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Sustainable Supersonic Transport:
a Case Study on Variable Pitot Inlets

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Abstract
An overview of aero-engine inlets, the design process in aviation and a safe design approach for academic studies is provided. By means of a safe design approach, a variable inlet concept is developed up to technology readiness level (TRL) 3 and described. The application of safety and reliability methods, aerodynamic and structural analyses, as well as functional demonstrators proves the feasibility of the present variable inlet concept and highlights its potential for application in future supersonic transport (SST).

Nomenclature

AMC	Acceptable Means of Compliance
ARP	Aerospace Recommended Practices
CCA	Common Cause Analysis
CMA	Common Mode Analysis
CS	Certification Specifications
FHA	Functional Hazard Assessment
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
PRA	Particular Risks Analysis
PSSA	Preliminary System Safety Assessment
SST	Supersonic Transport
TRL	Technology Readiness Level
VDI	Verein Deutscher Ingenieure; Association of German Engineers
ZSA	Zonal Safety Analysis

1. Introduction

Achieving high efficiency, reliability and safety are major goals for future aviation [1]. This affects projected applications for supersonic transport (SST) in particular. Variable pitot inlets that adjust the inlet geometries for different flight conditions can be a way to attain high efficiency by reducing the aircraft drag [2]. Furthermore, they can support the prevention of engine surge during operation at high angles of incidence or crosswind. Hence, variable inlets have been investigated in a number of subsonic studies [3], [4], [5]. As subsonic variable inlets are currently not in use, potential reasons for this absence of application are that their limitations concerning complexity, reliability and costs outweigh their provided aerodynamic benefits.
Variable pitot inlets for SST applications up to Mach 1.6 offer higher aerodynamic benefits, which could compensate these limitations [6]. Furthermore, variable pitot inlets have several advantages over other supersonic inlet types in terms of flow uniformity, length and weight. The increased complexity of a variable inlet system can entail reliability and safety issues. These issues can be addressed by the application of a safe design approach.
This paper presents the development of a variable inlet concept for SST by means of a safe design approach. First, an overview of aero-engine inlet design is given. The design process in aviation according to Aerospace Recommended Practices ARP 4754A [7] is described. Subsequently, the applied safe design process is introduced. Based on this process, the development of a feasible variable inlet concept is explained. The feasibility of the concept is proved by analyses and functional demonstrators, whereby TRL 3 is achieved. These results highlight the high potential of variable pitot inlets for future SST.

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2. Aero Engine Inlets

Lift and thrust forces are necessary for an aircraft to fly. The thrust is produced by the aero engines, which require a certain air mass flow. At all operation conditions, this air mass flow needs to be slower than Mach 0.6 and to be highly uniform [8]. Otherwise, hazardous events due to increased fan stresses or flow separations up to engine surge can occur. The inlet, which is the part of the engine nacelle that is located in front of the fan, must ensure the air supply for all operation conditions. Hence, highly diverse aerodynamic requirements must be satisfied during the design of rigid pitot inlets to achieve reliable operation combined with the highest possible efficiency [9], see Figure 1. During take-off and climb operation up to Mach 0.3 it is necessary to circumvent flow separations and potentially resulting hazardous events. On the other hand, high efficiency is required during cruise operation at flight velocities above Mach 0.8.

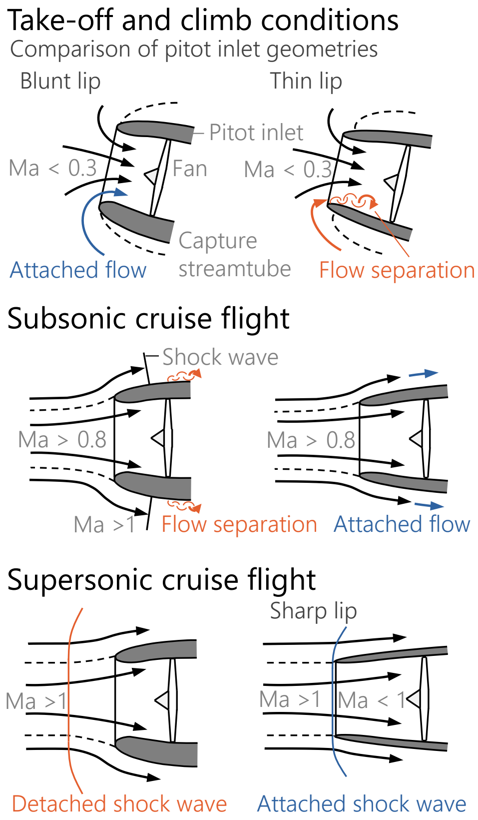

Figure 1: Inlet geometries at different flight phases

Avoidance of flow separation due to high angles of incidence and crosswind at low aircraft velocities is achieved by utilising a round and thick inlet lip [8]. This lip geometry causes increased drag, and thus reduced efficiency during cruise operation [8]. At subsonic cruise conditions a thin lip contour accomplishes reduced drag and higher efficiency [10]. However, such a geometry is susceptible to flow separation at take-off and climb conditions [8].

