness of the initial finding, a

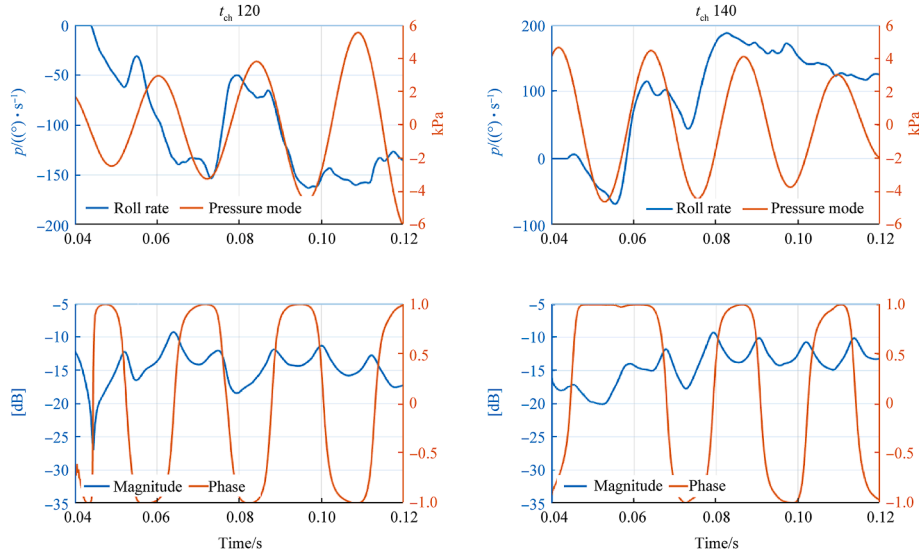


Fig. 10. Transfer function analysis (using HHT) between RH_2 (input) and store roll rate (output) for trajectories achieving high roll rate values and final roll angle values. Left column t_{ch} 120, right column t_{ch} 140. Upper row, temporal trend, lower row, transfer function magnitude and phase.

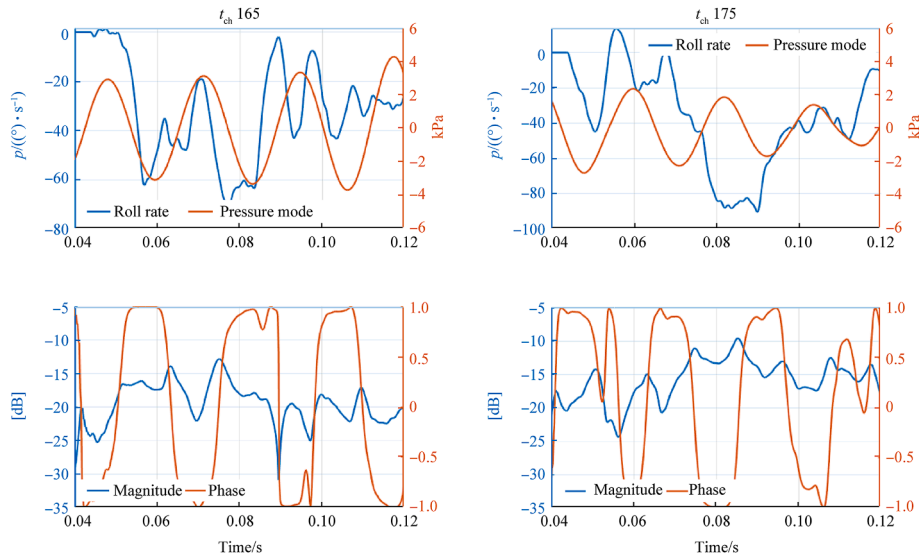


Fig. 11. Transfer function analysis (using HHT) between RH_2 (input) and store roll rate (output) for trajectories achieving low roll rate values and final roll angle values. Left column t_{ch} 165, right column t_{ch} 175. Upper row, temporal trend, lower row, transfer function magnitude and phase.

more structured approach to database analysis was necessary to best discriminate safe from unsafe releases. This was achieved through the analysis of the exposure time (t_{ex}), defined as:

$$t_{ex} = \sum_{i=1}^K \Phi(i) dt \quad (32)$$

$$\Phi(i) = \begin{cases} 1 & H_{md}(i) \geq tsh_a \text{ \& } H_{ph}(i) \geq tsh_p \\ 0 & \text{otherwise} \end{cases} \quad (33)$$

In Eq. (32), dt is the time step, whilst K is the total number of elements composing the time series of the release. Regarding the function $\Phi(i)$, here the value tsh_a is a threshold (in decibels) whilst tsh_p is the phase threshold.

