Multi-fidelity approach for sonic boom annoyance

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Abstract. The following abstract aims at summarizing the multi-fidelity approach developed in the framework of the H2020 MORE&LESS project for the evaluation of sonic boom phenomena from a physical and psychoacoustic point of views for different aircraft configurations. Starting from the conceptual design phase, new analytical formulations shall be developed and validated to accurately define sonic boom without the necessity of having high time-consuming simulations. Then, once a 3D CAD model is available, numerical higher-fidelity simulations can be carried out. This step consists of both the near-field CFD and the use of a propagation code to propagate the shocks from the aircraft altitude to the ground. The H2020 MORE&LESS offers the opportunity to validate formulations and numerical results thanks to open-field test campaigns with small-scale aircraft models. Finally, having all information regarding the ground signature, a psychoacoustics code can be employed to define the annoyance caused by sonic boom comparing different noise metrics. Throughout the paper, the preliminary results available for a Mach 5 waverider configuration are reported.

Introduction

Over the past few decades, several initiatives have aimed to create a civil supersonic aircraft capable of succeeding the Concorde [1]

However, these endeavors have encountered significant hurdles, ranging from environmental concerns to economic viability, efficiency, and the challenge of mitigating the effects of sonic booms. One of the primary obstacles facing the development of the next generation of supersonic aircraft is the need to reduce the impact of sonic booms to levels acceptable to the general population. Since 1973, supersonic flight over land for civil aircraft has been prohibited due to the disturbance caused by sonic booms. Despite the absence of clear regulations for supersonic flight over land, NASA outlined objectives in 2011 for future supersonic aircraft, which included criteria for acceptable sonic boom levels. [2] In recent years, considerable advancements have been made in the start-of-the-art technologies aimed at minimizing sonic boom and ensuring criteria. The new generation of supersonic transport (SST) aims to establish standards of acceptability for supersonic flight over land during cruising phases and for noise levels during takeoff and landing operations near airports. [3] However, the most influential factors affecting the sonic boom are linked to the aircraft's shape, as well as flight parameters such as Mach number, altitude, weight, and flight path angle. In this context, the H2020 MORE&LESS project has been funded by the European Commission to develop a multi-fidelity approach that can swiftly and accurately predict the sonic boom signature of new aircraft designs from the conceptual stage becomes paramount. Nevertheless, during this phase of the design process, conducting sensitivity analyses is essential for thoroughly evaluating the sonic boom throughout the mission profile.

