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Noise Prediction for Mach 8 Waverider vehicle during Take-Off and Landing

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This paper explores the possibility of extending a simplified Landing and Take-Off (LTO) noise prediction methodology for unconventional high-speed aircraft designs, considering a Mach 8 waverider cruiser as case-study. While several studies have examined the potential for future high-speed aircraft to offer civil passenger transport services worldwide, the significant noise impact near airport areas remains a primary issue for the regulatory framework of such aircraft. However, there are limited models available to assess the environmental effects of such innovative designs. Therefore, it is crucial to develop models and methods specifically tailored to novel high-speed aircraft configurations. This paper constitutes an initial endeavor towards this direction by attempting to apply methods found in the literature and identifying gaps or potentialities therein. Firstly, the setup for take-off and landing flight path simulation is presented, specifying the aircraft and engine operating conditions data needed as input for noise prediction, which have been derived by post-processing the simulations performed with the Analysis, Simulation and Trajectory Optimization Software for Space Applications (ASTOS) tool. Then, the noise prediction methodology proposed is applied, considering both airframe and jet noise relying respectively on Fink and Stone methods for noise prediction. The Maximum Tone Corrected Perceived Noise Levels (PNLTM) and Effective Perceived Noise Levels (EPNL) measured at the locations defined by the ICAO regulations are reported and compared with literature results for similar designs. An alternative takeoff procedure is described and tested. This paper seeks to enrich the existing understanding of the acoustic characteristics of hypersonic aircraft during LTO operations by summarizing some potential areas of improvement that may be worth exploring in order to mitigate noise.

I. Nomenclature

| | |
|----------------|--|
| a_∞ | = ambient speed of sound, m/s |
| A_e | = engine reference area, m^2 |
| A_j | = fully expanded jet area, m^2 |
| $C_{Dmax(TO)}$ | = drag coefficient at take-off |
| $C_{Lmax(TO)}$ | = lift coefficient at take-off |
| D | = directivity function |
| EPNL | = Effective Perceived Noise Level, EPNdB |
| F | = spectrum function |
| $f_{rolling}$ | = friction coefficient |
| g | = gravity acceleration, m/s^2 |
| M_∞ | = aircraft Mach number |

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| | |
|-------------------------|--|
| M_j | = jet Mach number |
| $MTOW$ | = Maximum Take-Off Weight, <i>tons</i> |
| $MLAN$ | = Maximum Landing Weight, <i>tons</i> |
| n | = load factor |
| $\langle p^2 \rangle^*$ | = mean-square acoustic pressure, re $\rho_\infty^2 a_\infty^4$ |
| PNLT | = Tone Corrected Perceived Noise Level, PNdB |
| PNLTM | = Maximum Tone Corrected Perceived Noise Level, PNdB |
| p_{ref} | = reference pressure, equal to $20^{-5} Pa$ |
| r_s | = distance from the noise source to the observer, <i>m</i> |
| S | = Strouhal number |
| S_{wing} | = wing surface, m^2 |
| T_j | = total jet temperature, <i>K</i> |
| T_{TO} | = thrust at Take-Off, <i>kN</i> |
| T_{LAN} | = thrust at Landing, <i>kN</i> |
| TOD | = Take-Off Distance, <i>m</i> |
| V_{APP} | = approach speed, <i>m/s</i> |
| V_{STALL} | = stall speed, <i>m/s</i> |
| V_{TD} | = touch down speed, <i>m/s</i> |
| V_2 | = take off safety speed, <i>m/s</i> |
| V_j | = exhaust jet speed, <i>m/s</i> |
| ρ_∞ | = ambient density, Kg/m^3 |
| ρ_j | = jet density, Kg/m^3 |
| γ | = trajectory angle, <i>deg</i> |
| θ | = polar directivity angle, <i>deg</i> |
| θ_m | = Mach angle, <i>deg</i> |
| ϕ | = azimuthal directivity angle, <i>deg</i> |
| Π^* | = overall acoustic power, re $4\pi r_s^2$ |

II. Introduction

Over the years several studies have examined the potential for future high-speed aircraft to offer civil passenger transport services worldwide [1, 2, 3, 4]. Outcomes of these investigations indicated that, with sufficient technology advancement, opportunity exists for long-term high-speed concepts. Progress in design and performance plays a critical role to guarantee the technical feasibility of such aircraft [5, 6, 7]. Nevertheless, to ensure the viability of future high-speed transportation also environmental and economic factors have to be considered as determining aspects.

Ever since the first supersonic aircraft took-off, significant attention has been devoted to assessing the potential environmental consequences of such high-speed vehicles. The environmental concern associated with the last civil supersonic aircraft ultimately led to its permanent cessation of commercial operation. Furthermore, the stringent environmental rules that followed have hindered the reintroduction of supersonic aircraft as well as the development of any other high-speed aircraft used for civil purposes thus far.

