

Computational assessment of non-axisymmetric separate-jet exhausts on test rig configurations

J. Hueso-Rebassa*, D. MacManus†, I. Goulos‡

Cranfield University, Cranfield, Bedfordshire, MK43 0 AL, United Kingdom

The next generation of civil turbofan engines are likely to have increased bypass ratios and lower fan pressure ratios to improve propulsive efficiency and to reduce specific fuel consumption. However, the larger size of these engines may result in increased overall aircraft drag partially that could offset the fuel consumption benefits. Non-axisymmetric exhaust configurations can contribute to the mitigation of these effects through an improved alignment of the thrust vector relative to the drag axis. However, there is a lack of knowledge on how to experimentally test non-axisymmetric exhaust designs. To address this, the study develops a non-axisymmetric configuration of the Dual Stream-Flow Reference Nozzle (DSFRN) and assesses it with computational fluid dynamics in various configurations and conditions. The objective is to establish a baseline approach for testing non-axisymmetric exhausts. Overall, it is recommended to test non-axisymmetric exhausts with the ambient wind-on effects included and to evaluate the three-dimensional exhaust characteristics using thrust vector angles, in addition to overall velocity and discharge coefficients. Moreover, the interaction between a swept wing and the non-axisymmetric exhaust was found not to have a notable impact on the exhaust characteristics.

Nomenclature

δ_{XZ}, δ_{XY}	Vertical and lateral force vector angles, respectively	[rad]
AIAA	American Institute of Aeronautics and Astronautics	
ARA	Aircraft Research Association	
C_F and C_d	Force and discharge coefficients, respectively	
CNPR	Core Nozzle Pessure Ratio = $P_{inlet}^{CR}/p_{\infty}$	
DSFRN	Dual Separate-Flow Reference Nozzle	
DSJP	Dual-Stream Jet Propulsion (Rig)	
ER	Extraction Rate = $FNPR/CNPR$	
FNPR	Fan Nozzle Pessure Ratio = $P_{inlet}^{BP}/p_{\infty}$	
P and T	Stagnation pressure and temperature, respectively	[Pa and K]
p and t	Static pressure and temperature, respectively	[Pa and K]
RMSD	Root Mean Squared Deviation	
UHBR	Ultra High Bypass Ratio (aero-engine)	

*Research Fellow in Propulsion Aerodynamics, Centre for Propulsion and Thermal Power Engineering, Cranfield University, j.hueso-rebassa@cranfield.ac.uk

†Head of Gas Turbine Technology Group, Centre for Propulsion and Thermal Power Engineering, Cranfield University

‡Lecturer in Propulsion Integration, Centre for Propulsion and Thermal Power Engineering, Cranfield University

I. Introduction

The next generation of aero-engines are likely to operate with higher bypass ratios (BPR) and lower fan pressure ratios [1] to reduce Specific Fuel Consumption (SFC) and improve propulsive efficiency [2, 3]. This is likely to be accompanied by increased dimensions of the power-plants. However, larger aero-engines could increase the overall aircraft drag and offset the benefits from the performance cycle [4]. Due to the increased size of the propulsion system, podded Ultra-High Bypass Ratio (UHBR) aero-engines may require a close coupled installation with the wing to meet ground clearance requirements [5]. However, this introduces an aerodynamic integration challenge. In such configurations, the aerodynamic interference between the propulsion system and airframe could penalise the aircraft cruise fuel consumption relative to a more conventional installation position [6]. The additional penalty in overall aircraft performance is partly related to a reduction of the exhaust propulsive force [6]. In close coupled configurations, the exhaust thrust vector may become misaligned laterally relative to the aerodynamic drag axis [7], which reduces axial thrust. In this example [7], the installation of the propulsion system increases the lateral thrust vector angle by approximately 2.5° . This, combined with the installation toe angle of the power-plant may result in a total lateral thrust vector angle of approximately 5° [7] which will adversely affect the gross thrust of the propulsion system.

A. Non-axisymmetric exhaust systems

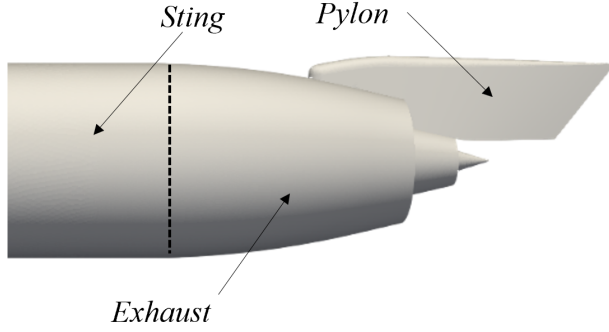
One way to mitigate the effects of propulsion system integration of UHBR aero-engines is with non-axisymmetric exhaust systems [7–12]. Previous research on the design and assessment of non-axisymmetric exhausts demonstrated that these configurations could reduce the lateral misalignment of the gross propulsive force (GPF) vector by approximately 2.3° . For low specific thrust configurations, this improvement in GPF can benefit the aircraft net vehicle force (NVF) by $0.5 - 0.8\%$ of the standard net thrust (F_N), relative to the baseline axisymmetric configuration and depending on the installation position [7, 11]. The best performing exhaust designs featured non-axisymmetric fan cowls where the bypass trailing edge is sheared towards the inboard side along with a reduction in the local radius [7, 11]. However, the research on non-axisymmetric exhaust systems for aircraft performance improvement is still at an early stage. Most of the research has been focused on computational assessments of full-scale aircraft configurations. In this context, the route for experimental testing of these concepts has not been investigated but will be required to demonstrate the capabilities of these novel designs and to improve the technology readiness level.

B. Exhaust test rigs

The axisymmetric Dual Stream Flow Reference Nozzle (DSFRN) is representative of the exhaust of a commercial transport turbofan with a bypass ratio (BPR) of approximately 10-12 [13]. The DSFRN was developed by the AIAA Dual Flow Reference Nozzle Working Group [13]. The purpose was to provide experimental data for the verification of computational models. The DSFRN was assessed experimentally and numerically. The original experiments were carried out by Mikkelsen et al. [13]. A rich set of experimental data was generated at static conditions ($M_\infty = 0$) which encompassed fan nozzle pressure ratios ($FNPR = P_{t^{BP-inlet}}/p_\infty$) from 1.4 to 2.8 at constant extraction ratio ($ER = FNPR/CNPR = 1.2$) to cover a wide range of nozzle operating conditions. The experimental data was used in the 2nd AIAA Propulsion Aerodynamics Workshop [14] and to validate a number of computational approaches. Some examples include Computational Fluid Dynamics (CFD) methodologies based on structured [15] and unstructured [6] grids.