Conventional rigid subsonic inlets can only attain a trade-off concerning minimum drag at high velocities and avoidance of flow separation at low velocities. While the identification of ideal trade-off geometries is subject of numerous studies [11], [12], [13], variable pitot inlets may eliminate the necessity of an aerodynamic trade-off. Hence, subsonic variable inlets have been investigated in different studies. However, they continue to be absent from commercial aviation yet. This can be explained by their additional weight and higher complexity, which eliminate the aerodynamic benefit at solely subsonic operation. Nevertheless, pitot inlets can be applied up to flight Mach numbers of 1.6 without significant losses [9]. Long pitot inlets with sharp lips are suitable to minimise losses at these supersonic conditions [9], [14]. However, sharp lips are even more susceptible to flow separations at low flight speeds than thin lips. This unveils a higher potential aerodynamic benefit of variable pitot inlets for SST up to Mach 1.6 compared to solely subsonic applications.

In addition to aerodynamic requirements, compliance with design requirements must be shown by the inlet. For instance, weight minimisation is elementary. Nonetheless, the inlet should still be resilient to foreign object damage, sand erosion, hail and bird strikes. Moreover, thrust has to be maintained to a certain level after a single bird strike to ensure the safe continuation of the flight [15]. Furthermore, it is necessary to integrate an ice protection system to avoid

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ice accretion and its potentially hazardous consequences, such as impact damage and flow separation [16]. Moreover, the inlet reduces the noise emissions caused by the fan and compressor system, usually by integration of an acoustic treatment into the diffuser wall. Additionally, pressure and temperature probes can be part of the inlet.

3. Methodology

The design of complex systems is usually supported by methodical design approaches, e.g. the Design for Six Sigma and the VDI guideline 2221 (Verein Deutscher Ingenieure, Association of German Engineers). Methodical design approaches reduce the complexity of a design task by breaking it down into simpler subtasks, while ensuring the recognition of complex dependencies. Furthermore, they support the identification and mitigation of weaknesses, as well as the management of requirements, interfaces and risks.
Most methodical design approaches are based on common iterative phases [17]:

- analysis of the design task and requirements,
- analysis of required functions and identification of potential solution principles,
- development of concepts and preselection,
- preliminary design of concepts and evaluation, as well as
- detailed design, including verification of the design.

In modern industries, the desired products become increasingly complex. Hence, particular safety efforts are necessary during early phases of the development process to ensure safety and reliability of a product in an efficient way [18]. This can be achieved by application of a mature design approach and analytical methods that identify potential weaknesses and determine the reliability of the product. The assignment of suitable safety and reliability methods to each phase of the development process can improve the product significantly.

3.1 Safety process in aviation

In aviation, failures can easily cause accidents with many fatalities. Nevertheless, in the period from 1990 to 2010 a rate of approximately one death per million flights was achieved [19]. This low safety risk is ensured by continuous improvements in the fields of flight operations, maintenance, air traffic management, regulations, as well as design methods and methodologies [20]. Aviation authorities have been publishing regulations and controlling their compliance to ensure safe operation since the Chicago Convention in 1944 [21]. In Europe, the European Aviation Safety Agency (EASA) releases Certification Specifications (CS), e.g. the CS-25 – Large Aeroplanes, which contains relevant regulations for inlets [22]. As part of the certification process for obtaining flight approval, compliance with these regulations must be demonstrated. For this purpose, the EASA proposes acceptable means of compliance (AMC), ranging from calculations and analyses up to tests.
Paragraph CS-25 AMC 25.1309 describes the safe design process in aviation based on ARP 4754A [7], which has been formulated by a consortium of various aviation companies and authorities. The according methods of this process are explained in ARP 4761 [23]. The process according to ARP 4754A is based on the V-model of systems engineering [7]. Within this process, the functions, requirements and architectures of a product are developed on different levels of detail: from aircraft level over system level up to element level [7], compare Figure 2. Throughout the development process, an emphasis is placed on the assurance of the functionality of the resulting product. On the one hand, this is achieved by validating the requirements at the next higher detail level [7]. On the other hand, tests and analyses verify that the design solutions comply with the requirements and desired functions at each level of detail [7].