One of the primary issues identified during the Concorde era was the significant noise impact near airport areas, which far exceeds that of subsonic aircraft. Advanced propulsion systems and flight procedures have been and are investigating as possible methods to mitigate the noise footprint resulting from supersonic aircraft [8, 9, 10]. Nonetheless, the development of an up-to-date regulatory framework for supersonic aircraft remains uncertain, and the regulatory status of potential civil hypersonic aircraft is even more up in the air. Although the analysis of the environmental impact of high-speed aircraft is underway, there are currently limited models available to assess the environmental effects of innovative designs. Therefore, to advance this field of research, it is crucial to develop models and methods that are specifically tailored to novel high-speed aircraft configurations.

An effective approach for evaluating the implications of innovative technologies, systems, and procedures on the design is to consider them since the beginning of the project. This can be achieved by enhancing the conceptual design process with complementary analyses for the consideration of the aspects that are necessary to ensure the feasibility of high-speed transport. By doing so, a comprehensive assessment of the potential benefits and drawbacks of the proposed measures can be conducted, resulting in a more informed and optimal design decision [11, 12].

Notwithstanding, the implementation of methodologies capable of estimating the noise impact at the conceptual design stage continues to be an area of ongoing research, especially for high-speed configurations.

To date, different tools have been developed to integrate noise prediction within the design process [13, 14]. The related methodologies are usually semi-empirical, leading to the prediction of the overall aircraft noise level as an assembly of the main aircraft noise sources. However, the main available applications cover subsonic case-studies or at most extension attempts to conventional supersonic aircraft configurations. Specifically, the most relevant example among these tools is the Aircraft Noise Prediction Program, developed by NASA. ANOPP is one of the achievements of the Supersonic Cruise Research (SCR) project, initiated in the early 1970s to support Federal Aviation Administration (FAA) study to determine economically reasonable and technologically feasible noise limits for future supersonic transports [15]. NASA has been continuing its activity in this area and have announced a new release of the program with ANOPP2, whose purpose has been extended to noise evaluation for unconventional aircraft configurations [16]. However, the full and most updated methods are generally not open access. Nevertheless, the available methods underlying the early versions of ANOPP could be exploited for high-speed aircraft noise prediction as first guess reference [17].

Given this background, the paper aims at evaluating the possible extension of a simplified Landing and Take-Off (LTO) noise prediction methodology based on the methods underlying the early versions of ANOPP towards unconventional high-speed aircraft, considering Mach 8 waverider cruiser as case study. This objective has been already partially pursued in the framework of the European project “High speed Key technologies for future Air transport - Research & Innovation cooperation scheme” (HIKARI) [19], where a modified Stone model for rectangular nozzles [18] has been used to predict jet noise of two hypersonic passenger aircraft concepts during the LTO cycle. Even if in that work the jet noise was assumed as the total source of noise without considering the other components of the aircraft, it demonstrates the ability of these semi-empirical models to be extended to innovative configurations to perform low-fidelity prediction. Additionally, the main issues related to high-speed aircraft noise analysis during conceptual design are addresses, as well as the need to investigate noise reduction measures for hypersonic (and supersonic) aircraft for engine design and flight procedures.

In line with the cited paper, this document will contribute to enrich the current knowledge about the acoustic performance of hypersonic aircraft during LTO operations looking at the development of a comprehensive noise prediction methodology, also adding the airframe noise source in the prediction of the overall aircraft noise. Besides, limitations of the applied methodology and recommendations for future improvements will be specified together with a brief overview of appropriate methods to improve the noise performance for hypersonic aircraft during LTO.

After the case-study description, Section 2 will present the setup for take-off and landing flight path simulation, specifying the aircraft and engine operating conditions data needed as input for noise prediction, which have been derived by the post-processing of the simulations performed with the Analysis, Simulation and Trajectory Optimization Software for Space Applications (ASTOS) tool [20]. Section 3 will disclose the proposed noise prediction methodology and related methods along with the results for the selected case-study. Precisely, the noise levels emitted by the reference aircraft will be expressed in terms of Effective Perceived Noise Level (EPNL) at the three certification measurement point defined by the ICAO, in order to compare these results with current noise standards for subsonic aircraft together with results found in literature for supersonic (i.e., Concorde and Tupolev TU-144) and hypersonic concepts (i.e. HST developed by JAXA and LAPCAT MR2.4 developed by ESA). At least, Section 4 will give the conclusions and suggestions for further advancement in the field.

A. STRATOFLY MR3

STRATOFLY MR3 has been designed under the STRATOFLY project to fulfil mission requirements for shorter time of fights and long-haul routes. The vehicle shall be able to fly along long-haul antipodal routes ($R > 16,000$ km) reaching Mach 8 during the cruise phase at a stratospheric altitude ($h > 30,000$ m), carrying 300 passengers as payload. The peculiar mission requirements led to different configuration with respect to conventional wing-and-tube aircraft.

