Recent results on tip vortex cavitation scale effects at high reynolds numbers

A. Pauchet & L. Briançon-Marjollet
Bassin d'Essais des Carènes, Chaussée du Vexin 27100, Val de Reuil, France

ABSTRACT

In order to verify the Reynolds extrapolation law on Tip Vortex Cavitation (TVC), basic experiments were conducted in the Grand Tunnel Hydrodynamic (GTH) on two 3.8 area ratio elliptical hydrofoils with a NACA0020 and a NACA16020 cross sections for Reynolds numbers reaching 8.2×10^6 (Pauchet *et al.* [1]). Critical cavitation numbers, axial and tangential velocity profiles of the tip vortex were measured. The NACA0020 foil displays much larger desinent cavitation numbers as well as larger tangential and axial velocities compared to the NACA16020. This is due to the increase of the lift coefficient, caused by the change of the cross section. The influence of the Reynolds number on TVC and its dependence with the angle of attack of the foil are determined. It is shown that the desinent cavitation number scales with the Reynolds to the power 0.4 and the square of the lift coefficient.

NOMENCLATURE

a	distance to the vortex axis for maximum tangential velocity
c_{max}	maximum chord
C_l	lift coefficient
C_p	pressure coefficient at the vortex axis
i	angle of attack
p_{ref}	pressure of the non perturbed flow
p_v	vapor pressure at the temperature of the water
r, y	distance to vortex axis
V_{ref}	free stream velocity
V_t	tangential velocity
V_a	axial velocity
δ	boundary layer thickness
Γ	tip vortex intensity
ν	liquid kinematic viscosity
ρ	liquid density
σ_d	desinent cavitation number

INTRODUCTION

Experiments conducted at Reynolds numbers, based on the chord length, ranging from 2.5×10^6 to 8.2×10^6 have shown a significant increase, more than a factor of two, of the desinent cavitation number for an elliptical planform hydrofoil having an aspect ratio of 3.8, changing the cross section from a NACA16020 to a NACA0020, at equal angle of attack and free steam velocity. Indeed, in spite of the fact that both cross sections are symmetrical, over most of the incidence angle range the NACA0020 foil shows lift coefficient values larger than the NACA16020 foil. The present work gives a rational explanation of the differences observed between the two foils and finally, shows the same dependency of the critical cavitation number with the Reynolds number. The changes might be due either by the increase of the load distribution between the two foils caused by the modification of the boundary layer development and the separation point associated to the local curvature of the cross section or by the contribution of the boundary layer modification in the vortex core dimension. The tangential and axial velocity profiles measured in the very near region downstream the tip of the hydrofoil has allowed us to analyse the viscous core radius extension and its contribution in the modification of the tip vortex intensity. The change of the boundary layer separation point is confirmed by the analysis of the flow by numerical calculations using a 3D Navier-Stokes code (STAR-CD). Recent measurements of the lift coefficients for both foils, have been performed at the Ecole Navale Cavitation Tunnel (BREST) for Reynolds number equal to 1.2×10^6. They confirmed the hypothesis that the increase of the desinent cavitation numbers for the NACA0020 is entirely explained by the modification of the lift.

EXPERIMENTAL

Experiments were performed in the GTH (Grand Tunnel Hydrodynamique), fitted with a square test section of 1.14 m side and a length of 6 m. Elliptical hydrofoils having a 475 mm maximum chord and 713 mm half span were tested in the same conditions. There were hung vertically on the top horizontal wall and attached, at a third of the maximum chord, to a mechanical system allowing the foils to be rotated from -18° to +18°. The hydrofoils have identical planform but different cross sections, NACA16020 and 0020. The main difference in the cross section is that the position of the maximum thickness is at 50% and 30% chord from the leading edge respectively. The free stream velocity is comprised between 2 m/s and 20 m/s. The axial turbulence level is 0.3% whatever the free stream velocity. The zero hydrodynamic angle was set, with a precision of ±0.1°, by checking the position of the leading edge with respect to the cover lateral sides. By using an optical counter, the actual angle of the foil was measured with a precision of ±0.01°.