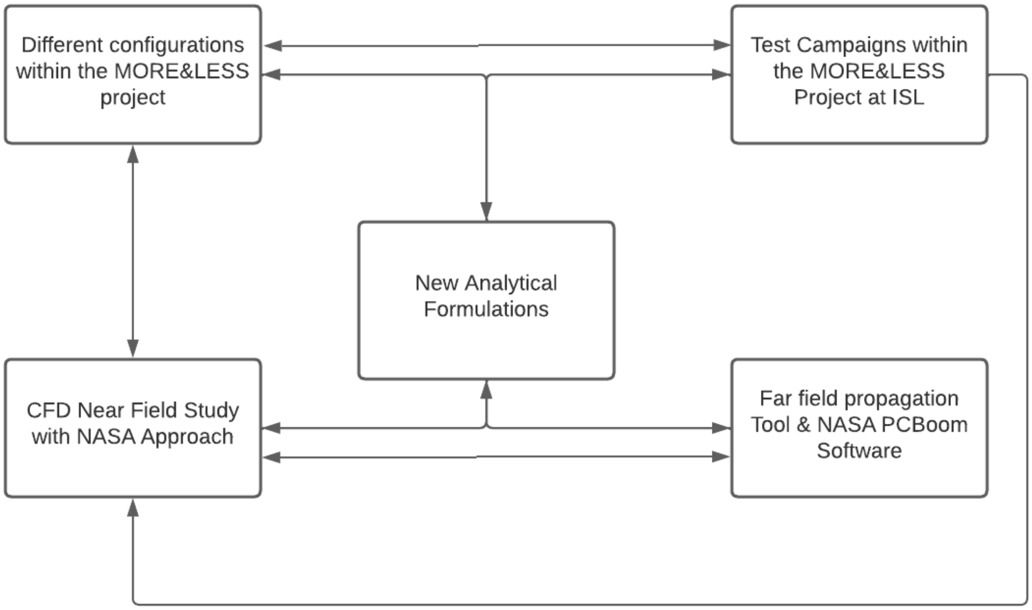

Figure 1: Scheme for New Analytical Formulations

Case study

In this framework, a mockup configuration used during a test campaign of one of the case studies of the MORE&LESS project is used. The experimental tests were carried out at ISL's facility in France. The original aircraft was re-scaled and suitably modified to meet the aerodynamic and structural requirements following the sabot separation. The final configuration possesses a mass of just over 500 grams, a length of 20.16 cm, with the center of gravity positioned approximately 11.2 cm from the aircraft's nose. The stability was evaluated both via CFD simulations and wind-tunnel tests. The results provided via CFD, and propagation tool are compared to the acoustic field microphones that are a Bruel & Kjaer 4938 ¼" microphones placed on the ground at different distances from the centerline. The results highlight a different behavior depending on roll angle region, with a global behavior in which the mean value increases with roll angle value.

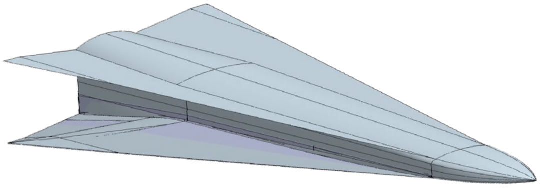

Figure 2: Model Used in the test campaign

Analytical formulations to evaluate sonic boom

There are many analytical models documented in literature that evaluate sonic booms during conceptual design phases. Among these, Carlson's simplified method [4] stands out as particularly renowned. This method offers a procedure for computing N-Wave sonic booms during steady flight or moderate descent/climb in a standard atmosphere. Its simplification lies in the reformulation of the Whitham F-function, which is approximated to a constant known as the aircraft shape factor. This factor varies based on the geometric and flight conditions of the aircraft. The first step in evaluating the sonic boom of a supersonic configuration using this methodology is the estimation of the equivalent area due to volume, which is the cross-sectional area normal to

the Mach cone. The following step is to define the equivalent area due to lift, which is approximated with the planform area distribution.
The final step consists in the combination of the two previous contributions to obtain the total effective area of the aircraft. With so, the evaluation of bow shock overpressure is written as:

$$\Delta p = K_p \cdot K_r \cdot \sqrt{p_v \cdot p_g} \cdot (M^2-1)^{\frac{1}{8}} \cdot h_e^{-\frac{3}{4}} \cdot l^{\frac{3}{4}} \cdot K_s \tag{1}$$

The time signature duration can be evaluated as:

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

Having the results of the experimental tests, validated with the numerical high-fidelity simulations, is possible to modify and improve the analytical formulations for better describing different configurations of supersonic and hypersonic aircraft.

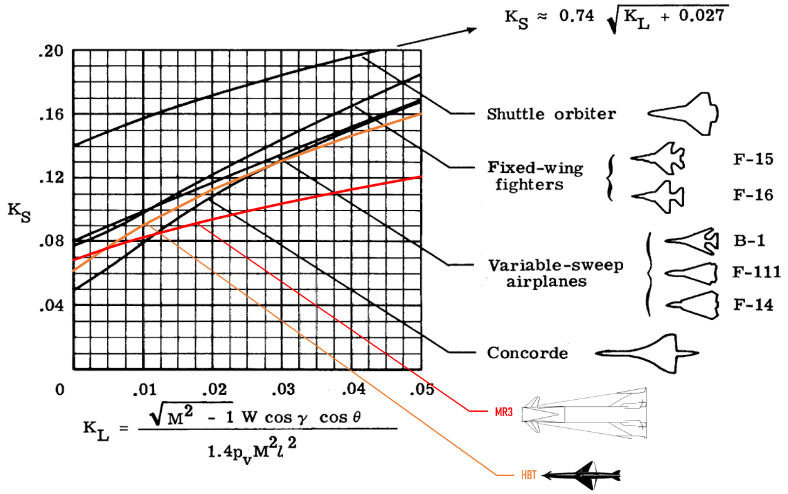

Figure 3:Modification of the Formulation for different test cases

Numerical high-fidelity simulations

Sonic boom prediction involves several complex physical phenomena, aerodynamics instabilities, pressure disturbances and high-speed aerodynamic flows. Numerical simulations provide an accurate estimation of the near-field aerodynamic perturbation. To accurately define the fluid domain and the nonlinearities for capturing the proper sonic boom signature, it is essential to have a proper numerical discretization and precision of advective terms.