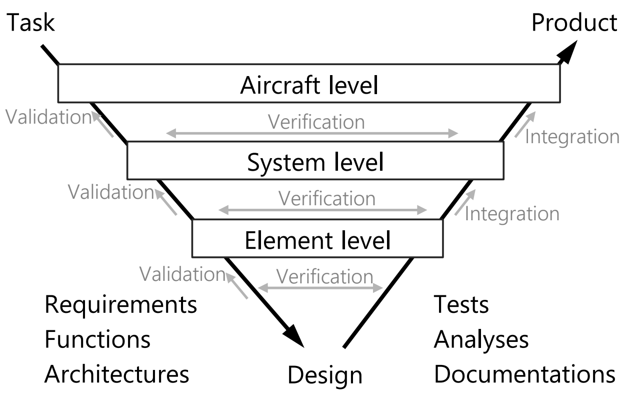

Figure 2: V-Modell in aviation

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For each phase of the development process, safety analysis and evaluation methods according to ARP 4761 [23] are assigned. The most important included methods are:

- the Functional Hazard Assessment (FHA),
- the Preliminary System Safety Assessment (PSSA),
- the System Safety Assessment (SSA),
- the Fault Tree Analysis (FTA,
- the Failure Mode and Effects Analysis (FMEA), and
- the Common Cause Analysis (CCA), comprising
  - the Zonal Safety Analysis (ZSA),
  - the Particular Risks Analysis (PRA), as well as
  - the Common Mode Analysis (CMA).

Furthermore, the conduction of reviews at the least after each phase of the design process is suggested [24], [25].

3.2 Safe design approach for academic studies

The goal of the safe design approach is to enable the development of feasible concept solutions for aviation within academic studies. By integration of the industry-specific standards for safety and reliability, the resulting concept solutions can achieve a higher practical relevance than comparable academic studies. It is not intended to develop the concepts to market maturity within academic studies. Instead, suitable concept ideas should be investigated to a level of detail that enables the evaluation of the feasibility of the technology. For this purpose, the Technology Readiness Level TRL 3 is suitable, which comprises the verification of the desired function by analyses, simulations and laboratory experiments [26]. Furthermore, academic studies are supposed to provide an outlook on the upcoming development steps to achieve market maturity.

Academic studies should also focus on obtaining new knowledge, for instance about the applicability of innovative principles or materials. In this regard, previous academic studies have often generated innovative solution ideas without sufficiently considering the feasibility of these ideas. A thorough coverage of the wide range of potential solutions and a similar level of detail of the solution alternatives can support the development of feasible and innovative solutions. A thorough investigation should be prioritised over time and cost efficiency, despite the comparatively low personnel and equipment budgets. These boundary conditions limit the scope of the studies and the achievable level of detail of the developed concepts to TRL 3.

Therefore, an approach is required, which supports the verification of the desired functions at the end of a study. Additionally, the approach should be based on a proven methodology, e.g. the VDI guideline 2221 [27]. Furthermore, methods of the safety assessment process according to ARP 4754A [7] and ARP 4761 [23] should be integrated for verification and validation of the partial solutions.

Relevant certification requirements should be thoroughly identified in the beginning of the process by means of a type investigation program [28]. This way, systematic design flaws that could prevent a product from complying with the certification requirements in the final stages of the development and would result in expensive elaborate design adaptations can be avoided. Potential weaknesses and risks should also be identified at an early stage, for example by means of an FHA or PRA, followed by respective detailed investigations. This demands for a certain degree of adaptability of the approach during the development process.

The approach should also support a broadly diversified investigation in order to achieve the largest possible extent of innovative and yet promising concepts. This can be achieved by a simultaneous investigation of multiple concepts and a commitment to a solution at comparably late phase.

Additionally, the approach should include the design of demonstrators for promising concepts at the earliest possible stage to verify the functionality and to identify potential weaknesses. This is the main improvement in comparison to the academic safe design approach of Grasselt et al. [29].

The utilised safe design approach for reliable and safe concepts of TRL 3 is shown in Figure 3. With reference to Roth [17], the approach is divided into five phases. The general design tasks of the individual phases are based on the VDI guideline 2221 [27]. Additionally, suitable methods of the safety assessment process according to ARP 4754A [7] are assigned to the respective phases and highlighted in Figure 3.

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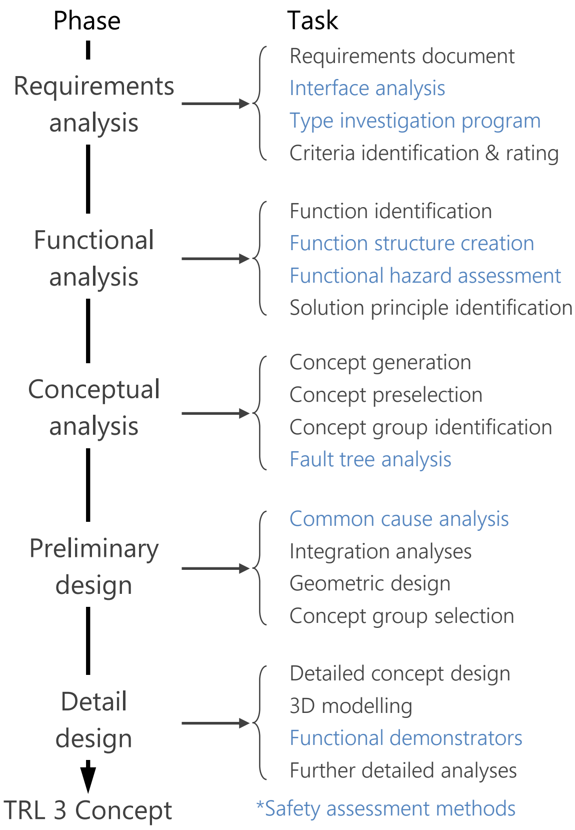