A second exhaust rig concept was subsequently developed based on the DSFRN configuration. This is the Dual Stream Jet Propulsion (DSJP) rig that has been tested in the Transonic Wind Tunnel (TWT) [16] of the Aircraft Research Association (ARA) in the United Kingdom [17]. The DSJP was designed to assess the effect of the integration of the propulsion system with the airframe on the exhaust performance. For that purpose, the DSJP is configured with a swept wing that approximates the local lift distribution of the wing of the NASA Common Research Model at cruise [18–20]. Initial testing was done for the DSJP at free-stream conditions that range from static ($M_\infty = 0$) up to transonic ($M_\infty = 0.85$) [17]. In addition, initial computational investigations were carried out with the aim of guiding the design and set-up of the rig. Goulos et al. [21] quantified the effect of the wing on the exhaust. The focus was on the flow suppression due to the presence of the wing. This was evaluated at wind-milling conditions with low exhaust pressure ratios, representative of end-of-runway operation. RANS CFD simulations were used to quantify the impact of the wing with and without simplified high-lift trailing edge flaps on the bypass (C_d^{BP}) and core (C_d^{CR}) discharge coefficients. For wind-milling end-of-runway conditions with simplified flaps, the installed pressure field could reduce the discharge coefficients by up to 16% and 13% for C_d^{BP} and C_d^{CR} , respectively, relative to an isolated configuration without the wing.

a. DSFRN configuration – side view



b. DSFRN configuration – oblique view

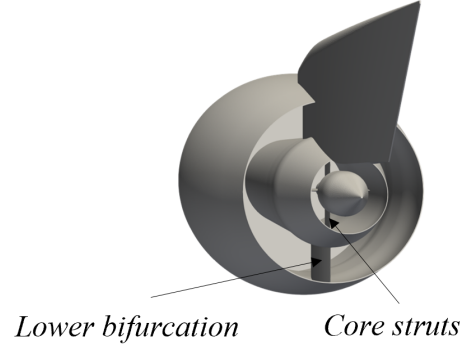


Fig. 1 DSFRN configuration. (a) Side view and (b) oblique view.

C. Scope

Previous work [7] indicated that non-axisymmetric exhaust configurations can potentially counteract the effects of the integration of the propulsion system with the airframe through an improved alignment of the thrust vector with the drag axis [7, 11]. As the technology of non-axisymmetric exhausts is being developed and becomes more mature, experimental tests will be required to demonstrate the effects of these novel configurations and to bring the technology level closer to exploitation. Although several exhaust test rigs have been developed, tested and analysed, none of the studies considered non-axisymmetric exhaust systems with significant three-dimensional shaping of the bypass nozzle. In this study, a non-axisymmetric configuration of the Dual Stream Flow Reference Nozzle [13] (DSFRN) is developed and assessed computationally in a range of experimental arrangements. The aim of this work is to quantify the changes in the exhaust thrust coefficient and thrust vector angles relative to the axisymmetric DSFRN that could potentially be measured in an experimental test. The performance of axisymmetric and non-axisymmetric designs are evaluated at wind-off and wind-on conditions to unveil more details about the sensitivity to the experimental arrangement.

II. Methodology

A. Dual-stream flow reference nozzle and test rig configurations

This work investigates both the AIAA DSFRN [13, 14] as well as the the DSJP [17, 21] configurations. The main focus is on the DSFRN arrangement that was investigated during the 2nd Propulsion Aerodynamics Workshop [14]. The baseline axisymmetric DSFRN includes the bypass and core nozzles, fan cowl, lower bifurcation, pylon and core struts (Fig. 1). In the CFD model of the DSFRN, the nozzle is coupled with a sting to facilitate the computational modelling of the experimental conditions [6, 15] (Fig. 1). The second configuration that is computationally investigated in this study is the DSJP exhaust. The DSJP is the same non-dimensional exhaust geometry as the DSFRN, but at a slightly smaller scale. It also encompasses configurations both with and without a swept wing (Fig. 2). The DSJP is used to evaluate the effect of the wing on the exhaust performance. In this work, the DSFRN acronym refers to the original test configuration (Fig. 1) [14] and DSJP refers to the the ARA wind tunnel configuration (Fig. 2) [17, 21].

1. Non-axisymmetric dual-stream flow reference nozzle

Test rig configurations are coupled with axisymmetric and non-axisymmetric versions of the DSFRN exhaust. A three-dimensional parametric representation of the axisymmetric nozzle geometry was developed with intuitive Class-Shape Transformation (iCST) functions [9, 22, 23]. The non-axisymmetric exhaust design was defined through perturbations of the the bypass nozzle trailing edge that were based on previous studies of full scale, installed Ultra-High Bypass Ratio (UHBR) engines [7, 11]. The non-axisymmetric exhaust system design used in this work was optimised for maximum aircraft net vehicle force (NVF) [7, 11] on a full-scale installed aero-engine arrangement. The optimisation was based on response surface models constructed with inviscid aerodynamic data and improved the NVF by 0.5 – 0.8% of the standard nominal thrust (F_N) when assessed with RANS, depending on the installation position. The improvement

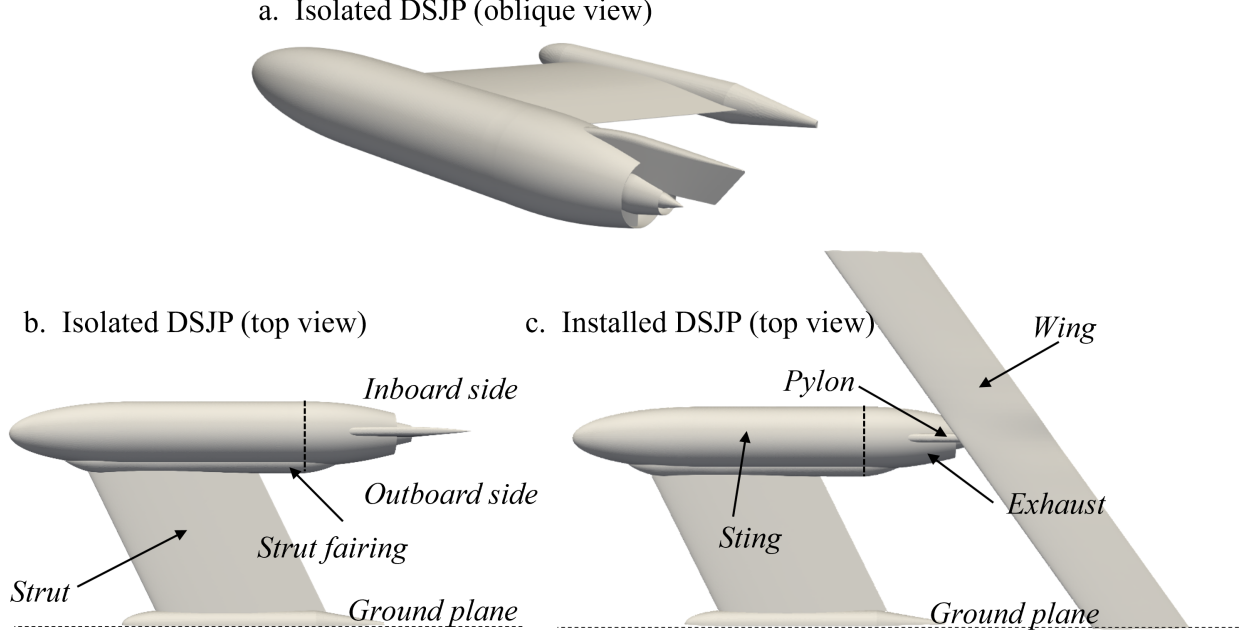


Fig. 2 DSJP configuration. (a,b) Isolated and (b) installed configurations.

arose partly from a reduction of the lateral thrust vector angle of approximately 2.3° , which offset the aerodynamic interference of the propulsion installation. The optimum non-axisymmetric exhaust design was configured with an inboard sheared bypass cowl together with a locally reduced bypass trailing edge radius, also at the inboard side (Fig. 3). Once the geometry of the non-axisymmetric DSFRN was developed, the pylon, lower bifurcation and core struts (Fig. 1b) were included for consistency with the axisymmetric version of the nozzle (Fig. 3).

