LTO NOISE AND SONIC BOOM PREDICTIONS IN EARLY CONCEPTUAL DESIGN PHASES

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# LTO NOISE AND SONIC BOOM PREDICTIONS IN EARLY CONCEPTUAL DESIGN PHASES

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## Abstract

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This paper discloses a workflow to integrate LTO noise and sonic boom predictions since the beginning of the design of future supersonic civil aircraft. The application of state-of-the-art models to future high-speed case study is discussed and solutions to overcome limitations are presented. The workflow is validated against Concorde literature data and then applied to the design of a future sustainable Mach 2 aircraft.

**Keywords:** supersonic civil aviation, LTO noise predictions, aircraft conceptual design,

## 1. Introduction and background

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Aviation industry has transformed dramatically over the past century, forever changing how we live and work by bringing people closer and connecting the world. While travelling thousands of miles in just a few hours is easier than ever before, travelling faster than the speed of sound is also in the air. The EU-funded MOREandLESS 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. This project covers the entire supersonic speed regime (from Mach 2 to Mach 5) and the most promising aircraft configurations, propulsive technologies and alternative fuels (in including biofuels and liquid hydrogen). The findings will inspire the future of environmentally sustainable supersonic aviation.

The recent interest in environmental issues and renewed interest in supersonic civil transport has led to scientific activities into the realization of a new generation of sustainable supersonic aircraft. Since Concorde entered service almost fifty years ago, there has been much debate about the environmental impact of Supersonic Transport (SST) have on both the environment and people. Two of the main problems that characterized the community acceptability of this aircraft were related to the high noise level it generated in the vicinity of airports due to high thrust and the high level of sonic boom overpressure when flying in supersonic regime. For these reasons, the creation of certain standards of acceptability for the population and the requirement for low noise and low boom future supersonic aircraft from the earliest stages of the project is essential. The following paper focuses on the application of methodologies that are aimed at predicting the level of noise emitted by a supersonic aircraft during the LTO cycle and the variation of the sonic boom level as flight conditions change since pre-conceptual studies. Consequently, the following paper provides a guideline in conceptual design for LTO noise assessment and sonic boom prediction analysis for future supersonic aircraft for different mission phases.

Several methodologies aimed at different fidelity-levels and objectives can be employed to predict noise generated by the aircraft and/or its components during take-off and landing operations (e.g., fully analytic method, CFD combined with the acoustic analogy, semi-empirical method, or fully numerical method). However, assuming a system-level point of view rather than a more detailed component-level, two main methods categories can be recognized [1]:

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- Theoretical (or scientific) methods, which rely on both experimental data (typically from flyover test campaigns) and physical-based aspects. The total aircraft noise is predicted as an assembly of each individual noise source, modeled through parametrical and semi-empirical relationships.
- Best practice methods, which rely almost exclusively on ground measurements of a specific

aircraft. The aircraft emission noise level is determined by the segmentation of the trajectory and then the noise contributions from each of these segments are subsequently summed at the observer position to provide an evaluation of medium to long term average noise levels around airports.

Being these the differences between the two approaches, theoretical methods are surely more appropriate than other prediction models to perform design trade-off studies and run noise sensitivity analyses. Indeed, theoretical methods can easily handle parametric changes in airframe/engine design and operational settings, enabling a fast evaluation of their impact on noise generation and facilitating the identification of the best low-noise aircraft solution. However, the major downsides of these methods are the reliability and the fidelity-level of the results, especially when applied to novel aircraft configuration, due to the variety of data required for models' validation. Nevertheless, the integration of semi-empirical aircraft noise prediction within the design process has been widely investigated over the years. The National Aeronautics and Space Administration (NASA) initiated research on this topic at Langley Research Center in the early 1970s, starting with the development of the Aircraft NOise Prediction Program (ANOPP) [2], the first computer program with noise prediction capabilities. ANOPP is incorporated within a design framework which provides all the input required to accomplish the noise analysis. The noise prediction is performed by dedicated modules to account for noise source modelling, noise propagation (spherical spreading, atmospheric attenuation, and ground reflection on the received noise) and calculation of certification noise levels. Advances in the fidelity-level and the capability to cover also unconvetional designs have been made over the years and included in the latest release ANOPP2 [3]. Currently, many others similar prediction tools can be found in literature, as the Parametric Aircraft Noise Analysis Module (PANAM) [4], developed by the German Aerospace Laboratory (DLR), and CARMEN [5], developed by the French aerospace laboratory ONERA. The methodology underlying these programs is almost analogous to what is present in ANOPP, with remaining differences in noise models and individual code implementation. Although, to date PANAM and CARMEN can be applied only to conventional tube-and-wing aircraft.

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All bodies moving at a speed greater than the local speed of sound $a_v$ generate a shockwave system, in particular for a supersonic aircraft there is the formation of a series of shock waves which at great distance from the source could coalescence into a bow and a tail shock to form the classical N-wave. These shock waves move at the same speed as the aircraft and extend from the aircraft itself to the ground both along the ground track and tens of kilometers to each side of the ground track itself, and are also reflected from the ground. Sonic boom minimization techniques have great interest due to the fact that sonic boom cause a considerable level of annoyance to both the population and structures. An adequate estimation of sonic boom pressure field could be obtained even with a simplified method that start from the linearized theory of supersonic flow. It is generally known that the factors that affect sonic boom in a relevant way are mainly due to aircraft design, aircraft operations and atmospheric effects while aircraft operations are related to flight altitude, Mach number, flightpath and weight. The first procedure for the shock formation was studied by Whitham [6] which correct the linearized theory including local variation of speed of sound and formation of shocks. Most early studies were conducted considering a standard atmosphere or a uniform, isothermal atmosphere such as those of George and Seebass [7,8,9]. The effect of a real atmosphere was first studied by Hayes [10] and then taken up by Pierce and Maglieri [11]. The most widely used methods are set out by [12]. Besides these methods, which are quite complex and require a great amount of computing power, simplified models have also been developed to approximate the Whitham F function. The most famous and immediate method was developed by Carlson and is called "Carlson's simplified method" [13] , in which the Whitham F function is reformulated in terms of a shape factor constant $K_S$ which includes information about the geometry of the aircraft and evolution of its shape. Another simplified methodology for sonic boom computation is formulated by Plotkin [14], in which he presents a method to derive the sonic boom from maneuvering aircraft in an arbitrary, horizontally stratified and windless atmosphere. The method uses ray shape function tables, whereby defined the atmosphere, ray tube areas are computed via tables and algebraic relations.