The principal characteristic of the vehicle is its waverider configuration (Figure 1), that has been selected to optimize the aerodynamic performance during cruise. When operating at on-design conditions, in the supersonic or hypersonic regime, these configurations have an attached shock wave along their leading edge allowing the high-pressure flow-field to be contained beneath the vehicle and avoiding “leakage” of high-pressure gas to the lower pressure flow field so that a high lift-drag ratio is expected to be provided. STRATOFLY MR3 integrates 6 Air Turbo Rocket engines (ATR) that operate up to Mach 4-4.5 and one Dual Mode Ramjet (DMR) that is used for hypersonic flight from Mach 4.5 up to Mach 8, exploiting liquid hydrogen.



Fig. 1 STRATOFly MR3 Vehicle

This unique powerplant can cover a wide range of speed and altitude, representing the ideal solution for hypersonic aircraft. The engines and related air ducts are embedded into the airframe and located at the top of the vehicle to increase the available planform for lift generation without additional drag penalties, thus further improving the aerodynamic efficiency. In addition, this configuration allows optimizing the internal volume and guarantees to expand the jet to a large exit nozzle area without the need to perturb the external shape, which would lead to extra pressure drag. The main technical parameters are listed in Table 1. The shape of the vehicle, the propulsive system and the operating conditions are the main differences with respect to conventional aircraft. As consequence, they will impact on noise generation during take-off and landing.

| Technical data | Value | Unit of measurement |
|-----------------------|--------------|----------------------------|
| Length | 94 | m |
| Height | 17 | m |
| MTOW | 400 | tons |
| Overall volume | 10,000 | m^3 |
| Fuel weight | 200 | tons |
| Maximum thrust | 3070 | kN |
| Range | 16,000 | km |

Tab. 1 Main technical data from STRATOFly MR3

To accurately predict the noise levels emitted by such unique configurations, dedicated models are necessary. However, this work aims to explore the potential use of conceptual design-level models for performing low-fidelity analyses, enabling comparisons between different configurations. For this reason, several aspects that could influence the noise generation cannot be fully considered, such as the impact of the singular movable surfaces or engines integrated into the configuration.

Beyond the waverider configuration, the engine is undoubtedly the major contributor to the noise. During take-off and landing, only the ATR engine is operational. The ATR is a hybrid propulsion system that employs both a turbojet engine and a rocket engine to produce thrust. In the take-off and initial climb phases, the ATR operates in turbojet mode, while in the cruise phase, it switches to rocket mode to achieve higher speeds and efficiency. The ATR has been demonstrated to significantly enhance the performance of supersonic aircraft, but its singular propulsion system also poses particular acoustic challenges, especially as no specific models have been tested and verified on this configuration. In this work, the ATR is assumed to operate as a turbojet engine during take-off and landing, while the nozzle is modeled as a simple convergent-divergent duct, and the exhaust jet is treated as a single circular stream.

III. Flight path simulation

A comprehensive collection of geometrical and performance parameters is needed to predict the noise generated by the aircraft. Table 2 presents the primary geometrical parameters associated with both the airframe and the engines.

| Geometrical parameters | Value | Unit of measurement |
|-------------------------------|--------------|----------------------------|
| Wingspan | 41 | m |
| Wing surface | 1365 | m^2 |
| Vertical tail height | 6.6 | m |

| | | |
|---|------|----------------|
| Vertical tail wing surface | 73 | m ² |
| Num. struts (main landing gear) | 2 | - |
| Num. wheels per struts (main landing gear) | 4 | - |
| Tyre diameter (main landing gear) | 1.32 | m |
| Length of struts (main landing gear) | 5 | m |
| Num. struts (forward landing gear) | 2 | - |
| Num. wheels per struts (forward landing gear) | 4 | - |
| Tyre diameter (forward landing gear) | 1.32 | m |
| Length of struts (forward landing gear) | 5 | m |
| Num. of engines | 6 | - |
| Engine max diameter | 1.92 | m |
| Inlet area | 1.82 | m ² |
| Exit area | 3.43 | m ² |

Tab. 2 MR3 geometrical parameters needed for noise prediction

Providing accurate estimates of performance parameters during take-off and landing is an additional difficulty in addressing the noise prediction problem at conceptual design level. This is even more true for hypersonic aircraft case-studies, as no specific datasets are currently available to be used as an initial reference or means of comparison.

To solve this complication, the results provided by the mission profile simulation performed through the ASTOS tool has been taken as reference for the aerodynamics and propulsive performance of the aircraft during take-off and landing. ASTOS is an object-oriented software dedicated to mission analysis, trajectory optimization, vehicle design and simulation that is mainly oriented towards space applications. Nevertheless, it can be used with proper considerations also for atmospheric flight applications. Since STRATOFly MR3 is not a conventional aircraft and for some aspects (e.g. the high speed cruise at high altitudes and the atmospheric re-entry) it can be considered as a space-like vehicle, it can also benefit from the ASTOS tool for trajectory simulation and optimization, as demonstrated in related examples in literature [23].

