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Sonic boom CFD near-field analysis of a Mach 5 configuration

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Abstract: The following paper compares experimental results obtained in free flight at Mach 4.7 within the MORE&LESS project of a configuration at Mach 5 with high-fidelity simulations based on CFD and propagation tools. The simulations replicate the flight and environmental conditions of the test days, and the CFD approach is based on dedicated workshops by NASA for accurate near-field study. Measurements are compared with CIRA acoustic microphones and contains four different stations positioned at a maximum of ten meters from the centreline of the trajectory.

Introduction and background

The world of civil aviation has changed dramatically over the past few decades. While traveling thousands of miles in a few hours has become easier and more affordable than a few decades ago, traveling faster than the speed of sound is in the air. 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.

As a result of recent technological advances for the second generation of supersonic civilian aircraft and given the future entry into service of the BOOM Overture aircraft, there is a need to set new standards regarding supersonic flight over the land for civilian aircraft purposes. Since 1973 commercial supersonic overland flight is prohibited in most countries, and the ability to break down this constraint is vital to the commercial success of the second generation of supersonic aircraft. Changing the current ban on supersonic flight overland with an international regulation with a noise emission ceiling is one of the goals of the industry itself. However, there is a need to accurately identify both the methods for calculating the noise emitted on the ground and to determine what the limit of acceptability might be to impose so as not to create excessive annoyance to the population. The following paper demonstrates the veracity of the methodology used to compute the grid by reproducing the experimental tests that were carried out at ISL, which is a partner of the MORE&LESS project in October 2022.

Sonic Boom Description and methodology in conceptual design phase

Any object traveling faster than the local speed of sound generates a disturbance in the atmosphere. Theoretically, for slender configurations, this phenomenon is governed by the linearized supersonic flow theory and computed from the supersonic area rule methods. On the other hand, for blunt bodies, such as a space shuttle, the aerodynamic flow is nonlinear, and the computation of the near field from the theoretical point of view is much more complex than in the previous case. [1,2,3,4]

The disturbance that is generated propagates through the atmosphere: in the region in the vicinity of the aircraft, there is the "near field" zone, in which the signature is a function only of the geometric characteristics and flight conditions of the vehicle and extends for a couple of lengths below the aircraft itself. In this small region, the atmospheric gradients do not have a significant role. In the "midfield" area the signature is a function of both geometric characteristics and disturbances related to atmospheric effects, in which there are significant nonlinear distortions of

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the signature itself, finally, in the "far field" region the signature is a function of the propagation in the real atmosphere and has the typical N-wave shape. For a classical supersonic aircraft configuration, there is an initial compression at the nose of the aircraft in which the local pressure increases from p_0 by an amount Δp. Following this first compression, there is a slow expansion occurs until there is a pressure value slightly lower than atmospheric, and finally, at the tail, there is a new compression that re-establishes the local pressure value. For a ground observer, the acoustic response of the ear is composed of two different booms as the human ear can detect changes beyond a specific frequency, and it manages to identify sudden changes in pressure. If the interval between those two rapid compressions is below 0.10 seconds, the ear would not be able to distinguish between them, and they would seem like one single sound.

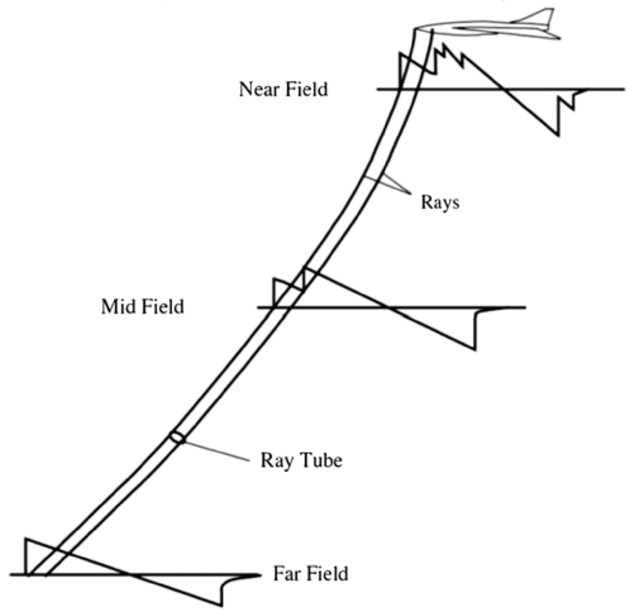

Figure 1: Sonic boom propagation through the atmosphere

In the slender body acoustic limit theory [5] , the near-field pressure can be calculated as:

$$\delta p(x-\beta r, r) = p_0 \cdot \frac{\gamma M^2 F(x-\beta r)}{\sqrt{2\beta r}} \tag{1}$$

