Review of variable leading-edge patents for aircraft wings and engine inlets and their relevance for variable pitot inlets in future supersonic transport

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Abstract

The motivation for designing variable pitot inlets for future supersonic transport (SST) is explained. A comprehensive overview of existing technological solutions for variable leading edges of aircraft wings and engine inlets is given. The advantages and limitations of over 80 solutions, as well as their relevance for application on variable pitot inlets for SST are described. The challenges of existing solution options concerning design methodologies, level of detail, and experience with a technology are identified.

Keywords Overview of variable inlet lips · Variable aero engine inlet · Morphing nacelle intake · SST

1 Introduction

Mitigating the global climate change and its consequences should be one of the primary goals of mankind. In aviation, climate protection is supported by the ACARE-goals (Advisory Council for Research and Innovation in Europe) of the European Union for 2020 [1] and 2050 [2]. These goals include the reduction of CO₂-emissions. This reduction can be achieved by improving the aircraft engines and their integration. Improved engine integration can reduce the aerodynamic drag of the aircraft and the propulsion efficiency of the system. This drag reduction has positive effects in terms of required thrust, achievable range, as well as fuel consumption, and hence, its produced CO₂-emissions.

The optimisation of the air flow around the engine inlet presents a way to reduce the aircraft drag. The inlet ensures the generation of thrust by supplying the required air mass flow to the engine. In subsonic aviation, this is mainly achieved by nearly annular, rigid pitot inlets. However, rigid inlets can only accomplish a trade-off concerning safety and aerodynamic drag, and thus, propulsive efficiency within the

highly diverse operation conditions. This trade-off can be mitigated by variable inlets, which have been investigated in a number of studies [3–5]. Nevertheless, subsonic variable inlets are currently not in use, as their aerodynamic benefits are outweighed by their limitations concerning complexity, reliability, and costs. Variable pitot inlets for SST applications up to Mach 1.6 offer higher aerodynamic benefits, which could compensate for these limitations [6]. Furthermore, variable pitot inlets have several advantages compared to other supersonic inlet types in terms of uniformity, length, and weight, while their increased complexity remains a challenge.

This paper supports the design of variable pitot inlets by identifying suitable solution principles and technologies. First, the trade-off in the design of pitot inlets and the potential benefits of variable inlets are introduced. Subsequently, existing technological solutions for variable leading edges of aircraft wings and engine inlets are identified and described regarding their functionality, complexity, and relevance for application on variable pitot inlets for SST.

2 Aero-engine inlets

The thrust generated by the engines enables the aircraft to fly. Thereby, the inlet ensures the thrust generation by supplying the required air mass flow to the engine. This air flow must be provided with high uniformity under all operating

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conditions, high-pressure recovery and limited to a maximum velocity of Mach 0.6 [7]. The fulfilment of this task is primarily determined by the geometry of the inlet.

Current commercial aircraft is operated exclusively under subsonic conditions. Applications in this range of flight speeds use approximately annular pitot inlets with a rigid geometry [8]. Such a rigid geometry can only provide a trade-off for the diverging aerodynamic requirements during the flight mission. During aircraft take-off and climb, flow disturbances due to the angle of attack and crosswind can occur. As a result, flow separations can occur in the area of the inlet. The inlet geometry must prevent these flow separations and potentially resulting in dangerous events [9]. For this purpose, a rounded, relatively thick geometry is utilised [10], see Fig. 1, top left. Conversely, during cruise flight, the emphasis is on minimising aerodynamic drag. Thus, a

relatively thin geometry is required in the subsonic cruise regime [10], see Fig. 1, middle right. Moreover, there are also non-commercial supersonic applications that use pitot inlets [9]. The geometry of pitot inlets for these supersonic applications is as sharp and thin as possible to generate minimal drag [11], see Fig. 1, bottom right.

The identification of the ideal geometry of rigid pitot inlets is the subject of numerous studies [12–15]. However, designing the inlet with a variable geometry offers many advantages, compare chapter 2.2 in detail. On one hand, by means of a variable design, an inlet geometry that is resilient to hazardous flow separations can be set during take-off and climb operation. On the other hand, a geometry with reduced drag can be implemented during cruise flight conditions. This drag reduction results in potential range benefits of up to 5% for solely subsonic applications and up to 30% for supersonic applications with flight speeds up to Mach 1.6 [16, 17].

Take-off and climb conditions

Subsonic cruise flight

Supersonic cruise flight

Fig. 1 Comparison of pitot inlet geometries

2.1 Variable pitot inlets

The geometry of pitot inlets can be adjusted in different regions of the inlet with diverse aerodynamic effects. The variation of the following geometric inlet parameters is reasonable for the respective flight conditions:

- the curvature of the inlet lip,
- the cross-sectional areas at inlet entry and throat level,
- the lengths of inlet lip, diffuser, and nacelle forebody, as well as
- the curvature of the nacelle forebody [16], compare Fig. 2.

