Aerospace Science and Technology 45 (2015) 398–407

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

High altitude propeller design and analysis

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ARTICLE INFO

Article history:
Received 17 December 2014
Received in revised form 7 June 2015
Accepted 9 June 2015
Available online 12 June 2015

Keywords:
JBLADE
Propeller inverse design
Propeller analysis
High altitude propeller
CFD propeller simulation

ABSTRACT

This paper presents the design and optimization of a new propeller to use on the MAAT cruiser airship. The inverse design methodology is based on minimum induced losses and was implemented in JBLADE software in order to obtain optimized geometries. In addition, the design procedure and the optimization steps of a new propeller to use at high altitudes are also described. The results of propellers designed with JBLADE are then analyzed and compared with conventional CFD results, since there is no experimental data for these particular geometries. Two different approaches were used to obtain the final geometries of the propellers. Instead of using the traditional lift coefficient prescription along the blade, the airfoil best $L^{3/2}/D$ and best L/D were used to produce different geometries. It is shown that this new design approach allows the minimization of the chord along the blade, while the thrust is maximized.

1. Introduction

The airships appeared in the end of 19th century and the first air transportation services were run by these controlled lighter-than-air vehicles. After a promising development in the beginning of 20th century, the crash of *LZ 129 Hindenburg* in May of 1937, led to the end of operations of the commercial airship transportation service and, thereafter, to almost 60 years of inactivity. Recently, the rapid progress of aerospace technologies [1,2], brought the airships back as a new platforms for undertaking multiple tasks [3]. In particular, stratospheric airships have been considered as an excellent platform for many different purposes such as aerial exploration, surveillance and monitoring or even as a solution for aerial transportation [4–9].

Multibody Concept for Advanced Airship for Transport (MAAT [10–12]) project is a collaborative European project which aims to develop a heavy lift cruiser-feeder airship system in order to provide middle and long range transport for passengers and goods. The MAAT airship will be composed by 3 different main modules: Airship Hub Airport (AHA) – located in the important logistic and near cities centers, where the airships will perform ground operations; Air Transport Efficient Network (ATEN) – feeder – an airship with its vertical take-off and landing capabilities used as connection between the ground and the cruiser; Photovoltaic Transport Airship for High-altitudes (PTAH) – cruiser – an airship to carry the cargo or passengers delivered by different feeders which remains airborne on stable routes on higher altitudes than civil aviation routes [11].

Propellers have been used as propulsion units in different types of aerial vehicles, including airships. In order to obtain an efficient propeller it is essential to have a reliable numerical tool to model its propulsive performance. The propeller optimization process can start from an inverse design method which gives us the blade geometric characteristics for a pre-determined operating point. This base blade geometry can then be used for a parametric/sensitivity analysis to judge its relative merit in the overall flight envelope.

The design of the propeller based on minimum induced losses started with Betz [13] and Goldstein [14] in the beginning of the 20th century. In 1936 Glauert [15] used the equations provided by Betz but without any organized procedure for designing the propellers. Also during 1936, Bierman [16] developed one of the first parametric studies, analyzing the influence of some parameters during propeller design. He analyzed the reduction in the design pitch angle in function of the propeller operating speed and the thrust and/or power increase. Theodorsen [17] showed that the Betz condition for minimum energy loss can also be applied for heavy disk loadings. Later in 1979, Larrabee [18] reviewed Glauert's work to produce a straightforward process to produce new propeller geometries. However, the method still has some problems: small angle of attack approximation, low disk loadings and does not include viscous terms in the induced velocity formulation. During 1990, Theodorsen's developments were later revisited by Riber and Foster [19]. Recently in 1994 Adkins and Liebeck [20] presented some improvements on the previous work bringing a new design method, without small angle of attack approximation

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http://dx.doi.org/10.1016/j.ast.2015.06.011
1270-9638/

Nomenclature

a_a	Axial induction factor	R	Propeller tip radius ... m
a_t	Tangential induction factor	Re	Reynolds number
B	Number of blades	T/A	Disk loading ... N/m^2
C_D	Airfoil drag coefficient	V	Freestream velocity ... m/s
C_f	Skin friction coefficient	x	Non-dimensional distance, $\Omega r/V$
C_L	Airfoil lift coefficient	y^+	Non-dimensional wall distance
C_p	Power coefficient	α	Angle of attack
C_t	Thrust coefficient	ε	Drag-to-lift ratio
Eta	Propeller efficiency	ζ	Displacement velocity ratio, v'/V
F	Prandtl's factor	θ	Incidence angle
G	Circulation function	λ	Speed ratio, $V/\Omega R$
L/D	Lift to drag ratio	ξ	Non-dimensional radius, r/R
M	Mach number	ϕ	Inflow angle
r	Radius of blade element position ... m	ϕ_t	Tip inflow angle

Table 1
High-altitude propeller data.

