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A Systems Engineering Approach to Variable Intakes for Civil Aviation

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Abstract

A systems engineering approach to develop variable nacelle intakes for aero engines in civil aviation is presented. The goal of this methodical approach is to find solutions to design problems that can be successfully utilised in aviation without further effort during the certification. By using variable intakes, aircraft and aero engine manufacturers can fulfil their customers' needs for safe, efficient and fast travelling. Therefore, a system shall be installed which is able to modify the nacelle intake contour between two extrema. On the one hand, a sharp thin contour, which produces low drag and allows to fly faster or more efficiently, is optimal during cruise condition. On the other hand, a round thick intake lip is necessary to avoid flow separations with the potential to cause dangerous events during take-off and climb conditions.

The utilised systems engineering approach is introduced. The executed steps and methods used for creating and evaluating concept variants for variable intakes are displayed particularly. Those contain the determination and evaluation of requirements and functions, as well as the generation and assessment of concepts. Finally yet importantly, following tasks are presented.

1. Introduction

There is an on-going competition between leading manufacturers of aircrafts (e.g. Airbus, Boeing, Gulfstream, Bombardier) and as well among the engine suppliers (e.g. Rolls-Royce, Pratt & Whitney, GE Aviation) to satisfy their customers' needs and to match the restrictions given by the aviation authorities. The private passengers want to travel fast, safe and at reasonable costs. In addition to that, the business passengers expect a high level of comfort and exclusiveness. The airlines' aim is to maximise the profit that requires high efficiency. Moreover, in consideration of the continuously increasing amount of aeronautic traffic the aviation authorities stipulate a reduction of the pollution per aircraft. In that context, the European Commission determines the ACARE Vision 2020 and the Flightpath 2050. Those documents aim for an abatement of noise, CO2 and NOx emissions [1], [2]. To meet those requirements enormous efforts are made to improve existing and to develop new technologies. A major possibility to increase efficiency, speed and safety can be identified in the improvement of the airflow around the engine nacelle intake. In this paper, this is done by developing concepts for variable nacelle intakes using a modified systems engineering approach. Therefore, this paper has two objectives. Firstly, a modified systems engineering approach, which could reduce developing times and thus costs for new products in the aviation industry, is described. Secondly, this paper examines how to solve the compromise in design of nacelle intakes in civil aviation.

Thus, this paper is divided into five sections. The first section gives a brief overview on the topic and contents of this paper. The second section describes the tasks of nacelle intakes and the design compromise that intakes have to fulfil. The used modified systems engineering approach is presented in the third section. In the fourth section, the first phases of the case study concerning variable intakes using this approach are presented. Furthermore, conclusions are drawn and an overview on following tasks is given in the final section.

2. Nacelle Intakes

2.1 Tasks

The primary objective of nacelle intakes for aero engines is to divide the airflow in front of the aero engine depending on the operating conditions in an internal and an external airflow. The external airflow shall flow over the nacelle at the lowest possible drag. In the domain of the intake lip, the primarily occurring types of drag are spillage

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drag and wave drag. The purpose of the internal streams is to supply the compressor system and the aero engine in general during each operating condition with the correct quantity of air [3]. To ensure a highly efficient and safe operation of the compressor system the inner contour of the intake has to be designed as a diffuser. This causes a required deceleration of the airflow. Furthermore, flow separations have to be avoided under all conditions to ensure a high uniformity of the airflow. Additionally, the intake has to reduce the fan and compressor induced noise. Furthermore, the intake has to protect itself from icing and its consequences. Moreover, probes for measuring pressure and temperature at the fan level can be part of the intake. Following, these measured data have to be transferred to a control system. [4], [5]

These functional objectives are reflected in the design of rigid subsonic intakes, which is shown in Figure 1. The intake lip typically is made of aluminium. Moreover, it is resilient to foreign object damage, sand erosion, hail and in special cases bird strikes. Furthermore, due to its good heat conduction properties aluminium has a high compatibility with the usually used bleed air anti ice system, which transfers hot air from the compressor to the intake lip to prevent the icing. To minimise weight, the outer planking is made of composites. The inner boundary is consisting of acoustic liners, which reduce the noise emissions of the fan and the compressor. Acoustic liners are honeycomb structures covered by a perforated layer. These honeycomb and further structural components stabilise the intake as well. This paper focuses on subsonic intakes as they are state of the art concerning civil aviation, although many investigations concerning variable supersonic intakes for civil aviation exist.