Boundary layer control offers a further option for variable inlets. Hereby, the geometric inlet contour remains unchanged, while flow separation is avoided, e.g., by means of tangential blowing into the boundary layer or by air suction. Also, blow-in doors, auxiliary intake doors, or bleed doors have been utilised in earlier applications.

Due to their considerable potential benefits, variable inlets have been investigated in previous studies, compare

Fig. 2 Generic pitot inlet geometry

chapter 3. Within the MorphElle project (morphing enabling technologies for propulsion system nacelles), different concepts for subsonic variable pitot inlets [3, 18–20] have been elaborated. In cooperation with the NASA, Kondor et al. have developed a further concept [4, 21, 22]. Moreover, many patents concerning variable inlet geometries exist, e.g., US5000399 [23] and US4075833A [24]. Nevertheless, the mentioned solutions are not used in modern aircraft yet.

The absence of applications with variable pitot inlets can be explained by the added function of variability, which requires additional or novel components, e.g., adjustment systems or elastic materials. These components can negatively influence the manufacturing costs and the mass of the system [25]. The increased mass also has a negative effect on the payload or range of the aircraft. Furthermore, the additional components of a variable system represent an increased risk for failures [25]. These can result in increased maintenance efforts, a shorter service life, and safety-critical events [26]. These disadvantages potentially outweigh the aerodynamic advantages of variable pitot inlets, so that aircraft manufacturers currently avoid applying them in current subsonic aviation.

Hence, within the scope of a feasibility study for variable inlet concepts, the methodological design process according to VDI 2221 [27] has been supplemented with the safety assessment process in aviation according to Aerospace Recommended Practices ARP 4754A [25]. The resulting development process comprises

- the review of relevant existing solution options for variable pitot inlets, compare chapter 3,
- the identification of ideal inlet geometries concerning drag and flow uniformity for different flight speeds up to Mach 1.6 and the potentially resulting aerodynamic benefit [6, 16],
- the development of concept groups that adjust the inlet geometry by adjustment of rigid segments, by deformation of elastic surface materials, or by boundary layer control [5, 28],
- the application of the safety methods Functional Hazard Assessment (FHA), Fault Tree Analysis (FTA), and Common Cause Analysis (CCA) [29, 30],
- integration studies concerning ice protection systems [31], as well as
- the manufacturing of functional prototypes to demonstrate the feasibility of the developed concepts [32, 33].

2.2 Advantages compared to rigid pitot inlets

The utilisation of variable pitot inlets provides numerous potential benefits for subsonic and supersonic aircraft in terms of fuel consumption, range, noise emissions, and operational safety.

During low-speed flight phases, such as take-off, go-around or climb, large angles of attack and severe crosswind conditions can lead to flow separation and non-uniform fan inflow, potentially along with many negative effects, e.g., loss of thrust. Using a variable inlet, which adapts the contour ideally to these conditions, the negative effects can be minimised. A variation of the lip geometry at these phases can achieve a reduced flow redirection and acceleration between the inlet entry area and throat area. As a result, turbulences, the frequency of compressible effects, and flow separations are reduced. This leads to a decreased noise generation, an increased inlet pressure recovery ratio, and a higher fan flow uniformity [10, 34]. A more uniform fan flow results in a higher fan efficiency and reduced fan noise. During low-speed flight phases, increasing the curvature (decreasing the radius) at the front of the outer nacelle forebody can also be beneficial to the inlet lip flow. An extension of the inlet can have a positive effect on the uniformity of the fan flow, as minor disturbances in the flow field can be smoothed out. An increase of the inlet entry area A_1 improves the matching with the capture stream tube at these low-speed flight phases. Thus, the necessary flow redirection around the inlet lip is reduced, which has similar effects to the lip geometry variation. An increased throat area A_{th} leads to lower throat Mach numbers, thereby local supersonic velocities and compressible effects can be avoided, leading to an improved inlet pressure recovery.

The improved resilience to flow separation and the higher flow uniformity due to variable inlets increase the surge margin and thus reduce the risk of engine surge [35]. The increased surge margin can also be used to achieve higher acceleration rates of the aero engine. This allows for shorter take-off distances, larger angles of attack, and increased climb rates. Consequently, the aircraft noise level and its duration can be decreased in the vicinity of the airport, positively impacting the aircraft certification and the operating costs at the airport. Additionally, the improved resilience to flow separation can increase the safety during severe crosswind conditions. This could also enable adjustments of the crosswind velocity limits according to CS 25.237 [26]. Moreover, the necessity of some aircraft for a rolling take-off could be avoided, allowing for shorter taxiways and thereby fuel savings.