On the other hand, no flight procedures have yet been outlined for certification purposes for supersonic and hypersonic aircraft. Despite work is ongoing in ICAO to achieve an appropriate and homogeneous regulation as soon as possible for supersonic aircraft, the hypersonic aircraft studies remain at experimental level. Hence, it is a well-established approach to consider current subsonic noise standards to have first guess reference procedures and limitations for high-speed aircraft. The ASTOS data have been post-processed to reproduce the flight path simulations complemented with the noise analysis, executed to evaluate the noise levels received on ground at the three-certification measurement point depicted in Figure 2 and defined by ICAO [21] as follows:

- 1) Sideline (full-power reference noise measurement point): the measurement point is along the line parallel to the axis of runway centre line at a distance of 450 m, where the noise level is maximum during take-off.
- 2) Flyover or Cutback (intermediate-power reference measurement point): the measurement point is along the extended runway centre line at a distance of 6500 m from the start to roll.
- 3) Approach (low-power condition): the measurement point on the ground it is along the extended runway centre line at 2000 m from the threshold. This corresponds to a position 120 m vertically below the 3° descent path originating from a point 300 m beyond the threshold.

Sideline and flyover measurement point are considered for take-off, whereas the approach phase has one single reference measurement point. The received acoustic signal on ground can be assumed to be weakly stationary only over some sufficiently small-time interval. However, use of too small analysis time intervals results in too few statistical degrees of freedom and poor confidence in the sound pressure level. As any type of aircraft noise criterion or index is estimated from a set of noise spectra (in third-octave frequency bands from 50 to 10,000 Hz) and sample duration 0.5 s, the noise analysis has been performed considering a sample time of 0.5 s during the trajectory simulation.

The next paragraphs provide detailed aircraft operating conditions for both flight paths. These data have been also used to derive input for jet noise prediction via one-dimensional model of the engine (assuming a Joule-Brayton cycle for LTO operations) and via isentropic flow relations applied to study the stream inside and outside the nozzle, in combination with some assumptions on the flow in correspondence to engine operating condition (e.g., critic and/or adapted nozzle).

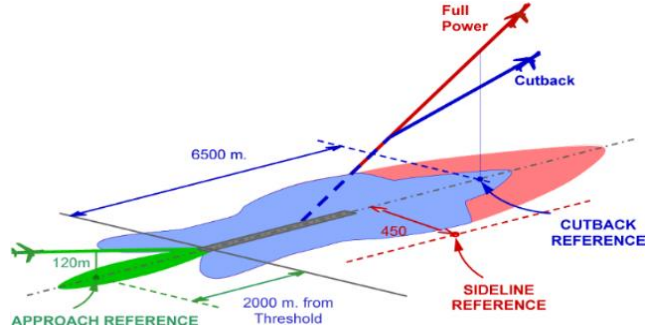


Fig. 2 ICAO certification noise measurement point

A. Take-Off

Basic take-off flight profile consists of ground roll and climb. One optionally manoeuvre that may be appended is the cutback in engine thrust, which is a procedure used to reduce noise levels on ground (blue line in Figure 2). Moreover, in order to conform to the standards of the majority of global ground infrastructure, the aircraft shall perform takeoff and landing operations within a distance of 4000 meters.

To preliminarily assess the potential of a proposed method for evaluating advanced noise abatement procedures, two scenarios for take-off have been reconstructed. The first scenario is the standard approach used for subsonic conventional aircraft and involves the aircraft using maximum power throughout the entire ground-roll and initial climb until it reaches an altitude of 250 meters. At that point, the thrust is cutback by 10%. Using this method, the aircraft can take off within a Take-Off Distance (TOD) of 2046 meters.

The second scenario involves reducing the thrust by 5% before the aircraft reaches an altitude of 250 meters, which is a sort of rated-power scenario. To reduce the ground roll phase (TOD is 1651 meters) and reach the sideline noise measurement point with a higher altitude as well as for flyover point, an acceleration increases of approximately 45% (from 4.79 m/s^2 to 7 m/s^2) has been assumed. This alternative procedure is being considered to assess the potential of achieving a noise reduction on the ground by flying at higher altitudes and using reduced thrust.

Reduction in thrust leads to a decrease in the climb angle; this is described by the Eq. (1):

$$\gamma = \sin^{-1} \left(\frac{T}{gW} - \frac{1}{L/D} \right) \quad (1)$$

Where T is the engine thrust and L/D the aircraft efficiency considered in the specific flight phase. The aircraft efficiency L/D during take-off has been estimated of about 6, thus keeping the same L/D and decreasing the thrust means to have climb angle reduction with lower altitude at the locations where noise measurement points are. Thus, the alternative procedure has been conceived as a compromise between reducing thrust and maintaining the initial climb angle at or above 18 deg .