B. Computational assessment

The computational methodology is based on the compressible Reynolds Averaged Navier-Stokes (RANS) equations. The solver is density-based, implicit and steady-state [24]. It is coupled with 2^{nd} order convective schemes and the $k - \omega$ SST turbulence model [25]. The dynamic viscosity of the fluid is calculated with Sutherland's law [26].

The computational model of the DSFRN has a sting that connects the nozzle to the external boundary of the domain (Fig. 1 and 4a). The nozzle geometry is located seven sting diameters downstream ($L_{sting} = 7D_{sting}$) from the external boundary [6, 15]. The sting is modelled as an inviscid slip wall to prevent the development of the boundary layer upstream of the nozzle and to reproduce the experimental conditions [13]. The other wall surfaces have a non-slip, adiabatic boundary conditions. The inflow conditions to the domain are set as pressure far field with M_∞ and static pressure (p_∞) according to the measured values [13]. The bypass and core duct inlets are defined as total pressure inlets based on the pressure ratio of the nozzles. Non-uniform total pressure profiles were imposed at the inlet of the bypass nozzle duct ($P_{t}^{BP-inlet}$) to account for the boundary layer that formed upstream. The profiles were adopted from the work of Otter [8] and were specified based on the available measurements [13].

The computational grids are unstructured with layers of triangular prisms in the boundary layer region and tetrahedra elsewhere (Fig. 4b). This approach ensures a $y^+ < 1$ over the whole geometry. A mesh independence study was undertaken at a $FNPR = 2.2$ and $ER = 1.2$ with three grids of 40×10^6 (coarse), 80×10^6 (medium) and 120×10^6 (fine) cells. The mesh independence was evaluated in terms of Grid Convergence Index (GCI) [27]. The grid convergence indexes for the medium mesh (GCI_{32}) was of $4 \times 10^{-4}\%$ and 0.11% for the overall thrust coefficient (C_F) and the vertical thrust angle (δ_{XZ}), respectively. Therefore, the medium mesh was used for the subsequent analyses.

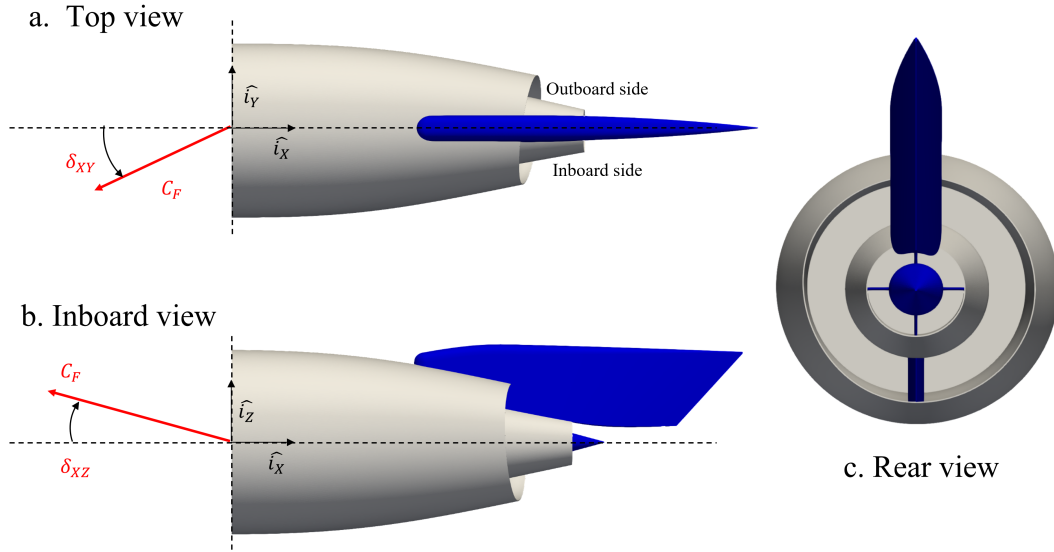


Fig. 3 Geometry of the non-axisymmetric DSFRN configuration. The blue surfaces in the figure represent the components that were added after the exhaust was designed, without further modification. The figure also includes schematics of the force vector angles of the non-axisymmetric configuration.

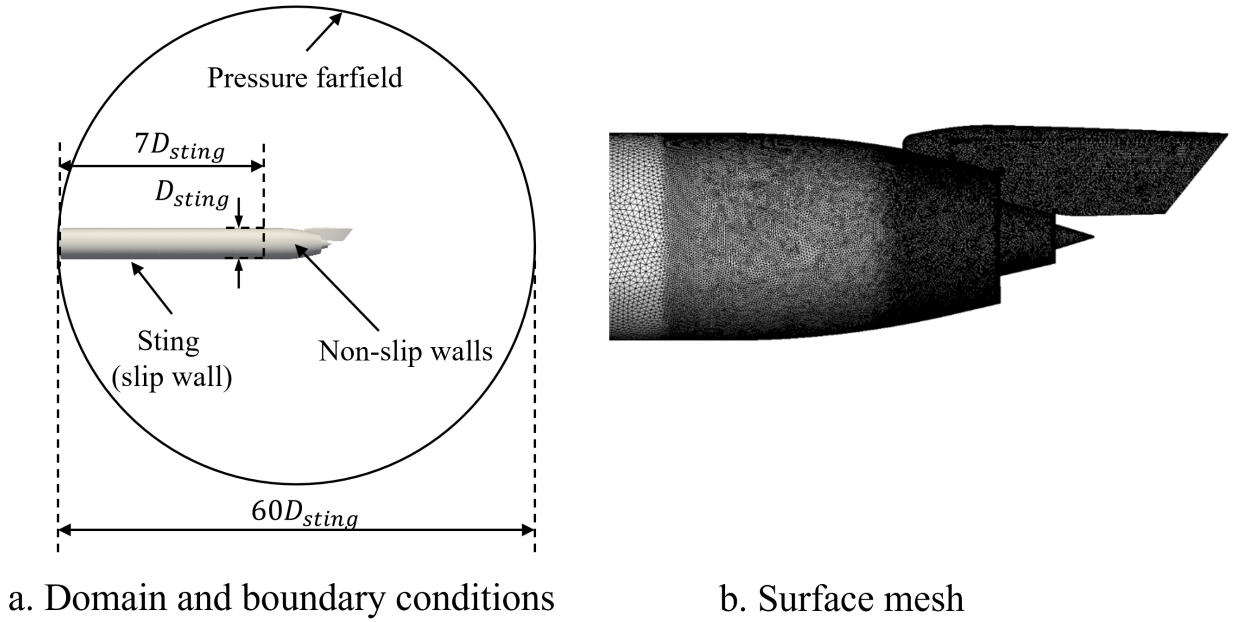


Fig. 4 (a) Computational domain of the DSFRN configuration and (b) surface mesh.

