

Parametric Design Study on Aerodynamic Characteristics of Variable Pitot Inlets for Transonic and Supersonic Civil Aviation

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Abstract. This paper reveals the influence of selected geometric parameters on the aerodynamic performance of circular variable aero engine inlets in transonic and supersonic civil aviation. The trade-off in inlet design and aerodynamic evaluation parameters are presented. The approach to investigate the dependencies between the aerodynamic and geometric parameters at different flight conditions by means of a parametric design study is introduced. The dependencies of inlet drag and efficiency from geometric parameters at flight speeds of Mach 0.95 up to Mach 1.6 are identified. Although entailing additional weight, the inlet length represents the parameter with the highest potential for drag reduction by up to 50% in the selected design space. Ideal geometries for variable pitot inlets are determined. After considering weight, their potential range benefit nearly disappears for subsonic applications, but remains above 20% for supersonic flight at Mach 1.6.

1 Introduction

Major development goals of the civil aviation industry are improvements in efficiency, emissions and travel speed, while ensuring safety and reliability [1]. The aero engine and its subsystems, e.g. the inlet, influence these goals. Using variable pitot inlets, which provide the ideal geometry for different flight and operating conditions, instead of rigid inlets can decrease aerodynamic drag, allowing for increased efficiency and flight speed. Although research studies concerning subsonic circular variable inlets with adjustable lip and duct geometry have been carried out [2], [3], this technology has not yet made its way into service, as the aerodynamic benefit of subsonic variable inlets may not compensate for the increased complexity and weight.

However, variable pitot inlets could also be utilised for supersonic business aircraft with flight speeds of up to Mach 1.6 [4], [5]. The only civil supersonic aircraft to date, the Tupolev Tu-144 and the Concorde, utilised two-dimensional non-circular inlets with variable ramps and bypass flaps. Due to their geometry, very long inlets were required to attenuate inlet distortion. This length and the required actuation system for the ramps resulted in high additional weight compared to circular pitot inlets.

Pitot inlets, which achieve minimal aerodynamic drag, differ significantly between subsonic and supersonic applications concerning lip, diffuser duct and forebody geometry. A potential variable inlet must be able to convert these geometries into each other in order

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to avoid flow separation during take-off and climb, while ensuring maximum efficiency at high cruise speeds. This requirement results in geometric constraints, e.g. concerning feasible inlet lip thickness or radius. There is little knowledge about feasible geometries for variable supersonic pitot inlets and their potential aerodynamic benefit. Hence, a parametric design approach has been developed to identify ideal high speed flight geometries that can be realised by variable pitot inlets [6].

This paper introduces the influence of selected geometric parameters on the aerodynamic performance of circular variable aero engine inlets in transonic and supersonic civil aviation. Hence, the trade-off in inlet design and aerodynamic inlet evaluation parameters are presented. The approach to investigate the dependencies between the aerodynamic and geometric parameters at the respective diverging flight conditions is introduced. The advantages and limitations of the presented approach are addressed. The dependencies of inlet drag and efficiency from geometric inlet parameters at flight speeds of Mach 0.95 up to Mach 1.6 are identified by means of a parametric design study. This way, ideal geometries for variable pitot inlets and their potential range benefit are determined and feasible concepts for variable pitot inlets [7], [8], [9], [10], [11] can be developed.

2 Aero engine inlets

2.1 Tasks and trade-off in design

An aero engine requires air to produce thrust for the aircraft. The air is provided by the nacelle inlet, also called intake. The primary objective of the inlet is to divide the free stream air in front of the aero engine at the stagnation point depending on the operating conditions into internal and external air flow. Thereby, the external air flow shall stream along the outer nacelle surface, while avoiding flow separation and minimising aerodynamic drag [12]. The internal air flow must provide the aero engine with the correct quantity of air at a desired flow velocity and high uniformity during each operating condition, while minimising aerodynamic losses [13], which is achieved by the geometry of the inlet duct.

During the geometric design of subsonic pitot inlets, different requirements have to be satisfied to ensure reliable operation, while achieving high efficiency [5]. On the one hand, it is necessary to avoid flow separations and potentially resulting hazardous events during take-off and climb operation up to Mach 0.3. On the other hand, the inlet should be highly efficient during cruise operation at high subsonic flight velocities above Mach 0.8.