The parameters used to model the aircraft performance and then the departure procedure are listed in the Table 3, while flight paths, thrust, and True Air Speed (TAS) profiles are reported in Figure 3.

| Parameter | Value | Unit of measurements |
|----------------|-------|----------------------|
| MTOW | 400 | tons |
| S_{wing} | 1365 | m^2 |
| $C_{Lmax}(TO)$ | 0.21 | - |
| $C_{Dmax}(TO)$ | 0.035 | - |
| T_{T0} | 2334 | kN |
| $f_{rolling}$ | 0.035 | - |
| V_2 | 104 | m/s |
| $n_x(TO)$ | 0.59 | - |
| $n_z(TO)$ | 1.12 | - |

Tab. 3 Input parameters for take-off flight path simulation

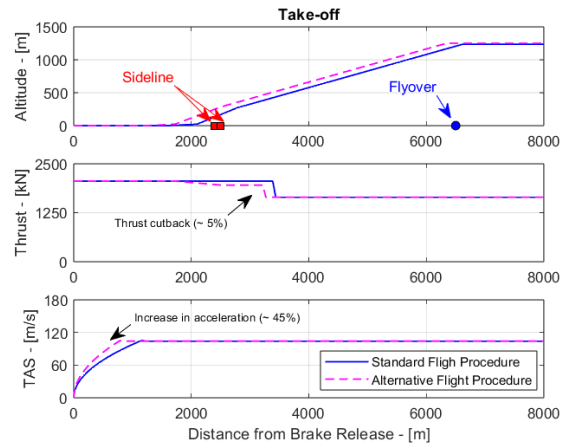


Fig. 3 Take-off flight paths, thrust and speed profiles: standard and alternative flight procedure

B. Landing

Certification guidelines for high-speed aircraft, particularly supersonic ones, indicates no significant differences in regulations from subsonic aircraft during landing. Thus, the flight path simulation was carried out using the same 3-degree glide path. The landing flight path was divided into four segments: approach, flare, touch down, and ground roll, with the total estimated landing distance being 2360 meters. The noise measurement point was identified as the location where the aircraft is expected to reach an altitude of approximately 120 meters. The approach speed was set to $V_A = 1.3V_{STALL}$, while $V_{TD} = 1.15V_{STAL}$ was the speed until touch down, followed by a deceleration of about 3 m/s. The simulation did not account for the effects of thrust reversal. Most of the information required for the landing flight path simulation are the same needed for take-off, additional ones can be found in Table 4. The resulting flight path, thrust and speed profiles are in Figure 3.

| Parameter | Value | Unit of measurements |
|------------------|--------------|----------------------|
| MLAN | 55% MTOW | tons |
| T_{LAN} | 30% T_{TO} | kN |
| C_{Lmax} (LAN) | 0.21 | - |
| C_{Dmax} (LAN) | 0.035 | - |

Tab. 4 Input parameters for landing flight path simulation

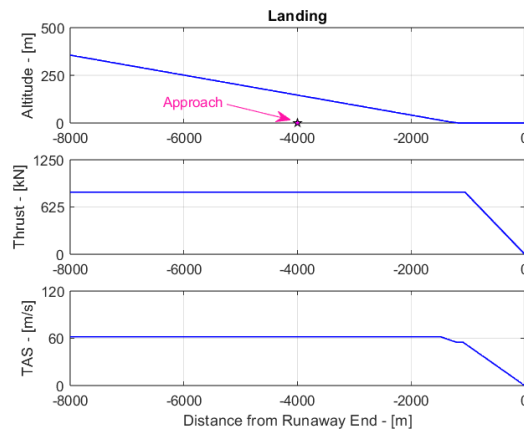


Fig. 3 Landing flight path, thrust and speed profiles

IV. Noise prediction

The take-off and landing analysis is enhanced by a simplified noise prediction methodology that employs widely recognized semi-empirical methods found in literature. Figure 4 illustrates the workflow adopted to incorporate these methods into the flight path simulation. This approach facilitates the exchange of information regarding the atmospheric model, including ambient temperature and pressure, the aircraft and engine operating conditions such as altitude, thrust, aircraft speed, and climb angle, along with the aircraft's position relative to the selected measurement point on the ground, which includes distance and directivity angles. Of course, configuration and performance data necessary to characterize the vehicle are also considered.

Precisely, the atmosphere in the vicinity of airport has been modelled as the International Standard Atmosphere (ISA) model, considering an ambient temperature of 15 °C at sea level. As previously said, the operating conditions have been verified by the ASTOS tool, whereas the position of the aircraft is updated along the trajectory during the calculation of the noise performance with a sample time of 0.5 sec. The operating conditions parameters are used as input also for the simplified engine model, thus jet exhaust flow parameters (fully expanded area, total temperature, static pressure, static density, Mach number and jet velocity) needed for jet noise prediction are estimated. Temperature and humidity significantly affect sound propagating in the atmosphere. Hence, to predict the noise level received on ground, sound losses over the 1/3 octave frequency band have been estimated in accordance with SAE ARP 866B [22]. Then, the ICAO procedure to convert the predicted Sound Pressure Level (SPL) firstly in Tone Corrected Perceived Noise Level (PNLT) and then in Effective Perceived Noise Level (EPNL) [21] has been used.