Finally, the most commonly found and used sonic boom computer models are:

- ARAP which calculates the sonic boom for an aircraft maneuvering in an arbitrary horizontally stratified atmosphere.
- Thomas[15], developed by NASA that use the waveform parameter method of signature aging.
- TRAPS[16], that use Hayes' formulation with the use of ray distance instead altitude as the independent variable and accepts atmospheric data in standard meteorological format.

- ZEPHYRUS [17], which reformulates Hayes' method by incorporating more physical effects and treats over-the-top booms.
- PCBoom3 [18], represents an evolution of Thomas' code with the addition of a focal zones by application of the Gill–Seebass focus solution and Guiraud's scaling law. It manages to accept initial signature of both F function or can generate simplified Carlson F functions from built in aircrafts.
- MDBOOM [19], similar to PCBoom3 which incorporates area rule F function calculation.

This brief introduction and background of the research activities provides an overview of the state-of-the-art modelling regarding aircraft noise and sonic boom prediction methods. ~~Section 2 describes the overall methodologies accurately used in conceptual design focusing on the most significant parts for sonic boom and aircraft noise evaluations. Therefore, Section 3 includes the correlation with experimental results for Concorde in terms of both departure and approach procedures noise and sonic boom analysis in terms of bow shock overpressure and time signature duration. Thereupon, Section 4 describes the same procedure for a different type of aircraft, which is 20 meters shorter and capable of reaching Mach 3 as a cruise Mach number. Lastly, Section 5 includes conclusions and possible future improvements to the methods.~~

Section 2 reveals how LTO noise and sonic boom evaluations have been included within the conceptual design process, along with detailed description of the methodologies used for noise predictions. To check the capabilities of the selected methodologies, they have been initially applied to a well-known case-study, i.e. the Concorde, and the results are provided in Section 3. Then, the proposed workflow has been used to evaluate a conceptual supersonic aircraft, which is 20 meters shorter than Concorde and capable of reaching Mach 3 as a cruise Mach number. Results for this case-study are shown in Section 4, underlying the comparison with the Concorde. Lastly, conclusions and possible future improvements to the methods are outlined in Section 5.

## 2. LTO noise and sonic boom prediction in conceptual design

### 2.1 Proposed workflow

The primary purpose at conceptual design level is to provide technical and feasibility information for guiding larger efforts during the detailed design phases. Therefore, performance analyses should be carried out to properly explore the many suggested configurations offered during the early definition of the vehicle. Furthermore, sustainability should be considered already at this stage, as it is a key factor impacting on the viability of future supersonic transport. According to the aim of the MOREandLESS project cited in the introduction, an integrated workflow to support future supersonic aircraft conceptual design including preliminary noise requirements verifications within initial assessment studies is proposed (Figure 1). The integration begins considering additional environmental targets as project constraints together with the traditional performance requirements. Precisely, this paper will focus only on the verification of maximum allowable noise levels related to LTO and sonic boom. Once the concept is sized and the mission profile is defined, first guess database is available to perform initial analyses. As far as environmental analysis is concerned, input data are required from aerodynamics, propulsion and weights, as well as mission data for dedicated flight simulations. Boxes framed with the green dashed line in Figure 1 highlights also the methods employed, the simulations performed, and the results obtained in this study, that will be disclosed in detail in the next Sections. As the last step, the verification of current and available noise standards is suggested to implement modifications in the design and identify the optimal solution for feasible low-noise supersonic aircraft. In this way, the procedure could be useful to assess the benefits of new technologies as a function of the design to which they are applied.

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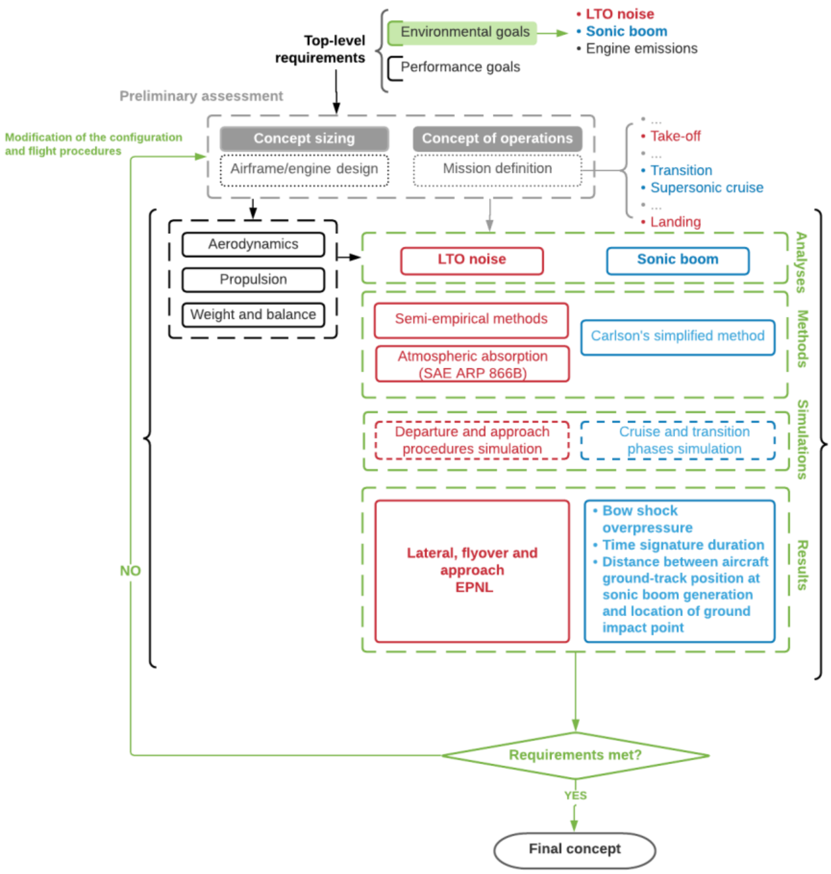