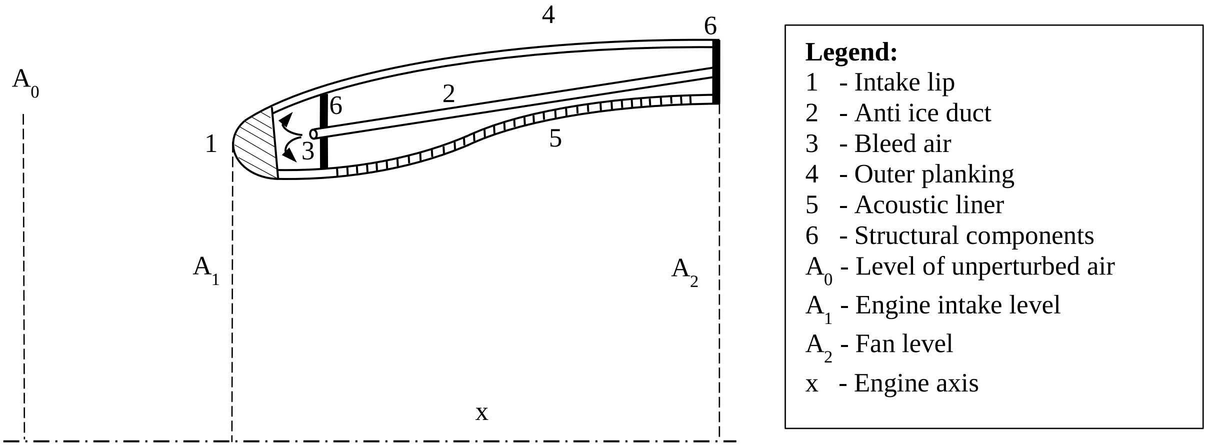

Figure 1: Typical structural design of a rigid subsonic nacelle intake

2.2 Compromise in Design

There are two contrary requirements that have to be unified during the geometric design process of nacelle intakes [6]. On the one hand, efficiency losses due to high drag at high flight velocities during cruise condition have to be minimised [7]. In subsonic business aviation maximum Mach operating speeds of Ma 0,925 are already realised with an ascending tendency [8]. On the other hand, it is necessary to avoid flow separations and hazardous events during take-off and climb operation at Ma 0,3 and at lower velocities. The first goal can be achieved by a sharp thin contour (See Figure 2). However, a sharp thin contour is susceptible to flow separation at incidence operation and crosswind at low aircraft velocities. Those separations can result in increased fan strains and in the worst case in engine surge [3]. A rounder and thicker intake geometry is required to solve that issue at the cost of higher drag and thus less efficiency during cruise operation at higher Ma numbers [4]. Hence, the geometric contour of rigid subsonic nacelle intakes is only accomplished by a compromise.

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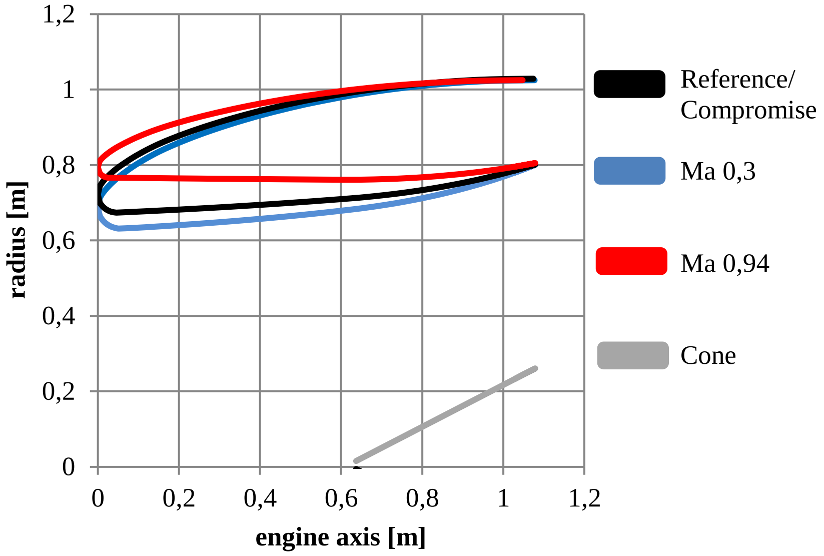

Figure 2: Optimal subsonic intake contours for different aircraft velocities

Various scientific treatises, e.g. [9], [10] and [11], are concerned with the optimization of that compromise. Nevertheless, the potential for optimization and improvement of a technology is limited. Therefore, at a certain point the invested effort is not compensated by the profit [12]. This theory is backed and explained by the s-curve concept that is shown for nacelle intakes in Figure 3. Since the first jet engines had been built in the 1930s it can be assumed that the technology ‘rigid subsonic intake’ has nearly reached its limitations [4]. Therefore, new technologies and their potential should be investigated, in that case variable subsonic nacelle intakes.