Velocity measurements procedure

Axial and "tangential" velocities were measured with a two components (three beams) forward scattering LDA system using a 15 Watt Argon source at several stations situated from 0.58 to 4 maximum chord downstream the mid-span leading edge. Because of the extremely large distance between the emission and reception optics, their position was simultaneously monitored by two three-axis independent computer-controlled (Dantec) traversing mechanism systems. The measuring volume, of 4.7 mm

long and 0.18 mm wide, was positioned with a precision of ±50 μm and the step sizes (0.25 to 5 mm) were adapted to the local tangential velocity gradients. LDA data were analysed using two Dantec Burst Spectrum Analyser and stored on a PC computer for further treatment.

Critical cavitation number measurements procedure

Angles of attack were varied between 0 and 17° and the free stream velocity comprised between 5 m/s and 15 m/s for the cavitation tests. Data reported here were obtained without seeding the flow with nuclei at oxygen contents of about 3.2 ppm. Tip vortex cavitation inception and desinence were obtained from direct visual observation of the test section or by delayed inspection of the video recordings of the region close to the tip of the wing. Tests were conducted at a fixed cavitation number (constant free stream velocity and test section pressure) by slowly varying the angle of attack of the foil until cavitation occurred. The incidence was then increased slightly to obtain well developed tip vortex cavitation. Desinence conditions were obtained by reducing the angle of attack. In the present work, only desinence cavitation numbers have been analysed since, as already mentioned by McCormick [2], they are less sensitive to changes in water quality, and thus reduce the scatter of the results.

RESULTS

Critical cavitation number

The cavitation number is defined as usual by:

$$\sigma = 2\,\frac{p_{ref} - p_v}{\rho V_{ref}^2}$$

The relative error on σ can be estimated to be less than ±1%. Different types of tip vortex cavitation inception and desinence have been observed. These correspond to different levels of cavitation; the first corresponds to the initial occurrence of streaks created by the passage of bubbles. The second stage occurs when a nearly continuous cavity is attached to the tip. When looking for desinence, the third stage corresponds to the cavity detachment, and the last one to the disappearance of all streaks from the observation field. As the cavitation data associated with the third stage (cavity detachment) were the less scattered, this criterion will be the only one to be considered in the following. If we assume that the desinent cavitation number is equal to the minimum pressure coefficient at the center of the vortex given by Lamb [3] vortex, the σ_d can be defined by:

$$\sigma_d = -C_p = \frac{0.87}{2\pi^2}\left[\frac{\Gamma}{a V_{ref}}\right]^2 \qquad (1)$$

where Γ is the strength of the vortex and can be expressed as

$$\Gamma = \text{Const}.\, C_l\, c_{max}\, V_{ref} \qquad (2)$$

Employing equations (1) and (2) yields: $\sigma_d = \text{Const}.\, C_l^2/a^2$. (3)

The cavitation number dependency displayed by this equation is approximated fairly well by the data of Figure 1 excepted for the lowest velocity tested (5 m/s). The effects associated with the free stream velocity on the radial extension of the viscous core are

clearly apparent for the NACA0020 foil, the desinent cavitation number is increasing with the increase of the free stream velocity. These effects can be taken into account by assuming that the size of the vortex core is proportional to a turbulent boundary layer thickness as already suggested by McCormick [2] for the very first time, Billet [4], Fruman *et al.* [5], Arndt and Dugué [6], with **a** = cons. $c_{max}\ Re^{-1/5}$ in equation (1), equation (3) can be also expressed:

$$\sigma_d = \text{Const}.C_l^2\ Re^{0.4} \qquad (4)$$

This scale effect on cavitation occurrence can be understood by plotting the σ_d results divided by the Reynolds number to the 0.4 power as a function of the square of the lift coefficient. This is showed in Figure 2 for the NACA0020 foil and the NACA16020 foil. In this figure,we used the lift coefficients measured (Figure 3) by the ENCT.

