Innovative design methodology with LTO noise prediction capabilities for future supersonic aircraft

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Innovative design methodology with LTO noise prediction capabilities for future supersonic aircraft

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Abstract. To bring supersonic flight back to reality, it is crucial to demonstrate that future supersonic aircraft can reduce their environmental impact compared to the past. In line with this effort, the EU-funded MORE&LESS project is reviewing the environmental impact of supersonic aviation, by applying a multidisciplinary holistic framework to help check how enabling technologies of supersonic aircraft, trajectories, and operations comply with environmental requirements. The present study is part of this project and focuses on updating the traditional conceptual design process with methods for estimating the noise generated at airport level by supersonic aircraft. To achieve this, it is necessary to include some basic capability in the design flow, such as modelling for aircraft noise prediction and simulation of take-off and landing procedures. The approach used to consider these two elements is described in this paper. Preliminary results from Concorde-like case study are presented.

Introduction

It is well known that environmental impact was one of the most relevant factors leading to the retirement of Concorde, the first supersonic airliner. High fuel consumption, high noise levels, and the emission of nitrogen oxides (NOx) into the atmosphere raised concerns about public health and air pollution, causing Concorde to restrict its routes. Furthermore, the Concorde accident in 2000 reinforced concerns about the safety of the aircraft, bringing to the decision to permanently withdraw it from service in 2003.

Since then, significant progress has been made to better understand the environmental footprint associated with SuperSonic Transport (SST) operations [1, 2]. Consequently, research into the design of a new generation of greener supersonic aircraft have become more concrete in recent years. NASA is leading an experimental supersonic aircraft project called the "X-59 QueSST" to reduce noise pollution caused by the sonic boom [3]. Additionally, private companies, such as Boom Supersonic, are developing commercial supersonic aircraft projects for long-haul air travel [4]. Alongside these developments, regulatory efforts are being made to address the environmental impacts of supersonic aircraft. The International Civil Aviation Organization's Committee on Aviation Environmental Protection (CAEP) is collaborating with industry and research organizations to update existing environmental regulations and improve knowledge of the environmental consequences of introducing supersonic aircraft [5].

Aligned with this undertaking, the EU-funded MORE&LESS project aims at supporting Europe to shape global environmental regulations for future supersonic aviation [6]. The main goal is to review the environmental impact of supersonic aviation by applying a multidisciplinary holistic framework, called ESATTO, to help check how enabling technologies of supersonic aircraft, trajectories, and operations comply with environmental requirements. The routines and software tools used from aircraft design to trajectory simulation activities will be updated to extend their field of application to supersonic aircraft (considering the exploitation of both biofuel and liquid hydrogen as fuel) and then integrated into this unique framework. In this way, the ESATTO framework will encompass different disciplines (aerodynamics, propulsion, aeroacoustics, pollutant emissions and environmental impact) and their mutual relationships, thus allowing to perform a multidisciplinary optimization of supersonic aircraft' trajectories and operations. Recommendations to suggest new guidelines to allow for the introduction of supersonic aircraft with the least possible environmental impact will follow consequently.

The initial stage of this multidisciplinary optimization approach is the design of the reference supersonic concept. To make the whole process more effective, an upgrade of the traditional conceptual design methodology could be needed, not only to improve the prediction capabilities of the aircraft performance but also to anticipate environmental impact evaluations and identify the effects of environmental constraints on aircraft design and determine the extent to which sustainability requirements are met or not.

This study addresses this need and contributes to the MORE&LESS project. Precisely, it aims at including new methods and models to support the introduction of noise analysis since the early stages of the design process for the next generation of supersonic aircraft. Therefore, it is focused on the estimation of Landing and Take-Off (LTO) noise at airport level. Indeed, one of the primary issues surrounding supersonic aircraft was the noise impact near airport areas, which far exceeds that of subsonic aircraft. High thrust and speed required by supersonic aircraft taking-off result in higher and unacceptable noise levels. Breakthrough technologies, improved performance and advanced flight procedures are acknowledged as potential measures to mitigate the noise footprint of such aircraft [7, 8]. To enable these assessments as early as possible in the design process, this paper suggests an innovative design approach that includes the capability to predict aircraft LTO noise in order to facilitate the identification of most promising concepts and procedures.