During windmilling operation in case of an engine failure, the resulting spillage drag could be significantly reduced by a variable inlet that decreases the inlet entry area A_1 . Due to the drag reduction, the remaining operating engines would also have to generate significantly less thrust. This could enable a reduction of the safety-related oversizing of aero engines.

For cruise flight, the influence of crosswinds is almost negligible due to the comparatively much higher flight speed. In addition, the usual angles of attack of civil

applications are significantly smaller in cruise flight, thus permitting the assumption of a nearly undisturbed axial inlet flow. Hence, different circumferential cross-sections can be avoided during cruise flight and the entire inlet geometry can be optimised for these conditions. Moreover, for subsonic cruise flight, the inlet entry area A_1 could be reduced to better match the capture stream tube A_0 . Consequently, the spill from the inlet lip to the outer nacelle forebody and the resulting drag are reduced. The geometry of the outer nacelle forebody could also be adapted to maximise the generated suction force [6]. This way, the resulting aircraft drag could be reduced, allowing for lower thrust requirements for the aero engines. Lower required thrust can enable lower fuel consumption and a longer flight range with an unchanged amount of fuel carried. The amount of fuel carried could also be reduced, thus increasing the payload of the aircraft. Furthermore, the drag reduction supports an increase of the cruise flight speed in the subsonic regime.

A further increase of the flight velocity up to supersonic velocities of Mach 1.6 requires additional geometry adjustments. Due to the normal shock in front of the inlet, no large suction force can be achieved on the nacelle forebody, so it is important to minimise its frontal area and to avoid additional shocks on the outer contour. However, the frontal area depends on the maximum nacelle diameter, which is limited by currently integrated accessories. Furthermore, the lip geometry should be as thin to sharp as possible, whereby the inlet throat relocates into the entry plane [36]. In this regard, the capability to reduce the lip length is beneficial. Simultaneously, a longer diffuser is also useful to smooth out local turbulences in the flow field after the initial normal shock. By adapting the inlet entry area A_1 to the required engine air mass flow, the distance between normal shock and inlet entry plane can be decreased [36]. This reduces the generated spillage drag significantly [36]. While the effects of a drag reduction are similar to subsonic cases, the potential benefit is much higher for supersonic conditions.

In contrast to rigid pitot inlets, variable pitot inlets offer increased resilience to flow separation at low flight speeds and the possibility to extend the operating range of aircraft towards more severe crosswind conditions. They can also support increased climb rates and thus reduce noise near the airport. Additionally, they enable more efficient subsonic and supersonic cruise flight. The variation of the inlet geometry could also be used as a de-icing mechanism. Due to the improved inlet flow, the generated noise can be reduced as well.

2.3 Advantages compared to other inlet types

Pitot inlets up to Mach 1.6 have numerous advantages compared to rectangular inlets with external compression, which have to compensate for the limited pressure recovery

during supersonic operation. The main advantages are the low aerodynamic drag, the stable flow behaviour, and the high uniformity of the fan inflow [9, 11, 39]. The higher uniformity enables a significantly shorter inlet length and thus a reduction of the required installation space and mass [9]. Besides, a shorter length has a positive influence on the boundary layer thickness, thus avoiding the necessity of additional components like boundary layer separators. The stable flow behaviour includes in particular the fact that the compression shock is in a stable position due to the sharp lip [36]. In contrast, inlets with external or mixed compression may be subject to severe instabilities at the transition from subsonic to supersonic operation [36, 38]. These instabilities can require complex starting and control mechanisms, such as movable flow duct walls or bypass doors [36, 38].

3 Variable leading-edge solutions

Given the potential advantages compared to limited rigid trade-off designs, there are numerous solution options for the variable design of wing leading edges and inlets. Partly, variable pitot inlets are the primary field of application for these solutions. However, most of them have been developed for other applications, but show a certain potential for application in variable pitot inlets.

Table 1 presents an overview of existing patents regarding variable geometries for wing leading edges and inlets. Additionally, it is shown which geometric parameters can be varied by the respective patents:

- the inlet entry area (**A**),
- the leading-edge curvature (**R**),
- the length of the aerofoil or inlet (**L**) and/or
- the thickness of the aerofoil or inlet (**T**),

on which functional principle the variation is based:

- adjustment of rigid surface segments of a continuous contour (**F**),
- deformation of elastic surface materials (**E**),
- moving of forebodies/flaps/ramps/cones (**V**) and/or
- aerodynamic boundary layer control (**G**),

for which spatial dimension the patents are mainly suitable:

- planar (**2D**) or
- annular (**3D**) applications,

as well as which potential weaknesses the respective patents reveal:

Table 1 List of relevant patents

Year	Variation			Principle		Description	References
2019	A	R		F		Rotatable flaps, 3D, L, Z	[39]
2019			L		V G	Extendable cascades, 3D, L	[40]
2016				T	E	Shape memory alloys, 2D	[41]
2016	A	R		T	E	Pneumatically adjustable elastomer, 3D, Z	[42]
2016	A			T	F	Axially adjustable leading edge, 90° sector	[43]
2016			L		F	Telescope principle, 3D, D	[44]
2016	A	R		T	E	Adjustable aerofoil, 2D, Z	[45]
2015	A	R		T	E	Adjustable aerofoil, 2D	[46]
2015			L		E	Shape memory alloys, 2D, D	[47]
2014	A				E	Adjustable inlet lip, 3D, D	[48]
2014	A				V	Rotatable cone, 90° sector	[49]
2014	A	R		T	E	Adjustable inlet lip, 3D, D	[50, 51]
2014	A				V	Multiple fans, 2D	[52]
2014	A			T	F	Segmented cowl, 3D, D	[53]
2014					G	Boundary layer ingestion, 3D	[54]
2013	A	R		T	E	Segmented cowl, 3D, D	[55]
2013					V G	Radially extendable aerofoils, 3D, D, L	[56]
2013					G	Boundary layer suction, 3D, D, Z	[57]
2013					V	Tilttable rigid inlet, 3D, D, Z	[58]
2013		R		T	V	Rotatable, overlapping inlet lip, 3D, D, Z	[59]
2013	A	R	L	T	E	Pneumatically adjustable elastomer, 2D, Z	[60]
2013					V G	Radially extendable aerofoils, 3D, D, L	[61]
2013	A				E	Shape memory alloys in nozzle, D	[62]
2012	A				V	Adjustable duct wall, 2D, D	[63]
2012					G	Boundary layer suction, 3D, D	[64]
2012					G	Boundary layer suction, 3D, D, Z	[65]
2012					V G	Radially extendable aerofoils, 3D, D, L	[66, 67]
2012					V G	Movable vortex generators, 3D, D, Z	[68]
2012				F		Segmented leading edge, D	[69]
2012	A	R		T	E	Elastic wing deformation, 2D	[70]
2011	A	R			E	Elastic deformation, 3D, D	[71]
2011					G	Boundary layer injection, 3D, D	[72]
2010					V	Adjustable inlet flaps, D	[73]
2010		R			E	Elastic wing deformation, 2D, Z	[74]
2010	A					Inlet with turbochargers, 3D, Z, D	[75]
2009					G	Vortex generators, 3D, D	[76]
2009					G	Active boundary layer control, 3D, D	[77]
2009	A	R	L	T	E	Elastic lip deformation, 3D, D	[78]
2009			L		F	Axially extendable inlet, 3D	[79]
2009	A		L		V G	Axially extendable aerofoils, 3D	[80]
2009	A		L		V G	Extendable lip ring, 3D	[81]
2008	A		L		V G	Axially extendable aerofoils, 3D	[82]
2008		R		T	E	Elastic deformation, 3D, D	[83]
2008	A				V	Variable center body, 3D, D	[84]
2006	A				E	Shape memory alloys in nozzle, D	[85]
2005	A	R	L	T	V	Rotatable inlet in wing, 3D, D, Z	[86]
2005		R	L		E	Adjustable inlet lip, 2D	[87]
2004	A				V	Adjustable duct wall, 2D	[88]
2004					V	Rotatable and tilttable inlet, 3D, D	[89]
2003					E	Flexible surface, D	[90]
2003	A				V	Blockage flaps, 3D, D, Z, L	[91]

Table 1 (continued)

Year	Variation				Principle	Description	References
2002	A				T F	Internal compression inlet, 2D	[92]
2001	A	R			E	Segmented elastomer, 3D, D	[93]
2000	A				V	Bleed doors, 3D, L	[94]
1999	A				V	Bleed doors, 2D, D, L	[95]
1994	A				V	Variable center body, 3D	[96]
1992	A	R			T	Bleed doors, 3D, D, L	[97]
1992	A				V	Adjustable duct wall, 2D	[98]
1991	A	R			T F	Segmented adjustable inlet lip, 3D, Z, L	[23]
1989	A	R			T	Adjustable flaps, 3D, D, L	[99]
1988	A				V	G Bleed doors, 3D, L	[100]
1987	A				V	Adjustable duct wall, 2D	[101]
1986	A				V	G Bleed doors, 3D	[102]
1984	A				V	G Bleed doors, 3D	[103]
1984	A	R	L		T	E Adjustable aerofoil, 2D	[104]
1982	A	R			T	E Adjustable aerofoil, 2D	[105]
1979	A	R	L		T F	Bleed doors, 3D, L	[106]
1978	A	R			T F	Segmented adjustable inlet lip, 3D, Z	[24]
1977	A	R			T	E Adjustable inlet lip, 2D	[107]
1975					V	Adjustable internal inlet rings, 3D	[108]
1975	A				F	G Bleed doors, 2D	[109]
1973	A				V	Rotatable flaps, 3D, L, Z	[110]
1973	A				F	Adjustable segmented inlet lip, 3D, D	[111]
1972	A	R	L		T F	G Adjustable segmented inlet lip, 3D, L, Z	[112]
1971	A	R			T F	G Adjustable segmented inlet lip, 3D, D	[113]
1970		R			T	V Rotatable inlet in fuselage, 3D, D, Z	[114]
1969	A	R	L			V Tiltable rigid inlet, 2D, D	[115]
1966	A	R	L		T F	Rotatable segmented inlet lip, 3D, L, Z	[116]