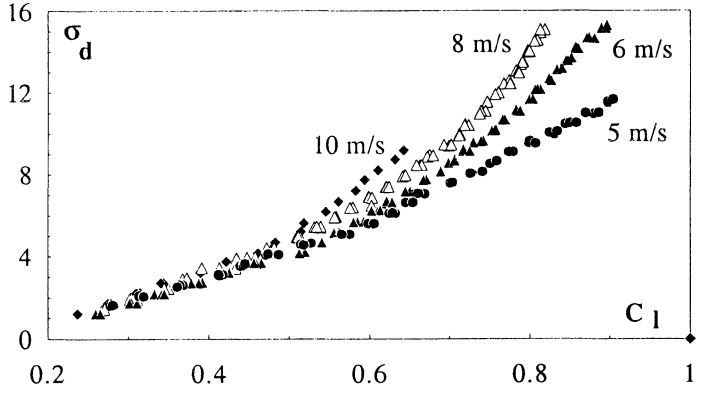


Fig. 1 : Desinent cavitation number as a function of the lift coefficient for the NACA0020 foil.

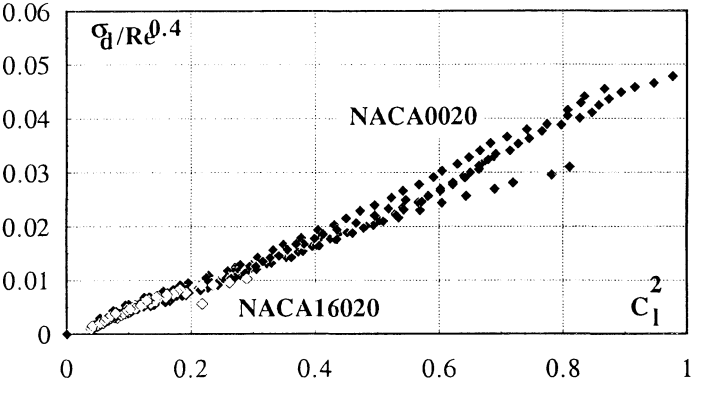


Fig. 2 : Desinent cavitation number divided by the Reynolds number to the power 0.4 as a function of the square of the lift coefficient for elliptical foils with NACA16020 (open symbols) and NACA0020 (closed symbols) cross sections.

This can be done because it has been shown that the lift curve of the NACA16020 elliptical foil remains unchanged for Reynolds numbers greatest than 1.2×10^6 Fruman *et al.*[7]. Concerning the NACA0020 elliptical foil, Dugué [8] has recently completed experiments showing that the lift coefficients are practically independent of Reynolds numbers. As it can be clearly seen on Figure 2, for each foils the data fall in a nearly straight line whose slopes are approximately equal. The scatter of the data increases with the lift coefficient, but this results is satisfactory considering that the lift-curve for the NACA0020 foil is completely different from the NACA16020 foil for angle of attack greater than 3°.

Lift Coefficients

Figure 3 shows the lift coefficient as a function of the angle of attack for both foils. Under 3 degrees the two lift curve slopes are equals but over this angle of attack the NACA16020 shows an important loss of lift, getting greater with increasing angle of attract.

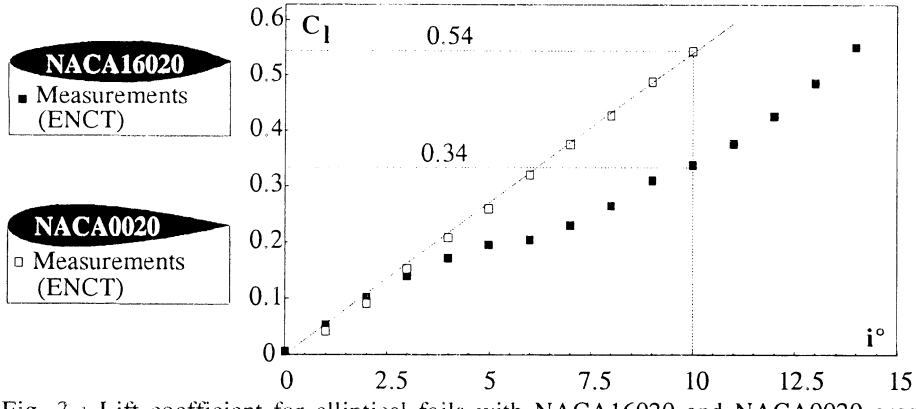


Fig. 3 : Lift coefficient for elliptical foils with NACA16020 and NACA0020 cross sections as a function of the angle of attack measured at the ENCT at a Reynolds number of 1.25×10^6.