Figure 1 – Integrated conceptual design workflow with noise requirements evaluation.

## 2.2 LTO noise prediction model (Grazia)

The LTO noise prediction model is described in Figure 2. Following well-established methodologies to introduce noise emissions estimation within the aircraft design process, a semi-empirical modelling approach has been selected. The main aircraft noise sources are identified (airframe, jet and fan). Then, each noise source contribution is further detailed, as specified in Figure 2. At this purpose, it is necessary to account for the peculiarities of supersonic aircraft case-study with respect to subsonic aircraft, such as the absence of high-lift devices and horizontal stabilizer, the delta wing and the noise induced by shock cells structure resulting from the high jet exhaust velocity at take-off. Open literature on semi-empirical methods considering these aspects is restricted to NASA research activity to support ANOPP development. Hence, the models applied in this work for each aircraft main noise source and related sub-components are based on the available early version's methods of ANOPP [20]. All these methods were validated against experimental data, and, even if some limitation or shortcoming exist, these models have been widely used over the years, due to their capability to provide a sufficiently reliable and fast noise prediction correlated with the main design and operational parameters.



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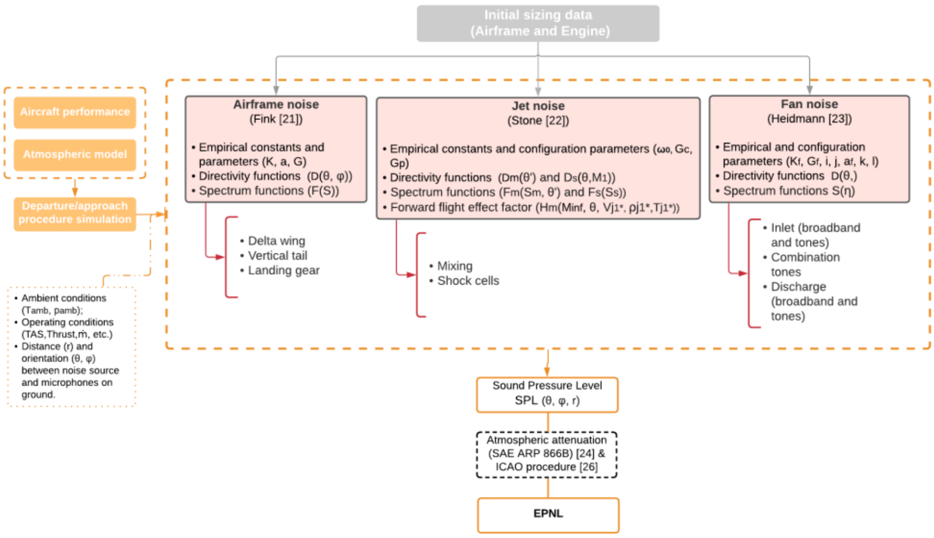


Figure 2 – LTO noise prediction model applied for supersonic aircraft conceptual studies.