While using variable intakes the optimal contour can be applied during each flight condition and thus safety, efficiency and maximum speed can be increased. First studies and projects, e.g. Morphelle, concerning variable intakes have been performed, which is proven by the existence of patents, e.g. US 4075833 and US 5000399, and conference papers [13]. Although those first studies did not find use in modern aviation yet, the s-curve theory implies that there could be a high potential left in that new technology. For that reason, subsonic variable nacelle intakes are investigated in the context of an internal research project at the chair of Aero Engine Design at the BTU Cottbus-Senftenberg. Within the scope of that project, concepts for variable subsonic nacelle intakes are developed and analysed using a methodical approach.

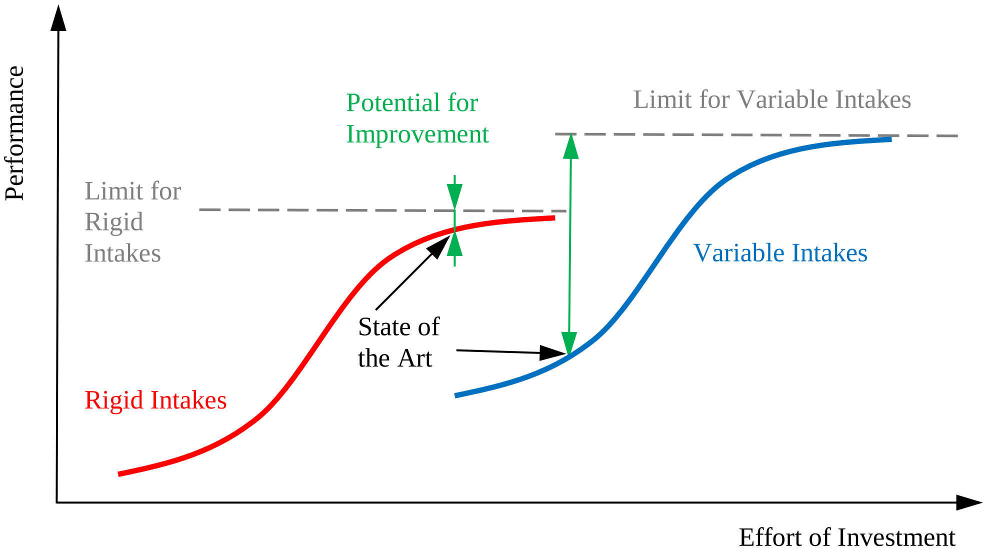

Figure 3: S-curve concept for rigid and variable subsonic nacelle intakes

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3. Systems Engineering Approach

While designing aero engines in general and variable subsonic nacelle intakes in detail, many different partial aspects have to be observed, e.g.

- aerodynamics,
- structure,
- engineering design
- and performance [14].

These disciplines require both calculations and logical decisions to provide the most suitable solution. Uniting all separate requirements can be a highly complex and comprehensive task. As a result, a single person mostly cannot solve this task. Therefore, a coordinated teamwork of different specialists is necessary. At the same time, interfaces between the single jobs have to be determined to ensure an efficient and accurate collaboration. The systems engineering is a tool to simplify complex problems by breaking a complex task into simpler ones and connecting these subtasks. These subtasks can be solved more efficiently by specific specialists and as a result be combined to find the best solution. [15]

There are numerous different systems engineering approaches, e.g.:

- the VDI 2221 guideline for a systematic approach to the development and design of technical systems and products [16],
- the Design for Six Sigma [17], [18],
- standardised systems engineering according to IEEE 1220-2005 [19],
- Ehrlenspiel’s approach [20]
- and the Lindemann model [21].

All of them are based on a related strategy [15]. In the beginning, the problem has to be analysed regarding which requirements and functions the product shall fulfil. Afterwards solution options are generated. The best variants are selected for detailed consideration and tests. If those investigations are passed successfully, the best concept will be realised, else the existing variants have to be improved or new ideas have to be found. [22]

These mentioned improvements of designs or new designs are expensive and time-consuming. Therefore, the risk of a product failing tests during the late stages of the design process has to be minimised. In civil aviation, the most critical tests for new products to pass are those required to certify the product for aviation. The local aviation authorities, e.g. the European Aviation Safety Agency (EASA), publish regulations, which contain acceptable means of compliance, e.g. tests, to ensure a safe operation of certified aircraft. Given the consequences of failing these certification tests, it should be mandatory to analyse every relevant regulation during the first stages of the design process. In the case of variable intakes, research has tended to focus on creative inventions rather than feasible ideas that may be certified. Therefore, during the requirements phase of the following modified systems engineering approach a type certification investigation program and corresponding means of compliance are worked out. This design approach is adaptable to every new development of aviation products and reduces the on average necessary resources.