Since 2014, NASA has been promoting the Sonic Boom Prediction Workshop [5-6-7], aimed at refining numerical methods for predicting sonic booms. The workshop's findings have paved the way for establishing guidelines on computationally forecasting noise generated by supersonic aircraft. Specifically, attention is focused on mesh strategies, including refinement and adaptation approaches, to accurately track discontinuities, demanding specific considerations. The computational grids topology adopts a hybrid methodology, comprising two distinct parts: an unstructured region close to the aircraft geometry and a structured segment for the distant domain. The unstructured portion resembles a cylinder integrated into the domain, while the structured section is constructed utilizing a blocking technique. The numerical elements are hexahedral in the structured part, tetrahedral in the unstructured zone, and pyramids to connect the two zones.

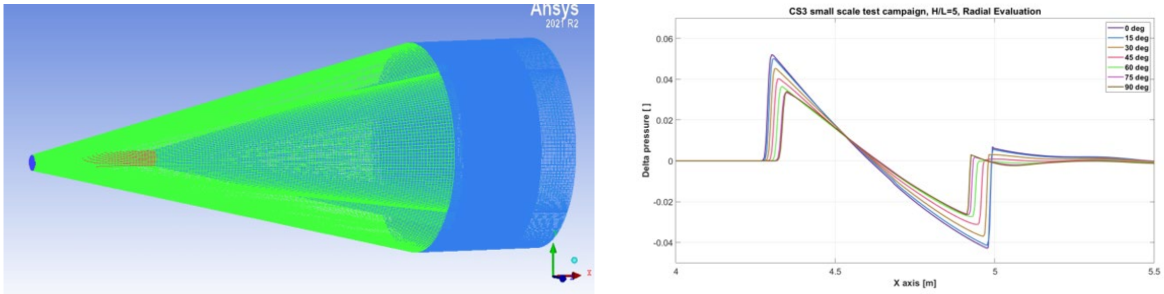

Figure 4: CFD Mesh and Signature H/L=5

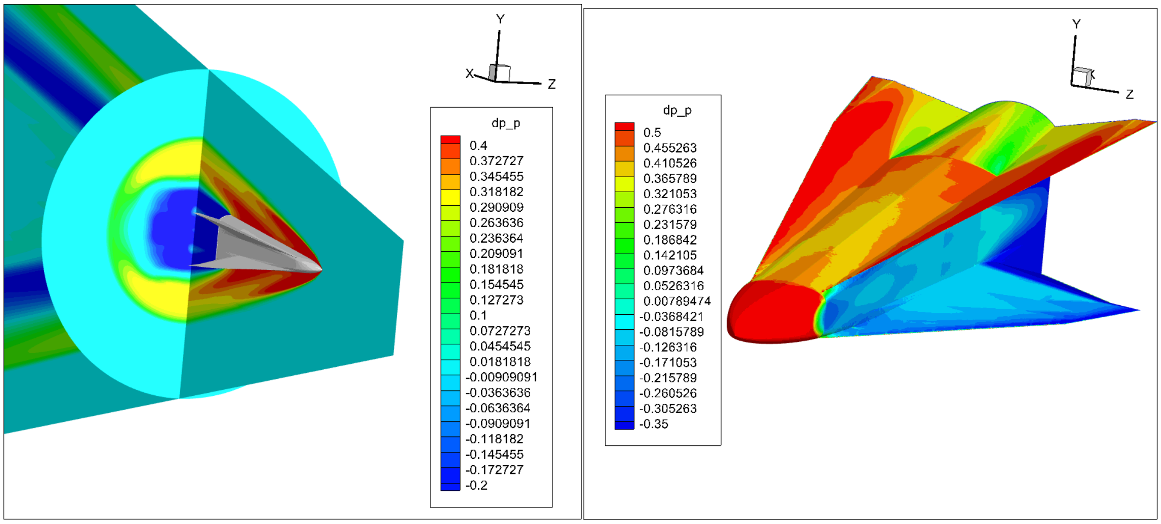

Figure 5: Contour of Delta Pressure distribution

To simulate the propagation of sonic boom shock waves reaching the ground, there is the need to employ a detailed far-field propagation algorithm. Unlike Computational Fluid Dynamics (CFD) simulations that focus on analyzing the pressure field around the aircraft, our tool prioritizes accounting for atmospheric inhomogeneities while neglecting wave refraction effects. It operates based on the Augmented Burgers Equation specifically formulated for sonic boom propagation, comprising a 1-D nonlinear wave equation assessed within the unidimensional realm of the acoustic ray.

Prior to simulation, acoustic rays must be determined using linear principles. The software utilizes the Augmented Burgers Equation to propagate the sonic boom shock waves along these acoustic rays, incorporating a stratified atmospheric profile encompassing pressure, wind, temperature, and relative humidity. Then it was able to derive pressure signature lines from CFD simulations conducted to evaluate local pressure near the aircraft. These signatures are extracted along lines parallel to the vehicle's trajectory, their positioning defined by azimuth angle ϕ and radial distance H. In preparation for propagation, a slight fading out is introduced at the end of the pressure signatures to ensure a smooth return to zero. Additional zeros, known as zero-padding, are inserted before propagation to optimize the computational process.

Annoyance metrics