For constructive interference, that is, input (Rossiter-Heller mode) generating a diverging output (roll rate), the input-to-

output correlation must be "in-phase". This made the selection of tsh_p straightforward, and for this study, the standard value of ~ 0.7071 (corresponding to a maximum phase difference of 45°) was selected.

On the other hand, the definition of tsh_a had to be explored using a sensitivity analysis. For the previous "hand-picked" cases, the value of -15dB seemed a good threshold for raw data (that is, dimensional input and output). On the other hand, a better picture could be obtained if the signals were made dimensionless. It is possible to show that, if an a priori bound on normalisation between input and output is selected, the transfer function will diverge (and hence even if the input is kept constant, the output will continue to increase) when its absolute magnitude exceeds 1 (or 0 dB) [40,47]. Assuming that the full set of releases could be considered a representative population sample, the non-dimensionalisation factors for roll rate and pressure were

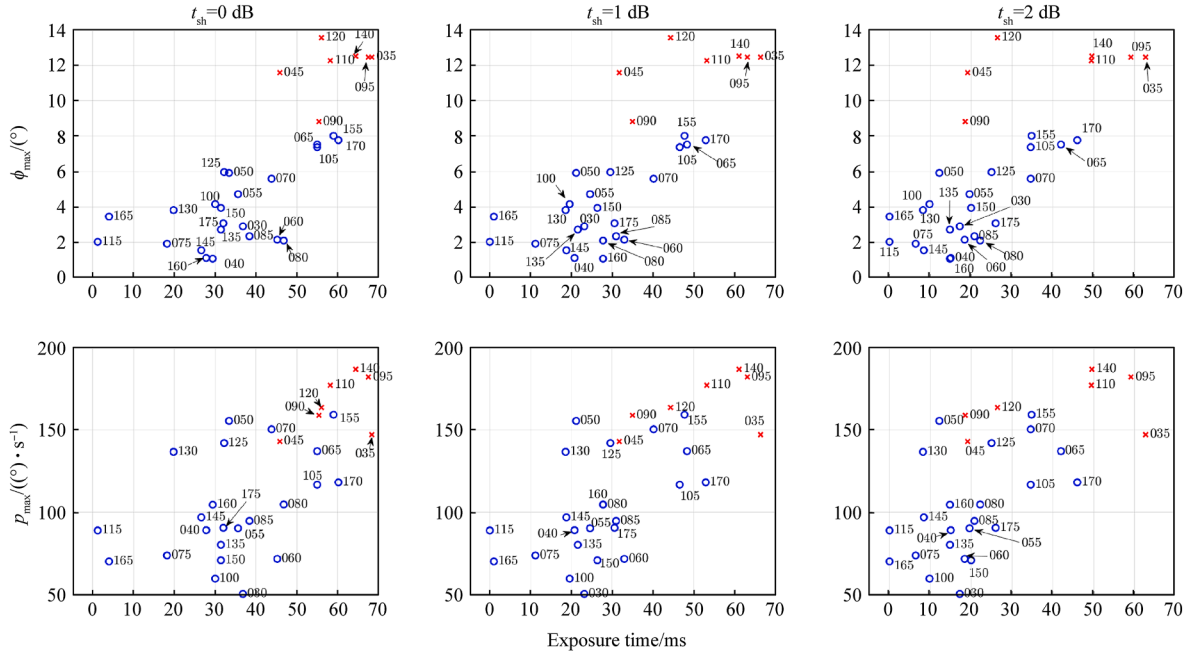


Fig. 12. Scatter plot of exposure time vs final roll angle (upper row) and roll rate (lower row). Each column represents different t_{sh} levels. Data refers to TF_{m_2} (i.e., input RH_2). Red markers represent the most critical releases.