The utilised systems engineering approach for the investigation of subsonic variable nacelle intakes is presented in Figure 4. First of all, the problem is identified. Afterwards, requirements of the variable nacelle intake have to be collected. Therefore, literature searches and brainstorming session are performed. Additionally, the state of the art, including existing applications and patents, as well as statutory provisions and standards concerning variable intakes are investigated. The identified requirements are structured and rated for later concept down selections. Conceptual ideas, which are found during the requirements phase, are memorised for later consideration. Following, for obtaining a functional structure a functional analysis for the intake system is done. By the means of this, the complexness of the problem can be reduced to obtain faster and easier solvable subtasks. For each subtasks multiple solving principles are assigned. The suitability of a solving principle is determined by the help of rated requirements. Thereafter, in a morphological box the best solving principles for the separate subtasks are combined [23]. That way further solution concepts are found. All concepts are examined and evaluated regarding the main requirements, which have been identified. Additionally, newfound ideas can be patented. During the preliminary design phase, the best solution concepts are investigated particularly. First computer aided analyses and design calculations for the main components of the intake system are performed during this phase, as well as system safety analyses according to aerospace recommend practise (ARP4761). Based on these analyses, a technological evaluation of the concepts is done and as a result, the optimal solution is found. This concept is designed completely, and after that validated by the means of prototype tests and numerical investigations. Finally, the product can be certified for aviation. For improving the quality of the partial results and thus of the final product, it should be noted, that every separate phase can be repeated while using different methods.

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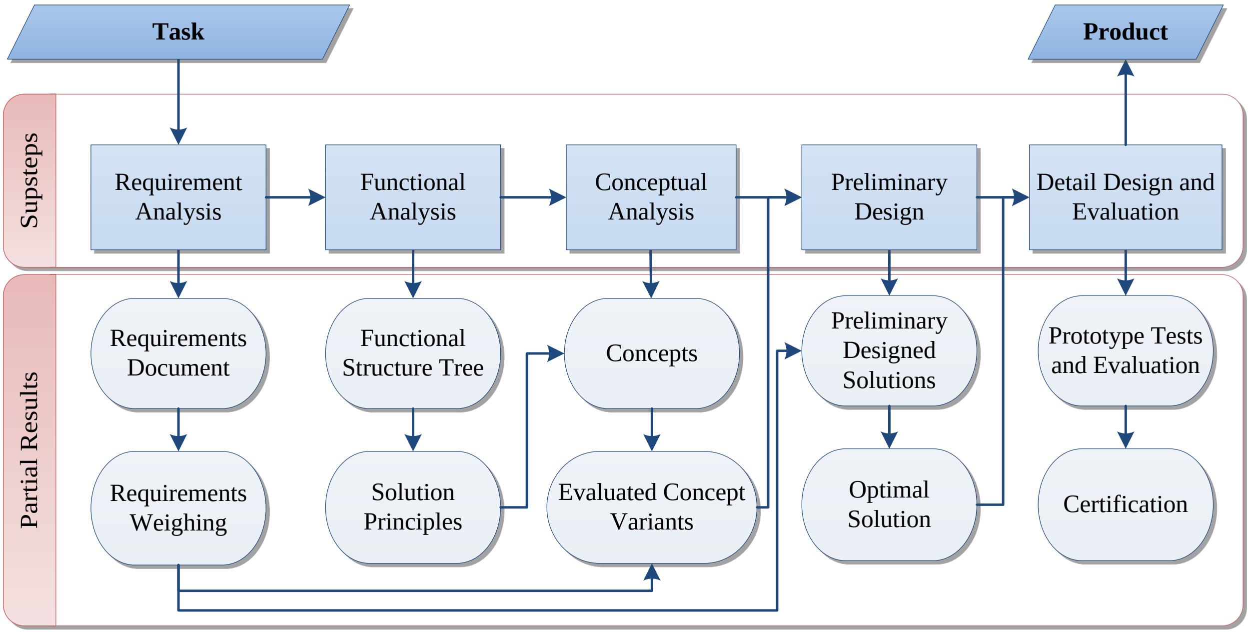

Figure 4: Systems engineering approach

4. Results

4.1 Requirement Analysis

Within the scope of this phase, requirements for the variable subsonic intake nacelle system were collected. This was accomplished by the means of literature search, e.g. [4], [5], [14] and brainstorming sessions. Requirements of the system are set by:

- the passenger,
- the pilot,
- the engine manufacturer,
- the aircraft manufacturer,
- the airline or the aircraft operator,
- the maintenance enterprise,
- the airport operator
- and the authorities.

