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Construction methodology for lip surface of a submerged inlet

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ABSTRACT

The design of submerged inlet remains a challenge as the design involves both the fuselage and the inlet internal duct. The inlet lip surface blending needs to meet stringent conditions, which vary considerably from fore lip to aft lip. The need for high aerodynamics performance also adds to the difficulty of the design process. In this paper a methodology is presented by which the inlet lip surface is mapped to a rectangular grid system which is topologically similar to the surface to be blended. A number of key grid lines can be identified, through the construction of the key curves, which are outer profile curve, inner profile curve, ridge curve and multiple blending curves. Furthermore, lip surface can be blended through the application of sweeping algorithm. A detailed example as presented in this paper illustrates the whole design procedure and technique to transform the design of a spatial curve into that of two planar curves on two developable surfaces. The above method facilitates the design of spatial curves for outer profile curve and ridge curve. The lip surface blending leaves a number of design parameters which can be manipulated to offer the scope of optimization of the aerodynamic performance in the subsequent CFD phase of the development. The numerical simulation conducted indicates that actual performances meet the design objectives well, which demonstrates the effectiveness of this design methodology.

1. Introduction

Subsonic flying vehicle is due to play a more significant role in the years to come, as aviation is an essential element of today's global society. As a very important component of an air-breathing flying vehicle, inlet affects not only the propulsion but also the aerodynamic characteristics. Having the function to deliver the freestream air to the engine, the inlet needs to provide a proper amount of air flow in each state within the flight envelope. Meanwhile, the inlet is responsible for the quality of the air in terms of high total pressure and low distortion. As a very important type of subsonic inlet, submerged inlet is increasingly used in subsonic flying vehicles [1]. Different from conventional nacelle-mounted inlet and S-duct inlet, the submerged inlet has a good stealth performance, and reduces the flying vehicle's drag dramatically [2].

The design procedure of submerged inlet consists of two steps, the design of inlet internal duct surface and design of lip surface, with the latter being the top issue [3]. Basically, the difficulty of designing the lip surface comes from two factors, the topological one and aerodynamic one.

The topological factor is mainly from the fuselage and the inlet internal duct. The lip surface is bordered with both fuselage surface and inlet internal duct surface. On the one hand, the lip surface must satisfy the angle boundary conditions along the curve shared by lip surface and fuselage surface. On the other hand, the restrictions are equally applicable to the other curve shared by lip surface and inlet internal duct surface. Since the relative relationship between fuselage surface and inlet internal duct surface varies considerably from the fore lip to the aft lip, it still remains a challenge to bridge the two surfaces [4].

As for the aerodynamic factor, the fact that the inlet is a part of the wetted area of the flying vehicle makes the position and shape of inlet directly affect the aerodynamic performance of the flying vehicle. Meanwhile, since the shape of submerged inlet varies in cross-sectional area and centerline, it results in cross stream pressure gradients, which in turn leads to secondary flows and hence non-uniform velocity gradients [5].

The first submerged inlet was designed and analyzed by NACA [6–8] in the 1940s and could be used only for the auxiliary appli-

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cations in aircrafts [9]. Now great changes have taken place since then, and the submerged inlet has been used as the main air induction system of the propulsion engine [10,11]. Zhang et al. [12,13] proposed a shape optimization method to improve the performance of submerged inlet. Nichols et al. [14] analyzed the effects of design variables on the performance of the submerged inlet, namely drag and pressure recovery. Blaize et al. [15] carried out research to show that an innovative search process was capable of finding better inlet designs for specific missions with better performance than conventional methods. The computational work obtained by Pérez et al. [16] studied the influence of a delta wing vortex generator on the boundary layer that developed upstream of a submerged air intake. Using the technique, the conventional NACA inlet demonstrated a higher performance in terms of mass flow rate.

However, there are few papers concentrating on the whole design procedure of a submerged inlet. A complete design method is presented in this paper from the initial generation of aerodynamic S-duct to the final determination of lip surface. The methods are summarized and listed as follows.