Figure 3: Safe design approach

4. Results

4.1 Application of the safe design process

The application of the individual process tasks for the design of a feasible variable inlet concept is presented in several respective publications. In the following, the most significant results of these tasks are summarised.
The initial identification of requirements has been performed by means of brainstorming sessions, literature reviews, checklists and comparable products [30]. These requirements have been gathered in a quantitative requirements document. This document has been updated throughout the design process.
Based on an interface analysis, potential synergies and interactions between subsystems of a variable inlet have been determined. These interactions have also been considered during the elaboration of the type investigation program, which comprises relevant certification requirements and according acceptable means of compliance [31].
At the end of the requirements analysis phase, mandatory requirements and evaluation criteria have been determined. The established evaluation criteria have been weighted via a pairwise comparison [32], [33]. These criteria are:

- aerodynamic efficiency,
- ease of integration,
- weight und structural strength,
- safety,
- reliability and life cycle costs, as well as
- development and manufacturing costs.

During the functional analysis, the necessary functions of a variable inlet system have been determined and structured [30], [34]. The resulting function structure trees have been utilised during the FHA to systematically assess failure modes and their effects on aircraft, system and subsystem level. Thereby, a loss of thrust on multiple engines due to inlet malfunctions has been assessed as hazardous event [34]. Within the next task, potential solution principles have been identified for the determined functions [30].

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More than 30 concepts have been generated by means of brainstorming sessions and the morphologic box method [30]. This method is conducted by assigning the potential solution principles to the respective functions and combining them with each other to create concepts. Subsequently, the concepts have been examined and evaluated regarding their compliance of mandatory requirements. This way, a preselection of the concept has been achieved [30].
The remaining concepts have been considered for patenting and the manufacturing of an early functional demonstrator with a scale of one to three [35], see Figure 4. Additionally, the suitable concepts have been categorised for further investigations [32]. The resulting concept groups are inlets that adjust the geometry

- by repositioning of rigid segments,
- by deformation of elastic surface material and
- by boundary layer control.

Subsequently, an FTA has been conducted to identify and mitigate failure modes of single or multiple subsystems or components that can cause hazards [34].
Afterwards, the CCA comprising ZSA, PRA and CMA has been conducted on the concept groups [36]. Selected resulting design adaptations are flexible wiring and pipe installation, heat protection for the adjustment system, extended ice protection surfaces and redundant subsystems [36].
The subsequent system integration analysis enabled the identification of the most suitable combinations of necessary subsystems, e.g. the adjustment system and the ice protection system for the respective inlet concept groups [33]. For instance, the combination of electric actuators and electrothermal ice protection offers many potential synergies for the concept group that adjusts the inlet geometry by repositioning of rigid segments [33].
During the geometric design, it has been determined that the concept should only adjust two different geometries to minimise its complexity; one geometry for subsonic and one for supersonic flight, both highly efficient and reliable at the respective conditions [6]. This way, an aircraft with variable inlets instead of rigid ones would achieve a range benefit of about 35% at a supersonic flight speed of Mach 1.6 without considering additional weight and aerodynamic losses due to steps and gaps [37], [38].
Based on the evaluation criteria and the conducted analyses, the concept groups have been evaluated by means of a weighted point rating. This evaluation reveals necessary improvements for all respective concept groups, e.g. regarding ice protection or erosion resistance. Furthermore, the concept group that adjusts the inlet geometry by rigid segment repositioning has been identified as the most suitable concept group [32].
During the detail design a concept of this group has been derived, modelled and manufactured. These steps are introduced in the following chapter.

Figure 4: First functional demonstrator

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4.2 Variable inlet concept

The adjustment mechanism of the derived concept is illustrated in Figure 5. In this concept, an electrically driven actuator A is used to axially move an adjustment ring R. The movement of the adjustment ring R is supported and guided by rails F, which reduce the loads on the actuator. The linear movement of the adjustment ring R causes a variation of the axially and circumferentially segmented inlet surface.