- an insufficient degree of detail (**D**),
- high noise emissions, e.g. due to exposed flaps (**L**) or
- very high complexity or functional weaknesses that can lead to a reduced reliability of the system (**Z**).

Numerous models for the structured classification of patents exist [117]. In the following, the primary differentiation is based on the spatial dimension of the application and the subsequent subdivisions are made according to the associated component and the type of geometry variation, compare Fig. 3.

Generating variable geometries is considerably easier for plane structures than for annular structures in three-dimensional space. Hence, many applications of planar 2D solutions exist in the shape of variable wing designs and variable rectangular supersonic inlets. In the three-dimensional space, different variable solutions exist for the center body and for the inlet cowl, especially for supersonic applications. Thereby, most of the solutions

Fig. 3 Overview variable solution principles

in the field of the inlet cowl have never surpassed the status of a patent idea.

3.1 Variable wing leading edge

Aerofoils of aircraft wings represent high-lift systems, in which the curvature and the projected area are maximised, while the risk of flow separation is minimised [34]. In this context, gapless applications with continuous contours and those with gaps can be found [34]. Especially in the region of the leading edge, the emphasis is on the prevention of flow separations [34]. Therefore, the surface contour is designed in an aerodynamically smooth way and the flow accelerations in the lip region are limited. [34].

Niu [118] summarises the various solution options for the geometry variation of aircraft wing leading edges. These solutions can be categorised into three main types, which are illustrated in Fig. 4:

- the droop nose [34, 118],
- slats [34, 60, 118], and
- the Krüger flap [34, 118].

Furthermore, there are combinations of droop nose and Krüger flap [104].

Whereas concepts for adjustable slats and Krüger flaps generate considerable amounts of noise due to their gap involving design, modified droop nose concepts [45, 46, 70, 74, 105] could also be applied for the lip of a pitot inlet. In particular, the adaptation of the geometry variation from the almost flat aircraft wing to the three-dimensional, annular shape of the pitot inlet presents a considerable technical challenge. Recent studies [119–122] on

droop nose implementations by means of smart materials could assist this adaptation.

3.2 Variable rectangular inlet cowl

As shown in Fig. 5, the nacelle geometry of rectangular inlets for supersonic applications can be varied by

- adjusting the lip shape and angle,
- modifications of the flow duct geometry, and
- bleed doors or flaps within the duct [123]

The variation of the lip angle and lip shape [87, 107] is comparable to the solution approaches for variable aircraft wing leading edges, especially to the droop nose. The lip variation provides an adaptation to the capture stream tube, to the inflow direction and enables the desired shock configurations [9]. As an example, variable metallic inlet lips are installed in the F-15 and Eurofighter aircraft [9]. The Hawker P1127 featured inflatable rubber inlet lips; however, due to their limited service life, these were later replaced by metallic designs [9]. Smart materials also offer considerable potentials that have been investigated, for instance, in the SAMPSON project (Smart Aircraft and Marine Project System Demonstration) [124–128].

The variation of the flow duct geometry [63, 92, 101] allows to control the engine mass flow, as well as the position and the intensity of occurring compression shocks, mitigating the difficulties concerning the starting of supersonic inlets [10, 36]. The variation of the duct geometry is often combined with flaps, blow-in doors, or bleed doors

Droop Nose

Fig. 4 Variable high-lift systems on aircraft wings

Lip angle

Fig. 5 Variable geometries for rectangular inlet cowls

[88, 95, 107]. By means of these vents, additional required air can flow into the inlet or excessive air can be ventilated from the inlet. Depending on the door design, flow separation can be avoided by boundary layer suction or ingestion. Blow-in and bleed doors have also been installed in former pitot inlets; however, they entail the disadvantage of considerable noise generation [9].