The document refers to ongoing activities and therefore a simplified approach has been adopted at this early stage, which will be refined in due course. Some key points have been addressed, including the implementation of an appropriate model for estimating the noise generated by supersonic aircraft and the evaluation of performance for defining LTO flight paths. The related noise model is based on semi-empirical relationships known in literature. Moreover, the application to the reference case-study will be used to demonstrate its capabilities in the estimation of aircraft emissions noise levels at the three certification measurement points and define possible flight procedures for noise certifications. The major outcome will be the estimation of the noise impact of future supersonic aircraft during the early stages of the design process. Finally, the results will serve to verify the technical feasibility of future supersonic concepts, identifying design guidelines and advanced flight procedures aimed at reducing noise at the airport level.

The method of analysis is disclosed in Section 2. The principles of conceptual design process are recalled and then the main steps of the proposed innovative workflow are described. Hence, the analyses needed to support the noise performance estimation will be described. After that, the method used to assess LTO noise in conceptual design is presented, specifying details about the aircraft noise model and its future updates. Then, further information about the flight procedure modelling is included. Lastly, Section 3 deals with the description of the current results and the future expected outcome. Conclusions are drawn in Section 4.

Method of analysis

To enable the environmental assessment of supersonic aircraft during the design process, it is necessary to review the traditional workflow, first verifying the ability to provide all necessary inputs related to vehicle geometry, operations, and performance. In doing this, the integrated multidisciplinary methodology for the design of high-speed aircraft adopted in ASTRID-H has been taken as a reference [9].

Once the overarching process has been described, the proposed method to assess aircraft noise levels at this stage of the project is disclosed. Supersonic aircraft noise model is the core of this method of analysis. During the initial phase of the activities, this model will be maintained as simple as possible, using semi-empirical methods found in literature with low accuracy for supersonic aircraft case-studies. Then, the model will be improved benefitting from the results of high-fidelity aeroacoustics simulations for the prediction of jet noise. Another relevant element is the introduction of operational procedures modelling capability for the selected case-study. This will open the possibility for the definition of advanced noise reduction procedures for novel aircraft concepts. The final objective of the described method is to evaluate noise levels at the three certification measurement points defined by ICAO. Details available at this stage of the study regarding the proposed approach, the models implemented, and the input/output data exchanged are reported in the next paragraphs.

Upgraded conceptual design process

Addressing the design of future sustainable supersonic aircraft requires the consideration of different and improved methods and models than those typically used for subsonic aircraft. However, from the earliest stages of design, several problems can be encountered, including the lack of reference data for preliminary aircraft sizing and engine characterization or adequate simplified models for evaluating some of the most critical phases of the mission (e.g., take-off, supersonic cruise). In the frame of this work, the methodology implemented in the conceptual design tool to support high-speed vehicles design developed at Politecnico di Torino, ASTRID-H, will be used as a reference, with the aim of integrating the developed models for environmental impact analysis in an updated version, helping to move towards ASTRID-H 2.0.

ASTRID (Aircraft on-board Systems sizing and TRade-off analysis in Initial Design) is a proprietary tool of the research group of Politecnico di Torino and it has been developed for almost a decade through research activities. This tool allows to carry out the aircraft conceptual and preliminary design, the sizing and integration of subsystems for a wide range of aircraft, from conventional to innovative configurations, mainly in the subsonic and low supersonic speed regime. Then, ASTRID-H is an extension dedicated to high-speed vehicle applications. Based on its structure, our focus is the conceptual design phase at vehicle level. To better characterize supersonic aircraft improvements in aerothermodynamic and propulsive modelling capabilities are ongoing, with the inclusion of medium to high fidelity routines. Specifically, these routines will contain surrogate models relying on more accurate databases for aircraft performance prediction. The surrogate models will be integrated in the conceptual design flow to refine the first guess data obtained during the first iteration loop for the conceptual design of the aircraft, ensuring reliable output data. The iterative procedure will serve to improve the thrust requirement estimation derived from the Matching Chart analysis and to provide a preliminary mission profile (Fig. 1). The new tool version will be tailored to civil supersonic concepts covering the entire range of supersonic aircraft speeds from Mach 2 to 5.