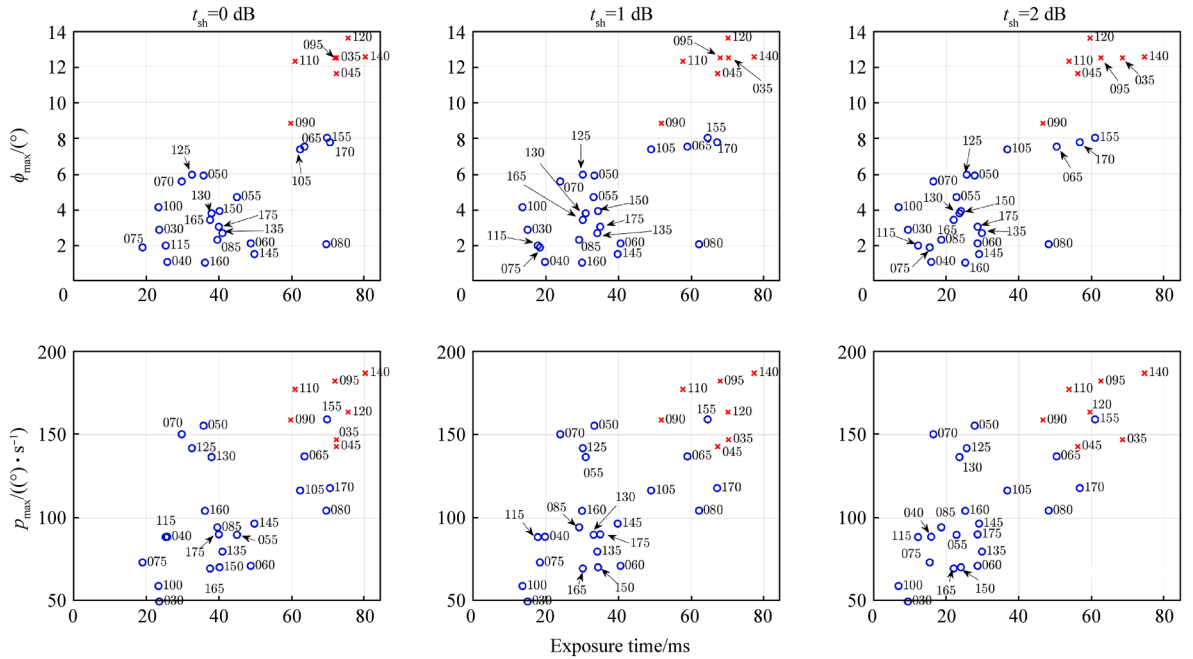


Fig. 13. Scatter plot of exposure time vs final roll angle (upper row) and roll rate (lower row). Each column represents different t_{sh} levels. Data refers to TF_{m_3} (i.e., input RH_3). Red markers represent the most critical releases.

selected to be the maximum value observed globally. Hence, the pressure and roll rate signals were made non-dimensional (before the calculation of H_{md} and H_{ph}) using the value of 7000 [Pa] for the former, and 180 [$^{\circ}/s$] for the latter.

A sensitivity analysis was then conducted to explore different t_{sh} levels (0 dB, 1 dB, and 2 dB) and final roll rate and angle to derive the dataset trend. Results are presented in Fig. 12 (transfer function between roll rate and RH_2) and in Fig. 13 (transfer function between roll rate and RH_3). As stated before, RH_1 did not

played a role in the releases, whilst other Rossiter-Heller modes were not present, as shown in Fig. 9. In these figures, the numbers represent the t_{ch} value of the trajectories.

From an initial analysis of the plot, it was evident that, independently of the threshold value selected (0 dB, 1 dB, or 2 dB), high values of exposure time were a necessary condition for trajectory divergence in roll.

Considering the worst cases (red markers in Figs. 12 and 13. See also Fig. 8 for trajectory roll and roll rate histories), as a

Table 5Safe trajectories included in the unsafe group using minimum exposure time as a discriminant. Data for TF_{m_2} and TF_{m_3} .

tsh_a /dB			0	1	2
Transfer Function	TF_{m_2}	Discriminant t_{ex} /ms	45	31	19
		Trajectories (t_{ch})	060, 065, 080, 105, 155, 170	065, 070 105, 155, 170	055 060, 065, 070, 080, 085 105, 125, 155, 170, 175
	TF_{m_3}	Discriminant t_{ex} /ms	59	51	46
		Trajectories (t_{ch})	065, 080, 105, 155, 170	0.65, 0.80, 155, 170	0.65, 080, 155, 170

Table 6Safe trajectories included in the unsafe group using minimum exposure time as a discriminant. Data for the intersection of TF_{m_2} and TF_{m_3} .

