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Comparative CFD Investigation on the Performance of a New Family of Super-Cavitating Hydrofoils

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Abstract. We present a CFD characterization of a new type of super-cavitating hydrofoil section designed to have optimal performance both in super-cavitating conditions and in sub-cavitating conditions (including transitional regime). The basic concepts of the new profile family are first introduced. Lift, drag and cavity shapes at different cavitation numbers are calculated for a new foil and compared with those of conventional sub-cavitating and super-cavitating profiles. Numerical calculations confirm the superior characteristics of the new hydrofoil family, which is able to attain high lift and efficiency both in sub-cavitating and super-cavitating conditions. Numerical calculations are based on a multi-phase fully turbulent URANSE solver with a bubble dynamic cavitation model to follow the generation and evaporation of the vapor phase. The new profile family, initially devised for ultra-high speed hydrofoil crafts, may result useful for diverse applications such as super-cavitating or surface-piercing propellers or high-speed sailing boats.

1. Introduction

In high speed crafts, the option offered by hydrofoils in sustaining at least a portion of the vessel weight becomes an inevitable design choice to take when speed increases. The higher efficiency of hydrofoil supported crafts have been demonstrated in the 30-50 knots range (with few exceptions above) also in passenger ferries, a recent example reaching the broad public being the AC-72 catamaran hydrofoils of the 34th America's cup. Most hydrofoil applications including this last one are limited to the sub-cavitating or partially cavitating regime and yet few of them have been designed for speeds in the super-cavitating regime. At sailing speeds higher than approximately 50 knots traditional hydrofoils creating a meaningful lift force start to experience super-cavitation

(i.e. the conditions at which the hydrofoil suction side is fully contained inside the vapor cavity that forms at its leading edge, see Figure 1). In this condition, conventional hydrofoils lose most of their ability to create lift and a different hydrofoil shape need to be designed. Conventional super-cavitating (SC) hydrofoils are designed to produce lift on the face and are optimized to operate in this regime: they have a pointed or sharp leading edge, a very slender entrance body to maintain the back inside the cavity and they recover strength (or inertia) by increasing their thickness at the trailing edge. The trailing edge

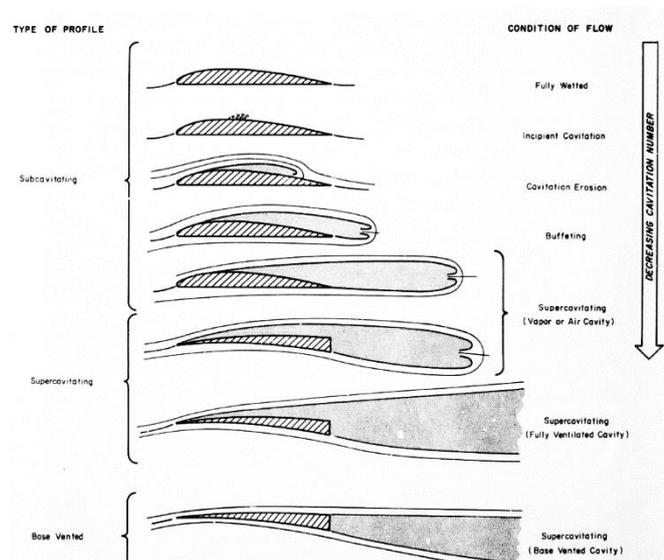


Figure 1 – Cavitation Regimes and Hydrofoil types (after [10])

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usually carries the max thickness and it is sharp cut, to facilitate base cavitation. Different design by analysis methods have been proposed starting from the asymptotic theory of Tulin and Burkart [1], engineered by Johnson [2] and more recently optimization methods based on numerical solution of the potential flow with sheet cavitation, such as Mishima & Kinnas [3] or Pearce and Brandner [4].