Year	Aircraft name	Propeller thrust, *N*	Propeller diameter, m	T/A, N/m^2
1987	Egrett [21,22]	2773	3.04	305.42
1988	Condor [23]	1129	4.90	59.87
1993	Pathfinder [23,24]	23	2.01	7.25
1994	Perseus [25]	388	4.40	102.07
1995	Strato 2C [26]	2500	6.00	88.42
1996	Theseus [27]	409	2.74	69.36

and some of the light disk loading limitations, which better agrees with the analysis of the designed propeller.

Design and optimization of a high altitude propeller can be a challenging problem due to the extremely low air density. Even so, propellers are being used in many high altitude aircrafts such as: Egrett (1987) [21,22], Condor (1988) [23], Pathfinder (1993) [23, 24], Perseus A (1993), Perseus B (1994) [25], Strato 2C (1995) [26], Theseus (1997) [27], Pathfinder Plus (1998), Centurion (1998) and Helios (1999). Although there is only little information about high altitude propeller design, a summary of the propellers characteristics is given in Table 1.

2. Methodology

2.1. JBLADE overview

JBLADE [28–32] is a numerical open-source propeller design and analysis software written in the C++/QML programming language [33]. The code is based on QBLADE [34,35] and XFLR5 [36] codes. It can estimate the performance of a given propeller geometry for off-design analysis and has a graphical interface making easier to build and analyze the propeller simulations.

With the coupling between a BEM formulation module and XFOIL [37], the airfoil characteristics needed for the blades simulation can be obtained through a direct analysis of each airfoil. The coupling between these modules allows the design of airfoils and the computation of their lift and drag polars. Furthermore, in order to improve the accuracy of the propeller analysis, the software allows the integration of airfoil data from experiments.

The simulation procedure starts by importing the blade's sections airfoils coordinates into the XFOIL module. An analysis of the performance for each airfoil over the largest possible angle of attack range is then executed. To ensure good accuracy in the propeller simulation results it is important to define the blade operational Reynolds and Mach numbers within XFOIL. Therefore, some iterations may be needed for a complete propeller simulation. These XFOIL airfoil performance polars are used to obtain a full 360° range of angle of attack airfoil polar. This polar extrapolation calculates the lift and drag coefficients of each airfoil for the complete range of angle of attack, removing any blade twist angle limitations.

The introduction of the blade geometry is made by specifying an arbitrary number of sections characterized by their radial position, chord, twist, length, airfoil and its associated *360°* angle of attack range lift and drag polar. The propeller number of blades and hub radius must be specified as well.

The propeller performance results, which characterize the propeller, are then calculated and stored. It is possible to define different simulations for the same propeller, making easy to perform parametric studies. The density viscosity and speed of sound of the fluid can be modified according to the altitude in which the propeller will operate.

2.2. Propeller inverse design in JBLADE

Although the detailed description of the inverse design method can be found in Adkins and Liebeck [20] paper, a brief description of the method is given herein. To initiate the design, the user should specify the number of blades, the hub radius and define the position and airfoil of each section of the blade. The number of sections and their location can be arbitrarily chosen. Furthermore, to obtain an initial geometry of the propeller, the free stream speed, air density and the power that the propeller absorbs or the thrust that it needs to produce must be given. The implemented method requires the equivalence between momentum equations and circulation equations which results in the relation between ζ and the induction factors as presented in Eqs. (1) and (2):

$$a_a = \frac{\zeta}{2}\cos^2\phi(1-\varepsilon\tan\phi) \tag{1}$$

$$a_t = \frac{\zeta}{2x}\sin\phi\cos\phi\left(1+\frac{\varepsilon}{\tan\phi}\right) \tag{2}$$

After the determination of the drag-to-lift ratio and angle of attack for each station, the blade chord and blade twist angle are computed as presented in Eqs. (3) and (4) respectively:

$$c = \frac{4\pi\lambda G V R\zeta/C_L B}{V(1+a_a)/\sin\phi} \tag{3}$$

$$\theta = \alpha + \phi \tag{4}$$

The four derivatives of I and J should be calculated and integrated along the radius in order to calculate the new ζ. Since the updated ζ is calculated, it is necessary to compare it with the previously calculated value to check for convergence. If it is not the case, the