At low aircraft velocities during take-off and climb, where high angles of incidence and crosswind can occur, a round and thick inlet lip with a large inlet area is ideal [14]. However, such a 'blunt' lip geometry causes higher drag, and thus reduced efficiency during cruise operation [14]. High efficiency at these operating conditions can be achieved by a thin lip contour [4], which is susceptible to flow separation at take-off and climb conditions [14].

Hence, conventional rigid subsonic inlets can only accomplish a trade-off concerning minimum drag at high velocities and avoidance of flow separation at low velocities. While numerous studies [15], [16], [17] focus on the identification of ideal trade-off geometries, variable pitot inlets could eliminate the necessity for said trade-off.

Subsonic variable inlets that adjust the ideal inlet geometry for each flight condition have been investigated [2], [3] and [18], but did not yet find their way in service in commercial aviation. A potential reason is that the expectable limited aerodynamic benefit at subsonic conditions is eliminated or even negated by the additional weight and the higher complexity of the design.

Nevertheless, pitot inlets can be applied for flight Mach numbers up to 1.6 without significant losses [5], [4]. At these supersonic regimes a long inlet with a sharp inlet lip is

suitable to minimise losses, e.g. due to spillage drag [5], [19]. Thus, a variable supersonic pitot inlet could provide geometries that are efficient and reliable for subsonic and for supersonic conditions. However, the exact aerodynamic potential of supersonic pitot inlets must be identified by determining and evaluating the ideal geometries for the expected operating conditions, which is done in the following chapters.

2.2 Inlet evaluation criteria

The performance of an aero engine inlet is primarily evaluated by its achieved pressure recovery, provided flow uniformity and produced external drag [5], [4].

The pressure recovery ratio represents the reduction of the free stream total pressure p_{t0} due to losses, e.g. caused by surface friction, flow separation, shock waves, to a value p_{t2} at the fan face [5]:

$$\pi_{int} = p_{t2} / p_{t0} \tag{1}$$

The pressure recovery influences the amount of thrust that an engine can provide, as 1 % loss of pressure recovery is equal to 1 % up to 1.5 % loss of thrust [5]. For subsonic conditions, pressure recovery values of pitot inlets are higher than 0.90 at low flight speeds and can increase with flight speed up to 0.99 [5], [14]. Due to the total pressure loss from the single normal shock that results from using a pitot inlet at supersonic conditions, the pressure recovery value decreases to a theoretical maximum of $\pi_{int} = 0.98$ at Mach 1.3, $\pi_{int} = 0.90$ at Mach 1.6, and $\pi_{int} = 0.72$ at Mach 2 [5].

Flow uniformity at the fan face is necessary to avoid vibration excitations and flow separations, which influence the efficiency and can lead to engine surge or flame out, resulting in loss of thrust and reduced lifetime [20], [21]. Therefore, the air, delivered by the inlet to the engine, shall be aligned with the engine axis, as well as uniform in velocity, temperature and pressure [5]. The uniformity of the air flow at the fan face A_2 can be influenced negatively by high angles of attack, high angles of incidence, crosswind and the inlet design [5]. At cruise conditions, flow separation due to unsuitable inlet design is the main reason for low quality flow uniformity.

The external nacelle front drag $D_{nac,ext}$ comprises the pre-entry drag D_{pre} and the cowl forebody drag D_{fb} , see Fig. 1. The forebody describes the outer nacelle surface from the inlet lip stagnation point area A_1 to the area of the maximum diameter A_{max} . Although the inlet only represents the forebody up to the fan face plane A_2 , the forebody drag mainly depends on the inlet design, as inlet design changes largely influence the static pressure distribution on the forebody between A_2 and A_{max} .

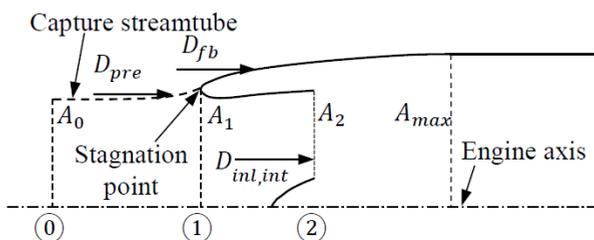


Fig. 1. Components of inlet drag

3 Approach

The utilised process to determine the dependencies of inlet drag and efficiency from geometric inlet parameters and to roughly identify ideal inlet geometries concerning range at Mach 0.95, 1.3 and 1.6 is shown in Fig. 2 and explained in detail in Kazula [6]. This process comprises the development of an aerodynamic model, the parametric study and the genetic response surface optimisation.