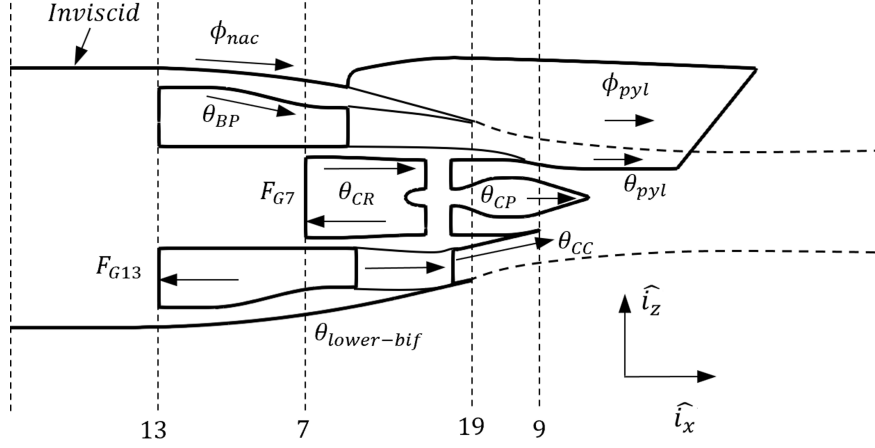


Fig. 5 Schematics of the forces acting on the DSFRN.

C. Thrust and drag accounting system

The thrust and drag accounting system used by Mikkelsen et al.[13] is used for the assessment of the performance of the DSFRN. The thrust measured during the experiments included all forces over the DSFRN geometry (Fig. 5). These were gauge-stream forces on the duct inlets (F_G , Eq. 1) and wall forces on the exhaust (ϕ and θ). Gauge-stream forces are composed by the momentum flux ($\dot{m}V$) and pressure terms ($(p - p_{atm})A$) while wall forces comprise viscous and pressure forces over the bypass and core nozzles, ducts, bifurcations, core struts and the nacelle after-body. The force coefficient C_F is defined as the exhaust force divided by the ideal thrust ($\sum \dot{m}V^{ideal}$) from the core and bypass flows (Eq. 2, 3). Note that due to the measurement system, the nacelle after-body terms (ϕ_{nac}) are also accounted in the definition of C_F . C_F is a vector composed by the axial (C_{F_x}), lateral (C_{F_y}) and vertical (C_{F_z}) components where the norm of the vector is referred to the overall force coefficient. Vertical (δ_{XZ}) and lateral (δ_{XY}) force vector angles are defined as the angles of the force coefficient vector (Fig. 3, Eq. 4). In general, such a rig includes the forces over the nacelle after-body (ϕ_{nac}). ϕ_{nac} is negligible for wind-off conditions and therefore C_F is equivalent to thrust coefficient definition used by Mikkelsen et al. [13]. However, for wind-on conditions ϕ_{nac} is not negligible. For this reason more generic terms such as force coefficient and force vector angles will be used instead of thrust and thrust vectoring.

$$F_G = \dot{m}V + (p - p_{atm})A \quad (1)$$

$$C_F = \frac{F_{G13} + F_{G7} + \sum \phi + \sum \theta}{\sum \dot{m}V^{ideal}} \quad (2)$$

$$\sum \dot{m}V^{ideal} = \dot{m}_{BP}V_{BP}^{ideal} + \dot{m}_{CR}V_{CR}^{ideal} \quad (3)$$

$$\delta_{XZ} = \text{atan}\left(\frac{C_{F_z}}{C_{F_x}}\right), \delta_{XY} = \text{atan}\left(\frac{C_{F_y}}{C_{F_x}}\right) \quad (4)$$

III. Results and discussion

A. Validation of the computational model for separate-jet exhaust flows

To validate the computational model, the meshes with 40×10^6 and 80×10^6 cells were compared with the experimental data of Mikkelsen et al. [13]. The experimental data encompassed measurements across a range of fan nozzle pressure ratios (FNPR) from $FNPR = 1.4$ to 2.8 at a constant extraction ratio ($ER = FNPR/CNPR = 1.2$). The experiments were undertaken at wind-off conditions ($M_\infty = 0$). However, the CFD model was specified at $M_\infty = 0.03$ to improve the stability of the solver. A summary of the computations carried out is included in table 1.

The comparison between CFD results and experimental data was quantified with two different metrics. One is the difference between the CFD results and the experimental data at $FNPR = 2.2$ (ΔC , Eq. 5). The second is the

Table 1 Summary of the operating conditions assessed for the axisymmetric DSFRN configuration. The table includes the operating conditions tested in the experiments [13].

Exhaust system	Type	M_∞	FNPR	ER
Axisymmetric DSFRN	Experiment [13]	0.00	1.4 - 2.8	1.2
Axisymmetric DSFRN	CFD	0.03	1.4 - 2.8	1.2

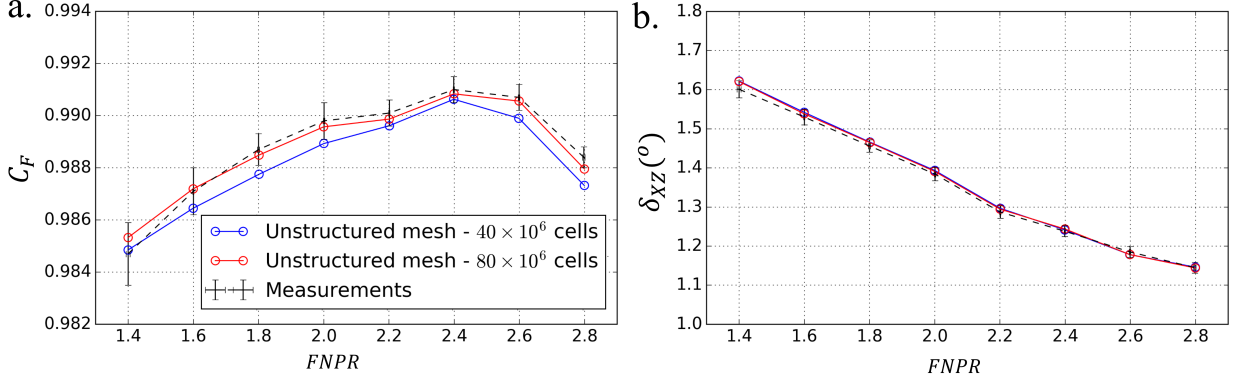


Fig. 6 Summary of the validation of the computational methodology for the axisymmetric DSFRN. The results include unstructured mesh solutions and the experimental results [13] for the metrics of interest ((a) C_F and (b) δ_{XZ}).

Root Mean Squared Deviation (RMSD) of the metrics of interest across the FNPR range (C_{RMSD} , Eq. 6). The target performance metrics were the overall force coefficient (C_F) and the vertical thrust vector angle (δ_{XZ}). Both ΔC and C_{RMSD} are expressed as percentage (%) difference for C_F and degrees for δ_{XZ} . Note that at wind-off conditions, the force coefficient is equivalent to the thrust coefficient defined by Mikkelsen et al. [13].

$$\Delta C = C_{CFD} - C_{Exp}(\%) \quad (5)$$

$$C_{RMSD} = \sqrt{\frac{\sum_{i=1}^N (C_{CFDi} - C_{Exp_i})^2}{N}}(\%) \quad (6)$$

Overall, the computational results are in agreement with the experimental data [13]. The characteristic of C_F for the unstructured mesh with 80×10^6 cells was predicted within the bands of $\pm 2\sigma$ of the experimental measurements for all operating conditions (Fig. 6 and Table 2). For the same mesh (80×10^6 cells), the difference in C_F at $FNPR = 2.2$ was approximately $\Delta C_F = 0.023\%$ (Table. 2). The RMSD of the same metric was $C_{FRMSD} = 0.033\%$. The CFD method predicted the vertical force vector angle effectively within the noise of the measurements. Relative to the measurements, the computations had a difference of $\Delta\delta_{XZ} = 0.007^\circ$ at $FNPR = 2.2$ and a $\delta_{XZ_{RMSD}} = 0.01^\circ$ (Table. 2).