In equation (1) δp is the overpressure with the wave, p_0 is the ambient pressure, x is the axial coordinate in body fixed, γ is the ratio of specific heats, M is the Mach number and $\beta = \sqrt{M^2-1}$. The quantity F is the acoustic source strength, it is based on linearized supersonic flow area rule theory and can be evaluated as:

$$F(x) = \frac{1}{2\pi}\int_0^x \frac{A''(\xi)}{\sqrt{x-\xi}} d\xi \tag{2}$$

In equation (2) A is the cross sectional area of the vehicle along cuts aligned with the Mach angle. Some early methods for studying sonic boom were based on Walkden's theory and involved a simplified study of the atmosphere. One formulation used for volume-induced sonic boom is:

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

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In equation (3) K_r is the ground reflection factor and it is equal to 2.0, K_S is the aircraft shape factor, D is the aircraft equivalent diameter, p_v & p_g are the ambient pressure at the vehicle altitude and on the ground. The $\sqrt{p_v p_g}$ factor is the consideration to the fact that atmosphere is not uniform, while a complete adjustment for the atmosphere uses the theory of geometric acousticsAnother simplified model for the complete study of sonic boom is given by Carlson's method. It manage to study the sonic boom characteristics concerning both bow shock overpressure and time signature duration for different configurations for aircraft flying at an altitude of up to 76 km.[6]

The method contains many limitations and is easily applicable in the conceptual design phase to get an indication of the order of magnitude of the shock intensity. The methodology is valid for aircraft in level flight or moderate climb or descent flight phases, the effect of flight path curvature and acceleration is neglected, and it is just applicable for the classical N-wave in the far-field region. The formulation for the maximum bow shock overpressure is :

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

Where K_p pressure amplification factor, K_r is the ground reflection factor, h_e is the effective altitude and K_S is the aircraft shape factor. The formulation for the time duration is equal to :

$$\Delta t = K_t \cdot \frac{3.42}{a_v} \cdot \frac{M}{(M^2 - 1)^{\frac{3}{8}}} \cdot h_e^{\frac{1}{4}} \cdot l^{\frac{3}{4}} \cdot K_s \tag{5}$$

Where K_t signature duration factor and a_v is the local speed of sound.
The core of the methodology is the calculation of the constant related to the shape factor: the first step is the calculation of the equivalent area due to volume, which can be defined with the cross-sectional area of the aircraft along the longitudinal axis. The second step involves the evaluation of the equivalent area due to lift, which can be calculated as the distribution of planform area along the longitudinal axis. The third step is the combination of these two measurements to obtain the total effective area of the aircraft, from which it is possible to go on to derive some parameters for deriving the shape factor, such as maximum effective area $A_{e_{max}}$and the effective length l_e.

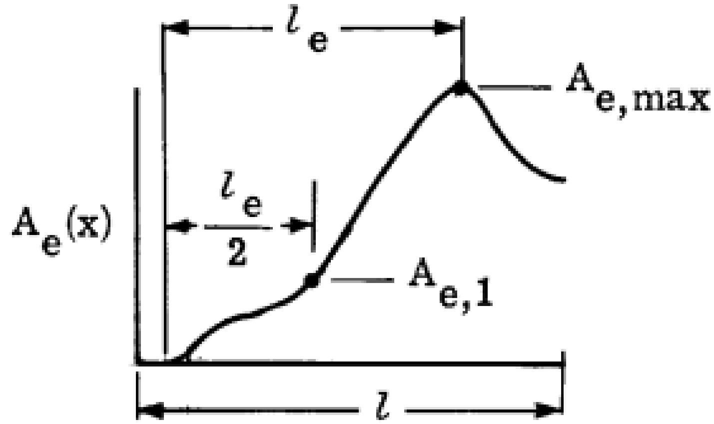

Figure 2 : Calculation of the effective area

In the final step, the aircraft shape factor may it is found by specific shape factor curve with the insertion of appropriate maximum effective area and effective length.

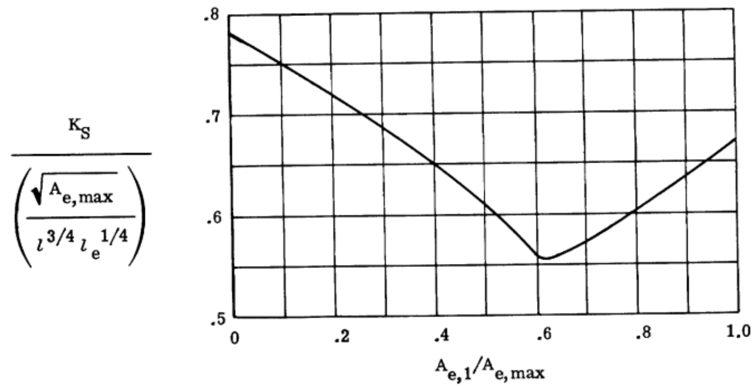

Figure 3 : Shape factor charts

Within the method, all the parameters of equations 4 and 5 can be calculated from dedicated graphs that are a function of Mach and altitude.

