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EDF SILENT project: towards a European hypersonic quiet tunnel

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Abstract

The SILENT project is a new research initiative backed by the European Defence Fund. Its main objective is to enhance the EU hypersonic testing capabilities by designing hypersonic quiet wind tunnels. Such state-of-the-art facilities are crucial to replicate the flight conditions of hypersonic cruise and re-entry vehicles, for which traditional wind tunnels fail to generate correct free-stream disturbance levels. By focusing on both low-enthalpy and the more challenging flight-enthalpy quiet tunnel designs, SILENT addresses a strategic, technological and operational need in the EU defense and research sector. This paper outlines the project goals, its methodology and expected outcomes, while covering the links to application requirements and to the current state-of-the-art. The potential for disruptive innovation in hypersonic technologies, enhanced vehicle design capabilities and strengthened European defence and civil R&D collaborations are highlighted.

Keywords: *Hypersonic, Transition, Stability*

1. Introduction

The development of hypersonic vehicles (Mach number higher than 5) is strategically vital for advancing aerospace capabilities in both defense and civil sectors. Such complex vehicles require mastering various key technologies, including aerodynamic prediction tools and thermal protection systems, which are strongly impacted by the state of the boundary layer – the thin region close the wall in which flow viscosity plays an important role. A transition may occur from an initially stationary/smooth boundary layer (i.e. laminar) to a chaotic/unsteady one (i.e. turbulent). The transition process is initiated by the amplification of external disturbances of various kinds (roughness, sound waves, free-stream turbulence, etc.); when these disturbances reach a certain energy threshold, transition occurs. While a turbulent boundary layer produces larger friction and heat flux, a laminar boundary layer is more sensitive to flow detachment over complex geometries. Hence, maintaining a laminar flow is beneficial for increasing the payload and reducing the thermal protection, while triggering a turbulent flow is of interest in regions where flow separation can dramatically affect vehicle performance. The latter may occur inside intakes of air-breathing concepts, or on top of glider control surfaces as shown in figure 1.
Studying the transition phenomenon has therefore become essential in the race to design hypersonic vehicles in order to predict transition location and develop control technologies which are crucial for improving both external and internal aerodynamics, reducing design margins, and minimizing the risk of mission failure. However, studying and mastering the transition phenomenon requires numerous and reliable experimental databases generated from flight experiments or ground hypersonic test facilities. Although potentially less costly and less complex to realize than flight tests, experiments in classical

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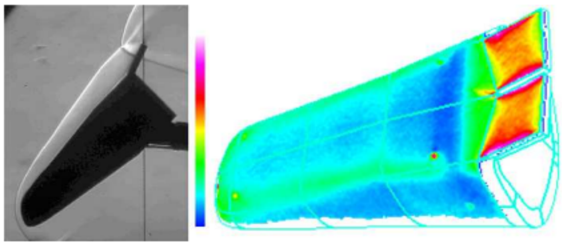

Fig 1. Illustration of the impact of transition and shock-boundary layer interactions on control surfaces on the pre-X vehicle. Reprinted from [5].

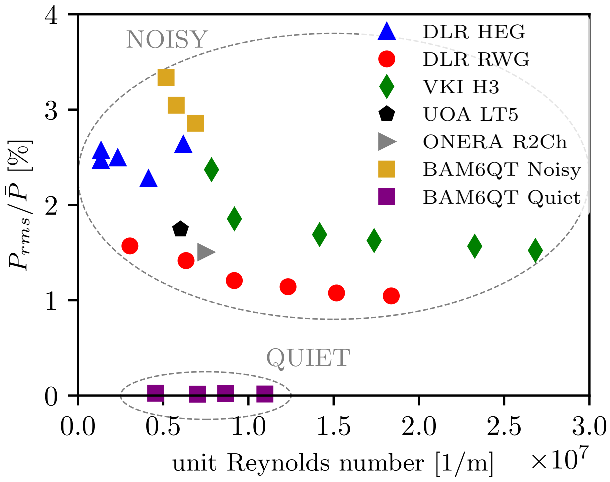

Fig 2. Level of free-stream pressure fluctuation in various hypersonic wind tunnels, highlighting the differences between quiet and conventional facilities. Data points from [25], [32] and [35].

wind tunnels are unable to reproduce the free-stream turbulence levels present in high-altitude flight. As noise levels directly influence the transition phenomenon (location, physical mechanisms, etc.), quiet wind tunnels (i.e. wind tunnels with very low free-stream turbulence levels, see figure 2) are essential in order to reproduce as faithfully as possible the transition processes observed in flight.