In this context, the objective is a further updating of the methodology with the introduction of environmental targets as high-level requirements. Of course, for this evaluation to be effective, it is necessary to include in the process relationships, models or methods that allow even an initial assessment of these aircraft characteristics. The surrogate models and the definition of a preliminary mission profile will support the fulfilment of this need. Environmental constraints for supersonic aviation may concern engine emissions, sonic boom and LTO noise. Regarding LTO noise, so that a complete analysis can be carried out towards a noise assessment at airport level, at least three elements must be introduced: an aircraft noise model (Aircraft noise model), the simulation of take-off and landing flight procedures (Departure/approach flight path), and the assessment of noise perceived on the ground at certification points (Noise at certification points), as indicated in the green box in Fig. 1.

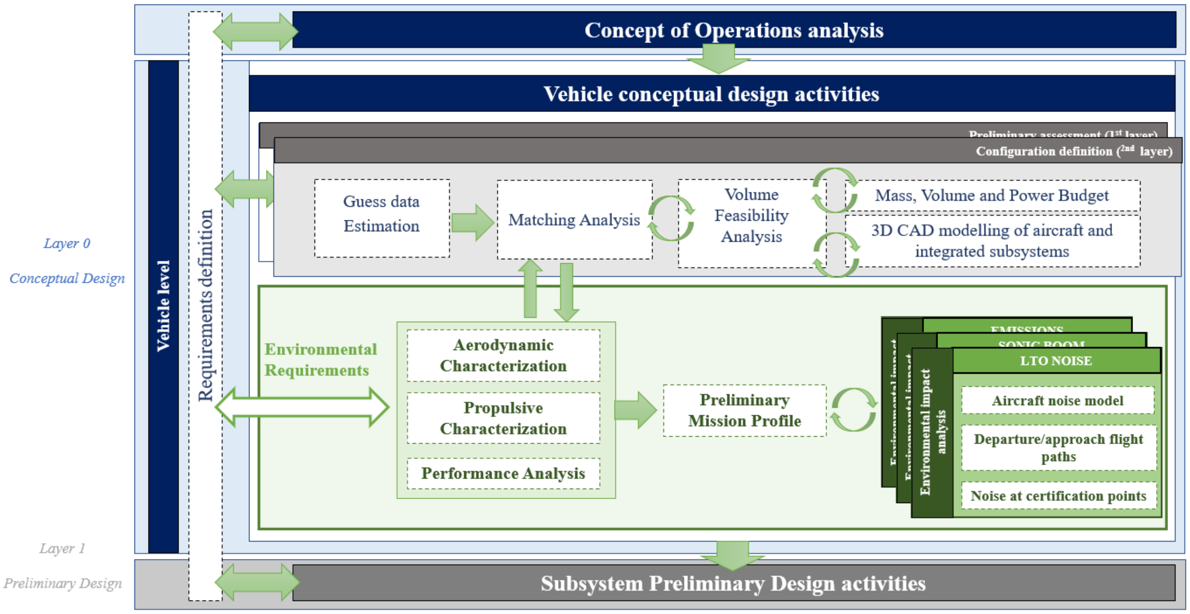

Fig. 1 – Upgrade of the rapid aircraft modelling methodology implemented in ASTRID-H for conceptual design of future supersonic aircraft.

