Goals, tasks and technic concept of Russian flight civil supersonic jet technology demonstrator

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Abstract. The fundamental difference between the new-generation supersonic civil aircraft (SST) and the existing supersonic aircraft is the need to ensure a minimum level of environmental impact. The task of achieving highly efficient faster-than-sonic flight with minimum impact on the environment requires the development and implementation of a whole set of new technical solutions and technologies for aerodynamic layout, power plant, structural design, control system, etc. The technological advance on the topic formed in Russia to date requires verification of the effectiveness, feasibility and the possibility of integrating a set of technologies and technical solutions in the real flight conditions using a flight demonstrator of SST technologies, which will increase the level of readiness of key technologies, reduce the technical risks of developing a new generation SST and provide a basis for the development of draft regulatory requirements for the environmental performance of advanced SSTs. This paper outlines the goals and objectives of such a demonstrator and discusses some of the key technologies in the interests of creating a new generation SST.

1. Main problems in creating a new generation SST

Development of the new generation supersonic transport (SST) is one of the main challenges in aeronautics today. Supersonic cruising flight can substantially reduce the air travel time and increase one day round trip range up to 7000-8000 km. Respective R&D work in this area is being carried out in the USA, Japan, the European Union and Russia [1-3]. New aircraft configurations providing high aerodynamic performance and low sonic boom, variable cycle power plants and their integration with the airframe, new materials and airframe structural design, etc. are under investigation. Achieving the positive effect of integrating a number of technical solutions while minimizing the environmental impact of the SST requires complex multidisciplinary research. Sonic boom, airport noise at take-off and landing flight modes and engine emission characteristics must be addressed during the SST conceptual design. At the same time, the SST development is often complicated by the contradictory technical requirements for this type of an aircraft (figure 1). For example, aircraft configurations that provide a minimum level of sonic boom are not characterized by very high lift-to-drag ratio, which determines the level of aircraft aerodynamic efficiency. The development of the SST with a low environmental impact requires research and multidisciplinary testing of a wide range of new technical solutions and technologies for the aerodynamic layout, power plant, structural design, control system, etc. It is also an important task to validate the results of the conceptual design for the effectiveness of key technologies through experimental verification in the real flight conditions.
A significant problem for the next generation SST is the lack of ready-to-use engines providing the required flight range and acceptable noise level in the airport area. This requires the development and creation of a new class of moderate bypass ratio (m≤3) engines without afterburning, providing simultaneously a high level of thrust and low fuel consumption at supersonic flight modes; low values of jet velocity at take-off and landing modes to reduce the noise level in the airport area, automatic control, high reliability and service life. The task of designing such engines is quite complex and requires considerable material and time costs, which, combined with a relatively small series of supersonic passenger aircraft, can become a key problem for the next generation SSTs. The creation of an efficient engine for the SST in the near future is only possible if the requirements for airport noise level for this class of aircraft are reduced.

The main obstacle to the development of a new generation SSTs and their following operations is lack of internationally approved regulation and norms for the acceptable level of sonic boom. Research to support the development of norms is conducted by ICAO, NASA, and other organizations. At the same time, in the absence of experimental data on the propagation of low-intensity shock waves in the real atmosphere, the development of norms for the SST is constantly delayed. It is expected that the draft regulatory requirements can be formed no earlier than 2025 as the statistics become available on flights of the SST technology demonstrators, the first of which may be the NASA X-59 QueSST sonic boom reduction technology demonstrator [1]. The first flight is expected in 2022, the research test program will include a large number of flights over populated areas to estimate the sonic boom perception by volunteers. It is expected that at the Mach number M=1.42 and flight altitude 16.5 km, the ~11 tons MTOW X-59 sonic boom loudness will not exceed 75 PLdB.

In the absence of standards on the sonic boom level, some designers of new generation SST are creating two-mode aircraft. Supersonic flight in such airplanes is realized only over water surface (BOOM Overture project [4]), or is performed over populated land at a low Mach number M<1.2, when, under favourable atmospheric conditions, shock waves are reflected from the warm near-earth atmosphere layer and do not reach the ground (Aerion AS2 project [5]).