3.3 Variable inlet center body

The variation of the conical center body is primarily used for supersonic inlets with mixed compression to create the intended shock configurations. Hereby, the center body can be axially movable [84, 96] or provide an adjustable diameter [96, 123], see Fig. 6. Moreover, vent ducts for boundary layer suction are often integrated into adjustable center bodies [9].

A further option to vary the inlet cross section is the use of the iris diaphragm principle. This principle is similar to a camera iris, where the opening cross section is adjusted,

Translating

Variable area

Iris diaphragm

Fig. 6 Variable inlet center body solutions

see Fig. 6 bottom. This solution principle is applied in the Sukhoi Su-29 [129].

3.4 Variable annular inlet cowl

There are three basic approaches for the implementation of variable pitot inlet cowls, compare Fig. 3. The first of these approaches is the variation of the inlet by moving large components. This involves the tilting, rotation, or extension of large sections or components of the inlet cowl. Furthermore, there is a concept option [89], where the inlet can be rotated and tilted simultaneously.

Concept variations for the tilting of large areas of the inlet cowl have been developed, which tilt the entire inlet [58, 115] or only a large sector of the inlet [115] along an axis, see Fig. 7. For instance, these variants can be used to adapt to different angles of attack or to block the fan noise from the ground.

The rotation of large components represents a further solution option. Hereby, the entire inlet ring or the inlet lip is rotated around the engine axis [59, 114], see Fig. 8, or around an offset axis [86]. This solution is particularly useful for engines whose inlet is semi-circular and mounted close to the fuselage. In this way, a more suitable geometry can be set for the respective flight phase, while the less favourable geometry is stowed inside of the fuselage. Within the HISAC

Tiltable inlet ring

Tiltable inlet sector

Fig. 7 Tiltable pitot inlet options

Rotation around engine axis

State 1

State 2

Fig. 8 Example of a rotatable pitot inlet

project different inlet configurations with semi-circular and circular inlets have been investigated in detail [37].

The extension of large annular inlet components can be achieved using the telescopic principle [44, 79], by axial translation of an inlet lip ring [81, 82], or by axial translation of vane rings out of the lip [40, 80], see Fig. 9. The telescopic principle describes the idea of having a part of the inlet stowed inside the inlet cowl in its nominal state and being able to deploy this part to create a part of the inlet contour when required. Using this principle, only the length of the inlet can be varied. The solutions of translating inlet lips or vanes are functionally comparable to the principle of the opening flaps, blow-in doors, or bleed doors in the flow duct, compare Fig. 5 bottom. Hereby, the goal is to maximise the incoming air mass flow, while avoiding flow separations. A major challenge presents the resulting noise from the flow around the extended components.

Axially adjustable rings within the inlet duct [108] represent a special option for the redirection of the inlet flow and to provide design space for acoustic treatment. However, the influence of these rings on the inlet flow is to investigate.

The concepts that vary the geometry of the inlet by moving large components are mainly characterised by their simple kinematics. However, the disadvantage of these concepts is that the degree of the geometry variation is very limited.

Telescope principle

Stowed

Deployed

Translating ring

Translating vanes

Fig. 9 Inlet variation by axial extension

The functionality of these concepts must be investigated as well. The level of detail of most of these concepts is also too low to be able to estimate their feasibility. For moving very large and hence heavy components, equally large actuating forces are necessary as well. Furthermore, the components of the adjustment system must be dimensioned accordingly.

The second basic approach for the implementation of variable pitot inlet cowls, namely the geometrical contour variation, offers greater aerodynamic potential. This approach comprises concepts with accepted surface gaps and steps on one hand, and concepts that provide almost gapless continuous contours on the other hand. Both concept types must be clearly distinguished from each other, as the former concept type usually features simpler kinematics, but generates more noise due to the created turbulence at the gaps and steps.

The geometrical variation requires movements of rigid surface components or elastic deformations of the surface material in the radial direction. Due to the annular structure of pitot inlets, radial variations of rigid components can cause circumferential gaps or component collisions. These gaps and collisions can be avoided by a circumferential segmentation of the components, including a sealing between the resulting segments. Potential solutions for circumferential sealings range from the acceptance of gaps [116] over rigid borders between the segments [24, 111] and overlapping adjacent segments [53] up to elastic material between the segments [23].

Examples of concepts with accepted or even desired surface gaps are

- radial adjustable vanes,
- adjustable inlet flaps, as well as
- blow-in and bleed doors, compare Fig. 10

Adjustable vanes can be moved radially inwards [61, 67] as well as radially outwards [56, 66, 67]. A combination with an axial translation [82] is also possible. As with the previously described solutions with movable vanes, the aim of these concepts is to maximise the incoming air mass flow and to minimise the occurrence of flow separations.

Adjustable inlet flaps can be installed on the outside of the inlet [39, 100] to create a bell-mouth-like geometry that is resilient to flow separations [10]. The flaps can also be mounted on the inside [91] or in front of inlet [97], for instance, to regulate the air mass flow.