2. SCSB hydrofoil family

We propose a new hydrofoil design that was initially developed [5] and patented [6] for application on ultra-high speed autonomous surface-piercing hydrofoil crafts (120 knots design speed). The design method of this new family was presented in [7]. The SCSB profile, in Figure 2, combines the shape of a SC profile with the pointed tail typical of conventional sub-cavitating profile, through two steps, which act as cavitation inception points (cavitators). The pressure and suction side of the entrance part are designed according [7], while the tail may be tuned (as a kind of flap) to give the required lift coefficient in sub-cavitating conditions. A member of the new family is identified by a code with two numbers SCSB-XX-YY: the first integer (XX) gives the design lift coefficient $100 \cdot C_L$ in supercavitating conditions; the second (YY) gives the design cavitation number $100 \cdot \sigma_0$.

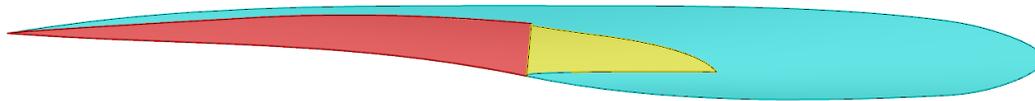


Figure 2 – SBSC profile (patented in [6]) working in a super-cavity (blue). In red the entrance part, in yellow the tail.

3. CFD Analysis of the SCSB-25-5 and equivalent NACA-65 profile

Figure 3 summarizes the global hydrodynamic characteristics of the SCSB profile, in terms of lift and efficiency versus the cavitation index $\sigma_0 = (p - p_{vap}) / (0.5 \rho V^2)$, at the design angle of attack $\alpha = 5$ deg. Its performances are compared to those of a good equivalent NACA profile, having the same maximum thickness to chord ratio, $(t/c)_{max} = 0.10$, and the same effective chord of the SBSC profile in super-cavitating conditions. Furthermore the camber of the NACA profile is designed for the same lift at the same angle of attack in non-cavitating conditions. Figure 4 presents the cavity shapes predicted at different cavitation number (at the design angle of attack). Predictions were obtained by fully turbulent URANSE solver with Schnell-Sauer cavitation model, validated for instance in [8] [9] on different SC hydrofoils and with different solvers (StarCCM+ / OpenFoam). Full scale $Re = Vc/\nu = O(10^7)$ is considered.

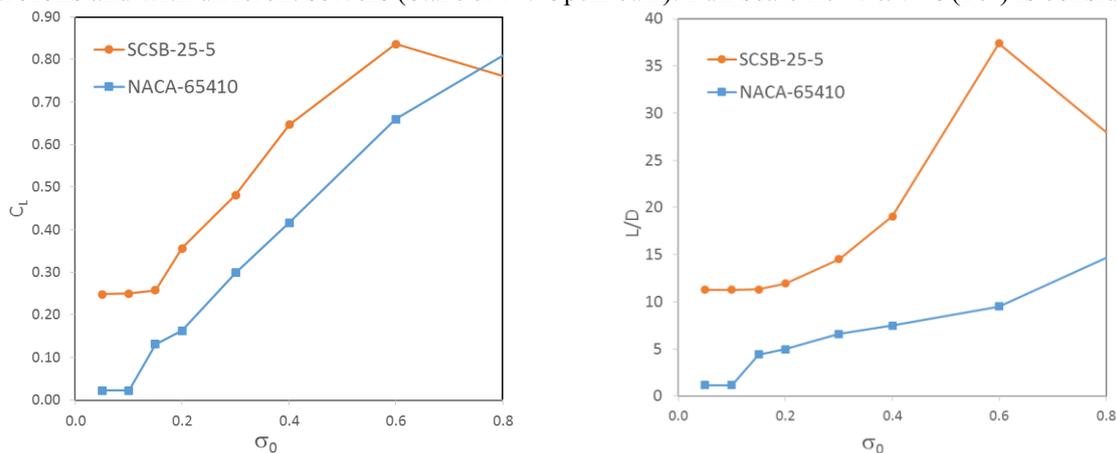


Figure 3 – Lift coefficient C_L and lift over drag L/D of NACA65-410 and SBSC-25-5 profiles versus cavitation number σ_0