The search for technical solutions to reduce the sonic boom level has been going on for several decades. Very unconventional aerodynamic configurations were proposed (biplanes or even an array of...
wing, solid-sized retractable rods, remote power supply in front of the body, heating and plasma initiation, etc. [6-9]). The main problem is that possible technical solutions to this problem involve global changes in the airplane design and cannot be reduced to partial and local modifications of existing, well-developed approaches and principles. Therefore, the determining factor in the SST concept is the efficiency of integrating new technologies and technical solutions into a single technical design, ensuring simultaneous achievement of high flight performance and low environmental impact.

In TsAGI using numerical and experimental simulations, a number of critical technologies and new technical solutions are developed to TRL=3-4 to ensure the creation of an effective next generation SST (figure 2). Aerodynamic layouts with low sonic boom level, efficient power plant air intakes, jet propulsion nozzles with noise suppression systems were created and tested in wind tunnels. Hybrid metal-composite airframe structural design; principle algorithms of the intelligent control system; techniques for calculating the sonic boom propagation are under investigation, too.

![Figure 2. Existing Russian technological advance on SST topics.](image)

Further development of technologies up to TRL = 6, requires their testing in real flight conditions on technology demonstrators including a flight demonstrator implementing the main approaches to sonic boom reduction. The practice of creating flight new technologies demonstrators is widely used. Thus, in the USA, by order of NASA, a number of flight demonstrators of various-purpose vehicles (X-series) have been developed and tested in real flight conditions. In relation to the SST topic, technology demonstrators were used to test new technical solutions in the creation of the first generation SSTs and to verify new knowledge on possible modification of the overpressure signature. For example, in the USSR, the MiG-21 I demonstrator (A-144) was developed for testing the S-shaped wing of the Tu-144 aircraft. In the USA in the early 2000s, a large amount of numerical, experimental and flight studies [10] of the F5 SSBD aircraft were performed to prove the possibility of modifying the overpressure signature by changing the fuselage shape.
The greatest progress in the development of the SST technology demonstrator has been achieved in the United States, where Lockheed-Martin is building the X-59 QueSST demonstrator of sonic boom reduction technology for NASA’s Low-boom flight demonstrator program [1] (figure 3). Production of the X-59 QueSST began in 2019, after test flights in 2022 to validate the acoustic characteristics, flights over populated land are planned for 2023-2025 to assess the perception of sonic boom by volunteers. The research materials will be submitted to ICAO for formulating standards on sonic boom level for advanced supersonic civil aircraft. It should be noted that the goal of the project is to show only the possibility of reducing the sonic boom level. Neither aerodynamic efficiency, nor airport noise reduction are stated in the project. In developing the X-59 demonstrator, units and assemblies of serial airplanes are used: the GE F414-100 afterburner engine used in the McDonnell Douglas F/A-18 aircraft, the cockpit of the Northrop T-38 aircraft, the landing gear of the General Dynamics F-16 aircraft, etc.

In Japan, JAXA, within the framework of the NEXST (National EXperimental Supersonic Transport) and S3 (Silent SuperSonic Technology Research) programs, conducted a number of experimental studies in a real atmosphere of large-size SST models (technology demonstrators) using sonic boom reduction technologies [2]. In 2015, the S3CM model was tested by launching from an altitude of 30 km using a balloon and measuring sonic boom characteristics in the controlled flight leg at a speed corresponding to the Mach number M~1.4. The model is 7.9 m long, has a 3.5 m wingspan and weighs 1000 kg. As a part of the S4 program (Research and Development for System integration of S3 program), it is planned to develop an unmanned SST technology demonstrator to confirm the possibility of reducing the sonic boom level, aerodynamic drag and airport noise.

In the European Union, the development of the SST technologies demonstrator was one of the objectives of the RUMBLE research project [3]. Dassault, ONERA and Airbus along with the Russian scientific institutions TsAGI, CIAM and MAI are participating in the development of the LBFD (Low Boom Flight Demonstrator) project. To date, modelling of the demonstrator geometry and numerical evaluation of its aerodynamic and sonic boom characteristics have been performed and a model for wind tunnel testing has been made.