If lifting surface theory is applied for foils having the same planform but different cross sections the same load distribution along the span is obtained and hence the same lift-curve slope, 0.066 deg^{-1} for an elliptical foil for example. Experimental measurements generally give values below this theoretical slope because of various effects, the most important one being the viscous effect. The modification of boundary layer development and the position of the separation point on the suction side of the foil might be an important reason for a modification of the lift coefficient in our case. Moreover it is known that the local curvature of the cross section could highly influence the behaviour of the boundary layer. This problem incited us to perform computations using a CFD code (STAR-CD) to simulate the three dimensional viscous flow over both foils at 10° and 10 m/s in the GTH test section. The numerical model is based on a mesh, defining the test section over a length of one maximum chord behind and below the foil. This mesh has about 170 000 hexahedron elements which allowed a very precise definition of the viscous flow over the foil. The results obtained for both foils are over and under estimating the lift coefficient compared to the measurements by

respectively using the k-ε turbulence model or by making the computation in laminar condition. But in each case, the NACA0020 shows a higher lift coefficient. In spite of the fact that the code is not capable of predicting the transitional point (the calculation of the boundary layer is either completely turbulent or ether completely laminar), the influence of curvature of the cross section is well captured as shown in Figures 4a and 4b. These figures show that the separation point over the upper surface of the NACA16020 foil is closer to the leading edge than for the 0020 and leads to the formation of a recirculating zone near the trailing edge. There is no such situation for the NACA0020.

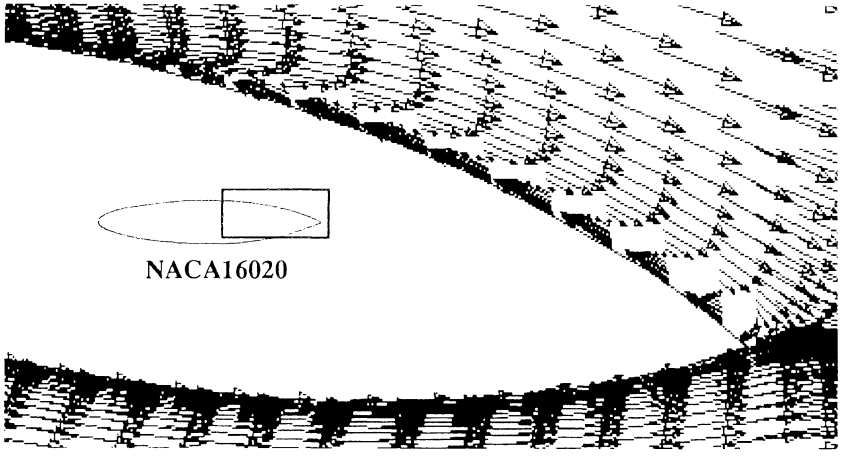


Figure 4a : Velocity field in a plane perpendicular to the span of the foil at 50% of the span for the NACA16020.

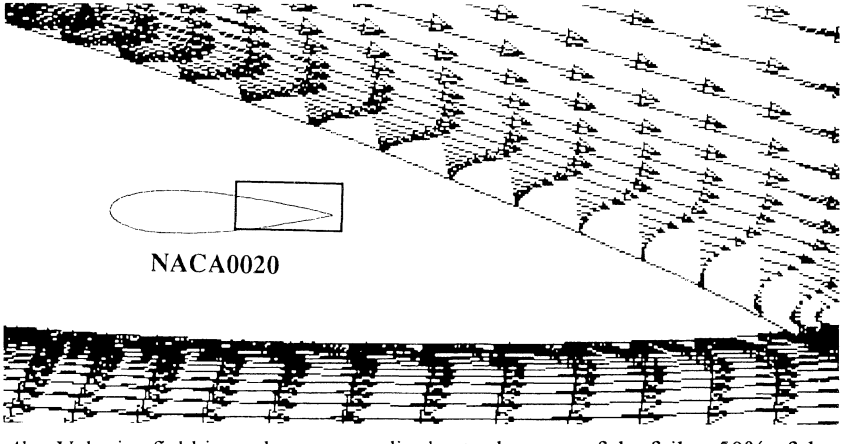


Figure 4b : Velocity field in a plane perpendicular to the span of the foil at 50% of the span for the NACA0020.