A simplified reference geometry has been derived from the rigid Rolls-Royce Pearl 15 engine inlet [22], [6], which belongs to the most modern engines for civil business aviation, the primary area of application for variable pitot inlets. The Pearl 15 engine is utilised in business jets like the Bombardier Global 6500, which are designed for cruise speeds of Mach 0.85 and top speeds of Mach 0.9 [23]. The inlet reference geometry has been converted into a parameterised Siemens NX12-sketch, compare Fig. 3. The geometric parameters, which are utilised to investigate the influence on the inlet evaluation criteria during the optimisation are the inlet length l_{inl} , the diffuser length l_{dif} and the lip length l_{lip} , as well as the radial lip height h_{lip} , the lip fineness ratio l_{lip}/h_{lip} , inlet throat radius r_{th} , and the forebody height h_{ext} [15].

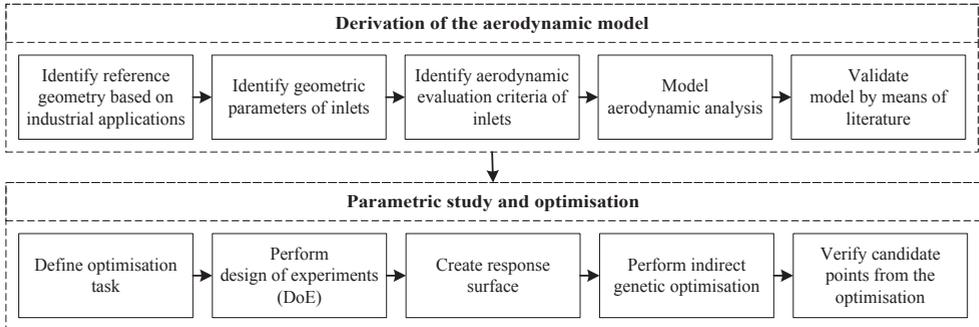


Fig. 2. Process of the parametric inlet design study

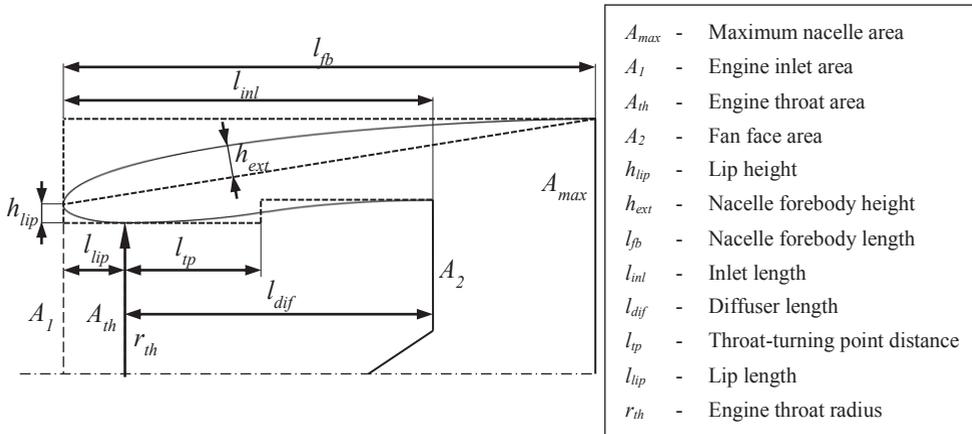


Fig. 3. Inlet parametrisation

4 Results

4.1 Subsonic cruise flight at Mach 0.95

4.1.1 External Drag

The external nacelle front drag $D_{nacf,ext}$ is reduced for increased lip heights h_{lip} at fixed throat areas A_{th} , as the provided suction force reveals to be the drag dominating component. Furthermore, thin inlets with low lip heights require a relatively large highlight radius r_l to produce low external drag, while inlets with larger lip heights achieve the lowest drag for relatively small highlight radii r_l [6].