The selection of proper noise metric for predicting human response to the low-amplitude sonic booms is the last key focus in the evaluation of the future impact of civil supersonic flights overland. The metrics that are currently under investigations include both engineering metrics, loudness metrics that considers the human perception of sounds and hybrid metrics that combines several metrics into one model.

An enroute Noise standard is the biggest challenge in supersonic aviation due to the requirements in new design approaches and due to the lack of relevant data to define limits.

Perceived Level has been widely used to describe the loudness of sonic boom and it is used as a target when optimizing supersonic aircraft and it works well in the explanation of human annoyance to outdoor booms. However, since man spend more than 70% of their time indoor, there is the need to define proper indoor metrics. Several alternate metrics have been proposed that treat lower frequencies differently, which is the critical point for the description of sonic boom noise.
In collaboration with University of Florida, a routine that will utilize prediction from the MOST program to analyze Sonic Boom metrics such as PL, ASEL, BSEL, DSEL, ESEL and ISBAP that employ post-processing routine to transform predicted sonic boom waveforms into annoyance metrics, thereby informing the design process.

In this paper, the steps for the evaluation of the Perceived Noise Level are highlighted using the Stevens Mark VII method [9]. In the method, the standard reference sound is defined as a 1/3 octave band centered at 3150 Hz. Starting from the band spectrum of noise, the procedure manages to predict the level of a reference signal that will be judged equal to the noise. Each band level is converted into a perceived value in sones, and the total perceived value is computed with a summation rule and converted in perceived level in dB called PLdB.

Having evaluate the sum of the perceived value for every sones, the final formulation for the calculation of the perceived level is:

$$P = 32 + 9 \cdot \log_2 S_t \tag{3}$$

Two plots of the procedure for the CS3 are viewed in Figure 6. In particular, the first one highlights the Sound Pressure Level (SPL) as a function of frequency for the various bands and the second one is Sonic Boom signature in the frequency domain. Since the extraction was made at H/L=3, the response is at high frequency compared to a classical signature on the ground.

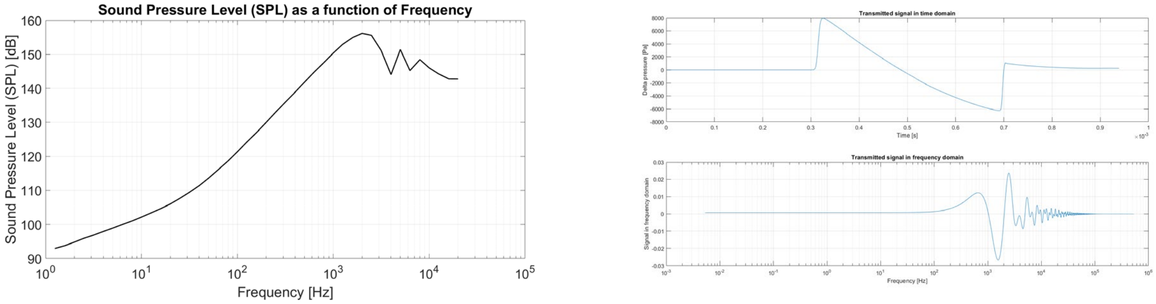

Figure 6: SPL and Frequency Spectrum of CS3 case study at H/L=3

The script is validated within a NASA test case for a low boom configuration as could be seen in Figure 7. However, in the NASA code, the application of a filter around 1000 Hz frequency is evident.