Precisely, airframe noise is modelled accordingly to Fink's method [21], where noise generated by the clean aerodynamic surfaces is assumed to be caused by the turbulent boundary layer flow over the trailing edges and noise due to landing gear is fully empirical determined. Jet noise is predicted following the Stone method (generally applicable for both turbojet and turbofan engines) for single stream and coaxial circular jets [22], which includes both jet mixing noise and shock-turbulence interaction noise. Specifically, jet mixing noise is generated by turbulent mixing of the exhaust stream with the external air, which produces noise having acoustic power whose variation strongly depends on jet exhaust speed. In the suggested method, this noise source is independent from the azimuthal directivity angle (between the symmetry plane of the vehicle and the observer on ground) and is calculated modifying the mean-square acoustic pressure for a stationary jet at the reference distance with a forward flight effect factor. On the other side, the shock cells noise occurs when the fully expanded jet Mach number is greater than 1 and the intensity this shock-associated noise is dependent on the degree of mismatch between the design Mach number and the fully expanded jet Mach number. Heidman method [23] is used to predict fan noise. It is applicable to turbojet compressors and to single-and-two-stage turbofans with and without inlet guide vanes. The total noise levels are obtained by spectrally summing the predicted levels of broadband, discrete-tone and combination-tone noise components. Specifically, the predicted noise radiation ~~consist~~consists of composite of the noise emitted from the fan or compressor inlet duct (broadband noise, direcrete-tone noise, combination-tone noise) and the noise emitted from the fan discharge duct (broadband noise, direcrete-tone noise). All these methods allow predicting the far-field noise radiation, and the mathematical representation of the noise sources relies on empirically-based constant, parameters, and functions. The overall acoustic power is estimated and then the mean-square acoustic pressure is calculated modulating along the frequency band this overall acoustic power through the directivity and spectrum functions, accounting also for Doppler effect and spherical spreading of sound. Thus, the mean-acoustic pressure is expressed as a function of frequency and directivity angles. The Sound Pressure Level (SPL) can be easily computed from it. Noise emission is estimated in this manner for each aircraft sub-component and then the mean-square acoustic pressures are assembled to predict the overall contribution. Ultimately, to predict the noise level received on ground with a sufficient accuracy level, at least the atmospheric attenuation of sound propagating through the atmosphere should be considered, as temperature and humidity significantly affect sound when distance between the noise source and the observer increases. To determine the entity of these losses, the mathematical procedure suggested in SAE ARP 866 B has been adopted [24]. Other phenomena influencing the sound received on ground are neglected, to keep the approach simple and applicable at conceptual design level. To predict effectively noise levels received at certain point on ground, these methods require information about initial geometrical and performance data of the aircraft and the engine~~, as listed in the Table~~ , that should be derived from the connection with the other aeronautical disciplines within the design process workflow. Once first-guess estimations derived from initial conceptual studies are available, basic departure and landing procedures should be simulated in order to provide point-to-point ambient and aircraft operating conditions, together with information about the relative position of the aircraft with respect to the microphones on ground. Therefore, selection of an atmospheric model is the first step in predicting aircraft noise along the flight path. Atmospheric properties affect the performance of the aircraft, the noise generated by the aircraft and its engines, and the propagation of this noise through the atmosphere. As the model has to be only representative of the atmosphere below 10 km, the International Standard Atmosphere (ISA) static atmospheric model has been selected. The atmospheric model shares ambient conditions data along the trajectory to update basic modules for flight path simulation and engine performance. Indeed, estimating all the needed parameters to predict aircraft noise (especially for what concerns the engine operating conditions) with simple and low-fidelity models typical of the conceptual design stage trying to obtain at the same time reliable results is one of the most challenging aspects in the integration of noise prediction methods at the very beginning of the design process, as well as uncertainties in the input data will affect the fidelity of the results. Hence, basic modules for flight path simulation and engine performance have been developed to overcome this issue. Specifically, the flight path is constructed from a set of standard procedural step, whereas the engine operating conditions are evaluated through a one-dimensional model of a two-spool turbojet based on Olympus 593 data [25]. At least, the overall SPL received at the three certification point defined by the ICAO, that are sideline (or lateral), flyover and approach ~~-~~(Figure 3)~~,~~ can be processed following the ICAO procedure [26] to get the perceived noise levels and then the Effective Perceived Noise Level (EPNL).

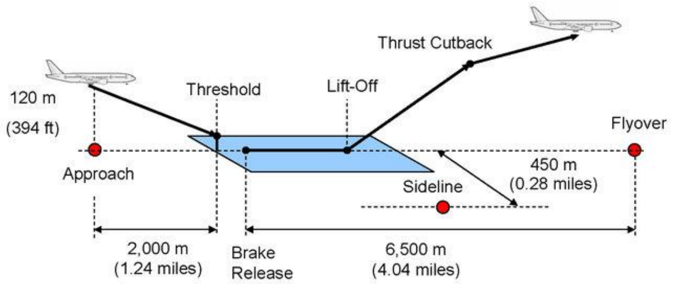


Figure 3 – ICAO noise certification measurement points.

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## 2.3 Sonic Boom prediction model

Moving to Sonic Boom predictions, the method used in this paper is the Carlson's simplified method, which allows the value of bow shock overpressure and time signature duration to be obtained since the earliest design phases , before moving to high-computational cost software or test campaigns. unlike the other methods, it does not require a large number of computer programs covering aircraft geometry and aerodynamic considerations, as well as wave propagation. This method is applicable for all categories of supersonic aircraft that are operated at an altitude below 76 km in level flight conditions or in moderate descents or ascents phases. However, it is worth listing the main limitations, such as the fact that it is only valid for N-wave signatures, that it considers a standard atmosphere without wind, that it takes into account only the positive portion of the signature and therefore not the tail shock and finally that it does not consider the acceleration phase, but only a stationary phase. The N wave assumption is true for most aircraft categories for the positive portion of the signature. Within the simplified method the Whitham F function is approximated by a constant called "aircraft shape factor" which is exclusively a function of the flight conditions of the aircraft and the evolution of the aircraft geometry along the longitudinal coordinate[13]. A certain number of aircraft have shape factor charts that allow an immediate estimation, while specific formulations shall be developed to fit new vehicle layouts. Regarding the final goal of the calculation of bow shock overpressure and time signature duration, the first step in the procedure is to derive the shape factor of the aircraft from the knowledge of the flight conditions and aircraft characteristics such as weight, altitude, Mach number, flight path

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angle and ray path azimuth angle. The following step concerns the determination of atmospheric parameters such as effective Mach number and effective flight altitude. From these values it is possible to interpolate the equations to obtain the parameters necessary for the calculation of the bow shock overpressure and time signature duration, such as the ray path distance factor, time signature factor and the pressure amplification factor. The third and final step concerns the application of the formulas for bow shock overpressure in equation 1 and time signature duration in equation 2.

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Equation 1

$$\Delta P_{max} = K_P \cdot K_R \cdot \sqrt{p_v \cdot p_g} \cdot (M^2 - 1)^{\frac{1}{8}} \cdot h_e^{-\frac{3}{4}} \cdot l^{\frac{3}{4}} \cdot K_S$$

Where $K_P$ is the pressure amplification factor, $K_R$ is the reflection factor that is assumed to be 2.0, $p_v$ is the atmospheric pressure at aircraft altitude, $p_g$ is the value of atmospheric pressure at ground level, $h_e$ is the effective altitude $K_S$ is the aircraft shape factor.