Velocity profiles

The modification of the critical cavitation number has a counter-part in the changes affecting the tip vortex velocity field. This can be seen in Figure 5 where, for equal angle of attack (10°), free stream velocity (10 m/s) and position downstream from the tip (x/c_{max}=0,7), the "tangential" velocity profiles obtained for each foil are shown. Tangential velocities are increased in the case of the NACA0020, particularly in the

area between the viscous core and the potential regions. A perturbation characterising the wake can be seen in the form of a local modification of the otherwise monotonically increasing tangential velocities measured on the pressure side (Figure 5). The distance between this perturbation and the vortex axis is larger for the NACA0020 than for the 16020. The viscous core size (taken as the distance between the two extreme values of the tangential velocity profile) is identical for both foils. This indicates that the modification of the location of the separation point over the suction side does not change the way the boundary layer feeds the core of the vortex.

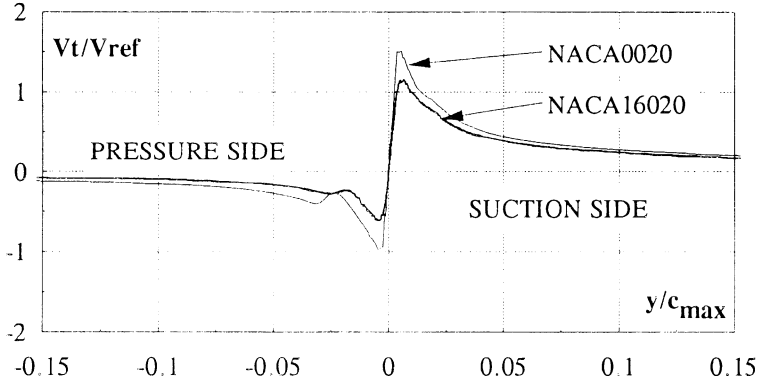


Fig. 5 : Axial (a) and tangential (b) velocities as a function of the distance to the vortex axis at $x/c_{max}=0.7$ for identical elliptical foils with NACA16020 and NACA0020 cross sections.

CONCLUSION

Tests conducted with a NACA0020 and NACA16020 elliptical foils have shown the significant impact of the cross section on the critical cavitation numbers even if the foil planform and the test conditions are kept equal. The modification of the desinent cavitation numbers can be related to the change of either the vortex intensity or the vortex viscous core. The LDA measurements have shown an increase of the tangential velocity without a measurable decrease of the viscous core dimension. This investigation has been conducted at the precise location where the minimum pressure at the vortex axis occurs $x/c_{max}=0.7$, and it has been already demonstrated that the approximation of Γ and **a** by fitting a Lamb profile to these data can give by using the equation (1) a very good estimation of the desinent cavitation number for both foils and different test conditions, Pauchet *et al.* [1]. Thus the analysis seems to be consistent and leads us to believe that the major effect of the increase of the desinent cavitation number for the NACA0020 is due to an increase of the lift. This is confirmed by the measurements of the hydrodynamic coefficients at the Ecole Navale Cavitation Tunnel for the NACA16020 and 0020 elliptical foils. It was surprising to see how large the changes were for two nearly identical foils, but finally by using these data, a very satisfactory correlation for desinent cavitation numbers for both foils were obtained. The modification of the load distribution between the two foils has been accounted for by change in the boundary layer behavior that could be induced by the different curvatures of the cross section. This analysis conducted by a numerical simulation of the flow around each foil using a CFD code, sheds a new light on the viscous phenomena that

occurs. It demonstrates that the loss of lift for the NACA16020 foil is due to the existence of a separation zone over the suction side which engender the formation of a recirculation zone. The data for both foils and for all tested conditions which represent a total of 770 cavitation points are well correlated by the expression (5) taking into account the sigma dependence with the lift coefficient and the Reynolds number:

$$\sigma_d = 0.048\, C_l^2\, Re^{0.4} \qquad (5)$$

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