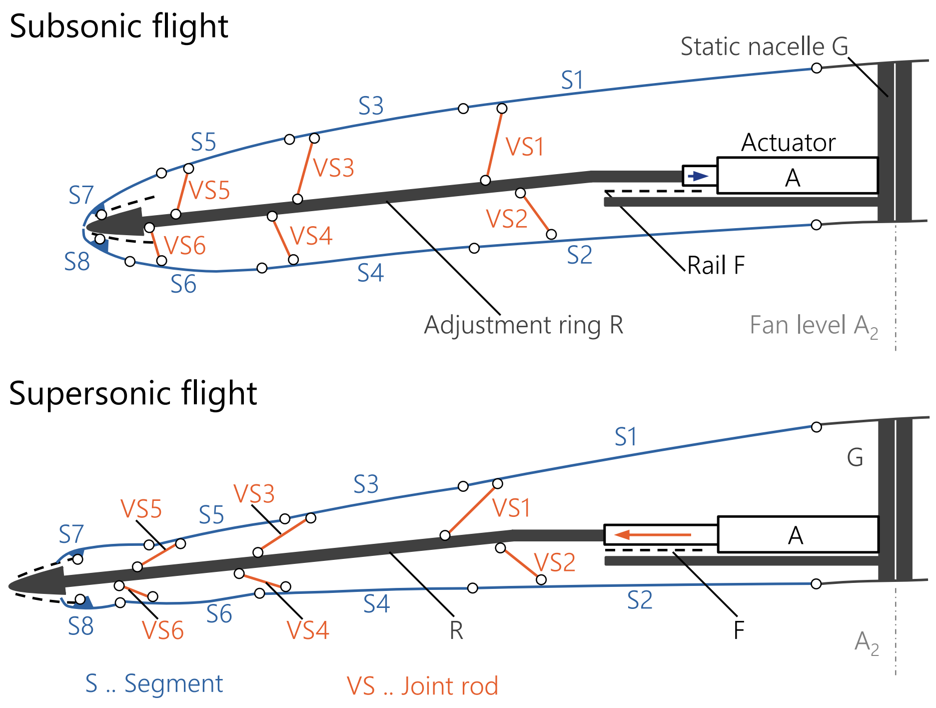

Figure 5: Adjustment mechanism of the concept

The axial segmentation is made into four segments each, on the outside S1, S3, S5 and S7 and on the inside S2, S4, S6 and S8. Segments that are axially adjacent to each other are connected to each other by joints. The segments S1 and S2 are also connected to the static part of the inlet.

The circumferential segmentation comprises a subdivision into circle sectors of 15°. This segmentation into circle segments is necessary to enable the variation of diameters and contour thicknesses when utilising rigid components, see Figure 6. However, due to the segmentation, circumferential gaps arise during the diameter enlargement. Therefore, sealing elements between adjacent segments are required. Existing approaches for this purpose include

- the acceptance of the gap [39],
- rigid frames between segments [40],
- overlapping segments [41], and
- elastic sealings [42].

The first two options are excluded from consideration due to their inferior aerodynamic properties. Elastic sealings offer only a very limited service life. Overlapping segments can be implemented by

- additional movable rigid sealing elements between circular segments [42],
- rotating circular segments, and
- tangential linear extensions of the circular segments.

Tangential extensions have been chosen, as they offer good aerodynamic properties, while being the least complex option. By variation of the inner and outer diameter, the thickness of the contour can also be varied, see Figure 7.

As the circle segments have a fixed radius, an exact circular cross-sectional area can only be set for one of the concept positions. By raising the number of segments, an almost circular geometry can be achieved, which enables a higher flow uniformity. However, this also creates more steps around the inlet surface and increases the complexity of the system. On the other hand, the use of only a few circular segments results in less complexity and higher reliability at the expense of inferior aerodynamic properties. Hence, a sector size of 15° has been chosen as a compromise.

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By means of a flange connection, the inlet assembly is mounted to the remaining nacelle at the fan level. For this purpose, a static inlet section exists between the segments S1 or S2 and the fan level. Furthermore, the functional and mechanical interfaces between inlet and remaining nacelle, as well as the actuation system A and the rails F must be integrated into the static inlet section. All static components of inlet and nacelle are summarised as static nacelle G.
Over its axial extension, the adjustment ring R is partially designed as a ring or segmented to minimise its weight. Via redundant joint rods VS1..6 and joint pins BSV1..6/BRV1..6, the adjustment ring R is connected to the respective surface segments S1..S6.
The leading edge of the adjustment ring R is a circumferential continuous ring with embedded rails. Within these rails, redundant joint pins BRV7/8 slide along, see Figure 8. These joint pins BRV7/8 have a fixed connection to the joint rod VS7/8, which are respectively integrated into the segments S7 and S8.