The list of requirements was arrayed. Unnecessary requirements were eliminated and related ones were grouped. If possible, target values and tolerances had been applied. Afterwards the requirements were subdivided into mandatory requirements and desired requirements.

The desired concept has to fulfil every mandatory requirement. Therefore, these requirements were utilised to reduce the number of considered concepts during the conceptual analysis phase. The following mandatory requirements had been identified:

- safety,
- functionality,
- aerodynamic suitability,
- simplicity
- and integrability.

On the other hand, desired requirements shall be met to the greatest possible extend. They were used for the technological valuation of the concepts to determine the best solution. Thus, the desired requirements had been rated among themselves. The comparison of couples, more precisely the analytic hierarchy process, was utilised as evaluation method [24], [18]. The result of this evaluation was normalised and is shown in Figure 5.

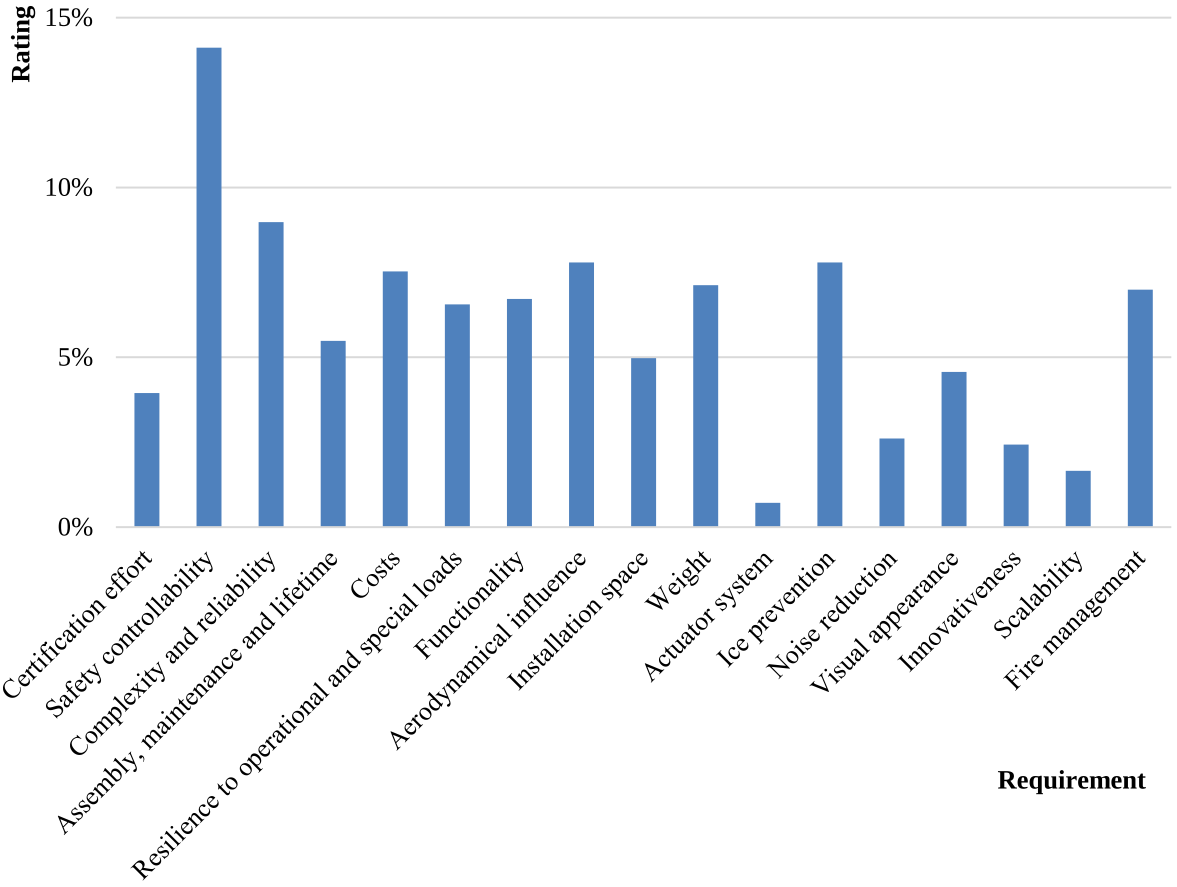

Figure 5: Rating of the evaluation criteria

4.2 Functional Analysis

The complexity of designing a variable subsonic nacelle intake had been reduced during the functional analysis by breaking down this task into primary functions. A function is described by its required input elements and mechanisms to generate the desired output elements under the influence of disturbances and losses [12]. Figure 6 illustrates a function structure tree, which contains the essential primary functions of a variable subsonic intake:

- prevent icing,
- adjust the ideal contour,
- reduce fan and compressor noise,
- take up structural tasks
- and measure and transfer data.