CFD mesh

As previously mentioned, supersonic flight over land is prohibited, and for there to be a chance for the economic success of the second generation of the supersonic vehicle there is a need to carefully define a standard in terms of regulations by imposing a maximum noise level. The study of the evolution of sound disturbance is usually divided into different regions to facilitate calculation. The area in the vicinity of the aircraft where shocks are formed and where there are numerous nonlinear phenomena such as shock-shock interactions, shock curvature, and crossflow is evaluated within Computational Fluid Dynamics (CFD). [7] However, it is impossible to study by CFD down to the ground because of the size of the domain and consequently, the large computing power required, so dedicated propagation models exist for detailed study. However, they need as input the results processed in the near-field region obtained by CFD.

In these sonic boom propagation methods, the details of the configuration geometry are less important than atmospheric variations and molecular relaxation phenomena. Particularly for the study of both the near field region and propagation methods, NASA, since 2014 has been conducting dedicated workshops every three years related to the study of these methods and verifying the goodness of the results by comparing the obtained data with wind tunnel values. For the case study, it was decided to follow the directions and suggestions of the last workshop for the creation of the grid: in particular, there is the creation of a hybrid one, with an unstructured core and a second region with a structured mesh. Concerning the structured mesh, there is an extrusion from the unstructured mesh of a series of layers to produce the grid elements that are aligned to the freestream Mach angle μ:

$$\mu = sin^{-1}\left(\frac{1}{M}\right) \tag{6}$$

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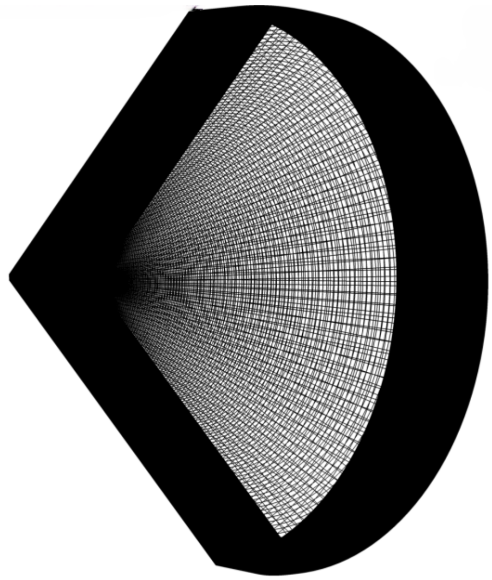

Figure 4 : Example of a CFD sonic boom grid

Case study

The near-field CFD simulations are based on one of the aircraft being studied within the MORE&LESS project and for which experimental data are available. Specifically, the aircraft is an appropriately scaled model of the MR5 aircraft, which consists of a re-design of the MR3 aircraft. For the MR5 aircraft, except for the length, all other dimensions are kept constant to the original configuration. In this way, the layout of the vehicle is modified, since its slenderness parameter is now different.

The final configuration of the MR5 aircraft has a length of 75 meters with a wingspan of 41 meters an MTOW of about 290 tons.

Figure 5 : MR5 aircraft configuration

As already mentioned above, the geometry that was studied by CFD is the same that was used in the experimental tests. This geometry, compared to the original configuration, is modified to avoid asymmetric lifting effects during the free-flight tests. First, the canards and the fins are removed. To maintain the bottom contour, which is responsible for the later investigated sonic-boom signature symmetry is obtained by mirroring the lower part to the top, which leads to a plane-symmetric model with no lift generation at zero angles of attack.