Blow-in and bleed doors within the pitot inlet cowl enable an adjustment of the effective inlet entry area by ingestion of additional required air [94, 106, 112, 113] or by ventilation of excessive air from the inlet [97, 100, 102, 103]. Thereby, the boundary layer is influenced positively, leading to a reduced risk of flow separation. The main difference between the doors for annular applications compared to those for rectangular inlets is that the doors can only cover a relatively small circumferential sector. Otherwise, the gap losses between the rotating flaps and the curved rigid inlet structure would increase significantly.

Concepts that achieve a continuous contour can be based on the principles of adjusting rigid contour segments or the elastic deformation of the surface material. Both solutions enable the fundamental variation of all geometrical parameters of the inlet cowl.

The principle of moving rigid segments comprises solution options for the adjustment of the inlet lip [23, 24, 111], the diffuser geometry [24, 53], as well as the outer contour [23]. Although, there is currently no according patent that can vary the geometry of all these three parts. For solutions that can vary the lip geometry and the inlet entry area, a higher risk of damage due to bird strikes must be considered.

Radial vanes

Stowed

Deployed

Inlet flaps

Bleed doors

Fig. 10 Variable vanes and flaps

However, two of the mentioned lip adjusting solution options [24, 111] utilise a segmented lip, which is particularly fragile in the event of a bird strike. The remaining solution [23] uses a circumferentially continuous ring as leading edge of the inlet lip, compare Fig. 11. This ring is axially translated to adjust the segmented outer contour. During this movement, a safety-critical gap arises between inner and outer geometry at the inlet entry plane [23]. For the implementation of cross-sectional variations, the displacement of rigid contour segments always requires a circumferential segmentation of the contour. This leads to an increase of the design complexity and results in small circumferential deviations from an ideal circular geometry.

For the principle of elastic surface deformation, segmented [55, 93] and circumferentially continuous [42, 48,

Fig. 11 Adjustment of rigid inlet segments

50, 51, 71, 78, 83] solution options exist. The segmented solutions that use this principle are comparable to the previously described concepts that adjust rigid segments. Thereby, the elastic surface material enables a smoother contour in the axial direction, while being more prone to heavy wear. Furthermore, the range of the achievable geometrical adjustments is comparatively small.

Circumferentially continuous solution options achieve the aerodynamically best inlet geometries by avoiding circumferential deviations from the ideal contour. For this purpose, the material must be able to expand in axial and circumferential directions. In this context, smart materials [83] or pneumatically deformable contour cells [42] could be utilised. The later principle is also used in the concept developed in the MorphElle project [3, 18–20]. When considering these pressurised contour cells, emphasis should be placed on their durability and resilience to erosion, foreign object damage, and bird strikes.

The third basic approach for the implementation of variable pitot inlet cowls is the control of the flow boundary layer [130]. By avoiding flow separations, boundary layer control allows the use of slim geometries with low aerodynamic drag [131]. Solutions for boundary layer control can be divided into passive and active mechanisms [34].

Passive mechanisms include, for instance, the introduced applications concerning adjustable vanes and bleed doors [132]. Solutions with bleed doors [97, 100, 102, 103] direct the flow in the vicinity of the duct wall through openable

Fig. 12 Options of boundary layer control

flow ducts to the outside of the inlet [132], compare Fig. 5 bottom and FIGURE 9 centrally. Similar to slats [34], adjustable aerofoils or vanes [40, 56, 61, 66, 67, 82, 99] prevent flow separations, compare Fig. 9 bottom and Fig. 10 top. A special case of vanes is vortex generators, which are integrated into the flow duct. These are intended to avoid flow separations by increasing the turbulence of the flow. Vortex generators can be designed as stationary [76] or extendable [68].

Active boundary layer control includes the suction of the flow boundary layer through small suction slots [57, 64], the tangential blowing into the boundary layer through blowing slots [54, 72], and combinations [65] of these types [34, 133], compare Fig. 12. The concept of Kondor et al. [4, 21, 22] also uses the principle of tangential blowing into the boundary layer. By blowing in or suctioning off air, the flow boundary layer is stabilized in the vicinity of the wall and flow separation is avoided [34]. A challenge for these concepts poses the protection of the respective slots from dirt or ice blockage. Additionally, a control system is required to regulate the air mass flow to be supplied or removed. For the event of a malfunction of the system, design precautions must be taken to ensure that the inlet still fulfils its function.

