Aerospace Science and Technology 45 (2015) 50–59

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Engine pre-entry thrust and standard net thrust evaluation based on the far-field method

Benoit Malouin *, Martin Gariépy, Jean-Yves Trépanier, Éric Laurendeau

Polytechnique Montréal, Dept. of Mechanical Engineering, 2900 Boul. Edouard-Montpetit, Montréal, Québec, H3T 1J4, Canada

A R T I C L E I N F O

Article history:
Received 7 November 2014
Received in revised form 15 April 2015
Accepted 21 April 2015
Available online 24 April 2015

Keywords:
CFD
Drag
Thrust
Far-field
Power-on
Bookkeeping

A B S T R A C T

Computation of engine pre-entry thrust is required to evaluate aircraft configuration drag. Numerical computation of this quantity requires knowledge of the captured streamtube, which depends on the stagnation line location. A new method that uses the far-field formulation is developed so that knowledge of the streamtube properties is no longer required. Using similar techniques, an alternative method to compute the standard net thrust, the basis of most thrust/drag bookkeeping systems, is introduced. The classical formulation to compute the standard net thrust needs interpolation of flow quantities in the nacelle's exit plane which leads to loss of accuracy. Theoretical development of the far-field method in power-on conditions is presented as well as an overview of the bookkeeping technique in CFD. Simulations are performed with ANSYS Fluent 13.0 on the isolated CFM56 nacelle in power-on conditions with varying boundary conditions. Results of the proposed approaches are in agreement with ESDU and classical formulations. Drag decomposition in terms of viscous, wave, spurious, induced, and through-flow drag is presented. Configuration drag is computed with two formulations which are in agreement.

1. Introduction

Drag extraction through near-field/far-field methods has been given attention since the last two decades so that the ultimate goal is to predict the drag coefficient within a drag count [1]. However, motorized configurations and bookkeeping between thrust and drag are less addressed in the scientific literature. Airframers rely on both wind tunnel tests and CFD to study the interaction between the engine, the jet and the airframe. In wind tunnel tests, a through-flow nacelle (TFN) is used to evaluate the interaction drag between the wing and the engine [2]. Nonetheless, special treatment, such as truncating the nacelle, has to be made to ensure that the mass flow rate through the TFN when attached under the wing is the same as on the powered nacelle. For more accuracy, the TFN may be replaced by a Turbine Powered Simulator (TPS) [3] where compressed air is injected through a turbine to simulate jet effects. Though, there are still limitations. For instance, the jet generated by the TPS is cold.

Considering these limitations, CFD might provide a superior approach because test cases can be easily implemented. In the past, Tognaccini [4] and van der Vooren et al. [5] addressed thrust/drag bookkeeping in CFD. The former proposed a way to compute the nacelle external drag while the latter introduced the concept of additive through-flow drag created at the fan entry and turbine exit planes. In both researches, the far-field method was used. Recently, Malouin et al. [6] proposed a method to compute the internal drag of a TFN with the far-field approach.

In power-on conditions, the net propulsive force, which corresponds to the difference between the thrust and the drag, is constant for a given configuration at given flow conditions. However, many definitions for the thrust are available and the drag will vary in accordance with the thrust used in the bookkeeping system. Usually, the standard net thrust is used [7,8] which leads to the computation of the pre-entry thrust by integrating the pressure distribution on the engine's captured streamtube. However, such procedure is not an easy task because results are dependent on the accuracy of the stagnation line location. The main objective of this paper is to propose a novel method to compute the pre-entry thrust derived from the far-field approach. Tests are performed on the CFM56 nacelle and results are compared to the ESDU [9] and to the classical pressure integration approaches. Results for the proposed method are in good agreement with both techniques. An alternative procedure to compute the standard net thrust is also presented. The classical way requires interpolation of flow quantities in the nacelle's exit plane which leads to loss of accuracy. The new formulation that uses the far-field method is shown to be more robust and less mesh-dependent.

---

* Corresponding author.
E-mail address: benoit.malouin@gmail.com (B. Malouin).

http://dx.doi.org/10.1016/j.ast.2015.04.014
1270-9638/© 2015 Elsevier Masson SAS. All rights reserved.