Furthermore, secondary functions were assigned to the primary functions. For instance, the secondary functions varying, locking and unlocking of the geometry, as well as data exchange with the control system refer to the primary function for contour adjustment.

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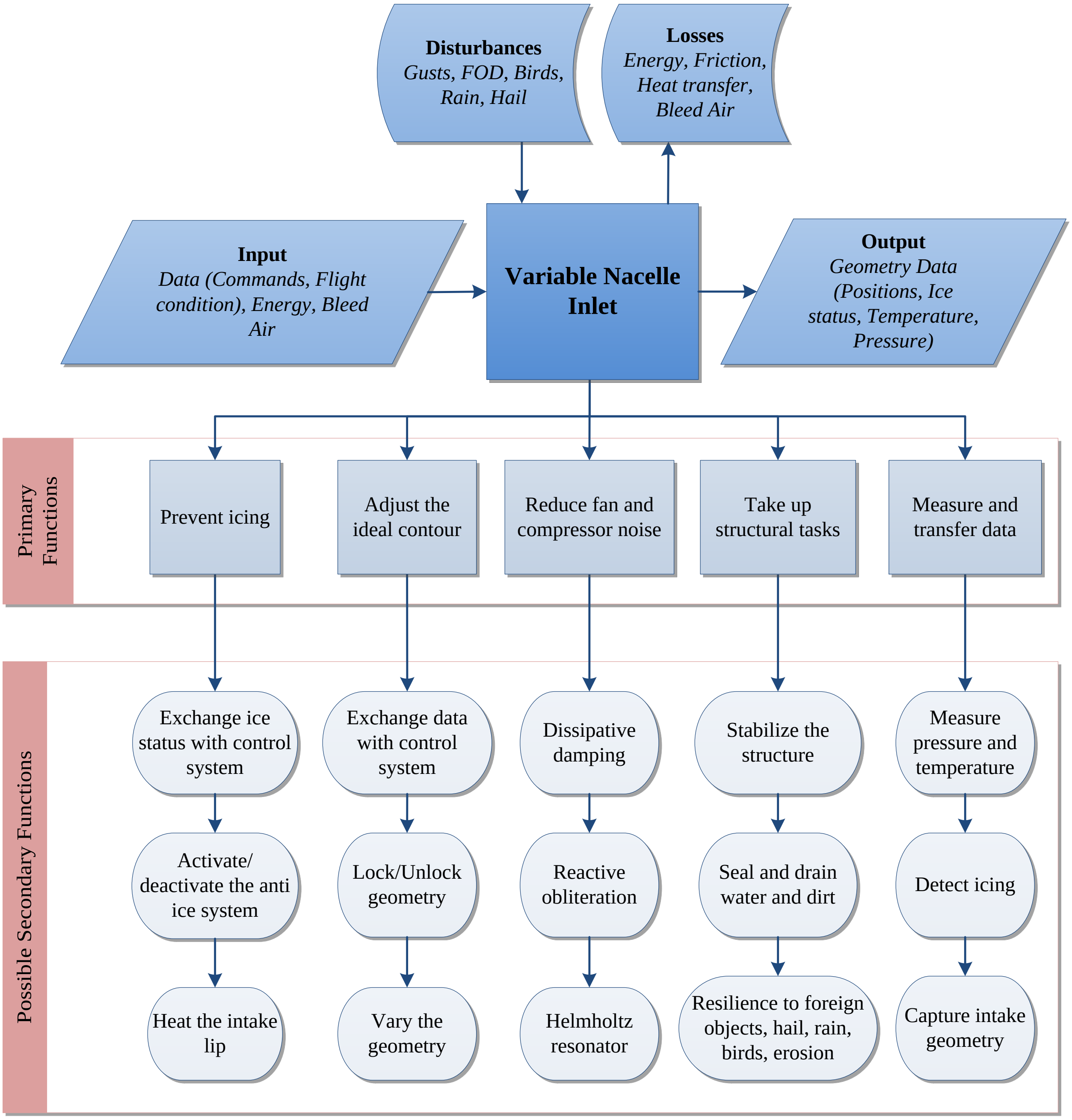

Figure 6: Function structure tree of a variable nacelle intake

Most of the presented primary and secondary functions rely on other functions, e.g. "prevent icing" and "detect icing". Therefore, a functional separation cannot be done clearly. The connections and dependences between functions have to be kept in mind during the valuation of solving principles.

The more detailed the functional structure is analysed the more suitable solution principles can be assigned to the functions. Therefore, the primary functions, e.g. "adjust the intake geometry" were investigated separately (see Figure 7). Nevertheless, time efficiency had to be considered; hence, a further breakdown into sub sub sub functions had been foregone.