The computational approach based on unstructured meshes can determine the overall force coefficient and the vertical force vector angle measured during the experiments [13]. Therefore, the CFD methodology can be used to evaluate the exhaust performance and vectoring. This is particularly relevant for non-axisymmetric exhausts. Non-axisymmetric exhaust systems have the potential of improving the performance at aircraft level through a better alignment of the thrust vector. For this reason, force vector angles can be considered as surrogate metrics for non-axisymmetric exhaust performance.

Table 2 Differences between CFD computations and experimental results[13] at $FNPR = 2.2$ and root mean squared deviations across the $FNPR$ range.

Mesh type	Mesh size	M_∞	ΔC_F	$\Delta \delta_{XZ}$	C_{FRMSD}	δ_{XZRMSD}
Unstructured	40×10^6 Cells	0.03	-0.049%	0.010°	0.073%	0.011°
Unstructured	80×10^6 Cells	0.03	-0.023%	0.007°	0.033%	0.010°

B. Wind-on effects on axisymmetric and non-axisymmetric exhausts

Axisymmetric and non-axisymmetric configurations of the DSFRN are assessed at wind-off ($M_\infty = 0.03$) and wind-on ($M_\infty = 0.85$) conditions (Table 3). The purpose of this analysis is to quantify the effects of non-axisymmetric exhausts at wind-off and wind-on on the C_F and force vector angles. The operating conditions for the wind-off assessment are defined as in the experiment [13]. For wind-on evaluations, the free-stream total pressure was kept the same as for wind-off calculations. For the DSFRN at wind-on conditions, the computational model did not include a strut which would be needed for a true wind tunnel arrangement.

The non-axisymmetric configuration of the bypass cowl has a notable impact on the performance of the nozzle at wind-off conditions ($M_\infty = 0.03$). For example, at $FNPR = 2.2$ the overall force coefficient (C_F , Fig. 7) of the non-axisymmetric configuration is $C_F = 0.9889$. This equates to a reduction of C_F of approximately -0.1% of the performance of the exhaust relative to the axisymmetric baseline at the same operating condition. However, the penalty in C_F of the non-axisymmetric configurations is negligible once the wind-on effects are included ($\Delta C_F = -0.04\%$). Even though the non-axisymmetric design reduces the overall performance if assessed wind-off, the C_F is almost the same as the axisymmetric baseline once the wind-on effects are included. However, for the same C_F , the force vector angles are different for axisymmetric and non-axisymmetric configurations. Therefore, force angles can be the target metric to assess the characteristics of non-axisymmetric exhausts.

Table 3 Summary of the operating conditions assessed for the axisymmetric and non-axisymmetric DSFRN configurations. The table includes the operating conditions tested in the experiments [13].

Configuration	Type	M_∞	$FNPR$	ER
Axisymmetric DSFRN	Experiment [13]	0.03	1.4 - 2.8	1.2
Axisymmetric DSFRN	CFD	0.03	1.4 - 2.8	1.2
Non-axisymmetric DSFRN	CFD	0.03	1.4 - 2.8	1.2
Axisymmetric DSFRN	CFD	0.85	1.4 - 2.8	1.2
Non-axisymmetric DSFRN	CFD	0.85	1.4 - 2.8	1.2

Previous work [7] indicated that non-axisymmetric exhaust configurations can potentially counteract the detrimental impact of the engine-airframe integration through an improved alignment of the thrust vector. The force vector angles for axisymmetric and non-axisymmetric DSFRN are presented in figure 8. For the axisymmetric exhaust at wind-off conditions ($M_\infty = 0.03$), the vertical force angle (δ_{XZ} , Fig. 8a) decreases monotonically with $FNPR$ from 1.6° at $FNPR = 1.4$ to 1.1° at $FNPR = 2.8$. The non-axisymmetric design reduces δ_{XZ} to values between 1.1° and 0.4° ($FNPR = 1.4$ to 2.8). Once the wind-on effects are included, δ_{XZ} varies non-monotonically with $FNPR$. Above the approximate choking conditions, the angle of the axisymmetric DSFRN is of the order of 1.2° to 1.5° . As the nozzle is unchoked ($FNPR < \approx 2.0$) the angle reduces notably to about 0.2° at $FNPR = 1.4$. The non-axisymmetric configuration has similar non-monotonic characteristics as a function of $FNPR$. Overall, the non-axisymmetric design reduces the vertical force vector angle between 0.7° and 1° across the $FNPR$ range. Although non-axisymmetric designs of the nozzle are effective to reduce the vertical force vector angle, this could adversely affect the performance of the aircraft as it changes the lift-to-drag (L/D) characteristics. For this reason, the main focus is on the lateral force angle (δ_{XY}). As the baseline DSFRN configuration is symmetric, the lateral force angle is 0° (δ_{XY} , Fig. 8b). However, the non-axisymmetric configuration of the nozzle successfully changes δ_{XY} . For wind-off conditions, the non-axisymmetric

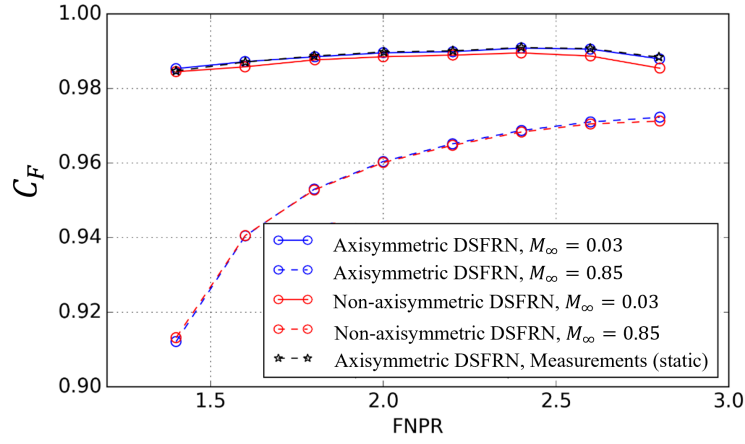


Fig. 7 Effect of FNPR, wind-on and non-axisymmetric exhaust on the overall force coefficient (C_F). The figure includes the experimental measurements of Mikkelsen et al. [13].