Nomenclature

α	Angle of attack	(°)
ΔH	Enthalpy variation from free stream	(J/kg)
Δs	Entropy variation from free stream	(J/K)
$\Delta \bar{u}$	Axial velocity defect	(m/s)
γ	Ratio of specific heats	
μ	Viscosity	(N s/m^2)
∇p	Pressure gradient	(kPa/m)
ρ	Density	(kg/m^3)
$\mathrm{D_A}$	Nacelle external drag	(N)
$\mathrm{D_c}$	Configuration drag	(N)
$\mathrm{D_f}$	Friction drag	(N)
$\mathrm{D_{irr}}$	Irreversible drag	(N)
$\mathrm{D_i}$	Induced drag	(N)
$\mathrm{D_{NF}}$	Near-field drag	(N)
$\mathrm{D_p}$	Pressure drag	(N)
$\mathrm{D_{scrub}}$	Scrubbing drag	(N)
$\mathrm{D_{sp}}$	Spurious drag	(N)
$\mathrm{D_{tf}}$	Additive through-flow drag	(N)
$\mathrm{D_v}$	Viscous drag	(N)
$\mathrm{D_w}$	Wave drag	(N)
$\mathrm{F_{FF}}$	Far-field net propulsive force	(N)
$\mathrm{F_{NF}}$	Near-field net propulsive force	(N)
$\mathrm{M_\infty}$	Free stream Mach number	
$\mathrm{S_{ref}}$	Reference area	(m^2)
T	Thrust	(N)
$\mathrm{T_B}$	Basic thrust	(N)
$\mathrm{T_{Int}}$	Intrinsic thrust	(N)
$\mathrm{T_N}$	Standard net thrust	(N)
$\mathrm{T_{Pre}}$	Pre-entry thrust	(N)
$\vec{\tau}_x = [\tau_{xx}, \tau_{xy}, \tau_{xz}]$	Viscous stresses vector	(N/m^2)
$\vec{f}$, $\vec{f}_x$	Momentum vectors	
$\vec{f}_i$	Momentum vector associated with reversible processes	
$\vec{f}_{vw}$	Momentum vector associated with irreversible processes	
$\vec{i}$	X-direction unit vector	
$\vec{n} = [n_x, n_y, n_z]$	Normal vector	
$\vec{V} = [u, v, w]$	Velocity vector	(m/s)
p	Static pressure	(kPa)
a	Speed of sound	(m/s)
c	Chord	(m)
F	Net propulsive force	(N)
MFR	Mass flow ratio	
R	Gas constant	(J/(kg K))

The next section presents an overview of all the forces and drag encountered in a motorized configuration as well as a review of the far-field theory and the development of the proposed approaches to compute the pre-entry thrust and the standard net thrust. It is then followed by application on the CFM56 isolated nacelle in power-on conditions.

2. Theory

The difference between the configuration drag $\mathrm{D_c}$ and the thrust T is the net propulsive force $\mathrm{F} = \mathrm{D_c} - \mathrm{T}$, which is constant at given flow conditions for a given configuration. However, many definitions for the thrust are available and, regarding the user's choice, the thrust and the drag can vary. In the following section, forces on a motorized isolated nacelle are described. It is followed by a summary of the far-field method which is used to compute these forces. Then, new approaches to compute the standard net thrust and the pre-entry thrust are proposed.

2.1. Forces on configuration

Let's consider the isolated nacelle in power-on conditions depicted in Fig. 1. Note that the small red arrows represent the normal vectors. The forces applied to this configuration are:

- Pre-entry thrust
- Standard net thrust
- Basic thrust
- Intrinsic net thrust
- Scrubbring drag
- Nacelle external drag

The pre-entry thrust $\mathrm{T_{Pre}}$, also known as additive drag, corresponds to the difference in stream forces between the nacelle's entry and the streamtube captation area located infinitely far upstream ($S_{-\infty}$) [9]. This force appears when the mass flow ratio is different than unit. The mass flow ratio MFR can be computed as follows:

$$\mathrm{MFR} = \frac{S_{-\infty}}{S_{inlet}} \tag{1}$$

where S_{inlet} is determined by the nacelle's most forward points plane.

The pre-entry thrust is defined as follows [5,7]:

$$\mathrm{T_{Pre}} = -\int_{S_T} \left[(p - p_\infty) n_x - (\vec{\tau}_x \cdot \vec{n})\right] dS \tag{2}$$

where S_T corresponds to the streamtube surface. In this paper, the hypothesis is made that the shear stress is negligible on S_T because it is far from a wall and, since the streamtube is located upstream of the nacelle, it is not affected by viscous wake.

The standard net thrust $\mathrm{T_N}$ constitutes the basis of most bookkeeping systems because it uses the captation surface $S_{-\infty}$ [7]. This surface is a clever choice because the flow is undisturbed infinitely far upstream and its definition is not function of the geometry. Therefore, it is free of ambiguity. The standard net thrust is defined as follows:

$$\mathrm{T_N} = \int_{S_{-\infty} \cup S_{exit}} \left[\rho u \left(\vec{V} \cdot \vec{n}\right) + (p - p_\infty) n_x - \left(\vec{\tau}_x \cdot \vec{n}\right)\right] dS \tag{3}$$

where S_{exit} corresponds to the nacelle's exit plane as shown in Fig. 1.

The basic thrust $\mathrm{T_B}$, which can be considered as the force generated by the engine, is defined by:

$$\mathrm{T_B} = -\int_{S_{in} \cup S_{out}} \left[\rho (u - u_\infty) \left(\vec{V} \cdot \vec{n}\right) + (p - p_\infty) n_x - \left(\vec{\tau}_x \cdot \vec{n}\right)\right] dS \tag{4}$$

where S_{in} and S_{out} correspond to the fan inlet and turbine exit respectively, as illustrated in Fig. 1.

The intrinsic net thrust $\mathrm{T_{Int}}$ is given by:

$$\mathrm{T_{Int}} = \int_{S_{inlet} \cup S_{exit}} \left[\rho u \left(\vec{V} \cdot \vec{n}\right) + (p - p_\infty) n_x - \left(\vec{\tau}_x \cdot \vec{n}\right)\right] dS \tag{5}$$