LTO noise assessment

The simplified methodology for the assessment of LTO noise at conceptual design level to be applied is described in Fig. 2. The first step involves the characterisation of an acoustic model that is appropriate for supersonic aircraft. This aircraft noise model has to be based on a mathematical formalism that is flexible and applicable at a design stage when detailed information about the aircraft is not yet available. Such a feature has been met by the semi-empirical noise source models available in literature. At this early phase of study, the relationships present in the early versions of the Aircraft Noise Prediction Program (ANOPP) developed by NASA around the 1970s were applied [10]. Overall aircraft noise is predicted as an assembly of major noise sources, each modelled with an individual semi-empirical noise source model. Specifically, the considered contributions are related to airframe noise and engine noise; then, these major noise sources are further decomposed in wing, landing gear and vertical tail for airframe noise, while jet (considering both mixing and shock-associated noise) and fan for engine noise. The reference equations can be found in [11]. The implemented model will give as output the mean-square acoustic pressure (p^2) as a function of directivity angles and frequency for each of the noise components and for total acoustic pressure, obtained by summing each of the individual ones. The Sound Pressure Level (SPL) can be easily computed from it (Eq. 1).

$$\mathrm{SPL} = 10\ \log_{10}\left(\frac{\mathrm{p}}{\mathrm{p}_0}\right)^2 \tag{1}$$

With $\mathrm{p}_0 = 0{,}000002$ Pa minimum audible sound pressure for the human ear. Although the implemented model is not highly accurate for supersonic case study applications, it proved to be reliable for general evaluations in the early stages of the project. To overcome this limitation, a study is underway to update the model by modifying the empirical parameters used to estimate jet noise, the dominant noise source, by the comparison with the results of simulations performed with more accurate models.

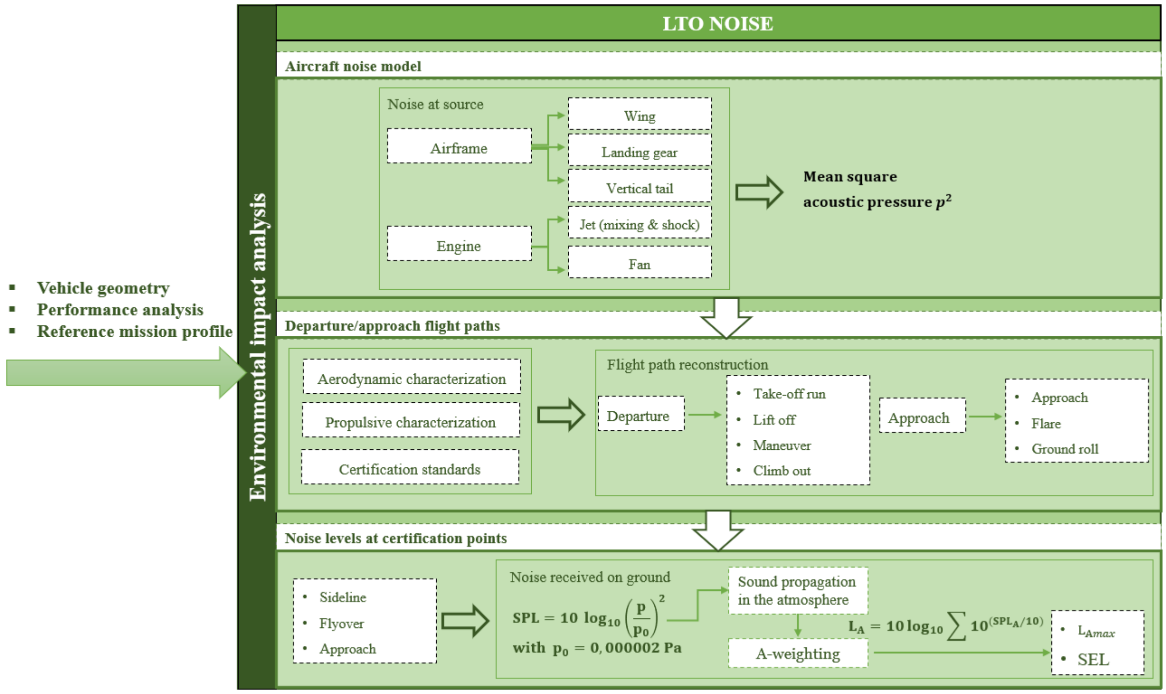

Fig. 2 – LTO noise assessment methodology

The calculated SPL refer to the noise at source. To predict the noise received on ground, flight paths for the LTO phases must be defined. Reliable input data are required to estimate the main operating parameters of the aircraft along defined trajectories (e.g. aerodynamic coefficients, thrust, speed). In this methodology, LTO trajectories are reconstructed from the segmentation of the flight path into sections with constant thrust and speed. This method allows a rapid evaluation of aircraft performance. The next step consists of selecting the noise measurement points defined for certification purposes, depicted in Fig. 3, and defined as follows:

1) Sideline (full-power reference noise measurement point): the measurement point is along the line parallel to the axis of runaway centre line at 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 runaway centre line at 6500 m from the start to roll.