Due to the arising suction force on the forebody, the inlet length has the biggest influence on the external nacelle front drag. The correlation between diffuser length and

external nacelle front drag reveals that a doubling of the reference diffuser length, and simultaneously a longer forebody result in a drag reduction of about 500 N.

The variation of the nacelle forebody curvature described by the forebody height h_{ext} has only a marginal influence on the capture streamtube, and the pre-entry drag D_{pre} . However, a reduced forebody height results in a suction force reduction, and hence increased external nacelle front drag.

4.1.2 Pressure recovery

A smaller throat radius r_{th} results in a reduced pressure recovery π_{inl} . The influence of the throat radius r_{th} on the pressure recovery is significantly lower in the range between 560 and 600 mm than for radii smaller than 560 mm, where high average throat Mach numbers Ma_{th} occur. These high Mach numbers can lead to shocks, as well as thickening or separation of the boundary layer flow.

4.1.3 Flow uniformity

Large diffuser divergence angles, internal shocks due to high Mach numbers and flow separations primarily cause non-uniform flow at cruise conditions. The maximum local throat Mach number $Ma_{th,max}$ can be higher than 1.0 for small lip fineness ratios, for the given configuration smaller than 2.7. Concurrently, axial shear stresses lower than 0 occur on the inlet surface, indicating reverse flow. Reverse flow can result from flow separation and boundary layer thickening caused by the high local Mach numbers.

The divergence angle of conical diffusers should be smaller than 8° to avoid flow separation [4]. The highest angles of divergence occur for inlets with small throat radii and short diffusers. In the investigated design space, only divergence angles smaller than 8° have been investigated. For these cases, the resulting shear stresses at the diffuser walls are positive, indicating that no flow separation occurs due to high divergence angles [6].

4.2 Supersonic cruise flight up to Mach 1.6

4.2.1 External Drag

Because of the normal shock in front of the inlet, the projected static pressure remains higher than the static ambient pressure for the largest part of the forebody; hence, the forebody cannot provide a suction force like in the subsonic case. Forebody geometries for supersonic cruise should be relatively sharp and with a low curvature compared to the subsonic geometries [6]. An extension of the forebody has a significant influence on drag, as longer geometries are sharper and less curved than shorter geometries. The low curvature leads to fewer and weaker oblique shocks and the resulting projected static pressure is reduced.

The external nacelle front drag $D_{nacf,ext}$ shows a significant relative increase with growing flight Mach number. A longer inlet results in decreased drag in all investigated cases. The influence of an increased engine throat radius r_{th} and corresponding an increased highlight radius r_l diminishes for longer inlets and faster Mach numbers.

A high curvature of the forebody increases the forebody drag, and therefore the external nacelle front drag for supersonic cases [6]. By utilising a longer inlet, the forebody curvature is reduced, resulting in a flattened surface.

4.2.2 Pressure recovery

Due to the normal shock upstream of the inlet, supersonic pitot inlets can only achieve maximum theoretical values for total pressure recovery π_{inl} of 0.98 for flight speeds at Mach 1.3 and of 0.9 for Mach 1.6 [5]. The investigated designs that reveal no disturbances attain an acceptable median value of 0.977 at Mach 1.3, respectively 0.893 at Mach 1.6. In a comparable study for flight speeds of Mach 1.6 by Slater [19] a pressure recovery value of 0.891 was determined.

4.2.3 Flow uniformity

Small throat radii r_{th} can influence flow uniformity, as they lead to larger diffuser divergence angles and high throat Mach numbers Ma_{th} [6]. Large throat radii r_{th} and corresponding large entry radii r_l lead to stronger oblique shocks on the forebody with potential consequential flow separation [6]. As a result, the throat radius should be implemented in the range between 580 and 620 mm for the given configuration. However, this range of radii can differ significantly with changing boundary conditions, for instance engine air mass flow requirements.

4.3 Ideal geometries and their Benefit

The tendencies of aerodynamically ideal values of the geometric parameters and the selected parameter values are presented in Table 1. For all subsonic flight conditions, a single geometry is chosen for potential variable inlets. This also applies for supersonic conditions. This way, the complexity of variable inlet concepts is minimised, as only two geometries have to be set by an inlet adjustment system [6].