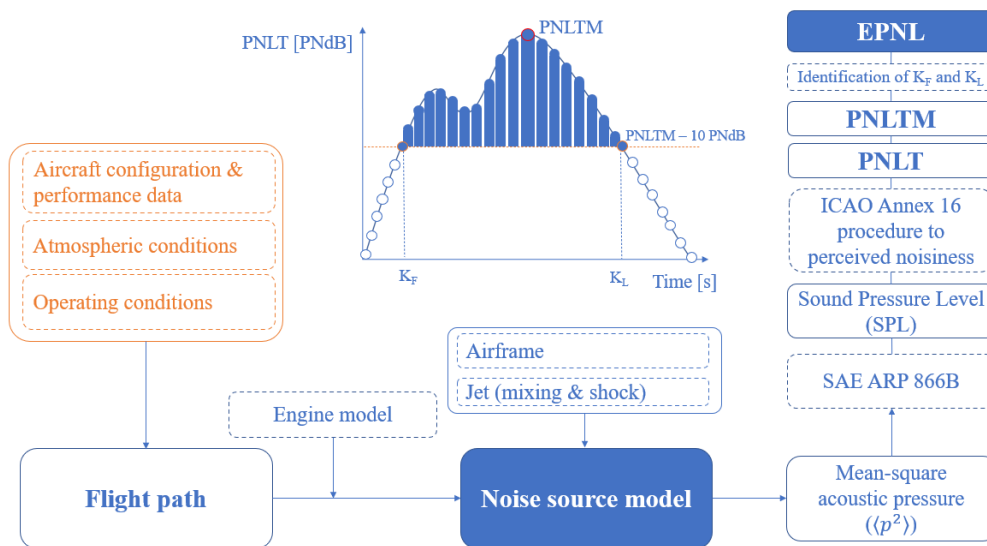


Fig. 4 Integration of the noise source model with take-off and landing analysis

A. Noise modelling

The semi-empirical noise model proposed for simplified LTO noise prediction of the selected waverider vehicle includes two main sources. One is the airframe noise, generated by motion of aircraft external surfaces through the air. Airframe noise is typically composed by several contributions, caused by aerodynamically clean surfaces, high-lift devices, and landing gear. To predict these contributions the method due to Fink [24] is applied, considering only the lifting surfaces and landing gear noise components. Noise generation mechanism for clean surfaces is assumed to be entirely associated with trailing edge noise, which originates from the scattering of the acoustic waves generated due to the passage of the turbulent boundary layers over the trailing edges of surfaces. The main parameter impacting on trailing edge noise is the aircraft speed, on which the noise intensity depends following the fifth power law.

Otherwise, landing gear noise, which is typically the dominant airframe noise source, is empirically determined. Fink's method has been validated against experimental data and is still widely used for conceptual airframe noise predictions. Over the years other models have also been developed, seeking to overcome some limitations. However, Fink's method has been retained appropriate to reliably capture the effect resulting from the variations of the most impacting parameters (aircraft speed, geometry of aerodynamic surfaces and landing gear) on noise generation, as the airframe noise intensity is fundamentally a function of aircraft size and mass. Implementing the methodology as it is

done in [17], the mean-square acoustic pressure is predicted as a function of directivity angles and frequency for each noise source by means of Eq. (2):

$$\langle p^2 \rangle = \frac{\Pi^* D(\theta, \phi) F(S)}{4\pi(r_s^*)^2 (1 - M_\infty \cos\theta)^4} \quad (2)$$

The acoustic power for the airframe Π^* can be expressed as:

$$\Pi^* = K(M_\infty)^a G \quad (3)$$

Where:

- 1) K and a are constants determined from empirical data.
- 2) G is a geometry function different for each airframe component and incorporated all geometrical effects on the acoustic power.

Π^* , $D(\theta, \phi)$ and $F(S)$ depends on the specific noise source, thus substituting these functions the correspondent noise contribution can be calculated. Then, spectrally summing each noise component along the 1/3 octave frequency band, the total airframe noise is predicted. The other main noise source is jet noise, which has been predicted with the Stone method [25]. Two mechanisms affect jet noise, that are the turbulent mixing of the exhaust stream with the external air and noise induced by shock structure generated when the exhaust flow evolves towards a supersonic regime. Jet mixing noise has an acoustic power whose variation strongly depends on jet exhaust speed. Stone method predicts this noise contribution starting from noise intensity produced by a stationary jet calculated at the reference distance $\sqrt{A_e}$ from the nozzle exit at $\theta = 90^\circ$ (Eq. (4)).

