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Numerical analysis of base-ventilated intercepted supercavitating hydrofoil sections

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ABSTRACT

A numerical analysis of the inviscid flow over a family of base-ventilated intercepted hydrofoils is presented using a low-order, non-linear boundary element formulation. The blunt-based section geometry used is based on the NACA 4-digit modified thickness distribution with the addition of a trailing edge fence (or interceptor) for lift production. An optimum section shape, in terms of stable cavity behaviour, was found to be a trade-off between the leading edge minimum pressure and the trailing edge slope. The former affecting the potential for leading edge cavitation and the latter flow separation from the trailing edge. The maximum hydrodynamic efficiency was obtained with a thin section, a small trailing edge slope and operation at a low cavitation number. For a profile with 15% thickness to chord, at zero incidence and an interceptor height of 1% of the chord length, a maximum lift/drag ratio of around 12 was achieved. The practical realization of this value is likely to be affected by structural limitations, cavity dynamics and serviceability constraints.

1. Introduction

Cavitating flows detaching from bluff bodies where the cavity closure occurs downstream of the body are termed supercavitating. The extent of the cavitating region which develops depends upon the flow conditions and the geometry of the body. The cavities are said to form either: "naturally" from the surrounding liquid as a vapor cavity, characterized by a cavitation number, $\sigma_v = (p_\infty - p_v)/0.5\rho\, U_\infty^2$, based on the liquid vapor pressure, p_v, or; "ventilated" from a source of free gas (e.g. from a connecting passage with the free surface) which together with some liquid vapor forms what is termed a ventilated cavity. In this case the cavitation number may alternatively be defined as $\sigma_c = (p_\infty - p_c)/0.5\rho U_\infty^2$ where the cavity pressure, p_c, is the sum of the partial pressures of both the free gas and vapor. In either case the difference between the free-stream static pressure, p_∞, and the pressure in the cavity is divided by the free-stream dynamic pressure where ρ is the fluid density and U_∞ is the reference velocity. The focus of the present study is on ventilated cavities and therefore all data have been presented in terms of the more general definition of the cavitation number σ_c. Note that similar flow conditions can be alternatively achieved by addition of free gas or by either increasing the flow speed or decreasing the static pressure.

The performance of supercavitating hydrofoils has been extensively investigated and reported on in the open literature, as reviewed in Pearce and Brandner (2007). These hydrofoil sections can be divided into those operating with one or two wetted sides, termed fully ventilated and base ventilated respectively (Auslaender, 1962). The former has the upper cavity surface detaching from a sharp leading edge, while the latter has both upper and lower surfaces wetted and cavity detachment from the edges of the unwetted blunt base.

Geometrically the blunt-based hydrofoil shape can be with or without camber – the latter is the focus of the present study. Unlike the fully ventilated type, there has been relatively little study undertaken on base-ventilated hydrofoils, as reviewed in Pearce and Brandner (2015). Within this field of study the subsection pertaining to symmetric section geometries is further limited. An experimental study by Brentjes (1962) examined a symmetric parabolic profile, but in contrast to the present work, with the maximum thickness located forward of the trailing edge (t.e.). Verron and Michel (1984) reported on an experimental investigation using simple wedge shaped geometries with rounded leading edges as the main interest was in the three-dimensional effects related to the planform shape. Historically the main interest in un-cambered base-ventilated sections has been in the application to surface piercing struts, rudders, etc. on high-speed craft (Tulin and Streeter, 1961; Johnson Jr. and Starley, 1962) rather than directly for lifting applications. A significant outcome from some earlier work, derived from linearized potential flow theory (Tulin, 1955), was that the optimum shape of these sections, as regards drag minimization, was found to be parabolic.

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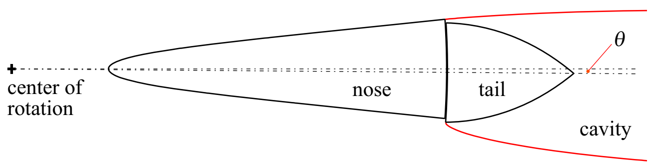

Fig. 1. Two-part hydrofoil with trailing supercavity (truncated). Bi-directional lift is generated by rotation of the tail section, either up or down, to form a BFS and FFS at the join between the hydrofoil sections. The consequent flow asymmetry results in lift generation from a symmetric hydrofoil at nominally zero incidence.

The motivation for the present work has been to investigate the suitability of a novel base-ventilated supercavitating hydrofoil design for use in high-speed vessel motion control devices and other possible marine applications. This concept has been proposed by Australian Naval Architect Tony Elms as embodied in the patent application entitled "Improved Hydrofoil Device"(Elms, 1999).