The model that is studied has the following characteristics:

I. Mass equal to $501.7\ g$
II. Length of $201.5\ mm$
III. CG/Nose of $104.2\ mm$
IV. Reference base surface $895.34\ mm^2$
V. Equivalent base diameter $33.76\ mm^2$

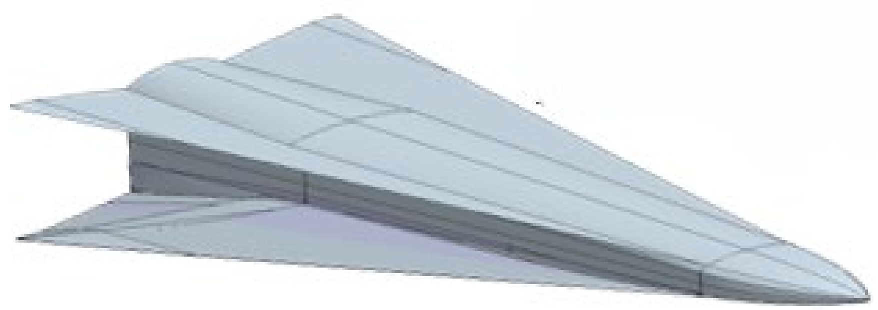

Figure 6 : Test case

The flight conditions that are studied by CFD are those of experimental tests, specifically the Mach number studied is 4.7 and the angle of attack is 0 deg. The geometry is modeled with the CAD program Solidworks and the meshes are generated with ICEMCFD 2020 R2. Regarding the mesh structure, as previously mentioned, the philosophy adopted during the NASA workshops devoted to the study of the near field for the sonic boom was followed. Thus, an inner cylinder formed by an unstructured mesh was constructed, in which the size of the elements is 10^{-3} m for the elements discretizing the surface of the aircraft and $4 \cdot 10^{-3}$ m for the elements of the cylinder itself: the total number of elements in the unstructured mesh is just over 8.5 million.

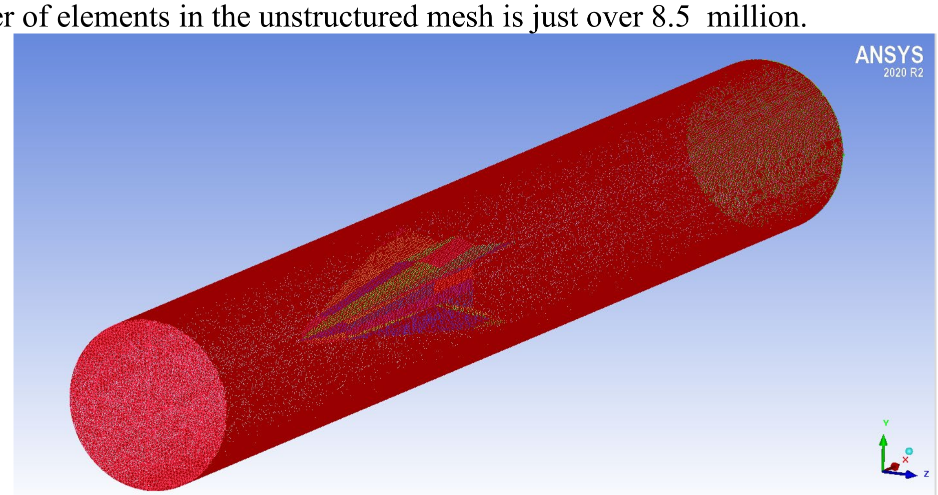

Figure 7 : Unstructured mesh with the particular of the aircraft

As for the generation of the structured mesh, 12 blocks were created for the correct description of the elements at a greater distance from the body.
Care was adopted for the generation of the structured part, to avoid the problem of the mesh interface.
The total number of elements in the structured mesh is just above 15 million.

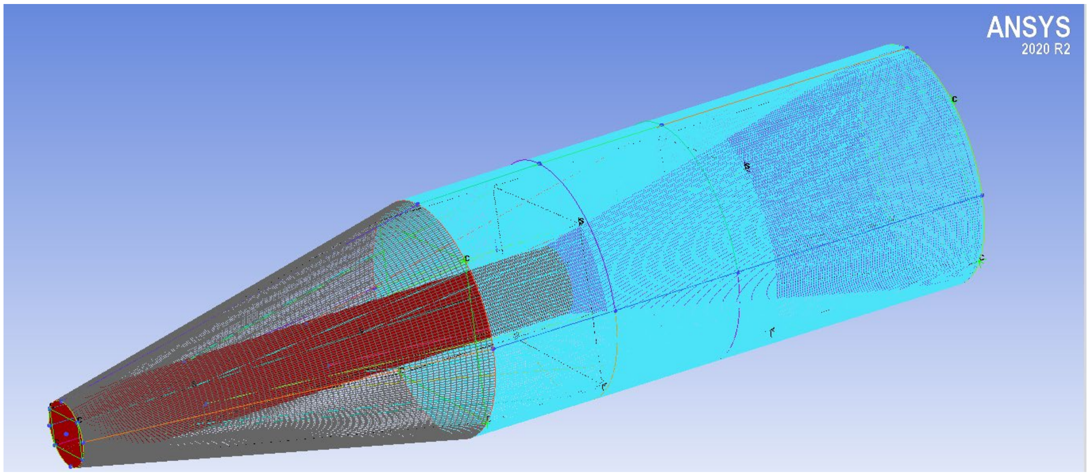

Figure 8 : Structured mesh aligned with Mach angle

Finally, the merge between the two meshes was performed going to create the interface surface, and after performing the necessary checks on the quality of the grid, the total number of elements is about 22.5 million.