It should be noted that the demonstrators being developed do not fully realize the entire set of key technologies of the next generation SST. Only a few of them are subject to validation in the experiment, e.g. the sonic boom reduction technology. A current problem is the use of existing afterburner engines, which does not allow for the testing of noise reduction technologies in the airport area. Thus, despite significant progress in some topical areas, the world’s technological advance to date is insufficient to initiate R&D on the creation of SST even of a light class. The development of medium and heavy class SST requires additional research and development to ensure that the expected regulatory requirements can be met. It is also worth noting that sonic boom and airport noise standards are very likely to be used as a competitive tool, so it is not advisable to disclose design and development work before the adoption of at least a preliminary draft of the standards by ICAO. World practice shows that starting the R&D on the aircraft with qualitatively new properties (supersonic speed) and requirements (for environmental characteristics) without bringing new technical solutions to TRL=6 leads to a waste of significant
resources without achieving practical results. Thus, in the 1980s…90s Boeing invested about $10 billion in the development of the second-generation SST (M=2, 200 pass.) with no result.

2. Goals and objectives of creating a Russian flight SST technologies demonstrator

The greatest technical risk of creating advanced SST is to provide a rational compromise between acceptable environmental (sonic boom, LTO noise), competitive flight performance (speed, range, basing) and economic characteristics of the applied layout solutions. The level of performance ensuring high competitiveness cannot be achieved using traditional approaches and requires the search and full-scale testing of a wide range of new technical solutions and technologies. The effectiveness of their integrating into a single technical design is of fundamental importance for advanced SST and this does not allow the direct use of technological advance obtained during the creation of existing aircraft and requires a specialized design optimized for solving a specific task.

TsAGI developed a Technical Proposal for the “Swift” SST Technologies Demonstrator [11], which allows the effectiveness and feasibility of the developed technologies to be tested in real flight conditions. To reduce the time of creating a demonstrator, the maximum use of existing systems, components and assemblies with minimum modifications is proposed. In addition to testing technologies in the real flight conditions and validating computational methods for estimating sonic boom characteristics in a real atmosphere, flying such a demonstrator over populated areas will determine the sonic boom level acceptable for flights over populated land, thus enabling the development of national regulations that cannot be developed in the absence of actual material.

The technological advance of Russian enterprises in the field of unmanned aerial vehicles makes possible the implementation of the SST demonstrator in an unmanned version at the first stage of work with further modification into an optionally piloted version.

The objectives of creating the Russian SST technologies demonstrator are:

1. To verify in the real flight conditions the effectiveness, feasibility and ability to integrate a set of technologies and technical solutions to ensure the creation of a new generation SST, including the aerodynamic layout, power plant, structural design, control system, on-board systems and equipment;
2. To verify in the real flight conditions the effectiveness of technologies to reduce the levels of sonic boom and airport noise while ensuring a high level of flight performance and economic characteristics of the future SSTs;
3. To provide a basis for the development of draft regulatory requirements for the environmental performance of the future SSTs;
4. To reduce the technical risks of the next generation SST development.

The design and construction of the demonstrator will enable a set of studies to be carried out for the development of the next-generation SST:

- testing in the real flight conditions of the efficiency of aerodynamic layout, aircraft stability and controllability at subsonic, transonic and supersonic flight speeds, taking into account the aeroelastic characteristics of the structure.
- testing in the real flight conditions of the SST sonic boom reduction methods.
- determination of sonic boom characteristics on the ground (including impact on humans, buildings, etc.) under various atmospheric conditions throughout the operational range of flight speeds and altitudes, taking maneuvering into account; development of draft standards for the acceptable sonic boom level for flights over populated land.
- development of technologies for long cruising flight at supersonic speeds, including technologies to ensure thermal and acoustic comfort of passengers.
- development of a system for predicting the level of sonic boom on the ground based on flight parameters and predicted atmospheric characteristics under the flight path.
- testing in the real flight conditions ensuring the stable operation of the upper located air intakes in all flight modes; setting up the air-intake boundary layer control systems.
- testing in the real flight conditions of rigidity and strength characteristics of advanced metal-composite structures in all flight modes.
• testing in the real flight conditions of systems for monitoring the thermal state and the level of structure loading in all flight modes.
• testing in the real flight conditions of methods and tools for reducing propulsion noise in the airport area, including shielding, jet noise suppression and noise reduction of blade machines using sound-absorbing structures while ensuring a low level of thrust loss in transonic and supersonic flight modes.
• development of a set of the SST onboard systems and equipment.
• development of systems to increase the autonomy of advanced SST control system (transition to a single-member crew), including automatic take-off and landing.
• development of the “technical vision” system and technology providing sufficient crew information field in a “closed cockpit”.
• validation of computational and experimental research methods.