2. A novel hydrofoil concept

The basis of this novel concept is in the use of a symmetric hydrofoil section from which a trailing ventilated supercavity is formed from geometric discontinuities, located between the mid-chord and trailing edge, on both the upper and lower surfaces. On one surface the discontinuity is a forward-facing step (FFS) whilst on the opposing surface a backward-facing step (BFS) is formed. This is achieved, as shown in Fig. 1, by rotating the tail section relative to the nose section. With the supercavity detaching from the steps formed on the hydrofoil surfaces the tail section of the hydrofoil is then, if suitably shaped, situated wholly within the cavity. Due to the flow asymmetry, caused by the steps with detached cavity surfaces, lift is consequently produced (Pearce and Brandner, 2014, 2015). The pressure side of the hydrofoil is the one with the FFS formed on it due to the consequent flow stagnation on the hydrofoil surface. With the ability to rotate the tail section and form a FFS on either the upper or lower hydrofoil surfaces, lift can then be produced in either direction from a symmetric hydrofoil section at nominally zero incidence.

As the hydrofoil tail section remains wholly inside the cavity, and therefore has no contribution to the resulting hydrodynamic performance, the two-part hydrofoil with cavity concept of interest herein is modelled using the forward section only with a sharp-edged flat plate or "fence" added to one of the trailing edges. The addition of the step to the hydrofoil surface is akin to an interceptor attached to the edge of a transom (Widmark, 2001; Faltinsen, 2005), so the term "intercepted" hydrofoil is used for this arrangement.

The hydrofoil chord length, c, used in the presentation of results is that relating to the forward section only. In Fig. 2, sketches of the intercepted hydrofoil and cavity, symmetrical blunt-based hydrofoil and trailing edge fence attachment are given showing the definition of the geometric and main hydrodynamic parameters. The hydrofoil angle of incidence is defined as positive if the hydrofoil, with the step attached to the lower surface, is rotated clockwise about its midchord point.

3. Hydrofoil section geometry

Due to the novelty of this concept, and therefore the lack of relevant previously published work to draw upon, a preliminary numerical analysis of two simple or basic hydrofoil profiles has been undertaken (Pearce and Brandner, 2015). The understanding gained from this initial analysis provided a basis for the selection of the bare blunt-based hydrofoil shape (i.e. the profile without

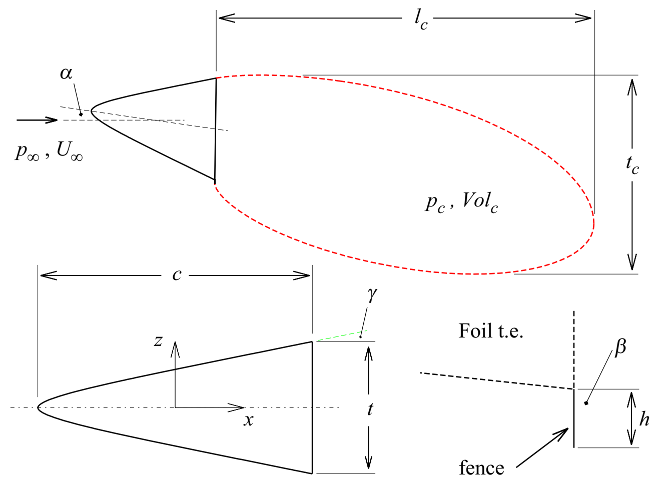

Fig. 2. Sketch of the intercepted hydrofoil/cavity indicating the definition of the main geometric and hydrodynamic parameters used. Also shown is the bare hydrofoil section profile and a magnified view of the hydrofoil lower surface trailing edge with a flat fence attached ($\beta = 90^\circ$).

interceptor). The following parameters were found to be significant:

- Thickness to chord ratio, t/c
- Leading edge radius (degree of profile bluntness), r
- Hydrofoil trailing edge slope, γ
- Height (and shape) of the trailing edge step, h/c (and β the angle of the fence to the hydrofoil base).

The present work reports on a systematic investigation of the effect of each of these parameters on the resulting cavity geometry and hydrodynamic performance. In view of the large parameter space of possible interest, only results for a normal fence, $\beta = 90^\circ$, are presented here.

Unless otherwise indicated, from here onwards, any reference to the hydrofoil or hydrofoil section shape pertains to the forward part only of the complete two-part hydrofoil (Fig. 1).

To maintain cavity detachment from the edge of the hydrofoil blunt base the flow should remain attached along the hydrofoil suction surface. Apart from aspects particular to the leading edge region (Davis, 1980), flow separation over the remainder of the hydrofoil surface is prevented if a favourable pressure gradient is maintained. This is achieved if the profile monotonically increases in thickness with chordwise distance from the leading edge such that the maximum thickness occurs at the trailing edge. By varying the leading edge radius of the hydrofoil section the degree of "bluntness" can be prescribed. The first derivative at the trailing edge must be able to be prescribed to obtain a desired γ.

A number of functions were investigated for suitability. One that satisfies all these requirements, and consequently chosen for the present investigation, is the design equation for the thickness distribution of the NACA 4-digit-modified-series airfoils (Stack and von Doenhoff, 1934). The modification over the basic series was introduced to allow variations in the leading-edge radius, providing differing degrees of "bluntness", and also to allow the chordwise location of maximum thickness to be prescribed (Ladson et al., 1996). The modified series also differs in that the profile definition is separated into two parts, one forward and one after the point of maximum thickness.

Eq. (1) defines the portion of the NACA 4-digit-modified-series hydrofoil profile up to the point of maximum thickness. It is this function that has been used to generate the hydrofoil geometry for the present work. The coefficient of the first term, a_0, is a function