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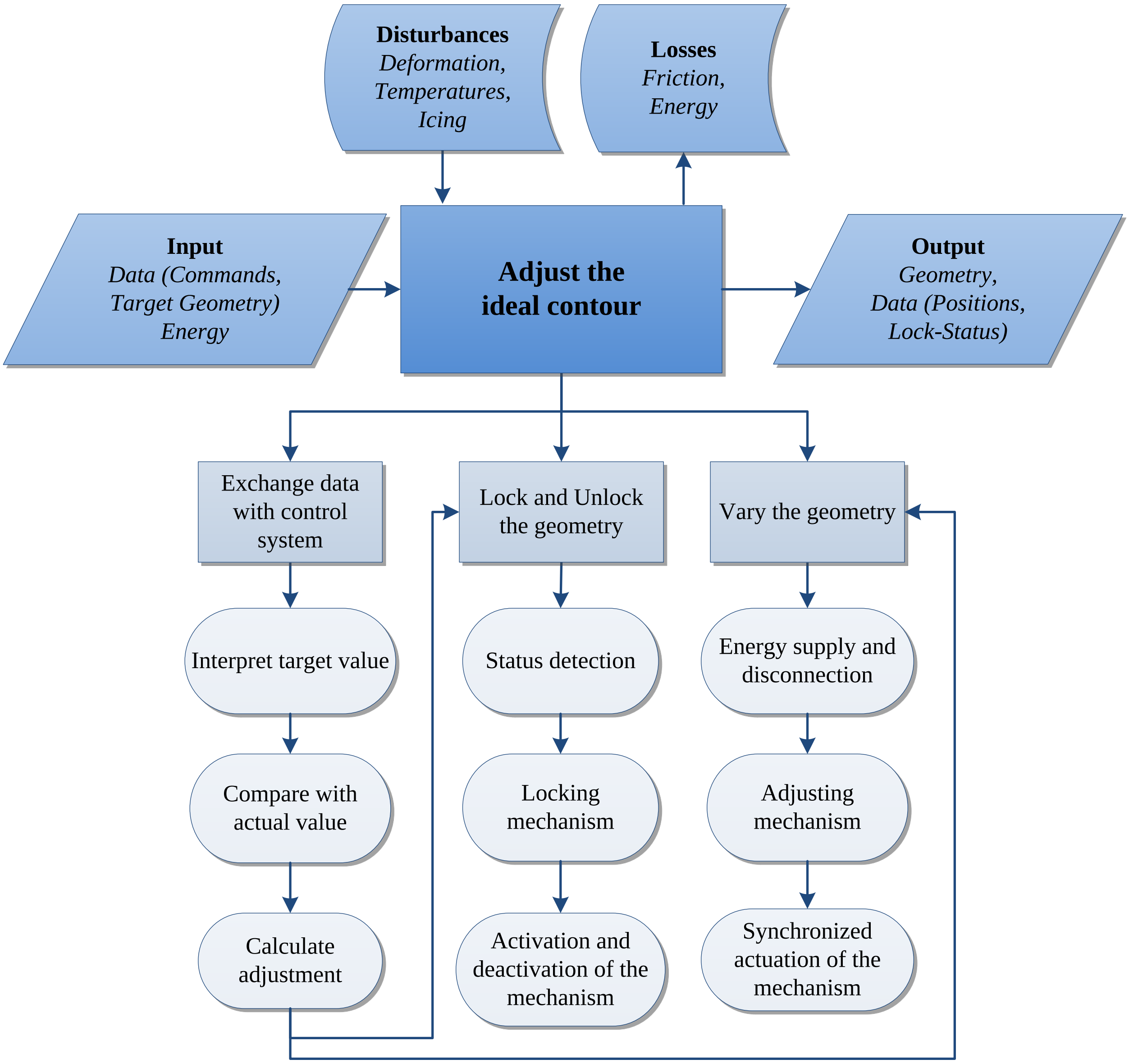

Figure 7: Function structure tree of the intake contour adjustment

Solving principles were assigned to the determined functions. For instance, the actuation of the mechanism can be powered by an

- electric,
- hydraulic
- or pneumatic source.

The motion can be implemented

- linear
- circular
- or elliptic.

The movement can be done

- in axial,
- in radial
- or in peripheral direction.

These solving principles were combined and mechanical solutions were found. For example, if a hydraulic linear axial actuation system was chosen as solution principle, a hydraulic cylinder would be a suitable mechanical solution.