Low-noise facilities do not yet exist in Europe, but their importance can be inferred from the fact that quiet tunnels have been operating for some time in the US [3, 30], and since more recently in China [12]. None replicates the Reynolds number nor the enthalpy levels encountered during flight. Several other facilities are currently planned in the US, highlighting their crucial role in fundamental research but also for validating the required tools to design high-speed vehicles. Furthermore, quiet tunnels ease the development of highly competitive hypersonic vehicles as multiple solutions for subsystems such as control surfaces, air-inlet, propulsion systems, etc. can be developed and tested in representative environments. This, in turn, allows to greatly reduce the design margins, which strongly benefits the overall performance of the vehicle. Finally, quiet tunnels also facilitate the design and validation of disruptive vehicle concepts that could strongly be impacted by boundary layer transition.

The physical mechanisms at play in the free-stream turbulence generation process within wind tunnels are complex, as illustrated in figure 3. Building a quiet tunnel requires a deep understanding of these processes on the one hand, and the essential know-how on how to control them on the other hand. A prerequisite to quiet flow generation is the ability to maintain a laminar boundary layer along the nozzle wall in order to suppress the noise radiated by an otherwise turbulent boundary layer – see figure 4. Avoiding such transition has to be achieved whilst generating unit Reynolds numbers in the central region of the nozzle outlet that are representative of flight conditions. The two requirements act in opposite directions, since higher Reynolds numbers in the core region also increase the strength of the instabilities in the boundary layer at the nozzle wall. To overcome this challenge, critical research activities are still necessary to enable the design and construction of the first European quiet hypersonic tunnel. Furthermore, studying the laminar-turbulent transition in conditions similar to flight should further require a flight enthalpy, quiet hypersonic tunnel. Such a concept poses formidable challenges, and the current solution involves building at least a low-enthalpy quiet tunnel that allows simulating

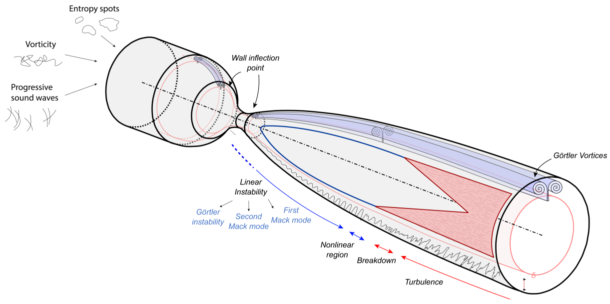

Fig 3. Free-stream disturbance sources in hypersonic wind tunnels. The eddy-Mach-wave radiation from the turbulent boundary layer on the nozzle wall is known to be the dominant noise source in hypersonic wind tunnels. Inspired from [30].

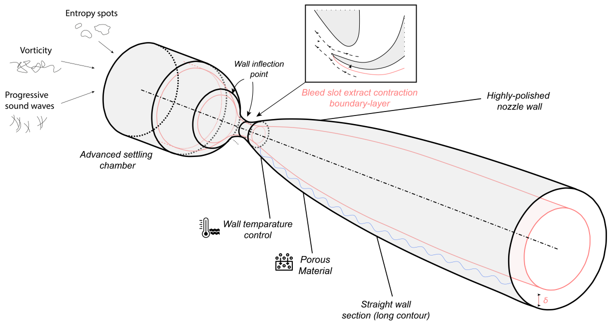

Fig 4. Example of a quiet wind tunnel nozzle design.

transition without the enthalpy effects.

2. The example of US facilities

The main examples of development and exploitation of quiet facilities as of today come from US-based facilities.

The best example in the literature is the BAM6QT Ludwieg tube at Purdue, which was developed by S.P. Schneider from 1996 onwards with funds from Boeing and the AFOSR. He benefited from the experience of earlier researchers from NASA Langley (mainly I.E. Beckwith, S.P. Wilkinson and F.J. Chen), but still required several years of sustained efforts and financial support before meeting with success – first run in 2001 yet first quiet run in 2005. Schneider has extensively documented the design, manufacturing, commissioning, characterization, and operation of this tunnel. An excellent summary is provided in [30]. The highest quiet Reynolds number reached by the facility seems to have fluctuated during the life of the facility, with major increases linked with re-machining and re-surfacing of different parts of the facility such as the nozzle throat and the boundary layer bleed lip. A key takeaway point from the BAM6QT development and operation is that one should be very careful regarding the machinability of the different components, the availability of subcontractors with the necessary know-how and the fact that supplied components meet the required specifications.