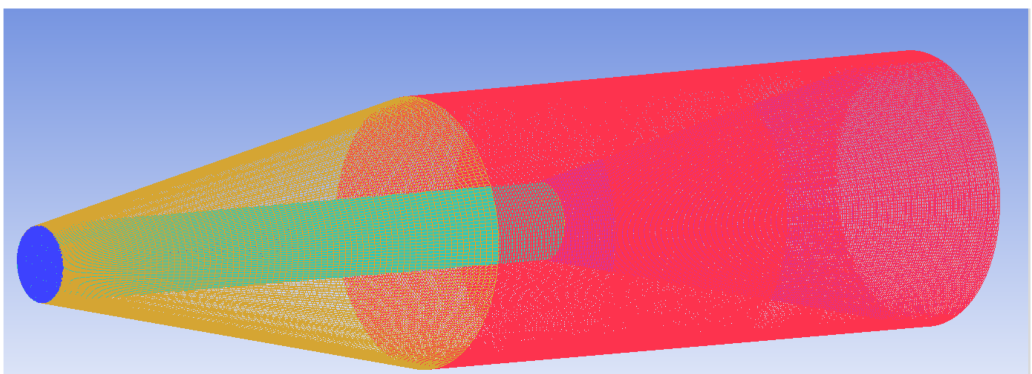

Figure 9 : Final mesh

The numerical simulations will be performed with the finite volume code ANSYS FLUENT version 2021R1. As for the simulation, the implicit, density-based solver with double precision is used, and the fluid is considered an ideal gas. The first simulations to be studied are those related to the test carried out at ISL: specifically, the Mach number is kept equal to 4.7. The reference flight altitude was about 2 meters in the tests performed. It will also have the calculation of drag, lift, and moment coefficients to have a comparison with the results obtained through the use of an alternative CFD approach based on only unstructured elements performed by ISL.

Conclusion and future work

This paper aims to demonstrate the veracity of the methodology proposed within the workshops organized by NASA related to the study of sonic boom in the near field region through comparison with experimental data from ISL. Due to the low flight altitude at which the flight tests were conducted, there is no need to adopt a propagation code for the study of the evolution of sonic disturbance in the atmosphere. For future case studies, the following method through CFD will be adopted to study the near field region of other configurations within the MORE&LESS project, and using specific propagation codes, it will be possible to have the creation of databases regarding the sonic boom of different types of aircraft having very different mission profiles and cruise Mach numbers.

The propagation code is currently studied by partners within the MORE&LESS project (TUHH) through the "Propaboom" code that can study the acoustic propagation for loudness determination on the ground based on the Augmented Burgers Equation. It requires the nearfield signature obtained by CFD and can evaluate the propagation considering the variations through the atmosphere of temperature, pressure, horizontal winds, and relative humidity.

Finally, from the use of high-fidelity simulations and code, within the creation of databases of numerous aircraft differing in characteristics, configuration, range, and Mach number, there will be the creation of low-fidelity surrogate models suitable for estimating the sonic boom of new aircraft from the conceptual design phases.

References

[1] K. J. Plotkin, State of the art of sonic boom modeling, © 2002 Acoustical Society of America. https://doi.org/10.1121/1.1379075]

[2] D. J. Maglieri, K. J. Plotkin, Aeroacoustics of Flight Vehicles: Theory and Practice. Volume 1: Noise Sources , 1991

[3] Y. S. Pan, W. A. Sotomayer, Sonic Boom of Hypersonic Vehicles, AIAA Journal, 2012, https://doi.org/10.2514/3.50150

[4] R. Cowart, Developing noise standards for future supersonic civil aircraft, 2013 , https://doi.org/10.1121/1.4800343

[5] H.W. Carlson, D.J. Maglieri, Review of Sonic-Boom Generation Theory and Prediction Methods, The Journal of the Acoustical Society of America, 1972, https://doi.org/10.1121/1.1912901

[6] H.W. Carlson, Simplified Sonic Boom Prediction, TP1122, 1978

[7] M.A.Park, R.L.Campbell, A. Elmiligui, Specialized CFD Grid Generation Methods for Near-Field Sonic Boom Prediction, AIAA Journal, 2014