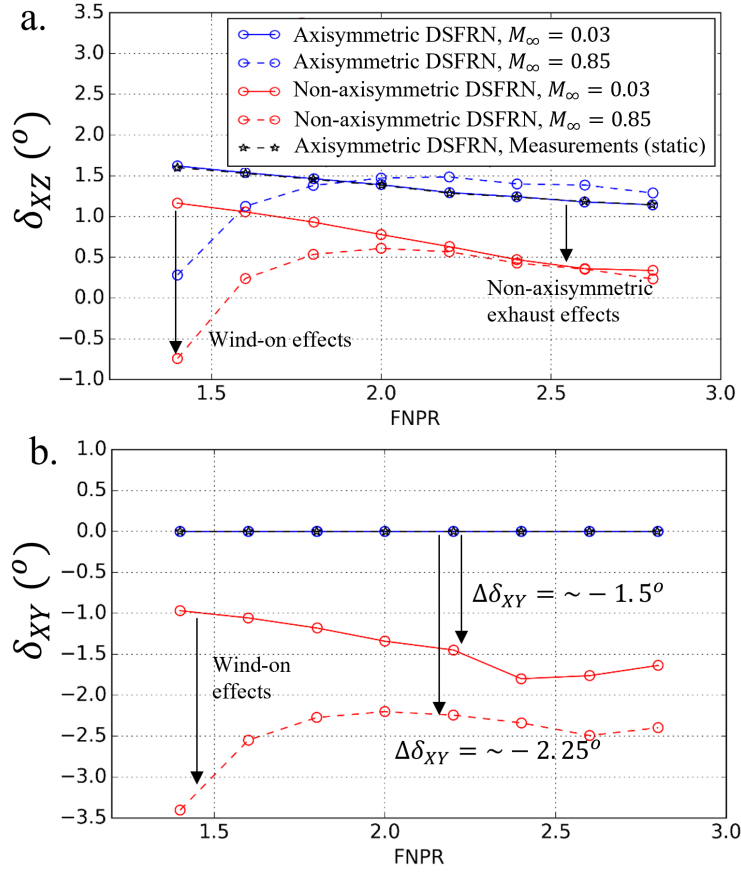


Fig. 8 Effect of FNPR, wind-on and non-axisymmetric exhaust on the (a) vertical (δ_{XZ}) and (b) lateral (δ_{XY}) force vector angles. The figure includes the experimental measurements of δ_{XZ} of Mikkelsen et al. [13].

design results in lateral angles (δ_{XY}) from -1.7° to about -1.0° across the FNPR range of 2.4 to 1.4 (Fig. 8b). With wind-on effects, across the FNPR range of 1.6 to 2.8, the lateral force vector angle of the non-axisymmetric DSFRN is relatively constant at about -2.2° to -2.5° . This change in lateral force vector angle is similar to the value reported for full-scale installed non-axisymmetric exhausts ($\Delta\delta_{XY} = -2.3^\circ$, [7]).

The differences in the vertical and lateral force vector angles between axisymmetric and non-axisymmetric configurations are related to the static pressure distributions over the fan and core cowls of the nozzle (Fig. 9). For wind-off conditions, the changes in force angles are attributed to an azimuthal distribution of static pressure over the core cowl that result from the non-axisymmetric design. However, once the wind-on effects are considered, the static pressure is also altered over the fan cowl after-body. For the non-axisymmetric design, inboard-outboard asymmetries of the pressure force over the bypass cowl increase δ_{XY} . For the same reason, the non-axisymmetric exhaust deflects the jet laterally by approximately 1.15° regardless of the effect of M_∞ (FNPR=2.2, Fig. 9).

In conclusion, the changes of force vector angles produced by non-axisymmetric exhausts can potentially be captured with experimental configurations. An experimental assessment at wind-off conditions would not be enough to capture the effects of non-axisymmetric exhausts on thrust vectoring. For example, under wind-off conditions, the $\Delta\delta_{XY}$ between non-axisymmetric and axisymmetric configurations is -1.45° at $FNPR = 2.2$. This is approximately 0.85° less compared with the values reported for full scale installed configurations ($\Delta\delta_{XY} = -2.3^\circ$ [7]). On the other hand, the assessment at $M_\infty = 0.85$ results in a $\Delta\delta_{XY} = -2.24^\circ$, similar to the full scale aircraft analysis [7, 11]. In addition, the experimental measurements of the axisymmetric DSFRN configuration at wind-off conditions could resolve variations of vertical force angles of about 0.1° (Figs. 6 and 7 [13]). This is approximately one order of magnitude lower relative to the expected changes produced by non-axisymmetric exhausts. However, this was for the previous wind-off test configuration. Additional work is needed to understand if the lateral force angles can be measured with sufficient resolution in a wind-on experiment.

C. Effect of the wing on axisymmetric and non-axisymmetric exhausts

As part of the analysis, the Dual Separate Jet Propulsion (DSJP) rig [17, 21] (Fig. 10) is used to quantify the effect of a swept wing on the exhaust force vectoring. Both, the isolated (Fig. 10a) and installed (Fig. 10b) DSJP configurations are composed by a strut, a fairing and a sting that are coupled to the exhaust and pylon. In addition, the installed configuration also includes a swept wing (Fig. 10b). DSJP configurations are assessed with the axisymmetric and non-axisymmetric nozzles at a range of FNPRs from 1.4 to 2.8 with $ER = 1.2$. As the DSJP was designed to also operate in a transonic wind tunnel [17], no wind-off evaluations were done in this work. Therefore, M_∞ is kept to 0.85 for all the simulations (Table 4).

Table 4 Summary of the operating conditions and configurations assessed for the axisymmetric and non-axisymmetric DSJP configurations.

Exhaust system	configuration	M_∞	FNPR	ER
Axisymmetric DSJP	isolated	0.85	1.4 - 2.8	1.2
Non-axisymmetric DSJP	isolated	0.85	1.4 - 2.8	1.2
Axisymmetric DSJP	installed	0.85	1.4 - 2.8	1.2
Non-axisymmetric DSJP	installed	0.85	1.4 - 2.8	1.2

The isolated DSJP with the axisymmetric nozzle is predicted to have a vertical force angle (δ_{XZ}) that ranges from 0.6° to 1.2° across a range of FNPR from 1.4 to 2.8 (Fig. 11a). This is similar to the axisymmetric DSFRN at wind-on conditions (Fig. 7b). However, the lateral force angle of the DSJP (δ_{XZ}) is greater than for the DSFRN (Fig. 11b), with values that range from 16° ($FNPR = 1.4$) to 3.9° ($FNPR = 2.8$). This is caused by the rig strut and strut fairing. The static pressure rises at the junction between the strut fairing and the fan cowl after-body, which increases the pressure force at the outboard side and consequently δ_{XY} (Fig. 12). Note that the force over the fan cowl after-body is accounted in the definition of δ_{XZ} and δ_{XY} due to the experimental measurement system. For this reason, great values of δ_{XZ} and δ_{XY} do not imply large deflections of the exhaust jet.

The wing modifies the vertical force vector angle of the axisymmetric DSJP configuration. For example, at $FNPR = 2.2$, the inclusion of the wing changes δ_{XZ} from 1.5° to -1.1° (Fig. 11a). This is caused by an increased