$$\langle p^2(\sqrt{A_e}, 90^\circ) \rangle^* = \frac{2.502 * 10^{-6} A_j^* (\rho_j^*) (V_j^*)^{7.5}}{\left[1 + (0.124 V_j^*)^2\right]^{\frac{3}{2}}} \quad (4)$$

Then, the mean-square acoustic pressure is calculated as:

$$\langle p^2(r_s^*, \theta) \rangle^* = \frac{\langle p^2(\sqrt{A_e}, 90^\circ) \rangle^*}{(r_s^*)^2} \left[\frac{1 + (0.124 V_j^*)^2}{(1 + 0.62 V_j^* \cos\theta)^2 + (0.124 V_j^*)^2} \right]^{\frac{3}{2}} \quad (5)$$

$$D_m(\theta') F_m(S_m, \theta') H_m(M_\infty, \theta, V_j^*, \rho_j^*, T_j^*) G_c G_p$$

Shock noise occurs when is greater than zero, with M_1 the primary stream Mach number and depends on the degree of mismatch between ambient and stream pressure. The 1/3 octave band mean-square acoustic pressure due to shock turbulence interaction noise is calculated through Eq. (6):

$$\langle p^2 \rangle^* = \frac{(3.15 * 10^{-4}) A_j^* \beta^4 F_s(S_s) D_s(\theta, M_1) G_c}{(r_s^*)^2 (1 - \beta^4) (1 - M_\infty \cos(\theta - \delta))} \quad (6)$$

When β is the pressure ratio parameter, equal to $\beta = \sqrt{M_1^2 - 1}$, which must be greater than zero for shock cell noise to occur. The function $D_s(\theta, M_1)$ provides the dependence of the shock cell noise, for a stationary jet, on the directivity angle θ and the fully expanded primary stream Mach number M_1 . The function is given by:

$$D_s(\theta, M_j) = \begin{cases} 1 & \theta \geq \theta_m \\ 1.189 & \theta < \theta_m \end{cases} \quad (7)$$

Where θ_m is the Mach angle defined by $\theta_m = \arcsin\left(\frac{1}{M_j}\right)$. Once airframe and jet mean-square acoustic pressure have been determined, the same assembly procedure is done to predict the total far-field aircraft noise. The semi-empirical equations accounts for changes in the spectrum of the received signal due to the directionality of the source, spherical spreading, and Doppler effect. The SPL can then calculate as:

$$SPL = 10 \log_{10} \langle p \rangle^2 + 20 \log_{10} \frac{\rho_\infty c_\infty^2}{p_{ref}} \quad (8)$$

To keep the approach simple, installation effects, shielding and ground reflection of sound are neglected.

Results

Noise levels associated with the simulated take-off and landing procedures are presented herein. The receivers on ground recorded the Tone Corrected Perceived Noise Level (PNLT) at certification measurement points, from which the Maximum Tone Corrected Perceived Noise Level (PNLTM) with respect to each location was derived. Figure 5 and Figure 6 show the noise contributions at the sideline and flyover measurement points, which include airframe noise, jet noise due to mixing, and jet noise due to shock. The data indicate that shock-associated noise is the most predominant noise source, followed by jet mixing noise, while airframe noise has a more significant impact than in conventional tube-and-wing aircraft applications.

Regarding the difference between the standard and alternative procedures, it can be stated that a slight noise reduction is achieved at both measurement points for the alternative procedure. Therefore, optimizing flight procedures for high-speed aircraft by considering combinations of altitude, thrust, and climb angle is a viable approach to achieve noise mitigation for these aircraft. However, the fact that there is still a predominant contribution due to shock-associated noise signals that certainly improvements in engine operation during take-off, and especially of the nozzle, are essential. In fact, since the nozzle is in non-adapted conditions and strongly overexpanded, a significant contribution of jet noise is inevitable. Finally, it can be observed that the increased acceleration in the initial phase of take-off for the alternative procedure results in a slight increase in airframe noise, which however does not have an impact on the total noise, that still achieves a reduction of about 1 PNdB. Reducing the aircraft ground time and improving the aerodynamic performance could also be a solution to mitigate noise.

Figure 7 presents the total and the singular noise contributions for approach measurement point. In this condition, the nozzle is adapted and therefore the contribution of shock-associated noise is not present. However, the obtained values are still higher than those of subsonic aircraft, but there are no particularly significant differences, as the standard procedure was simulated.