Another example is the ANDLM6QT at the University of Notre Dame [21]. One key approach used for the design of this tunnel was the adoption of a larger nozzle diameter, deliberately chosen to overcome a

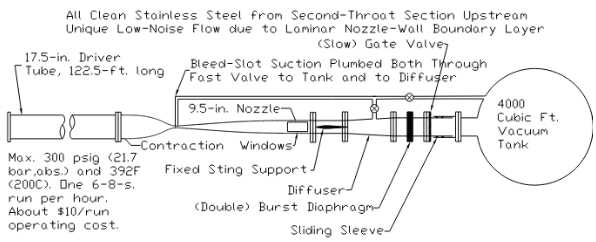

Fig 5. Schematic of the BAM6QT. Reprinted from [30].

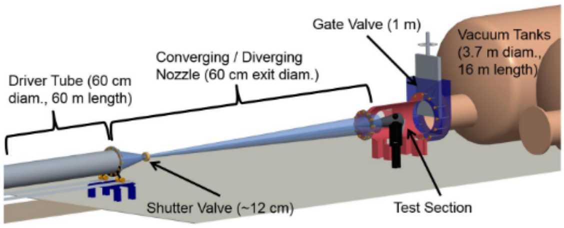

Fig 6. Schematic of the ANDLM6QT. Reprinted from [21].

recurring technical dilemma. Typically, increasing the Reynolds number (needed to simulate hypersonic transition), is achieved by raising the stagnation pressure. However, this classical approach inevitably leads to a decrease in the allowable roughness height at the nozzle throat, required to prevent boundary layer tripping and hence tunnel noise. By opting for a larger nozzle diameter, they were able to aim for high Reynolds numbers without resorting to a pressure increase yet staying in the range of achievable throat roughness. One key difference between the Notre-Dame Ludwieg tube and the Purdue one is the fact that the tunnel is "upstream started", meaning that the device separating the region at stagnation conditions from the one at vacuum conditions before the run is located upstream of the throat of the nozzle and thus upstream of the test section (see figures 5 and 6). This has numerous advantages, the main one being the use of an open jet test section. This in turn allows for the use of large and low-cost optical accesses, larger blunt models as well as a wider range of instrumentation. However, the upstream starting valve becomes one of the key elements of the tunnel. In the case of a Ludwieg tube, it must be placed as close as possible to the throat to feature suitable starting time and flow quality [18]. Both the opening time of the valve and the surface quality of the flow-through section once the valve is open become critical, as disturbances generated by the valve will directly impact the nozzle boundary layers. The operation of this upstream valve seems to have been one of the major blocking points for quiet operation of the facility [16].

Both given examples are Ludwieg tubes, a design choice that appears to be mainly driven by the cost of the facility [21] and not by requirements linked with quiet tunnels. A good example of a quiet blowdown facility is the Texas A&M Mach 6 tunnel (M6QT), which was previously built and operated at NASA Langley. While its current status is unknown as the nozzle seems to be in the process of refurbishing, quiet core Reynolds numbers up to 11 million per meter have been documented in the literature, making it the second highest Reynolds number for a quiet hypersonic facility. The use of a blow-down system, with a settling chamber between the starting valve and the test section, is also a way to alleviate the constraints linked to the valve itself. In addition, significantly longer test times can typically be achieved with a blow-down facility.

Other bigger projects in the USA for the development of hypersonic quiet tunnels include a Mach 8 tunnel in Purdue [17] and a Mach 10 tunnel in Notre Dame [2].

3. Possible improvement of the design methodology

Since the development of the two facilities detailed previously, both software and hardware improvements have opened up new possibilities in terms of computational design and optimization of quiet nozzles.

First, systematic and automated Navier-Stokes computations of the full laminar baseflow have become affordable. Although this may not be a game changer for nozzle profiles where the combination of the method of characteristics and a boundary layer solver proved very reliable, it expands the possibilities in terms of bleed lip design, for instance, which was found to benefit from full Navier-Stokes computations in the case of BAM6QT [31, 1]. Furthermore, computations on partitioned unstructured grids are now commonplace in open-source CFD tools, with adjoint-based shape optimization proving successful in tackling increasingly more complex aerodynamic problems [24].