Equation 2

$$\Delta t = K_t \cdot \frac{3.42}{a_v} \cdot \frac{M}{(M^2 - 1)^{\frac{3}{8}}} \cdot h_e^{\frac{1}{4}} \cdot l^{\frac{3}{4}} \cdot K_S$$

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Where $K_t$ is the signature duration factor, $a_v$ is the speed of sound at aircraft altitude, $h_e$ is the effective altitude and $K_S$ is the aircraft shape factor.
The calculation of the shape factor for aircraft that are not covered by shape factor charts consists of calculating some specific parameters. The first parameter to be calculated is related to the calculation of the equivalent area due to volume, which consists in the definition of the aircraft cross sectional area that requires only the normal contribution to the flight path instead of that defined by the Mach plane.

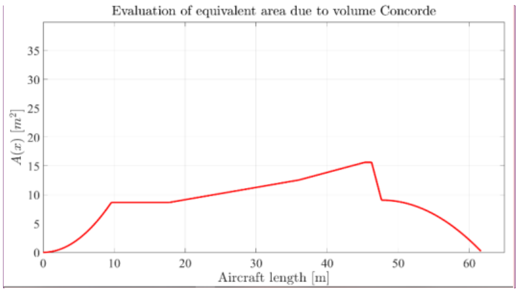


Figure 4 – Equivalent area due to volume, Concorde.

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In addition, the area of the stream tube of air that is entering in the engine inlet must subtracted from the equivalent area due to volume. The following step is to define the equivalent area due to lift. One of the simplifications of the method is to approximate this contribution by defining it by the planform area distribution and it is defined by equation 3:

Equation 3

$$B(x) = \frac{\sqrt{M^2 - 1} \cdot W \cdot \cos\gamma \cdot \cos\theta}{1.4 \cdot p_v \cdot M^2 \cdot S} \cdot \int_0^x b(x) \ \ dx$$

Where W is the aircraft weight, $\gamma$ is the flight path angle in deg, $\theta$ is the ray-path azimuth angle, $p_v$ is the atmospheric pressure at aircraft altitude, S is the aircraft planform area and b(x) is the local span of aircraft planform at a given value of x coordinate.

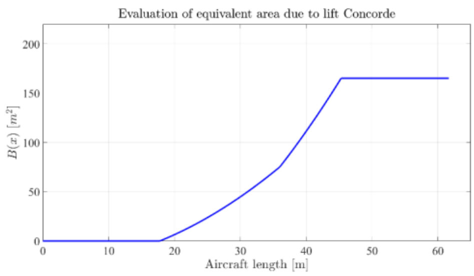


*Figure 5 – Equivalent area due to lift, Concorde.*

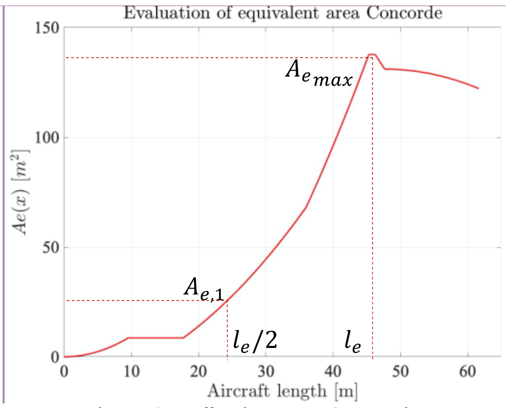


Figure 6 – Effective Area Concorde

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The next step is to add the two previous contributions to form the total effective area of the aircraft $A_{e,}$. From the obtained curve, it is possible to determine the value of the maximum effective area $A_{e,\max}$ , its position in terms of longitudinal coordinate or effective length $l_e$ of the aircraft and the effective area $A_{e,1}$ , that are essential for the calculation of the shape factor parameter. Finally the last step consist on the evaluation of the value of aircraft shape factor can be directly read from the shape factor parameter curve having known the ratio between the two areas that arises approximating the function $A_e(x) = k_1 \cdot x + k_2 \cdot x^2$ with the selected constants such that the curve passes through those points.

Pressure amplification factor, ray path distance factor and signature duration can be obtained by having the effective flight altitude and the effective Mach number. Interpolating functions have been created that manage to accurately describe the value of these constants as the effective Mach number and effective altitude change. The effective Mach number is described as the Mach number that would be given in level flight, which would have the same ray-path angle in the flight-track plane while the effective altitude is the distance perpendicular to the aircraft flight path. The simplified effective Mach number is defined by equation 4:

Equation 4

$$M_e = \frac{1}{\sin\left(\gamma + cot^{-1}\sqrt{M^2 - 1}\right)}$$

Where $M_e$ is the effective Mach number and $\gamma$ is the flight path angle in deg.
The component of distance in direction of aircraft ground track is essential for the calculation of the effective distance and it is defined as shown in equation 5:

Equation 5

$$d_x = K_d \cdot \left( \frac{h}{\sqrt{M_e^2 - 1}} \right)$$

Where $K_d$ is the ray path distance factor, h is the altitude of the aircraft, $M_e$ is the effective Mach number and $d_x$ is the component of distance in the direction of aircraft ground track

And finally the effective altitude is defined by equation 6:

Equation 6

$$h_e = h \cdot \cos\gamma + d_x \cdot \sin\gamma$$

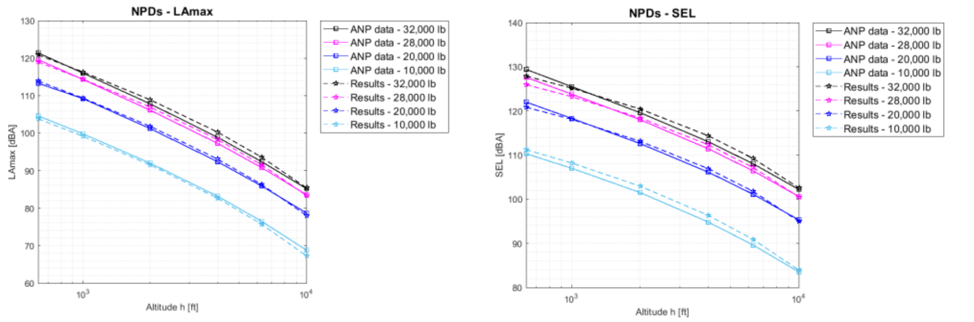
Where $h_e$ is the effective altitude, h is the altitude of the aircraft and $\gamma$ is the flight path angle.

The introduction of these parameters is mainly due to the fact that they significantly reduce the computational calculation. The values of the atmospheric factor constants were obtained by interpolating the remarkable points as a function of the effective Mach number and the effective altitude. A set of polynomial equations have been created to describe the evolution of these factors as the effective Mach number varies and the altitude varies. The cutoff Mach number as a function of altitude was also identified, for which the signal will not reach the ground.

## 3. Methodology validation with Concorde data

### 3.1 LTO noise for Concorde

In order to justify the applicability of such simplified methodology to supersonic aircraft with traditional Concorde-like configurations and assess the accuracy level in the prediction, the results of dedicated validation against Concorde data are presented. The validation has been carried out for flyover trajectories at different altitudes (630 ft - 10,000 ft) and thrust settings (10,000 lb and 32000 lb) and the methodology has been used to predict Noise Power Distance (NPD) data produced at these flight conditions. The aircraft speed is fixed to 160 knots (82 m/s), in accordance with the reference airspeed used to derive the NPD from experimental measurements, whereas the ambient conditions have been set to the reference conditions suggested in [27] for noise contours modelling around the airports (ambient temperature Tamb = 15 °C and the relative humidity HR = 0.7). To overcome the lack of available experimental data from flight campaigns or thanks to a comparison of the results from an already accepted and validated software, NPD data provided by the Aircraft Noise and Performace (ANP) database [28] (an open-source repository of noise data by Eurocontrol) have been taken as a reference to evaluate the correspondence with the predicted noise levels. Furthermore, as annoyance-based noise levels are more sensitive to signature and tonal content of noise rather than




loudness-based metrics, LAmax and SEL have been estimated to perform the validation. Graphical comparison between experimental and predicted NPDs is reported in Figure 7.

Figure 7 – Maching between experimental and predicted NPD curves for LAmax and SEL (Concorde)

The degree of matching between predicted and experimental curves has been quantitative estimated through a numerical indicator for each validation point, respectively defined for LAmax and SEL as follows:

$$E_{LA_{max}} = \left|\frac{LA_{max_p} - LA_{max_{ANP}}}{LA_{max_{ANP}}}\right|$$

$$E_{SEL} = \left|\frac{SEL_p - SEL_{ANP}}{SEL_{ANP}}\right|$$

Where $LA_{max_p}$ and $SEL_p$ are the predicted noise levels, thus $E_{LA_{max}}$ and $E_{SEL}$ are the correspondent relative errors. The maximum prediction error is $\pm$2.19% around the experimental value, attaining a good accuracy level for conceptual design applications.

## 3.2 Sonic Boom of Concorde (Samuele)

In order to prove the method for determining the sonic boom analysis of a supersonic configuration, various tests were carried out on Concorde. There are two main conditions under which a sonic boom analysis needs to be carried out: the first is the transition from a subsonic to a supersonic regime, while the second is the early stages of cruise, when the aircraft has reached the desired altitude and Mach number, and still has a value of weight not too far to the MTOW. Finally, a third important scenario to be analyzed is the effect of altitude variation. Regarding the first analysis, which is related to the transition phase from subsonic to supersonic flight, tests were carried out between 11500 and 13000 m, with a Mach number between 1.2 and 1.5. Lower Mach values would not lead to the creation of sonic booms as they are lower than the cutoff Mach number. The second test concerns the influence of weight, and was carried out at a fixed altitude of 18000 meters, varying the weight between 145000 and 165000 kg. Moreover a variation of the Mach number between 1.4 and 2.0 was made. Finally, regarding the influence of flight altitude, an analysis was made between 17000 and 19000 meters with the Mach number variation between 1.4 and 2.0 at an imposed weight of 165000 kg. All these analyses were carried out considering the aircraft in horizontal flight, in a standard atmosphere without wind and in stationary phase.

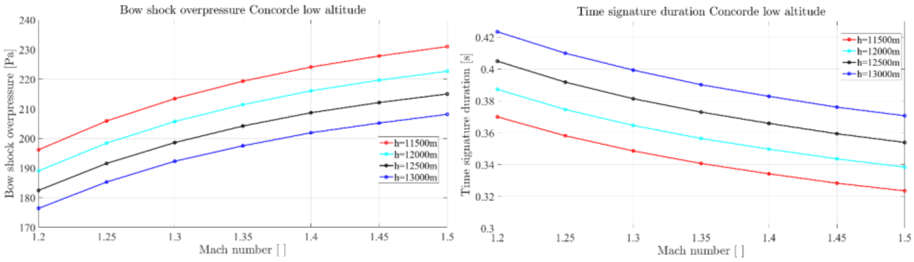



Figure 8 - Case 1: Bow shock overpressure and time signature duration with Low Mach and low altitude.