3.5 Relevance for variable pitot inlets

For the evaluation of the relevance of a solution option for variable pitot inlets, the most important advantages and

Table 2 Evaluation of relevance for variable pitot inlets

Component	Type of variation	Benefits	Weaknesses
Wing leading edge	Droop nose	Stepless surface, good drag reduction, avoidance of flow separation	Only 2D, reliability
	Slats	Proven technology, avoidance of flow separation, simple kinematic	Only 2D, large gaps, increased turbulences, and noise
	Krüger flap	Proven technology, avoidance of flow separation, simple kinematic	Only 2D, large steps, increased turbulences, and noise
Rectangular inlet cowl	Lip angle	Stepless surface, good drag reduction, avoidance of flow separation	Only 2D, reliability
	Duct geometry	Mass flow control	Only 2D, low drag reduction
	Bleed doors	Avoidance of flow separation	Only 2D, low drag reduction, increased turbulences and noise
Inlet center body	Translating	Mass flow control, simple kinematic	Low drag reduction, weight
	Variable area	Mass flow control	No drag reduction, complexity, weight
	Iris diaphragm	Mass flow control	No drag reduction, complexity
Annular inlet cowl	Tilttable large sections	Avoidance of flow separation	Low drag reduction, weight
	Rotatable large sections	Good drag reduction, avoidance of flow separation	Complexity, weight
	Extension of large sections	Simple kinematic	Low drag reduction, weight
	Geometric contour with flaps, steps, and/or gaps	Avoidance of flow separation	Low drag reduction, increased turbulences, and noise
	Continuous geometric contour with rigid segments	Good drag reduction, avoidance of flow separation	Complexity, reliability, remaining small steps and gaps
	Continuous geometric contour with elastic surface	Good drag reduction, avoidance of flow separation	Complexity, reliability, durability, remaining small steps and gaps
	Passive boundary layer control	Avoidance of flow separation	Low drag reduction, increased turbulences, and noise
	Active boundary layer control	Good drag reduction, avoidance of flow separation	Complexity, reliability, fail-safe mechanisms

disadvantages of the respective type of variation are listed in Table 2.

Thereby, solutions have been eliminated, which are solely developed for planar or two-dimensional applications, compare Fig. 4, 5. On one hand, 2D solutions with the same mass and length provide worse flow uniformity and aerodynamic drag compared to annular solutions. On the other hand, adapting the principles to a circular contour would lead to increased complexity and thus reliability issues.

Solutions, which vary the inlet center body (Fig. 6), have also been excluded, as they cannot provide a significant drag reduction in the investigated velocity range. Another challenge is presented by their increased complexity and weight.

Tilting (Fig. 7), rotation (Fig. 8), or extension (Fig. 9) of large sections requires large actuating forces, resulting in increased weight. While the rotation of large sections is very complex, tilting and extension of large sections can only provide small aerodynamic drag improvements.

All solution options, which utilise geometrical contour variation or boundary layer control for an annular inlet cowl, provide means to avoid flow separation and can achieve high uniformity. Options that vary the geometrical contour

with flaps, steps, and/or gaps (Fig. 10), as well as passive boundary layer control result in increased turbulences and noise due to the flaps, steps, and/or gaps. Furthermore, these options can only provide low drag reduction.

Solutions with nearly gap- and stepless geometrical contour variation either using rigid segments (Fig. 11) or an elastic surface material achieve reduced drag at cost of increased complexity and potential reliability issues. Additionally, the influence of the remaining small surface steps and gaps on the aerodynamic properties of these inlets must be investigated with solutions of a higher degree of detail. Active boundary layer control (Fig. 12) presents a further aerodynamically suitable option. However, detailed investigations are necessary to ensure the safety and reliability of this option.

4 Conclusions

The motivation for designing variable pitot inlets for future supersonic transport (SST) has been described. An overview of existing technological solutions for variable leading edges of aircraft wings and engine inlets has been given. The advantages and limitations of over 80 solutions, as well as their relevance for application on variable pitot inlets for SST have been identified. In this context, different solution categories have been established. These categories are based on the spatial dimension of the application, the associated component, and the type of variation.

Most of the identified solutions offer potential benefits for improvements of the inlet flow. However, all approaches have individual weaknesses regarding the fulfilment of requirements, e.g., flow characteristics, noise emissions, reliability, or safety. These weaknesses can be caused by unsuitable design methodologies, a low level of detail, and/or insufficient experience with innovative technologies.

The most suitable options for variable pitot inlets are represented by concepts that adjust the inlet geometry by

- repositioning of rigid inlet cowl segments of a continuous contour,
- elastic deformations of the inlet cowl surface material, and
- by active boundary layer control.

These results may assist further investigations concerning variable inlets in the context of research and development programmes with a high potential for application in supersonic aircraft. This way, the aircraft range could be significantly increased, and their fuel consumption reduced. This would result in considerable economic and ecological improvements. Thus, variable pitot inlets could become a key factor in the reintroduction of a more environmentally friendly supersonic transport.

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