3) Approach (low-power condition): the measurement point on the ground it is along the extended runaway 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.

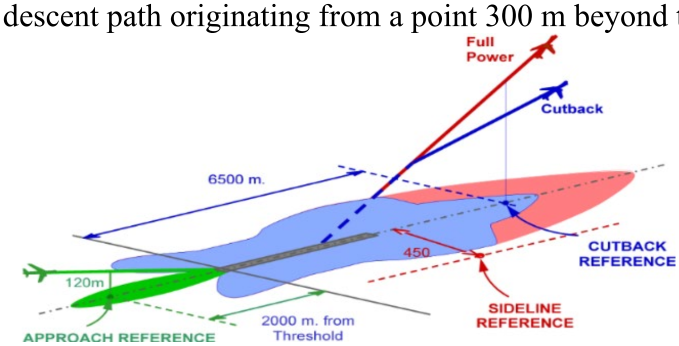

Fig. 3 - ICAO certification noise measurement points

Then, the received noise on ground is predicted considering the sound attenuation due to the propagation in the atmosphere (according to SAE ARP 866 B). Finally, the overall sound pressure level (L_A) is predicted from the A-weighted SPL (SPL_A) as indicated in Eq. 2:

$$L_A = 10 \log_{10} \sum 10^{(SPL_A/10)} \quad (2)$$

Consequently, both related A-weighted single event L_{Amax} and exposure noise metrics SEL are derived from it and used as evaluation variables to verify the noise requirements.

Results

Preliminary results that can be obtained from the proposed methodology are shown in this section.

For the aircraft that will be the subject of this study, performance has been estimated for the definition of standard take-off and landing trajectories. Precisely, the considered aircraft is Case-Study 1a (CS1a), that is the reference concept for Mach 2 in the MORE&LESS project. This vehicle has a conventional supersonic aircraft with Concorde-like configuration and propelled with biofuel. High-level requirements are listed in Tab. 1, while aircraft configuration is in Fig. 4. Medium to high fidelity datasets for the aerodynamic and propulsive characterization are available for this vehicle. Therefore, this data has been used to verify the take-off and landing performance.

Tab. 1 – High level requirements for the selected case study

High-level requirements for Case Study 1a (CS1a)	
Mach @ cruise	2
Range	7200 km
Payload	120 pax
Fuel	Biofuel

Fig. 4 – CS1a configuration

Different flight paths based on a standard flight procedure have been reconstructed. The maximum thrust per engine is 90 kN, and a thrust rating of 65% has been considered for the climb-out phase. Some performance output values are listed in Tab 2. Otherwise, performance data for approach phase are in Tab. 3. The final trajectories are reported in Fig. 4.

Tab. 2 – Performance variables for take-off flight path

C_{Lmax}	V_{LOF}	L/D_{climb}	γ_{climb}	R/C	V_{climb}	Thrust rating
[-]	[m/s]	[-]	[deg]	[m/s]	[m/s]	[-]
0.959	114.08	8.6	≅ 1	2.08	128	100 % (TO) 65% (CL)
1.171	103.24	8.6	≅ 1	2.08	128	100 % (TO) 65% (CL)
1.309	97.65	8.6	≅ 1	2.08	128	100 % (TO) 65% (CL)
1.384	94.95	8.6	≅ 1	2.08	128	100 % (TO) 65% (CL)

Tab. 3 – Performance variables for approach flight path

M_{Lan}	V_{APP}	V_{TD}	$L/D_{descent}$	$\gamma_{descent}$	Landing distance	Thrust rating
[kg]	[m/s]	[m/s]	[-]	[deg]	[m]	[-]
65 % M_{TOW}	111.85	98.94	6.83	3	3282	30 % (APP)