As it can be observed, the NACA profile enters earlier into partial cavitation, at $\sigma_0 = 0.8$ the length of the cavity l is already larger than half the chord. As the cavity grows on the back ($0.4 \leq \sigma_0 \leq 0.8$), the lift rapidly drops with almost the same slope in both profiles. At $\sigma_0 = 0.4$ the cavity spans almost the full length of profile, although it is still highly unstable (buffeting regime). The instability of the cavity is evident from the evolution of the shape over time and it influences also the value of the hydrodynamic forces which show a periodic fluctuation around the average value (reported in Figure 3). In this regime,

the difference of lift between the two profiles sets around $\Delta C_L \sim 0.25$. The SCSB-25-5 enters first into the stable super-cavitation regime, at about $\sigma_0 = 0.15$, at which the NACA 65-410 still tends to develop an oscillating (buffeting) cavity. At the lowest investigated $\sigma_0 < 0.15$, the difference of lift coefficient and efficiency between the two profiles is dramatic: the SBSC sets onto $C_L \sim 0.25$, its design value, while the NACA drops down to $C_L \sim 0.02$. The reason is clearly the loss of the back side for the NACA profile, which remains with its non-optimal face shape to develop lift in these conditions. On the other hand, as the cavity gets shorter ($\sigma_0 > 0.8$) the NACA profile considerably reduces its drag (without increasing lift) and in non-cavitating conditions ($\sigma_0 > \sim 1.5$) its efficiency rapidly climbs up to $L/D \approx 90$, as opposed to the SCSB which stays on $L/D \approx 35$. This is still a very attractive number, especially if compared to the efficiency of an equivalent conventional super-cavitating profile with blunt truncated trailing edge which typically stays around $L/D \approx 6$ (as presented in [7]).

4. Conclusions

We have briefly introduced the design feature and hydrodynamic characteristics of a new family of super-cavitating hydrofoil, named SCSB: they maintain high lift and efficiency at both sub-cavitating and supercavitating regimes, at the contrary to optimal conventional sub-cavitating or conventional SC hydrofoils. In particular, the presented profile, SCSB-25-5 at its design angle of attack $\alpha = 5$ degrees, produces about the same lift of a NACA-65-410 in non-cavitating conditions ($C_L \sim 0.8$).

The earlier entrance in cavitating condition (with respect to σ_0) is what keeps the lift of the NACA profile lower than the SCSB, in the whole investigated range of cavitation indexes. This difference is considerable and arrives up to 100% at $\sigma_0 = 0.15$. Then the SCSB-25-5 enters earlier also in the stable supercavitating condition ($\sigma_0 < 0.15$) and there it stabilizes on an $L/D = 11.3$, with an asymptotic $C_{Lmin} = 0.25$, while the NACA-65410 confirms its inadequacy to work in this regime, practically losing the ability to develop lift ($C_{Lmin} = 0.02$) and dragging the efficiency down to $L/D = 1$. Due to its particular shape, the SCSB leaves the buffeting regime first and anticipates stable supercavitating conditions with respect to the NACA profile: this is an advantage for applications to high speed hydrofoils, since the dangerous range of unsteadiness which needs to be carefully avoided, is reduced. The advantages offered by the new profiles can be handy for other types of application, such as super-cavitating propellers or active control surfaces for ultra-high speed water craft. It would be useful to experimentally verify the numerical results presented here in a dedicated tests in a high speed, low pressure cavitation tunnel.