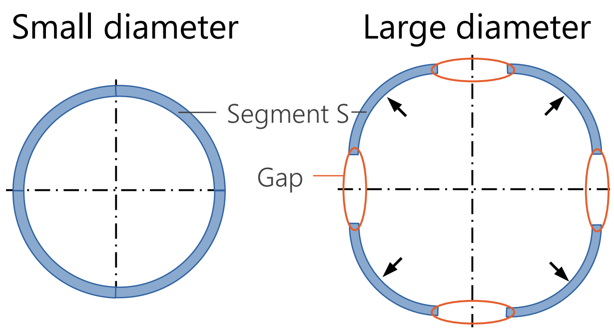

Figure 6: Circumferential segmentation

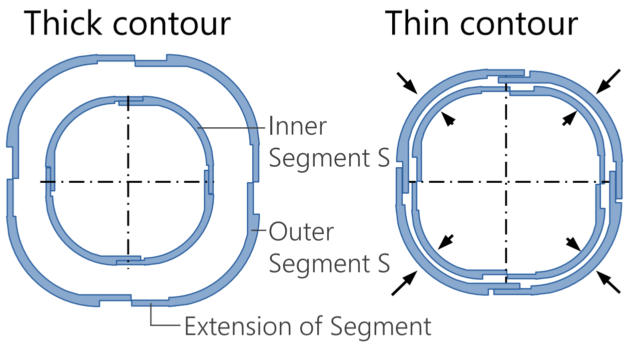

Figure 7: Variation of the contour thickness

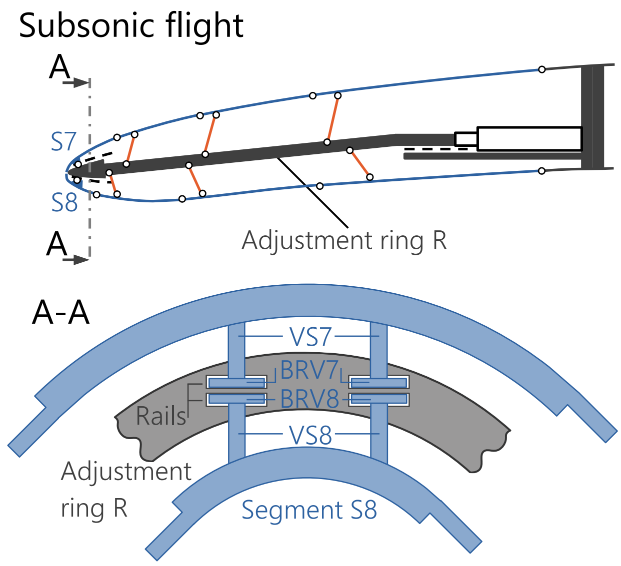

Figure 8: Sliding joint in adjustment ring

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Electro-thermal heating mats are utilised as ice protection system. These extend over the entire inlet surface to prevent ice formation between segments of adjacent sectors [33]. This way, ice accretion cannot affect the inlet geometry and its adjustability. The segments S2 and S4 contain conventional acoustic liners to mitigate fan noise emissions. A list of the most important concept components is presented in Table 1.

Table 1: Component list of the concept

ID	Description	Quantity
G	Static engine nacelle, including the static inlet section and interfaces between variable inlet and nacelle	1
A	Actuation system of the variable inlet, including motors, drives, sensors, control electronics, locking mechanisms and wires	6
F	Rails that carry and guide the adjustment ring R	24
R	Circumferential adjustment ring R; supported by rails F; actuated by actuation system A; connected to overflown segments S1..S6 via joint rods VS1..6; comprises annular leading edge with integrated rails; forms part of the inlet lip during supersonic flight; connected to segments S7/8 via sliding joints in integrated rails	1
S1	Segment on the outer inlet surface; hinged connection to static nacelle G, segment S3 and joint rod VS1	24
S2	Segment on the inner inlet surface; hinged connection to static nacelle G, segment S4 and joint rod VS2	24
S3	Segment on the outer inlet surface; hinged connection to segments S1, S5 and joint rod VS3	24
S4	Segment on the inner inlet surface; hinged connection to segments S2, S6 and joint rod VS4	24
S5	Segment on the outer inlet surface; hinged connection to segments S3, S7 and joint rod VS5	24
S6	Segment on the inner inlet surface; hinged connection to segments S4, S8 and joint rod VS6	24
S7	Segment on the outer inlet surface; hinged connection to segments S5; sliding joint connection to leading edge of adjustment ring R via integrated joint rod VS7 and joint pin BRV7	24
S8	Segment on the inner inlet surface; hinged connection to segments S6; sliding joint connection to leading edge of adjustment ring R via integrated joint rod VS8 and joint pin BRV8	24
VS1	Joint rod between adjustment ring R and segment S1	48
VS2	Joint rod between adjustment ring R and segment S2	48
VS3	Joint rod between adjustment ring R and segment S3	48
VS4	Joint rod between adjustment ring R and segment S4	48
VS5	Joint rod between adjustment ring R and segment S5	48
VS6	Joint rod between adjustment ring R and segment S6	48
VS7	In segment S7 integrated joint rod; sliding joint connection to leading edge of adjustment ring R	(48)
VS8	In segment S8 integrated joint rod; sliding joint connection to leading edge of adjustment ring R	(48)
BSG1	Joint pin between segment S1 and static nacelle G	48
BSG2	Joint pin between segment S2 and static nacelle G	48
BS13	Joint pin between segments S1 and S3	48
BS24	Joint pin between segments S2 and S4	48
BS35	Joint pin between segments S3 and S5	48