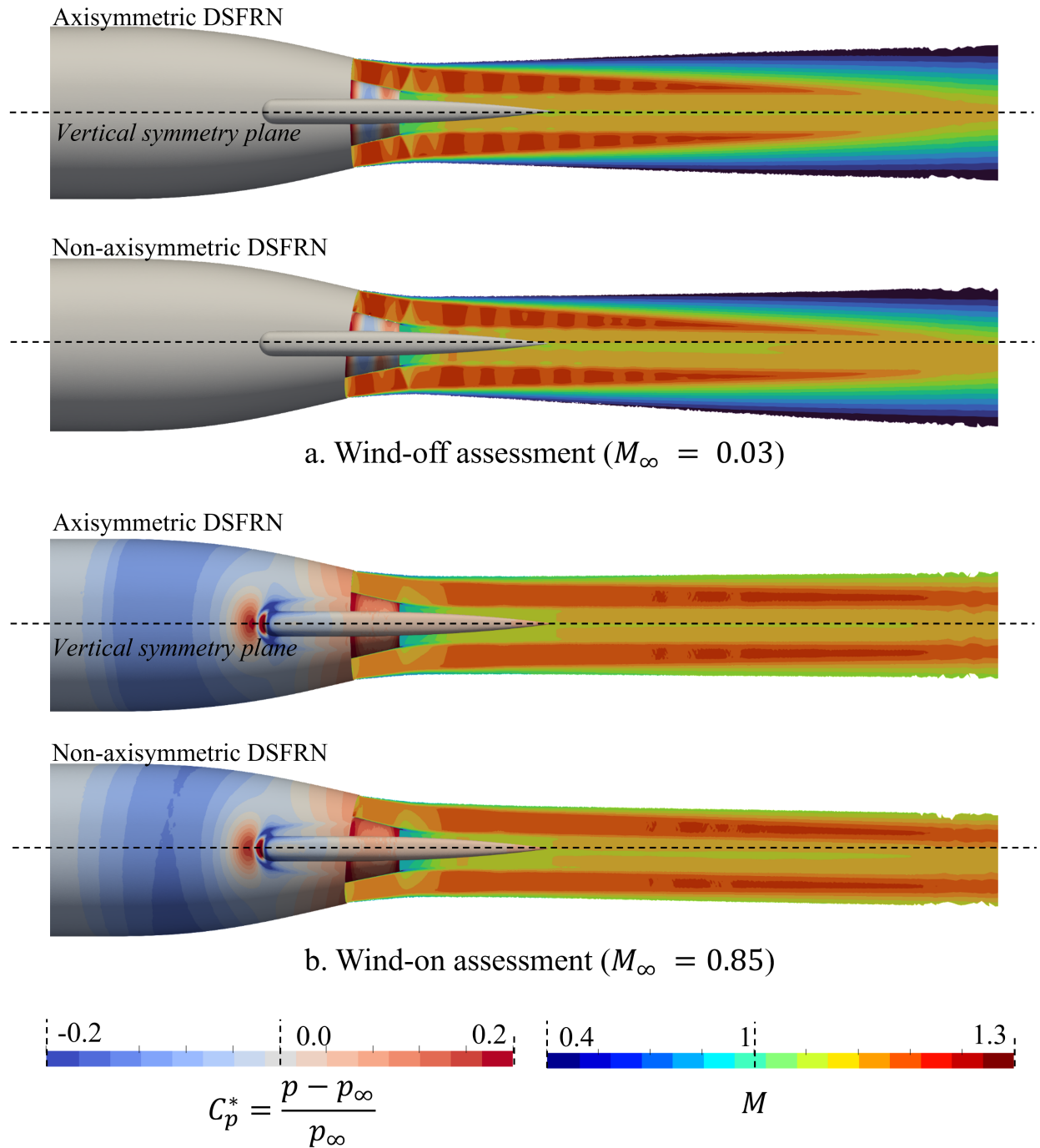


Fig. 9 Exhaust jet Mach number distributions in the horizontal plane and static pressure distributions on the surfaces of the axisymmetric and non-axisymmetric configurations of the DSFRN. The figure includes (a) wind-off and (b) wind-on assessments at FNPR=2.2.

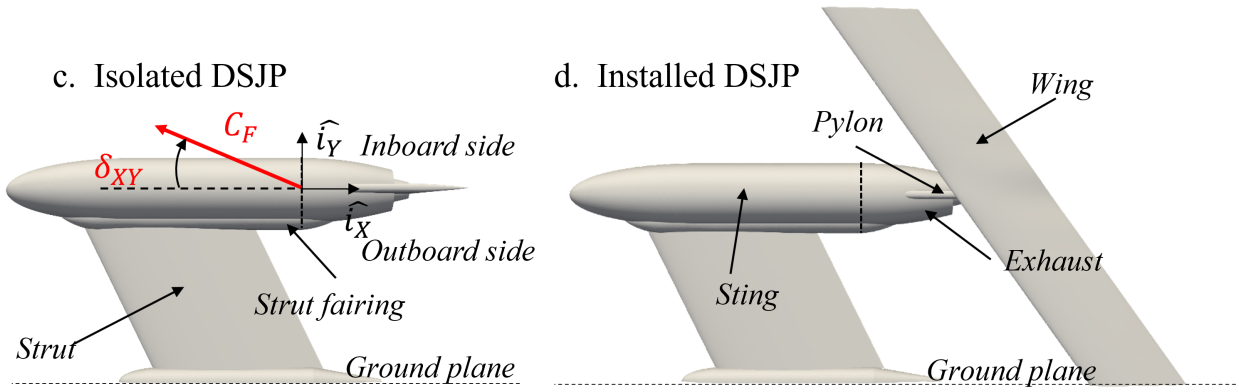


Fig. 10 (a) Isolated and (b) installed configurations of the DSJP.

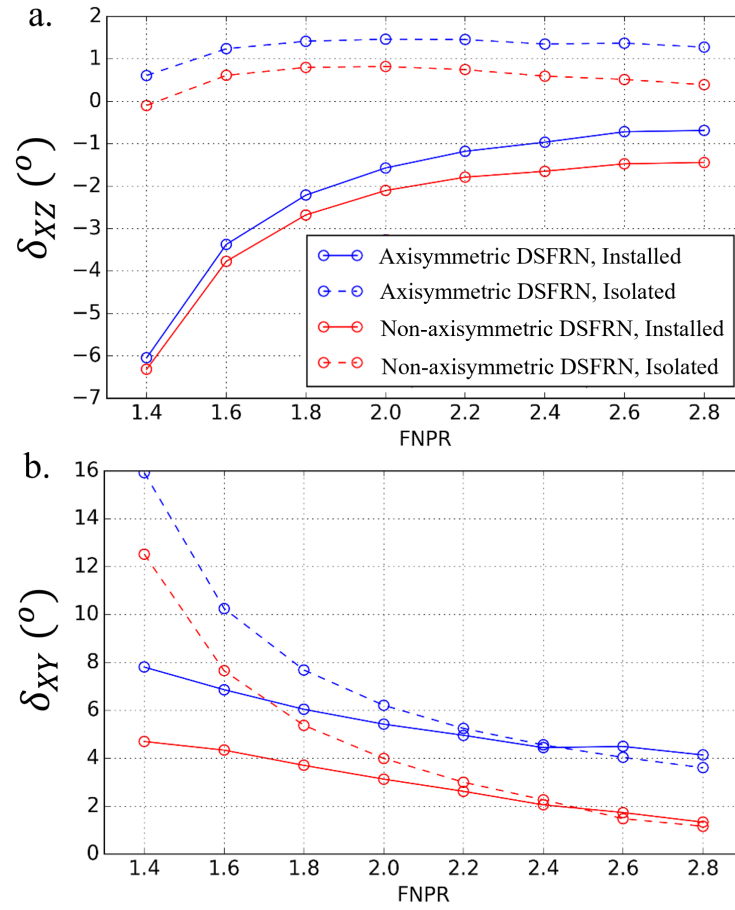


Fig. 11 (a) Vertical (δ_{XZ}) and (b) lateral (δ_{XY}) force vector angles of the DSJP with axisymmetric and non-axisymmetric exhausts.

pressurisation of the fan cowl near the pylon which affects the inboard and outboard sides of the exhaust (Fig. 12). The swept wing also has a notable effect on the lateral force vector angle, but only at reduced values of FNPR ($FNPR < 2.2$, Fig. 11b). The addition of the wing reduces the static pressure asymmetry as it also pressurises the inboard side of the fan cowl. This becomes more notable at operating conditions below the choking point.