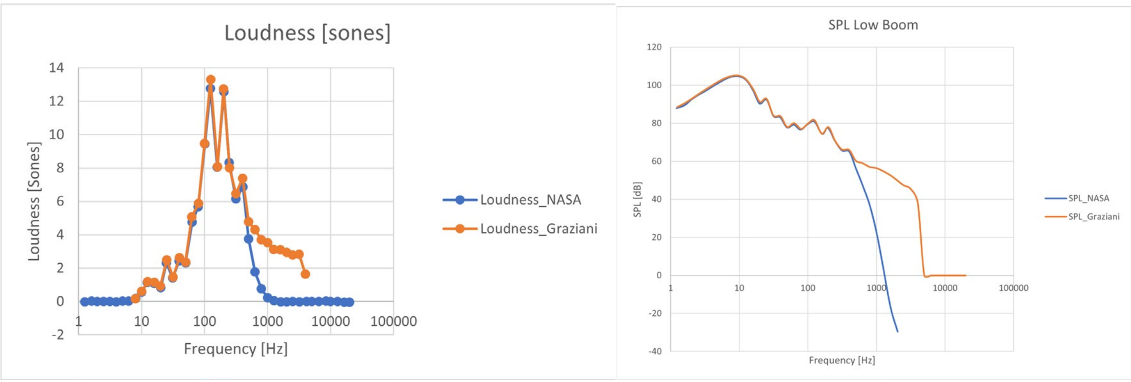

Figure 7:Psychoacoustic code validation with respect to NASA results

Conclusions

In the following paper, two methods for studying sonic booms are presented. The first consists of a low-fidelity analytical methodology adaptable to conceptual design, which does not require a high computational cost and does not require a large amount of data.

The second methodology consists of a high-fidelity study consisting of CFD for the near-field part near the aircraft, a propagation code based on the Augmented Burger Equation. Finally, for the second methodology, a psychoacoustic code was applied to assess the Perceived Noise Level according to Stevens' Mark VII method. The code was validated against an internal case study proposed by NASA.

The high-fidelity methodology could be replicated for any type of supersonic configuration, and a sensitivity analysis could be carried out to investigate the climate effects (such as humidity, temperature, winds) in the psychoacoustic response.

References

[1] B. Liebhardt, K. Lütjens, An Analysis of the market environment for supersonic business jets, 2011

[2] Advanced Concept Studies for Supersonic Commercial Transport Aircraft Entering Service in the 2030-2035 Period, 2011.

[3] Y. Sun, H. Smith, Review and prospect of supersonic business jet design. Progress in Aerospace Science, 2017, Volume 90, pages 12-38. https://doi.org/10.1016/j.paerosci.2016.12.003

[4] H. Carlson, Simplified Sonic-Boom Prediction, NASA technical paper 1122, 1978

[5] M. Park, J. Morgenstern, Summary and Statistical Analysis of the First AIAA Sonic Boom Prediction Workshop, 2014. https://doi.org/10.2514/6.2014-2006

[6] M. Park, M. Nemec, Nearfield Summary and Statistical Analysis of the Second AIAA Sonic Boom Prediction Workshop, Journal of Aircraft, Vol. 56, No. 3, 2019, pp. 851–875. https://doi.org/10.2514/1.C034866

[7] M. Park, M. Carter, Nearfield Summary and Analysis of the Third AIAA Sonic Boom Prediction Workshop C608 Low Boom Demonstrator, 2021. https://doi.org/10.2514/6.2021-0345

[8] S.S. Stevens, Perceived Level of Noise by Mark VII and Decibels (E), Journal of Acoustic Society of America, Vol 51., 575-601, 1972. https://doi.org/10.1121/1.1912880