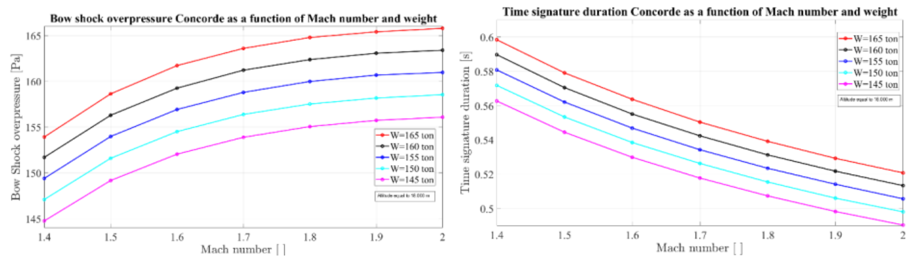



Figure 9 - Case 2: Bow shock overpressure and time signature duration with Mach number and weight variation.

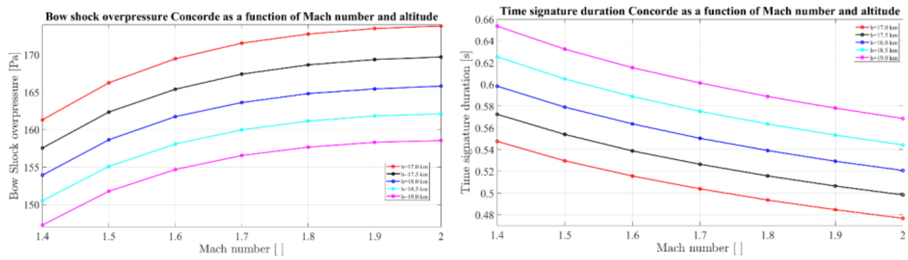



Figure 10- Case 3: Bow shock overpressure and time signature duration with Altitude and Mach number variation.

## 4. Application to Greenhawk3

### 4.1 Case study description


Figure 11: GreenHawk3 Aircraft

The GreenHawk3 aircraft is a concept created by a team of students from Politecnico di Torino between 2020 and 2021 with the aim of creating a conceptual design for a future sustainable supersonic business jet. The project aims to develop a first analysis project for aircraft that will be able to cover intercontinental distances, so that it can be a source of inspiration for the future. In order to realize the concept, the aircraft had a number of requirements set, such as the number of passengers set at 20, the use of biofuel as fuel and a cruising Mach number of 3. The choice of using HEFA biofuel is dictated by purely environmental reasons, in order to reduce carbon dioxide emissions and the fact that is already existing on the market. As it is a 'drop in fuel' it does not require any kind of modification to the structure of the aircraft tanks or ground equipment. The selected biofuel has physical characteristics similar to conventional fuel in terms of density and flash point. One of the biggest issues for this type of aircraft is the type of propulsion with which to equip the aircraft, the greatest challenge to high speed flight is having a propulsion system that can efficiently accelerate vehicles from rest to high-speed and then cruise at high speed. There are numerous combinations of engine types or engine cycle options, including turbojets/turbofans, turbines integrated with ramjets (turbo-ramjets) and integrated air-breathing and rocket cycles (air-turbo-rockets). After a trade-off analysis between a turbojet without afterburner and an engine cycle option, it was noted that the first configuration was more suitable. Regarding the engine, it was decided to use 2 prototype engines studied by NASA with a net thrust of 35667 lb for each engine and with a thrust to weight ratio of about 8.04. These propellers were studied by NASA for the construction of a 250 passengers supersonic aircraft that could replace Concorde and enter in service in the early 2000s. As the aim of this project is to make the aircraft fly by 2035, it is assumed that we can use all of today available technologies. It is also assumed that there is no cost constraints and the only constraint is to make the first flight test by 2035. Using the ASTRID software, it was possible to carry out a preliminary development of all the subsystems within the aircraft in terms of power budget and mass of components. In addition, the matching chart of the aircraft was obtained and the center of gravity was

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determined. The mission profile of the aircraft was also completed through ASTOS software, including a mission with origin in Sydney and final destination Tokyo. The mission profile through ASTOS shows an operational altitude of about 20000 meters at a Mach number close to 3.0. Regarding the lift to drag ratio during the supersonic phases demonstrates a value of about 6.0, while in subsonic phases the maximum lift to drag ratio is equal to 10.5. The final evaluation made on ASTOS regard the fuel consumption during the mission profile with about 2200 kg of fuel remained after the landing phase. Regarding tank it was decided to allocate 4 tanks for each half wing plus two in the fuselage in order to complete the mission safely and it was performed a center of gravity variation analysis during the phases of the mission in order to ensure if the airplane was statically stable during all the mission phases. The configuration was then developed with a CAD tool using SOLIDWORKS, including all on-board systems defined with ASTRID. At the end of the power budget and the mass budget, the final configuration of the aircraft is 42 meters long, with a wingspan of about 18 meters and a wing area of 131 square meters. A cranked arrow wing configuration was adopted because of the subsonic flight phases. As airfoil it was decided to use the profile NASA SC(02)-0404 with a centerline chord of 14474 mm with a first sweep angle of 64 deg and the second of 51 deg . Regarding the tail it was decided to use a tailess configuration due to high thermal load and high structural weight, the vertical surface is equal to 12.52 $m^2$ and the vertical tail high is just over 4.00 m. Wing loading is 326 kg/$m^2$ and the Thrust to weight ratio is just under 0.4. The total thrust in take-off conditions is approximately 320 kN, which can be obtained through two engines. The total maximum take-off weight is just below 40000 kg , with around 20 tons for the fuel and around 3 tons to passenger payload.