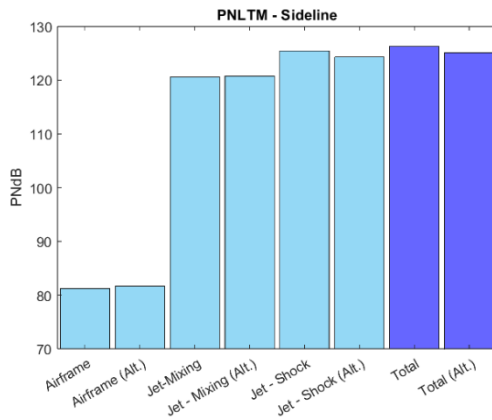


Fig. 5 PNLTM at sideline measurement point

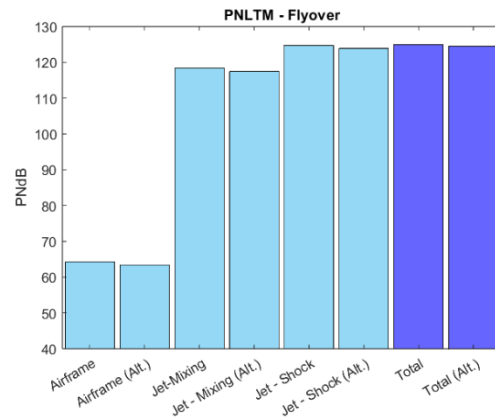


Fig. 6 PNLTM at flyover measurement point

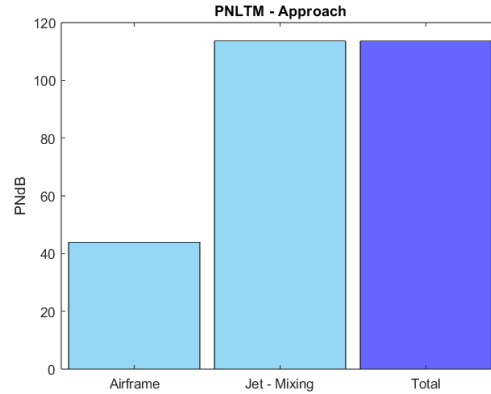


Fig. 7 PNLTM at approach measurement point

Comparison between current noise standards, Concorde, Tupolev TU-144, HyperSonic passenger aircraft Technology (HST) JAXA concept, LAPCAT MR.4 ESA concept and STRATOFLY MR3 certification noise levels is provided in Table 5 in terms of EPNL. STRATOFLY MR3 seems to be the noisier vehicle during take-off. However, in [18] only jet noise component has been considered as total aircraft noise contribution. In addition, it is possible to note the slight decrease in noise in the case of the alternative take-off procedure. However, this still does not make the aircraft quieter compared to similar ones.

| | ICAO [21] | Concorde [26] | Tu-144 [26] | HST [18] | LAPCAT MR2.4 [18] | STRATOFLY MR3 | STRATOFLY MR3 (*) |
|------------------|-----------|---------------|-------------|----------|-------------------|---------------|-------------------|
| Sideline [EPNdB] | 103 | 112.2 | 117 | 124.4 | 119.7 | 126.3 | 125.1 |
| Flyover [EPNdB] | 106 | 119.5 | 115.5 | 123.0 | 123.0 | 124.9 | 124.5 |
| Approach [EPNdB] | 105 | 116.7 | 114.5 | 110.3 | 121.5 | 115.65 | - |

Tab. 5 Comparison between current noise standards, Concorde, Tupolev, HST JAXA concept, LAPCAT MR2.4 ESA concept and STRATOFLY MR3 certification noise levels, considering both the standard and alternative flight procedure (*)

V. Conclusions

Improvements in conceptual design process of high-speed aircraft are currently undergoing to identify feasible and environmentally sustainable designs. This study presented an initial assessment of the applicability of a simplified LTO noise prediction methodology based on semiempirical methods to verify its possible extension to high-speed unconventional configurations. Furthermore, an upgraded approach with respect to current literature was proposed, accounting for airframe noise sources in the calculation of total aircraft noise. The workflow used to supplement the take-off and landing analysis with noise prediction was fully described. One of the primary challenges involved providing accurate estimates of the parameters required for noise analysis at the conceptual design level. This difficulty was overcome by obtaining simulation data from an external simulation tool and post-processing it to reproduce the flight paths and predict noise. In addition, a preliminary investigation was conducted on an alternative take-off procedure, acting on the acceleration during ground roll and thrust during initial climb. A slight reduction in noise was observed at both the sideline and flyover measurement points, with a more significant reduction at the sideline measurement point. This demonstrated that, although the accuracy level of these models remains low, they can be used in conjunction with mid-fidelity aerodynamic and propulsion data to evaluate the effectiveness of innovative flight procedures for high-speed aircraft. Based on this study, some general conclusion can be drawn:

- 1) Simplified semi-empirical methods can capture the effects of main design and operating parameters on noise generation also for unconventional configurations at low-fidelity level.

- 2) Airframe noise must be considered among the main aircraft noise sources also for unconventional designs, even if it is not the predominant contribution, since it has a more significant impact, especially on sideline measurement point (due to the higher aircraft speed), with respect to conventional tube-and-wing aircraft.
- 3) Engine and nozzle shall be optimized to reduce firstly shock-associated mixing noise.
- 4) Identification of proper flight procedures could be effective in reducing noise generated by high-speed aircraft around airport areas.

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