With respect to stability tools, a full range of methods are now available to complement local linear stability (LST). Linear and non-linear parabolized stability equations (PSE) solvers have gained widespread use [13] while resolvent analysis is being increasingly found in hypersonic flow studies [22, 29, 33]. Moreover, new stability metamodels are also being developed that could drastically reduce the cost of stability computations and, more importantly, facilitate the automation process of computing the growth rate and N factors of the instabilities at play [27].

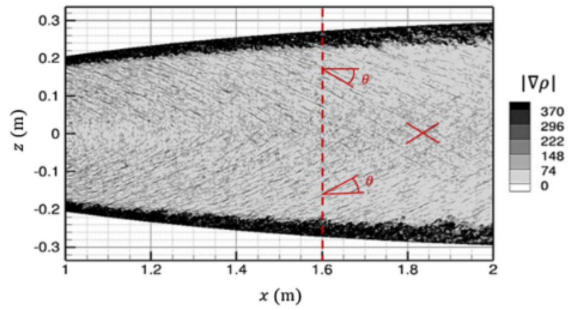

Fig 7. DNS of a turbulent hypersonic nozzle. Reprinted from [14].

Those metamodels could be used to perform fast gradient-free optimizations. Avoiding gradients can prove beneficial whenever a simulation code cannot be differentiated, for instance, or when the multi-dimensional domain in which a global minimum is searched has a large number of local minima. In such cases, efficient global optimization (EGO) methods have been successfully put to use [19], or subsequent evolutions thereof [9]. Mesh adaptive direct search [20] and Bayesian optimization with Gaussian process regression [26] are another two examples of gradient-free methods that have proven useful in the context of costly simulations. In addition to gradient-free approaches, newly available fully differentiable stability tools based on algorithmic differentiation [28] open up the possibility to conduct adjoint-based optimization of nozzle profiles, bleed systems and wall temperature control while taking into account all the possible instability modes that could lead to transition.

The progress in computational tools has taken place concurrently to that of computational resources. To best illustrate this point, it suffices to say that direct numerical simulations (DNS) of fully turbulent nozzle flows have been carried out over recent years [10, 15] (see figure 7), albeit at a cost which remains prohibitive for nozzle design and optimization purposes. A final nozzle design, however, could potentially be simulated with DNS in the near future for validation purposes. Beyond validation of quiet flow design, DNS also opens the door to a finer understanding and quantification of the acoustic noise radiated in conventional facilities.

Another recent development that could be leveraged relates to acoustic metasurfaces. They have been known to delay the onset of hypersonic transition when the latter is predominantly caused by the second Mack mode instability [11, 34]. Several mathematical models to capture the frequency-dependent absorptive properties of acoustic metasurfaces exist in the literature, as well as computational tools to include their effect - see for instance [37], [36] and references therein. This technology is one among several that could potentially improve design methodologies employed in the past.

4. Increasing enthalpy

It is common practice in many hypersonic wind tunnels to base the choice of the reservoir temperature to a level that is barely sufficient to prevent liquefaction during expansion through the nozzle. The resulting stream of working fluid may match the flight Reynolds and Mach numbers, yet the enthalpy levels are much lower than typically encountered during the flight, as shown in figure 8. This mismatch between ground and flight enthalpies, and hence temperatures, is certainly found in all hypersonic quiet tunnels built to date, and follows from practical considerations: it remains an open challenge to generate non-viciated hot air compatible with quiet flow conditions. Looking at the implications rather than the causes of the differences between free-stream temperatures in quiet tunnels and flight conditions, it appears that they are twofold. On the one hand, the relatively cooler gas flowing over a test specimen at room temperature leads to temperature ratios (fluid-to-wall, say) that may significantly depart from those found in flight. This, in turn, affects the stability of the boundary layer and hence the transition process observed in the quiet tunnel. On the other hand, the flight enthalpies encountered during mission conditions can lead to high temperature effects that are absent from quiet tunnels. If the physical model describing the fluid has implications on the transition process, as some studies have shown [23], then matching fluid-to-wall temperature ratios as well as Reynolds and Mach numbers in a quiet tunnel may not be sufficient to replicate the physics of the transition process in true flight conditions. A possible workaround to the temperature ratio problem is of course to cool the test specimen. There appears to be no simple solution for the lack of high temperature effects. For this reason, the SILENT project