3. Concept of Russian SST technologies demonstrator “Swift”
When creating the SST technologies flight demonstrator the following is fundamental:
• ensuring close to the future aircraft dimensions and flight conditions, since many of the investigated effects either do not scale or scale with significant poorly understood distortions, which will affect the quality of the research results and their subsequent implementation,
• confirming the feasibility and effectiveness of the integration of technical solutions.

The most important element of the technical concept of an aircraft is its aerodynamic layout as it determines the flight performance (range, speed, flight altitude, basing conditions); environmental characteristics; payload placement conditions; reliability and safety of the aircraft. The aerodynamic layout is the shape of the outer contours of the aircraft with the input and output devices of the power plant, that provides the required level of aerodynamic efficiency, stability and controllability in all flight modes, placement of equipment, power plant, aircraft systems, crew and passengers (cargo), landing gear and fuel with taking into account the possibility of forming a rational structural scheme and achieving the required levels of sonic boom and airport noise.

A high level of cruise lift-to-drag ratio, taking into account balancing, relatively large volumes for placing fuel (more than 50% of the take-off mass) and at the same time achieving a low sonic boom level at supersonic flight speeds, is possible only with simultaneous optimization of aerodynamic contours of the wing, fuselage and nacelle.

Studies on the analysis of the influence of various elements of the aircraft layout on the sonic boom overpressure signature [9] showed that the distribution of the thickness of the body, the deformation of its axis and the distribution of the lift force along the length of the aircraft have the greatest effect on the overpressure signature on the ground. V-shape of the wing increases its equivalent sweep and rate of increase in pressure from lift force. For a given size of the cabin, the task of reducing sonic boom levels and aerodynamic drag have a decisive influence on the shape of the fuselage. To minimize the sonic boom level, a peak increase in overpressure in the head shock from the fuselage followed by a smooth increase in pressure is useful.

The choice of location, parameters and characteristics of the power plant, including air intakes, engines and nozzles, also largely determines fuel consumption, the ability of selecting the optimum cruising altitude, the level of sonic boom and noise at take-off and landing modes. In addition, the external drag of the engine nacelle has a significant effect on the level of aerodynamic perfection of the supersonic aircraft. Integration of the power plant with the tail section of the fuselage provides the possibility to almost completely eliminate the additional wave drag of nacelles and reduce friction drag by reducing the fuselage length and reducing the total area of a single nacelle for both engines. The layout of the air intakes not only determines the thrust and economic characteristics of the power plant, but also largely determines the characteristics the sonic boom. The air intakes and the nacelle have a significant effect on the flow in the near field, which determines the propagation of the shock wave in the atmosphere and, ultimately, the magnitude of sonic boom overpressure. A possible solution to the problem is to move the air intakes to the upper surface of the wing so that the wing cuts off disturbances in the lower hemisphere. The upper layout requires careful optimization of the airframe geometry in the area of the air intake, as well as the geometry and systems of the air intake itself. The nozzles of the
The SST structural design should provide high weight efficiency; high rigidity of the airframe with a fuselage of large elongation and a wing of small relative thickness to maintain a rational geometry of the airplane to achieve an acceptable level of sonic boom and ensure the effectiveness of the controls; soundproofing of the passenger cabin; long service life under temperature stresses; thermal insulation of fuel tanks. A large elongation of the nose part of the new-generation SST fuselage, due to the task of minimizing the sonic boom, requires new approaches to the structural design of such an aircraft. Ensuring high rigidity at low weight costs is possible when using isogrid structures made of composite materials with topological optimization of load-bearing elements (“bionic” design).