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ID	Description	Quantity
BS46	Joint pin between segments S4 and S6	48
BS57	Joint pin between segments S5 and S7	48
BS68	Joint pin between segments S6 and S8	48
BSV1	Joint pin between segment S1 and joint rod VS1	48
BSV2	Joint pin between segment S2 and joint rod VS2	48
BSV3	Joint pin between segment S3 and joint rod VS3	48
BSV4	Joint pin between segment S4 and joint rod VS4	48
BSV5	Joint pin between segment S5 and joint rod VS5	48
BSV6	Joint pin between segment S6 and joint rod VS6	48
BRV1	Joint pin between adjustment ring R and joint rod VS1	48
BRV2	Joint pin between adjustment ring R and joint rod VS2	48
BRV3	Joint pin between adjustment ring R and joint rod VS3	48
BRV4	Joint pin between adjustment ring R and joint rod VS4	48
BRV5	Joint pin between adjustment ring R and joint rod VS5	48
BRV6	Joint pin between adjustment ring R and joint rod VS6	48
BRV7	In segment S7 integrated joint pin; sliding joint connection to leading edge of adjustment ring R	(48)
BRV8	In segment S8 integrated joint pin; sliding joint connection to leading edge of adjustment ring R	(48)
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While the concept could continuously adjust diverse geometries for every flight phase, the present concept uses only two states to minimise complexity of the required control process and to ensure safety. In the first state, a geometry for subsonic flight is set. This state also represents the nominal geometry, which should be implemented in the absence of loads or during failure conditions. The second state realises a geometry, which is suitable for supersonic flight. For reasons of safety, the supersonic geometry can only be set during stationary cruise flight conditions.

By axial movement of the actuation system A, switching between the states is accomplished. The movement of the actuators A results in an axial relocation of the adjustment ring R. This causes a positional change of the connected joint rods VS1..VS6, which pull the segments S1..S6 into the desired position. Additionally, the segments S7 and S8 slide along the leading edge of the adjustment ring R and form the requested lip geometry.

For the final concept, the sliding joint connection BRV7/8 within the leading edge of the adjustment ring R is enabled by internal rails, see Figure 9 on the left. This solution option offers good aerodynamic properties combined with a long lifetime. Thereby, the rails describe a curve that assists the minimisation of gaps between the leading edge and the segments S7/S8.

Alternatively, the rails could be mounted onto the leading edge ring, where they would lead to increased flow interactions. compare Figure 9 middle. The rails would also be more exposed to dirt, rain, hail and erosion, affecting their durability.

Another solution option is to go without rails and instead use an elastomer, which connects the segments S7 and S8 to the leading edge ring R, see Figure 9 on the right. However, the service life of this elastomer component would be severely limited due to the occurring mechanical and thermal stresses. Furthermore, the fixation of the elastomer would prevent a curvature of the lip surface, negatively affecting the inlet flow. Nevertheless, this method offers the benefit of a small required installation space. For this reason, it is applied in a second functional demonstrator with a scale of one to three, see Figure 10.

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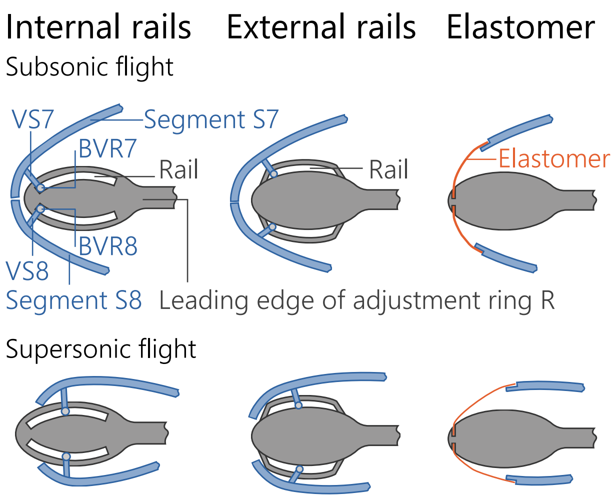