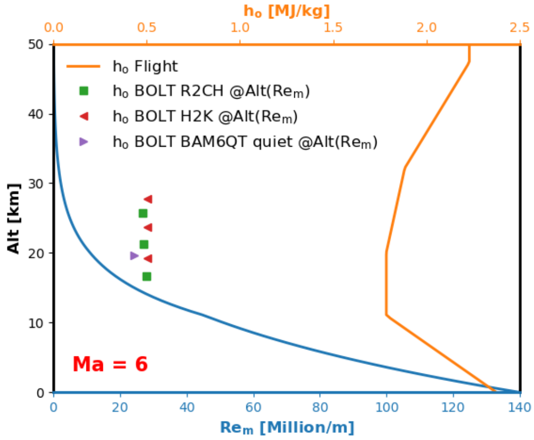

Fig 8. Reynolds number and specific enthalpy as a function of height for a vehicle traveling at Mach 6 across the standard atmosphere. The blue and orange lines show the Reynolds number and specific enthalpies, respectively, encountered at different heights. The symbols depict test conditions in 3 different facilities where transition experiments on BOLT have been carried out [8, 6]. The enthalpy of those tests can be read straight away by referring to the upper (orange) abscissa. To infer the Reynolds number of the tests, one needs to first project the symbol horizontally (i.e. at constant height) onto the blue line, and then read the corresponding Reynolds number by looking down on the lower (blue) abscissa.

includes a feasibility study of a quiet tunnel that replicates flight enthalpy levels encountered by certain types of hypersonic vehicles.

5. Objectives of SILENT

The SILENT project is driven by a consortium of six European partners, each bringing their expertise to the development of quiet wind tunnel technology. ONERA, as project coordinator (backed by ABGI for the management of the project), as well as VKI (Von Karman Institute for Fluid Dynamics) and DLR (German Aerospace Center), contribute to the project with their combined knowledge in high-speed flows and wind tunnel design and operation. The partners are not unfamiliar with the subject of quiet facilities, as shown by a previous attempt to develop a supersonic quiet tunnel [4] and by the documented need for such facilities that has been expressed in the past [7]. The project also benefits from the input of MBDA, a leading European defence industry player, which contributes to SILENT by expressing operational requirements and end-user needs. Their role ensures that the project outputs are relevant for real-world applications while helping to quantify the impact that a quiet tunnel could have on vehicle design. Finally, ERGON research, as a specialist engineering firm, provides expertise in designing and optimizing complex high-pressure and high-temperature systems.
While the SILENT partners intend to leverage proven quiet tunnel design techniques, their aim is also to apply new breakthrough methods and technologies which could lead to a significant improvement in the maximum Reynolds number achievable by the quiet facility. Most of the work to be conducted concerns the aerodynamic design of the circuit, and in particular the optimization of the nozzle. It will lead to a complete pre-design of a facility and a clear roadmap for the construction of the first European quiet tunnel. Furthermore, this initiative seeks to incorporate new solutions for minimizing inlet disturbances, initiating and maintaining laminar boundary layers, and consider the feasibility of replicating flight enthalpy levels - a crucial aspect currently lacking in existing facilities. Ultimately, the project's objectives converge towards a dual outcome: (1) enhanced European autonomy through the development of cutting-edge, domestically controlled hypersonic testing capabilities, and (2) accelerated innovation in high-speed vehicle design, thanks to the application of new computation and design methodologies developed during the project.

6. Conclusion

In conclusion, the SILENT project marks a step forward in European hypersonics research, bound to significantly enhance our innovation capability in hypersonic technologies. Through the design and feasibility studies of quiet wind tunnels, capable of simulating both low-enthalpy and flight-enthalpy conditions, SILENT will provide new perspectives for the study of aerothermodynamics of cruise and re-entry vehicles. The project approach relies on novel methodologies implemented through collaborative research efforts among EU partners, promising not only to align European strategies in hypersonic vehicle development but also to drive breakthroughs in vehicle design and performance optimization. As the project progresses, it is expected to have significant repercussions throughout the defense and civil R&D landscape, not only due to the development of quiet wind tunnels but also as a result of the improvement of computation and design methodologies linked with hypersonic laminar-to-turbulent transition.

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