Acknowledgments

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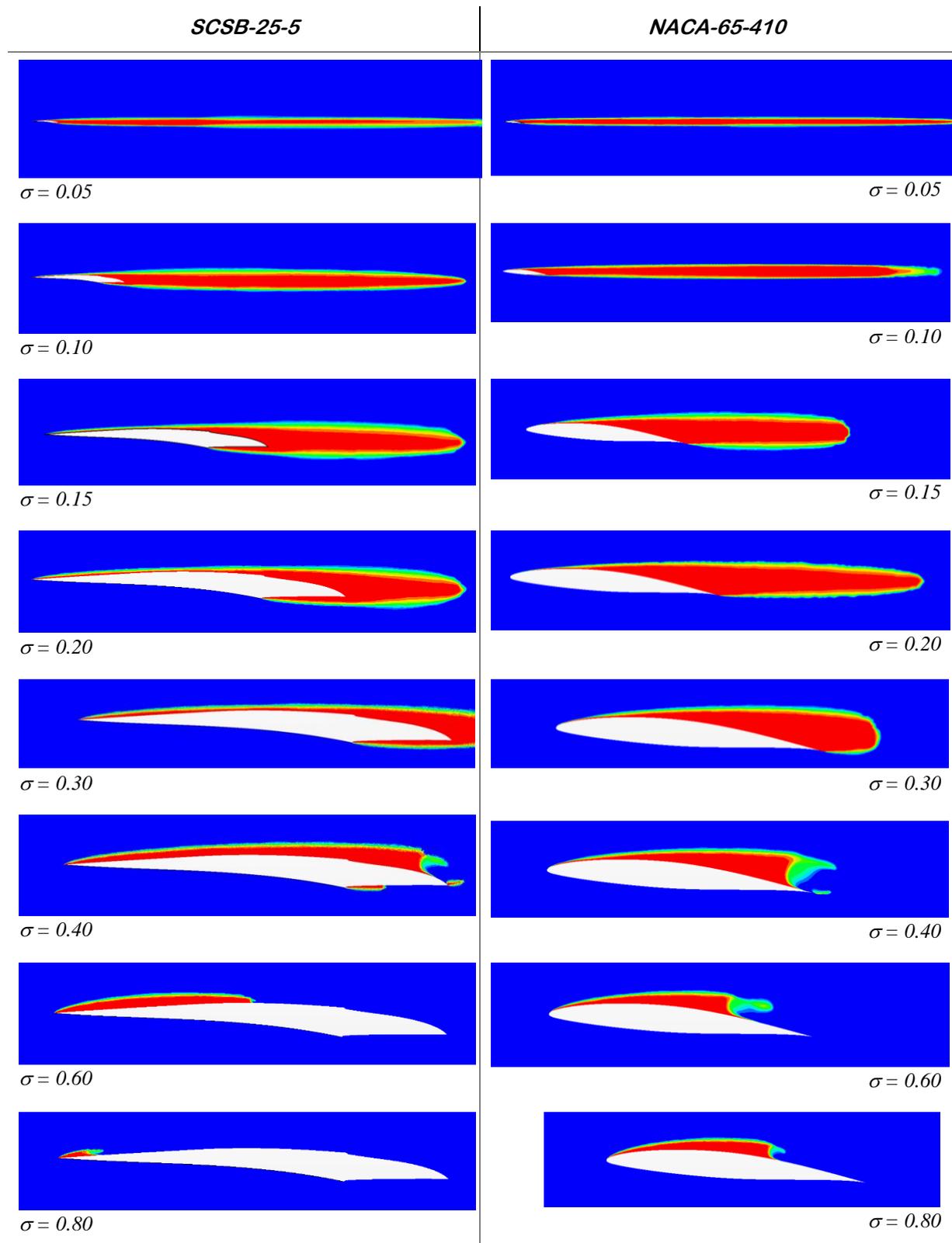


Figure 4 - Predicted cavity shapes at different cavitation numbers (indicated at the bottom of each picture).
SCSB-25-5 profile (left) and NACA-65-410 (right), angle of attack $\alpha=5$ deg for both.