Figure 9: Lip design options

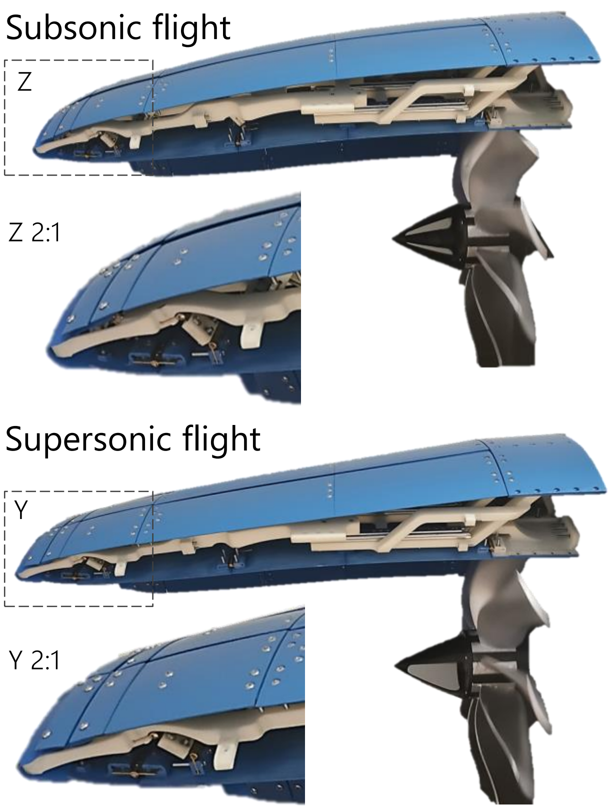

Figure 10: Second functional demonstrator

The lengths and positions of the joint rods VS1..8, as well as the number and positions of the axial inlet surface segmentations determine which geometries are adjustable by the system. This offers potential for optimisations and for application in other aircraft with different desired geometries.

Along with good aerodynamic properties due to a step- and gapless surface, the design of the leading edge as a continuous ring offers benefits regarding structural stability and safety in case of a bird strike. Thereby, a certain length and height is required to withstand bird strikes and to integrate the rails for the sliding joint connections to S7 and S8. Limitations of the leading edge ring are correlated constraints regarding adjustments of the inlet entry diameter. A completely segmented lip would enable a wider range of adjustable geometries; however, this design would cause larger gaps and be insufficiently resistant to bird strikes.

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In the event of a bird strike, there is a risk that components of the inlet concept may be subject to severe plastic deformation, fracture or even loss. This can lead to a disturbed inlet flow, potentially resulting in hazardous effects. Furthermore, lost components may hit and damage safety critical parts, such as the empennage. The loss of components can be avoided by designing them and their connections against bird strike loads or by integrating redundant precautions to hold the components. While the leading edge ring can be designed to withstand bird strike loads without fracture, the joint pints and joint rods would become unacceptably large and heavy. Hence, a second holding mechanism for the surface segments is applied, in case that the redundant joint pints or joint rod fracture. This holding mechanism utilises a steel net, which is unloaded during regular operation and becomes active in case of a structural failure of the joint rods or joint pins. This way, the hazardous loss of segments can be avoided, while only small flow disturbances are caused.

Further relevant failure modes include the unintentional actuator deployment and thus an unintentional adjustment of the geometry during take-off. As this failure can lead to hazardous effects, it is prevented by a redundant measure, in terms of an actuation locking mechanism that is independent from the actuator control system [36].

In case of an actuation system failure, e.g. missing energy supply, the variable inlet must adjust the subsonic geometry. If this is not automatically achieved by the flow force, an additional retraction of the adjustment ring R could be implemented by means of a spring mechanism. Additional means to ensure safety are the redundant design of all joint connections and the extended surface that is covered by the ice protection system.

The structural dimensioning of the inlet components from Table 1 reveals a conservative total weight of 146 kg. Although components, such as the ice protections system, the steel net, locking system, wires and screws, must be considered, an additional concept weight of less than 500 kg compared to rigid subsonic inlets is certainly achievable. Without considering the aerodynamic influence of steps and gaps, this results in a range benefit of at least 20% up to 30%, when applying this concept up to Mach 1.6 [38].

5. Conclusions

The development of a TRL 3 concept for variable inlets for SST by means of a safe design approach has been presented. An overview of inlet design and the design process in aviation has been given. The applied safe design process has been introduced and utilised to develop a feasible variable inlet concept.

Results from earlier safety, reliability, aerodynamic and structural analyses as well as the two manufactured functional demonstrators prove the feasibility of the inlet concept. Thereby, TRL 3 is achieved and a potential range benefit of 20% up to 30% is determined.

The concept can achieve TRL 4 by further analyses and an increased level of detail. For instance, bird strike and flow analyses should be conducted to prove the structural and aerodynamic capabilities of the final concept. Finally, tests must be performed to validate the results from these analyses. These tests can also be used to show compliance with the certification specifications.

The results of this paper highlight the high potential and feasibility of variable pitot inlets for future SST. Further concept investigations potentially enable this technology for future aircraft and this way, contribute to achieve high efficiency, reliability and safety in SST.

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