It is proposed that the inlet lip surface can be mapped to a 2-D rectangular grid system as an intrinsic geometry. A rectangular grid system has two families of grid lines, vertical and horizontal. Similarly, the lip surface has two types of key curves, with each having one parametric direction. The outer profile curve, inner profile curve and ridge curve, having the same parameter directions, can be mapped to the vertical lines of a rectangular grid system. Meanwhile, the blending curves, which have the other parametric direction, can be mapped to horizontal lines. Based on the above approach, the one-to-one mapping between the lip surface and the rectangular grid system can be established. Once the “vertical” curves and “horizontal” curves of the lip surface are available, the whole spatial surface can be obtained through the process of sweeping operation.

Actually, there remain two substantial problems while designing the key curves. The first problem is related to the generation of outer profile curve and ridge curve, which are both spatial curves and difficult to sketch. The second problem is related to the generation of multiple blending curves, whose shapes vary dramatically from fore lip to aft lip. Both problems are associated with the technique to deal with spatial curve but slightly different. According to the theory of differential geometry, it is necessary to determine the curvature and torsion of a spatial curve before sketching it. The transformation of spatial curves into planar curves will simplify the design problem, as there are no torsions for planar curves. Following from the above analysis, two individual methodologies to transform spatial curves into planar curves are presented in this paper, respectively.

For the first problem, it is proposed that a spatial curve can be determined by the intersection of two developable surfaces, namely cylindrical surface and meridional surface. The construction of spatial curve can therefore be summarized into two steps. The first step is to generate the projection of the spatial curve on the cylindrical surface and on the meridional surface, respectively. The second step is to combine the two projection curves to a spatial curve. The above method can be directly applied to the generation of ridge curve and partially used for the generation of outer profile curve, due to a constraint on the latter curve.

For the second problem, considering the fact that the fore lip section curve and aft lip section curve (on the fore lip and aft lip position, respectively) are planar curves, it is inferred that planar curves also exist in another positions of lip surface. Based on the principal normal vector, the tangential vector and normal plane, derived from aerodynamic S-duct and major design parameters, a set of datum planes can be determined to serve as the datum plane in which the blending planar curves can be constructed.

The major parts of the paper are organized as follows. Section 2 is devoted to generate inlet internal duct surface and lip surface in sequence. In Section 3, numerical verification is carried out to testify the effectiveness of the designed inlet configuration.

2. Design methodology of submerged inlet lip surface

2.1. Overview of the framework

The construction of lip surface is the establishment of a curvilinear coordinate system. The curvilinear coordinate system has families of u-curves and v-curves, representing two parametric directions. The definition of u-curve and v-curve is concerned with the theory of differential geometry [17].

The whole procedure of constructing submerged inlet lip surface is illustrated in Fig. 1. The starting point is a 3-D fuselage solid body which is available in Unigraphics format including .PRT and .X_T. The final output is 3-D solid models of lip surface. This whole process is automatic.

Six major steps involved in the construction phase are listed as follows:

(1) Generation of aerodynamic S-duct

The aerodynamic S-duct is the simulation of the stream tube of the air captured by the submerged inlet. The configuration of aerodynamic S-duct is jointly determined by the centerline and multiple cross sections, which is described in sub-section 2.2 in detail.

(2) Design of fore lip section curve and aft lip section curve

The fore lip section curve and aft lip section curve are in the symmetry plane of the fuselage. The design of these two curves plays a very important role in maintaining the high performance of submerged inlet. The design process is thoroughly presented in sub-section 2.4.

(3) Generation of inner profile curve

Inner profile curve is the boundary curve shared by lip surface and inlet internal duct surface, with its generating process presented in sub-section 2.5.

(4) Design of ridge curve and outer profile curve

The outer profile curve and ridge curve (shown in Fig. 16) can be understood as u-curves of the curvilinear coordinate system. Serving as a trajectory curve in the generation of lip surface, ridge curve is introduced to help manipulate the trend of lip surface. Meanwhile, outer profile curve is shared by the fuselage surface and the lip surface. The procedure of these two curves is described in detail in sub-section 2.6.

(5) Generation of lip blending curves

Lip blending curves can be understood as v-curves of the curvilinear coordinate system, with its generation process presented in sub-section 2.7.

(6) Generation of submerged inlet lip surface

The generation of submerged inlet lip surface is achieved by a sweeping operation based on the key curves mentioned above, and the procedure is described in sub-section 2.8.