Aerospace Science and Technology ••• (••••) •••–•••

Contents lists available at SciVerse ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Some compressibility effects on the lee side flow structures of cruciform wing–body configurations with very low aspect ratio wings

S. Tuling [a,*], L. Dala [b], C. Toomer [c]

[a] Council for Scientific and Industrial Research, Meiring Naude Rd, Pretoria, South Africa
[b] School of Mechanical Engineering, University of the Witwatersrand, Johannesburg, South Africa
[c] Faculty of Environment and Technology, University of the West of England, Bristol, United Kingdom

ARTICLE INFO

Article history:
Received 4 December 2012
Received in revised form 1 April 2013
Accepted 18 April 2013
Available online xxxx

Keywords:
Symmetric vortices
Vortex shedding
Slender bodies
Very low aspect ratio wings

ABSTRACT

A series of validated numerical simulations of a tangent ogive circular body in combination with very low aspect ratio cruciform wings at supersonic Mach numbers and angles of attack up 25° have been performed. Inspection of the flow in the cross flow planes revealed that symmetric vortex shedding occurs when the cross flow velocity is supersonic not only in the accelerated flow region outside the vortices, but in particular, the reverse flow in the recirculation region. Symmetric vortex shedding occurs for tangent ogive bodies at cross flow Mach numbers greater than 0.65, and for circular bodies with cruciform wings in the '+' orientation and span to body diameter ratios of 1.25 at cross flow Mach numbers greater than 0.55.

1. Introduction

The flows in the lee side of slender bluff bodies have been the subject of investigation for decades, particularly because above low angles of attack they comprise the dominant contribution to the normal force load. A significant amount of work has been performed on bodies, and in particular circular bodies, especially given that the separation characteristics are boundary layer dependent. These studies have been both theoretical and experimental. Theoretical methods by Bryson [2], Sarpkaya [26], Mendenhall [25], Angelucci [1], and Marshall and Deffenbaugh [23], and Wardlaw [33] have used single vortex models and discrete vortex models to model the flow over inclined bodies of revolution. These theoretical methods are based on experimental work performed by numerous investigators such as Thomson and Morrison [28], Mello [24], Wardlaw [32] and Lamont [21]. Experimental studies have provided significant insight to the various categories of flow ranging from attached, symmetric vortex, asymmetric vortex and bluff body flow, and the similarities and differences to the 2D flow over cylinders [12].

The unsteady flow regime for slender bodies has tended to be of more interest where a significant number of contributions have been made to the understanding of asymmetric vortex shedding that occurs at high angles of attack [12,28,36]. This regime corresponds analogously to the von Karman vortex shedding regime in the 2D case. From an application perspective the interest has been because of induced asymmetric loads and their implications on the control of any particular configuration. The emergence of asymmetric vortices triggered by microasymmetries is governed by a convective hydrodynamic instability, where a significant amount of work was performed by Degani and co-authors [7–11]. Not only have global loads been investigated [12,15], but other characteristics of this flow regime such as symmetric pair stability [3,4], secondary and tertiary vortex merging [31], shedding modes and frequencies, vortex interactions, surface pressure fluctuations and "flipping" have been investigated [36]. Vortex shedding has also been investigated for non-steady motions such as coning [13] and dynamic pitching [14,17,35].

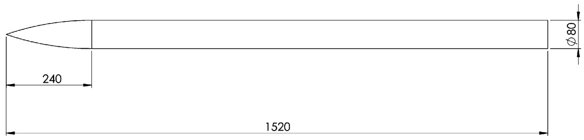
Less has been published by way of flow studies for slender bodies with very low aspect ratio wings. Simpson and Birch [27] do report on some of the flow features. Experimental data on flow fields are limited with work performed by Macha on 2D body–strake configurations [22], and vortex visualisation of pointed bodies with strakes along the complete length by Werle [34]. Whilst the study by Werle provides indications on the types of flow fields to be expected, the strake span to body diameter ratio is 2.16 whereas this study is focused on much lower ratios. Limited flow visualisation of vortices have been performed by Jorgensen [19] in a study which focussed on the effect of nose and body shapes and planar wings or strakes on asymmetric lateral loads arising

---

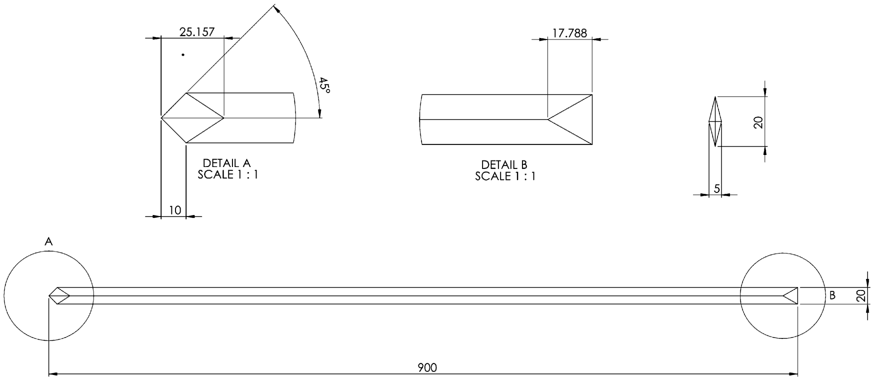
* Corresponding author.
E-mail addresses: stuling@csir.co.za (S. Tuling), laurent.dala@wits.ac.za (L. Dala), chris.toomer@uwe.ac.uk (C. Toomer).