## 4.2 LTO noise for Greenhawk3

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Comparison between Concorde and GreenHawk3 is shown in this section to verify the sensibility of the proposed simplified methodology in capturing the impact of design and performance variations on noise generation. Indeed, the same standard take-off and landing flight path specified in the ANP database for Concorde (Figure 11) have been simulated for both case studies to focus only on the effect due to aircraft and engine design and performance rather than flight procedures modification. Distance, altitude, thrust setting and True Air Speed (TAS) data are provided by this set of ANP fixed-point flight procedure. Specifically, the take-off path includes the cutback procedure, therefore after the climb segment the thrust setting is lowered and, consequently, the climb angle.

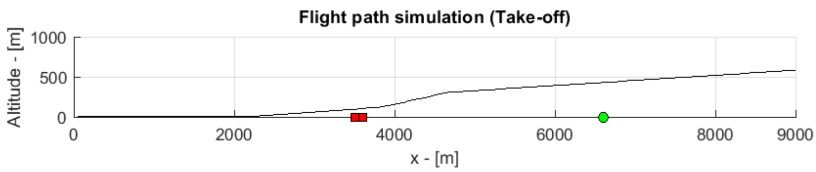


Figure 12 – Take-off procedure.

EPNL prediction at lateral and flyover measurement is presented in Figure 12. Significant EPNdB reduction, reaching almost -20EPNdB in single contribution, occurs for both measurement conditions. Looking in detail, the airframe noise level is the one that is lowered the least, while the fan noise is the most.

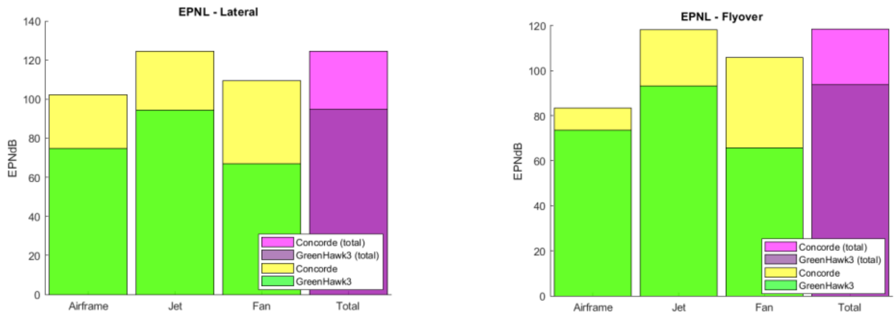


Figure 13 – Comparison between Concorde and GreenHawk3 EPNL measured during take-off procedure at a) Lateral noise measurement point b) Flyover measurement point.

Preliminary considerations can be drawn from these results. As expected, the absence of the afterburner, the reduced number of engines and the smaller configuration have a great impact on noise generation. It means that, for example, a target noise reduction of -20 EPNdB in cumulative noise level could be accomplished with design and performance parameters optimizations for supersonic aircraft since the beginning of the design process.

## 4.3 Sonic Boom for GreenHawk3

A comparison was made between Concorde and the GreenHawk3 in order to assess how differences in configuration can lead to more or less marked differences in sonic boom parameters. Case 1 was then carried out relating to the transition phase between subsonic to supersonic flight regime. The flight conditions were the same as previously discussed for Concorde. Case 2 was also analyzed in which there is a simultaneous change in Mach number and aircraft weight. The weight, following the indications provided by ASTOS was varied between 35000 kg to 25000 kg.

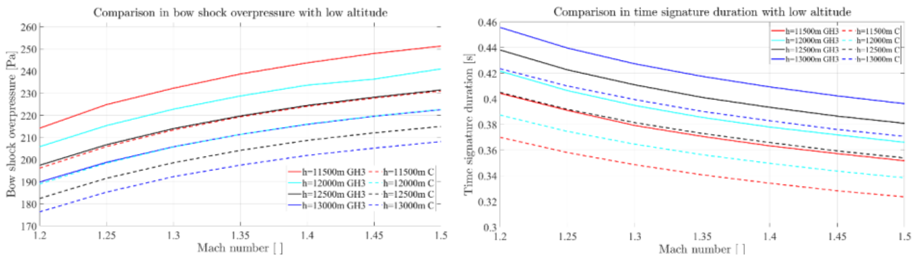


Figure 14 Case 1: Comparison in bow shock overpressure and time signature duration GH3 and Concorde

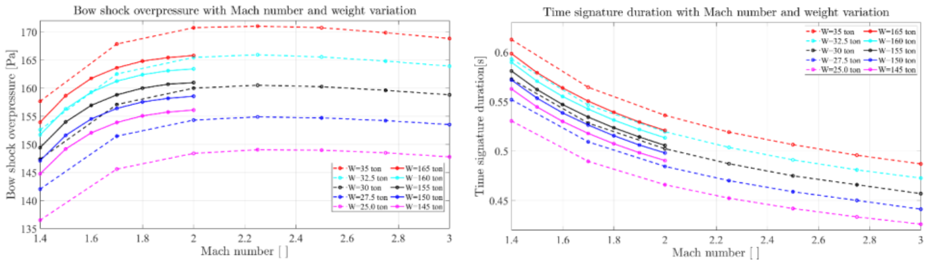


Figure 15 Case 2: Bow shock overpressure and time signature duration with Mach number and weight variation

As it can be seen from Figure 14, at low Mach number and low altitude, the value of both bow shock overpressure and time signature duration for the GreenHawk3 are higher than those from Concorde.

Regarding the variation of the two previous parameters when varying weight and Mach number, it can be seen that the trend is approximately the same.

## 5. Conclusions and Future works

## 6. Copyright Statement

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