The features of the SST as compared to conventional layouts (high moments of inertia in the longitudinal and lateral channels, low rigidity of the long fuselage and thin wing structure, significant displacement of the aerodynamic focus during the transition from subsonic to supersonic flight modes, etc.) require great efforts to create a highly reliable control system. It should ensure that the aircraft cannot reach supercritical flight modes; reduction of balancing losses in all flight modes by selecting the optimum combination of controls and controlling the center of mass position by fuel consumption and overflow; automatic control of the aircraft in all flight modes (including take-off and landing) to meet the requirements for flight safety; the necessary drives efficiency while reducing their dimensions to reduce aerodynamic drag. The significant length of the nose of the fuselage, the shape of which is optimized to reduce sonic boom, does not allow for the placement of a traditional crew cockpit with front glazing, which requires the development of alternative ways to provide a sufficient information-control field for the crew, such as “technical vision”.

The above-described features of the technical concept of advanced SSTs are implemented in the project of the Russian SST technologies demonstrator “Swift” (figure 4). Aerodynamic layout of the demonstrator was developed taking into account the need to minimize the sonic boom ensuring a high level of flight performance and is characterized by the upper integral arrangement of the twin serial RD-93MA engine powerplant. Modern CFD methods were widely used in the development of the demonstrator, its main characteristics confirmed in experimental studies in TsAGI wind tunnels and acoustic testbeds.

![Figure 4. Concept of a flight SST technologies demonstrator “Swift”.

- Dimensions – 16...20 ton-forces (close to a full-scale version of the light class SST).
- Speed – up to 1900 km/h (M = 1.8).
- Long (over an hour) cruising supersonic flight mode.
- Modular airframe design (interchangeable nose section and wing consoles).
- Top-mounted powerplant
- Non-adjustable air intake
- Nozzle with noise suppression system
- Serial export engine RD-93MA without afterburner
- Systems and avionics of serial production or with minimal modifications
- Scientific and technical groundwork of domestic manufacturers of unmanned aircraft technology allows the implementation of SST demonstrator in unmanned (optionally piloted) version to reduce the time and cost of creating the demonstrator.
- Aerodynamic configuration with low sonic boom level
- Innovative metal-composite modular airframe structure with passenger cabin imitation
- Intelligent control system

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The terms of development, construction and implementation of the flight test program of the SST technologies demonstrator will be about 5-6 years. Flight testing of the demonstrator combined with a set of applied research activities and exploratory studies will be the basis for the implementation of an agreed integrated approach to the creation of a new-generation SST, which will significantly reduce the technical risks of SST development, and allow for participation on equal terms in the preparation of international standards for acceptable levels of sonic boom and airport noise within the framework of ICAO.

4. Conclusion
The development of a new-generation SST is a complex multidisciplinary task. Russian scientific institutions have developed to TRL = 3-4 a number of critical technologies to ensure the creation of an efficient next-generation SST. Accumulated technological advance on the topic requires validation of the effectiveness, feasibility and possibility of integrating a set of technologies and technical solutions in the real flight conditions on a flight SST technologies demonstrator, which will increase the key technologies TRL and reduce the technical risks.

TsAGI has developed a Technical Proposal for a SST key technologies demonstrator “Swift”. In order to reduce the time required to build a demonstrator, it is proposed to use the existing engines, systems, components and assemblies with minimum modifications. The characteristics of the “Swift” demonstrator are verified by a large amount of computational and experimental studies. In addition to testing the technologies in the real flight conditions and validating computational methods for assessing the sonic boom characteristics in a real atmosphere, flying such a demonstrator will determine the acceptable sonic boom level for flights over populated land, enabling the development of national regulations that cannot be developed in the absence of factual material.

The construction and flight tests of the “Swift” demonstrator, combined with a set of applied research activities and exploratory studies, will be the basis for the implementation of an agreed integrated approach to creation of the new-generation SSTS.

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