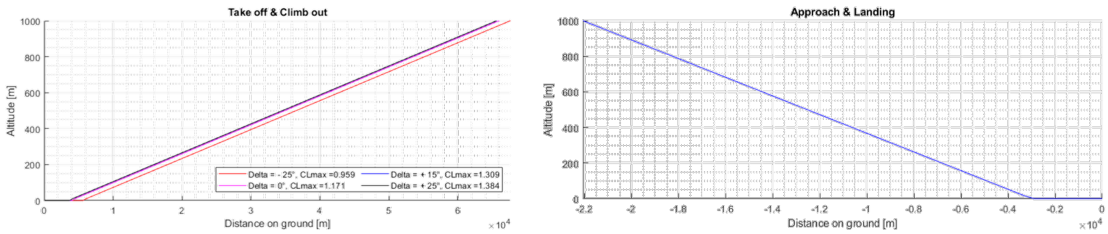

Fig. 5 – Take-off and Landing flight paths

To provide an indication of what is expected from the application of the proposed methodology, the results derived from Concorde case-study are shown in Fig. 6 from [11]. Noise levels in terms of $\mathbf{L_{Amax}}$ at the three certification points defined by ICAO will be derived from the simulation of take-off and landing trajectories. These will then be used to compare the values obtained with the current noise limits applied for supersonic aircraft.

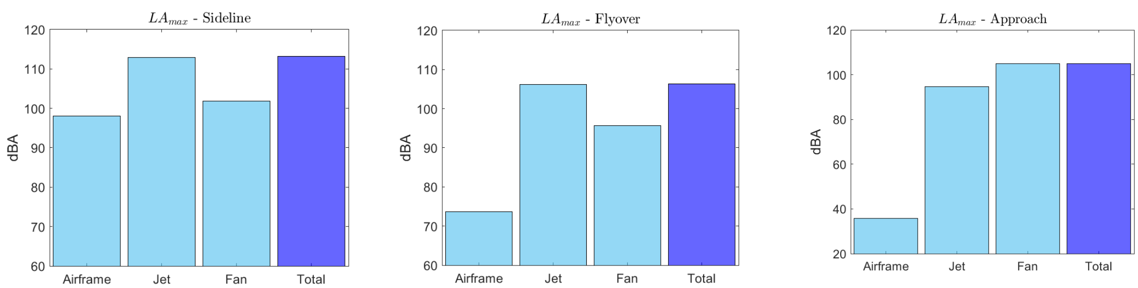

Fig. 6 – Noise levels at the three certification measurement points [10]

Conclusions

An approach for upgrading traditional design process for supersonic aircraft towards an innovative framework has been presented. Specifically, the paper focused on the introduction of LTO noise emissions estimations during conceptual studies. Simplified models and methods have been included for supersonic aircraft noise prediction and flight procedures modelling. Supersonic aircraft noise has been predicted using semi-empirical method well-established in literature, which consider the main aircraft noise sources as independent noise sources. The aircraft flight paths have been simulated dividing the aircraft trajectories in segments at constant thrust and speed. In this way, the aircraft noise levels at the three certification measurement points can be rapidly estimated. The case study to apply the approach is a supersonic aircraft with a Concorde-like configuration propelled with biofuel. Preliminary LTO trajectories have been calculated based on which noise levels will be estimated. To give an idea of the expected results, the estimations obtained considering the Concorde have been reported.

From the outcome of the current study, it is apparent that the conventional Concorde-like design is required by the incorporation of noise reduction measures from the earliest stage of the project, both from a design and operational point of view. Although these results pertain to ongoing preliminary activities, they demonstrate the potential of introducing a noise estimation methodology in the early stages of the design process, paving the way towards a design methodology that includes environmental analysis of the aircraft. The most significant limitations identified involve the requirement for a certain level of accuracy in input data and the fidelity level of the models used with respect to the considered case study. Therefore, research on possible updates to the methodology is ongoing.

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