Table 1. Tendencies of ideal parameter values and selected values of geometric parameters for inlet geometries

Geometric parameter	Subsonic flight		Supersonic flight	
	Ideal tendency	Chosen value	Ideal tendency	Chosen value
l_{dif} [mm]	Maximal	1388	Maximal	1623
l_{lip}/h_{lip} [-]	> 3	3.5	1	1.0
h_{ext} [mm]	High	112	Low	56
h_{lip} [mm]	High	70	Low	10
r_{th} [mm]	> 560	560	580..620	620

These candidate geometries have been verified by respective flow simulations [6], [24]. The verification simulations reveal that the optimised geometries achieve better flow properties in the investigated flow field and lead to lower drag than the reference geometry that is designed for flight at Mach 0.85. With almost neutral drag of 20 N, the optimised geometry achieves over 700 N less drag $D_{nacf,ext}$ for flight at Mach 0.95 [24]. At a flight speed of Mach 1.6, the produced drag $D_{nacf,ext}$ of 10620 N is 9080 N lower than that of the reference geometry [24].

The benefit of the drag reduction achieved by the utilising variable inlets concerning flight range R can be determined by means of the Breguet range equation [14], [6]. The application of variable inlets at Mach 0.95 on an aircraft with two engines and a reasonable aircraft drag coefficient c_D of 0.025 can lead to a range benefit of over 5% [6], compare Fig. 4. While most subsonic business jets use two engines, some supersonic concepts, e.g. the Aerion AS2 for flight speeds up to Mach 1.4, utilise three engines [25]. Utilising variable inlets at Mach 1.6 on an aircraft with three engines and a reasonable c_D -value of 0.035 results in a potential range benefit of about 35% [6].

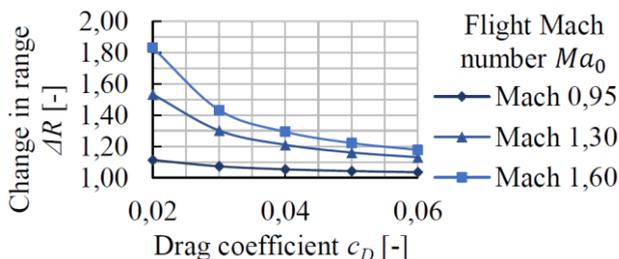


Fig. 4. Dependency of achievable range benefit of variable inlets from aircraft drag coefficient and flight Mach number for configurations with three engines with variable inlets

Variable inlets require an actuation system and are longer than the reference inlet, resulting in additional weight, and hence reduced achievable range. For a subsonic aircraft with two engines and a flight speed of Mach 0.95, a range benefit exists up to an additional mass of about 500 kg per variable inlet or a combined additional inlet mass of 1000 kg. Supersonic aircraft for a flight speed of Mach 1.6 with three engines would still achieve a range benefit of over 20% for an additional mass of about 500 kg per variable inlet or a combined additional inlet mass of 1500 kg.

5 Conclusions

The challenges in inlet design within a concept study for variable pitot inlets in transonic and supersonic civil aviation, as well as relevant geometric parameters and aerodynamic evaluation criteria of inlets have been shown. An approach for a parametric design study has been presented. The dependencies of inlet drag and efficiency from geometric inlet parameters at flight speeds of Mach 0.95 up to Mach 1.6 have been identified, highlighting extended inlets with adjustable surface curvature as the most efficient way to reduce inlet drag.

Ideal geometries for variable inlets have been identified and compared with the reference design, revealing a significant drag reduction for the investigated subsonic and supersonic cruise flight conditions. While the drag reduction potentially leads to an increased flight range, the application of variable inlet systems entails additional weight and complexity. For an additional weight of 500 kg per variable inlet, the range benefit nearly disappears for subsonic applications up to Mach 0.95. On the other hand, a range benefit of over 20% remains for supersonic flight at Mach 1.6.

Following this work, kinematic concepts for circular inlets, which can set the determined ideal geometries, are developed, designed and tested by means of a safe design approach [7], [8], [9], [10]. Subsequently, the remaining range benefit after considering additional weight, complexity and potential aerodynamic steps and gaps of the variable system can be determined. This way, the most suitable variable inlet concept can be identified. Concluding, the technology of circular variable pitot inlets for supersonic transport aircraft could be enabled and be a way to achieve the ambitious ecological, safety and economic goals for future civil aviation.

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