tsh_a /dB			0	1	2
Transfer Function	TF_{m_2}	Discriminant t_{ex} /ms	45 for TF_{m_2} /59 for TF_{m_3}	31 for TF_{m_2} /51 for TF_{m_3}	19 for TF_{m_2} /46 for TF_{m_3}
	TF_{m_3}	Trajectories (t_{ch})	0.65, 080, 105, 155, 170	065, 155, 170	065, 080, 155, 170

discriminant to determine a quantitative measure of the exposure time, it was found that for RH_2 (Fig. 12), these minimum values were 45 ms for a threshold of 0 dB, 31 ms for a threshold of 1 dB, and 19 ms for a threshold of 2 dB. Similarly, if RH_3 was considered in the derivation of the transfer functions, the minimal exposure time values derived from the scatter plot (still analysing the critical releases group) were 59 ms for a threshold of 0 dB, 51 ms for a threshold of 1 dB, and 46 ms for a threshold of 2 dB. Nevertheless, other non-critical trajectories were included if these exposure time values were considered as initial discriminants between a safe and an unsafe separation. This is reported in Table 5:

If the combined information obtained between TF_{m_2} and TF_{m_3} was used to filter out additional trajectories (that is the intersection of the obtained sub-groups) the resulting situation was (for each one of the values of tsh_a) as shown in Table 6.

A threshold value of 1 dB or above minimised the intersection number, with the optimum being 1 dB. If this tsh_a value was selected as an exposure time above 31 ms associated with RH_1 during the release process, an exposure time above 51 ms associated with RH_3 was a necessary condition for trajectory divergence (that is, elevated roll rate and roll angle achieved upon the store clearing the bay). Such a discriminant included 3 more trajectories in the critical group, t_{ch} 065, 155, and 170. Although these releases were not classified as unsafe using the original assumptions ($\pm 8^\circ$ of final roll angle, and $\pm 100^\circ/s$ of roll rate inside the cavity), they still achieved a final roll angle above 7° , and roll rates (outside the cavity) more than $100^\circ/s$. Hence, the conclusion was that exposure times, at a tsh_a of 1 dB, above the calculated values, would be a sufficient condition to mark a release as potentially unsafe.

5. Conclusions

This study presented a statistical study of a store release at transonic Mach numbers from a cavity simulating a typical weapon bay. The numerical analysis was based on 30 releases, at different times, to determine the mean trajectory and the relative scatter. The aim was the extraction of indicators that, following the initial flight phase of the store, could determine the likelihood of trajectory divergence, that is a flight attitude, at the end of the release, posing issues for the weapon's employment. Using the Fréchet distance and clustering, self-similar groups were generated, and those trajectories whose contribution increased the scattering relative to the mean, were identified.

Although ejector and inertial force effects resulted in a small scattering of the store translation along the three axes, high values of roll angle were observed in some cases. This event was considered critical during a release procedure, as high values of

roll rate and angles can lead quickly to a loss of control. Subsequent analysis of the critical releases identified a correlation between the cavity's strongest tones (2nd and 3rd Rossiter-Heller Tones) and the store's roll behaviour. A release event experiencing high values of roll rate/roll angle, was as a direct consequence of high values of coherence and phase between the resonant modes' pressure fluctuations, and store oscillations in roll, occurring in the time interval between ejector stroke end and the store passing through the cavity's aperture.

This work evidenced the possibility of extracting governing parameters that could be used as indicators of possible trajectory divergence in the initial phase of the release (when the store leaves the ejector but is still within the cavity), potentially reducing the required simulation time and the required number of releases necessary to characterise a launch from a weapon bay. The conclusion so far seems very reasonable, but further data and study need to be done to build understanding and confidence as to when such a procedure can predict an unsafe store separation from a weapon's bay in terms of oscillations along the roll axis.

Future work could explore different Mach numbers and ejector force effects. Additionally, a bigger dataset (> 50 releases) with smaller temporal spacing could be derived to further explore the correlation of cavity and shear layer aero-acoustics with trajectory dispersion and critical flight conditions. Finally, further correlations with the cavity's resonating modes and trajectory overall divergence (not just along the roll axis) would possibly give a more complete picture of the statistical variability of store release from a weapons bay.

CRedit authorship contribution statement

David Bacci: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Alistair J. Saddington:** Writing – review & editing, Investigation, Conceptualization.

Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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