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4.3 Conceptional Analysis

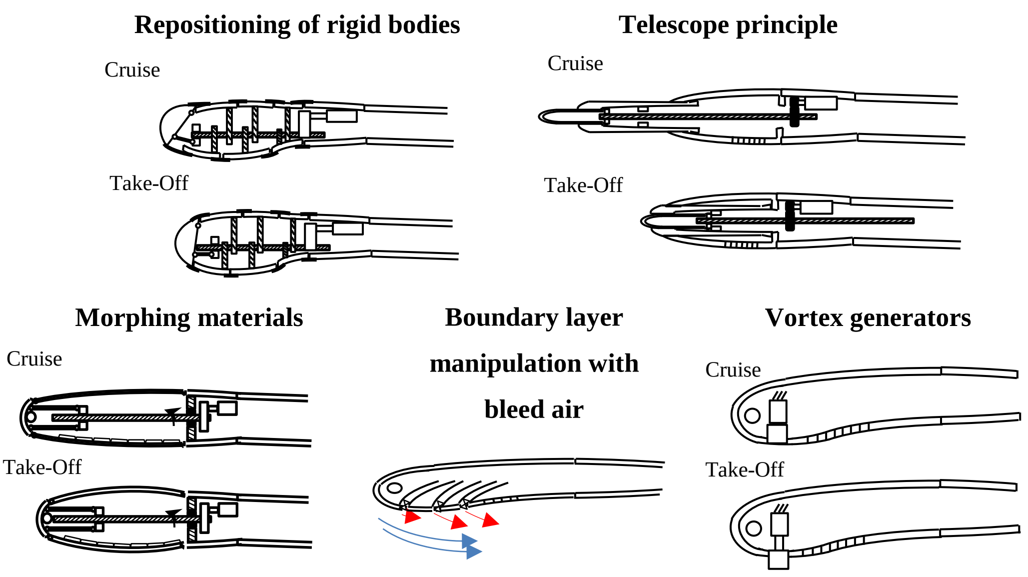
Utilizing the morphological box, the identified solutions for the separate function had been combined to concepts [23]. A simplified version of the generated box is presented in Table 1.

Table 1: Simplified morphological box for variable nacelle intakes

Function	**1st solution principle**	**2nd solution principle**	**3rd solution principle**
Prevent icing	Bleed air anti icing	Electrical anti icing	Chemical anti icing
Reduce noise	Acoustic liners	Counter-noise	Acoustic sponges
Take up structural loads	Stiffening rings	Monolithic structures	Framework structures
Adjusting mechanism	Movement of solid components	Elastic deformation of the surface material	Aerodynamic geometry manipulation
Actuation system	Electric	Hydraulic	Piezo mechanical
Detect intake geometry	Linear variable differential transformer	Rotary variable differential transformer	Optical methods

It has to be taken into account, that several sub solutions cannot be combined with each other without limitations. Given the certification regulation analysis during the requirements analysis, a combination of a bleed air anti icing system and a hydraulic actuator system could result in the fact that the inlet becomes a designated fire zone. Following, the intake would have to fulfil many challenging requirements.

By adding a variable geometry to the functionality of the intake, it is probable, that the most suitable systems for e.g. icing prevention or structural tasks are other than those for rigid intakes. For example, electrical anti icing could be more suited for variable intakes than bleed air anti icing. By utilising the morphological box and brainstorming sessions in total 30 concepts for variable subsonic nacelle intakes were identified. Some of these concepts are presented in Figure 8.


Repositioning of rigid bodies

Telescope principle

Morphing materials

Boundary layer manipulation with bleed air

Vortex generators

Figure 8: Selected examples of concepts

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Afterwards, each of the 30 concepts was checked by the means of the mandatory requirements. As a result, the number of considered concepts was reduced to ten of which the five most promising were chosen for preliminary design. Due to the ongoing patenting process and the following detail design, these concepts are not published in detail in this paper.

5. Conclusion and Outlook

The modified systems engineering approach was presented. By using this approach and thus analysing the certification requirements in the beginning of the new development of an aviation product, solutions that are more suitable can be found. This approach had been used to improve the efficiency, speed and safety of civil aircraft. In this case, concepts for variable nacelle intakes for aero engines in subsonic civil aviation were found and evaluated. These concepts can modify the nacelle intake contour between two extrema to better meet the aerodynamic requirements of the intake. In particular, the requirement and functional analysis were introduced. Furthermore, the used methods for concept development and evaluation were presented. As a result, 30 concepts were developed and are currently investigated for patenting. The five most promising concepts will be examined in detail and evaluated by the presented desired requirements, e.g. weight and costs. Afterwards a demonstrator of the most suitable concept will be manufactured and tested. To conclude this concept can be validated and certified for aviation whereby the product variable subsonic nacelle intake is finalised and can be produced.

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