1270-9638/$ – see front matter © 2013 Published by Elsevier Masson SAS.
http://dx.doi.org/10.1016/j.ast.2013.04.008

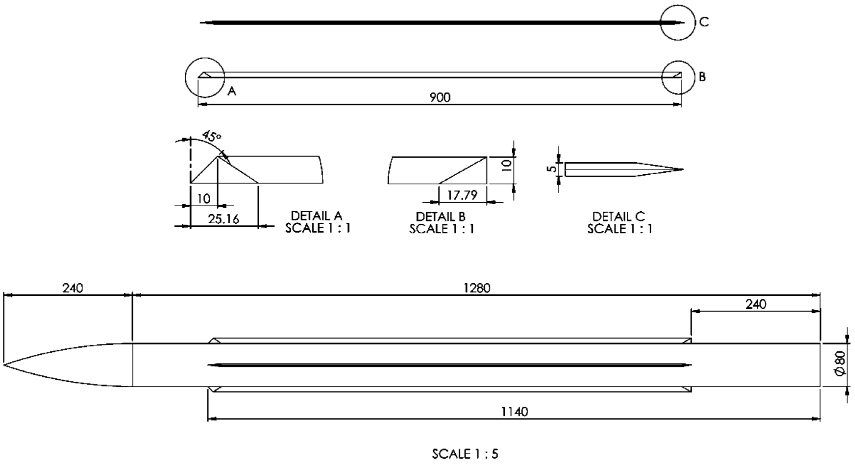
Please cite this article in press as: S. Tuling et al., Some compressibility effects on the lee side flow structures of cruciform wing–body configurations with very low aspect ratio wings, Aerospace Science and Technology (2013), http://dx.doi.org/10.1016/j.ast.2013.04.008



(a) Body only



(b) Strake only



(c) Body-strake

Fig. 1. Body only, strake only and body–strake geometry.

from asymmetric vortices for Mach numbers 0.6 to 2.0 and angles of attack up to at least 60°. At subsonic speeds two symmetric vortices were identified using wake surveys and is confirmed by the laser sheet visualisation of Jorgensen [19]. This study extended the work performed by Jorgensen [20] and Tinling et al. [29]. Tinling performed the tests at subsonic speeds between Mach 0.30 and 0.95 up to angles of attack of 24°. The body lengths used in these investigations were 10.3D for Ref. [20], 10.74D for Ref. [29] and 10D for Ref. [19]. Other investigators have focussed on vortex dynamics at subsonic speeds or higher angles of attack where asymmetric vortex shedding occurs. Four regions of flow have been identified for bodies through the angle of attack range from 0° to 90° [12], namely attached, symmetric vortices, asymmetric vortices and wake flow.

The region of interest in this paper is the symmetric vortex regime where the shed rolled up vortex sheet organises itself into two symmetric vortices, rather than becoming asymmetric as in a 2D case, because the axial flow component dominates the flow topology. This characteristic of the flow gave rise to the theoretical method by Bryson [2], alternatively known as the “NACA Vortex Model”. The flow is dominated by steady vortices rather than the unsteady vortices associated with the high angle asymmetric flow regime. For a pointed nose slender body, the angle of attack range is bounded by when vortices start appearing at approximately 4°, and until the angle of attack exceeds the total included angle of the nose [12].

In the study of Ref. [19] the flow topology at Mach 2.0 resembles that of subsonic speeds for the lower angles of attack ($\leqslant 20°$). At the angles of attack of 30° and above, the vortex region is elongated and the rolled up vortex sheet is not circular or elliptical as at subsonic speeds. Present under the same conditions is a local shock, located at the top end of the elongated vortex region.

A more recent study on configurations of this type were performed by Tuling et al. [30]. The work performed has been limited to circular bodies with cruciform wings (or strakes) of aspect ratio 0.0223 with a taper ratio of ≈ 1. The orientation of the wing with respect to the cross flow velocity vector is the ‘+’ configuration. The study focused on the supersonic speed regime with freestream

Please cite this article in press as: S. Tuling et al., Some compressibility effects on the lee side flow structures of cruciform wing–body configurations with very low aspect ratio wings, Aerospace Science and Technology (2013), http://dx.doi.org/10.1016/j.ast.2013.04.008