The interaction of the struct fairing, wing and fan cowl dominates the lateral force vectoring of the axisymmetric DSJP. However, it is more interesting to evaluate how the force vectoring changes with the non-axisymmetric exhaust. For example, for the non-axisymmetric configuration at $FNPR = 2.2$, the lateral force angle (δ_{XY}) is reduced by approximately 2.3° relative to the axisymmetric design. This is the result of an increased pressurisation at the inboard side of the fan cowl (Fig. 12). The non-axisymmetric DSJP changes the lateral force vectoring by a value similar to the full scale installed engine ($\Delta\delta_{XY} = -2.3^\circ$ [7]). In addition, the effect of the non-axisymmetric nozzle on δ_{XY} is similar for the isolated and installed configurations of the DSJP and consistent across the FNPR range, below the choking point.

IV. Conclusions

Non-axisymmetric configurations of the exhaust are effective to change the exhaust thrust vector angles for a separate-jet system. This could potentially result in aircraft net vehicle force benefits of the order of $0.5 - 0.8\%$ of the nominal net thrust by counteracting some of the penalising effects induced by the installation of the power-plant [7, 11]. Part of the benefit arises from a reduction of the lateral thrust vector angle of approximately 2.3° , which improves the alignment the exhaust thrust vector with the drag axis [7, 11]. Therefore, a future experimental test to quantify the effects of non-axisymmetric exhausts should target the measurement of force vector angles as surrogate metrics of the exhaust performance.

To capture the effects of non-axisymmetric exhausts on force vector angles, a computational methodology based on unstructured meshed was developed and validated with the experimental data for DSFRN test at wind-off conditions ($M_\infty = 0$) [13]. The effect of non-axisymmetric exhausts on the lateral force vector angle is captured with the 2nd Propulsion Aerodynamic Workshop DSFRN configuration [14] once the wind-on effects are included. Moreover, vectoring benefits are broadly insensitive to FNPR above the choking point. In addition, the expected changes in force vector angles produced by non-axisymmetric exhausts are approximately one order of magnitude greater relative to the measurement resolution of the vertical thrust angle in the experimental test at wind-off conditions [13]. For this reason, a test rig configuration such as the DSFRN could potentially measure non-axisymmetric exhaust effects. The DSJP configuration predictions show that it could also capture the effects of non-axisymmetric exhausts. Acceptable agreement with the full scale, installed configuration was obtained with both isolated and installed configurations of the rig.

This work highlights the potential for development of an experimental set up for non-axisymmetric exhaust systems. The knowledge extracted from these analyses has revealed how such experiments should be performed and what metrics need to be measured. The next steps could include the construction of the non-axisymmetric nozzle, the development of the force measurement system for wind-on conditions and the assessment in an experimental facility.

Acknowledgments

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Data availability

Due to commercial confidentiality agreements the supporting data is not available.

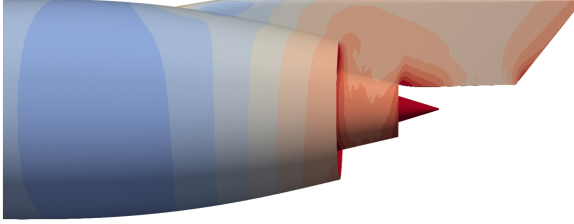
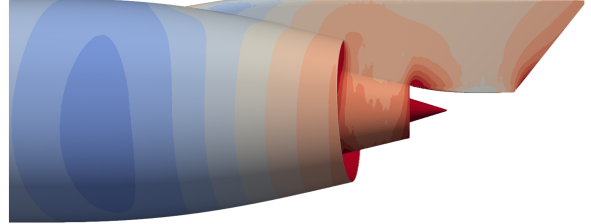
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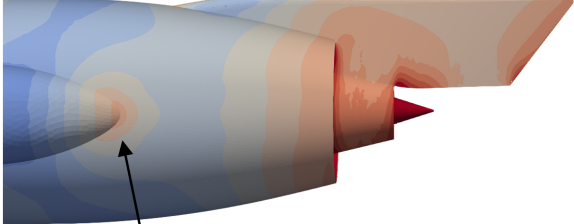
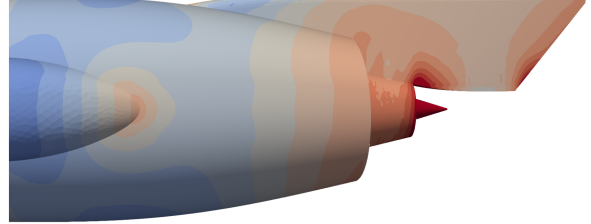
Axisymmetric DSJP

Non-axisymmetric DSJP

Inboard side



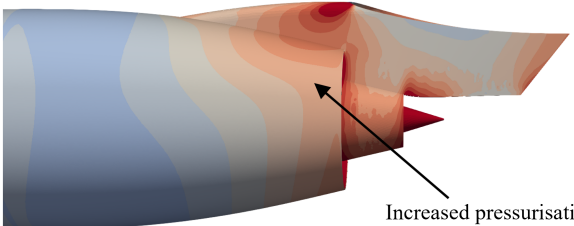
Outboard side



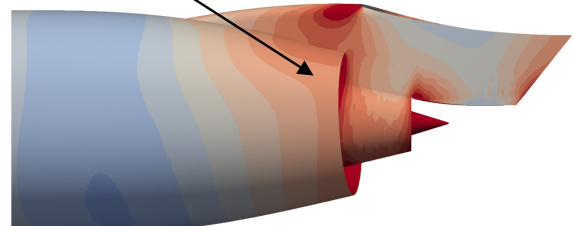
Strut fairing-cowl interaction

a. Isolated assessment

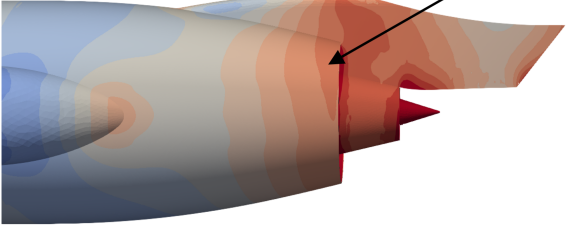
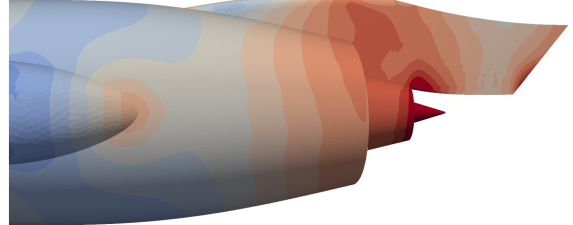
Inboard side



Increased pressurisation at the inboard side,
non-axisymmetric exhaust effect



Outboard side



b. Installed assessment



$$C_p^* = \frac{p - p_\infty}{p_\infty}$$

Fig. 12 Static pressure distributions over the (a) isolated and (b) installed configurations of the DSJP at FNPR = 2.2. The figure includes inboard and outboard side views of the axisymmetric (left) and non-axisymmetric (right) DSFRN.

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Computational assessment of non-axisymmetric separate-jet exhausts on test rig configurations

Hueso Rebassa, Josep; MacManus, David G.; Goulos, Ioannis

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