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Application of Coanda Effects to a Ship Hydrofoil

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Abstract

A Coanda foil is a high-lift generating device exploiting the phenomena that flow separation is delayed if a high-speed jet is applied tangential to the surface as well known to the aerodynamic fields. In the present study, a Coanda foil with a flap is investigated to seek the possibility of marine application. Model experiments are carried out both in a towing tank and cavitation tunnel and surface pressure distributions, forces and moments acting on the foil are measured at the various angle of attacks and flap angles. The results are also compared to the numerical ones to show good agreements. The results of the present study demonstrate the practical applicability of the Coanda foil in the design of ship control surfaces.

Keywords: Coanda foil, ship control surface, high lift device, boundary layer control

1 Introduction

It is well known that one of the most efficient ways to delay flow separation, and so to reduce the drag, is the control of boundary layer flow. For examples, boundary layer control (BLC) methods in which suction of retarded flow or blowing of high momentum flow to delay the separation of the boundary layer are frequently practiced and known to be as efficient as mechanical flaps, slats or spoilers in enhancing lift generation.

High-speed jet injected tangential to the surface of a foil is pretty effective in delaying flow separation. The idea that such delay of separation will increase the lift generated by the foil, the Coanda effect (Englar 1975, Englar 1971) has been extensively investigated in the aerospace industries and already found many practical applications (Attinello 1961). The Coanda foil is, hence, equivalent to an internally blowing BLC system injecting a fluid jet tangential to the wall surface for the purpose of delaying flow separation to improve the lift much higher than the level achievable without the jet blowing.

The same idea can be utilized in the marine applications but researches or utilizations related haven't been advent yet. The main intention of the present study is to find the possibility for practical application of the Coanda effects to the marine control surfaces such as rudders and hydrofoils since a hydrofoil or a fin able to generate high lifts, and easily controllable, will be necessary for efficient control of ship motions or attitudes. And also a high performance rudder has long been needed to improve low-speed manoeuvrability of surface ships and under-water vehicles.

A jet controlled high-lift hydrofoil with a flap, namely a Coanda hydrofoil with a flap is studied to understand the flow phenomena result in lift increase when implemented to Coanda devices. To this end, model experiments and numerical studies have been done in the present study. The global quantities such as lift, drag and momentum as well as the local ones such as surface pressure distribution are measured for various flow conditions. The results have been compared to the numerical ones to improve understanding on the physics involved and to get insight for optimum design of the devices.

2 Towing tank experiment

2.1 Model experiments

The experiments are being carried out in the towing tank of RIMSE, Seoul National University. A model of a Coanda rudder has been manufactured of aluminum to have constant NACA 0021 sections, the section frequently used for practical rudders, along the span. A span s of the model is 600 mm and the chord length c is 400 mm. A flap is installed to occupy $0.25c$, a quarter of the chord length of the model and slots for jet injection is placed inside the gap in between. The jet blowing system and measuring devices are adequately housed inside the main body of the model.

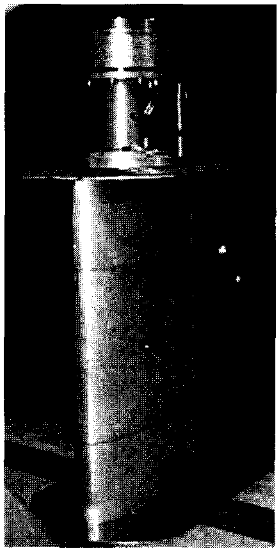


Figure 1: Rudder model with end plates

The model is consisted of three segments separated at the first and third quarter of the rudder span as shown in Figure 1. The hydrodynamic forces and moments are measured only at the center segment since the flow around the other segments cannot avoid interferences from the free surface or the tip. For further enhancement of the measuring environment, end plates are also attached at the both ends of the model.

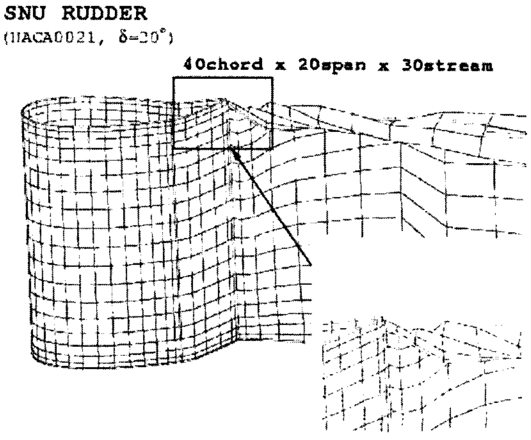


Figure 2: Hyperboloidal panels of the rudder

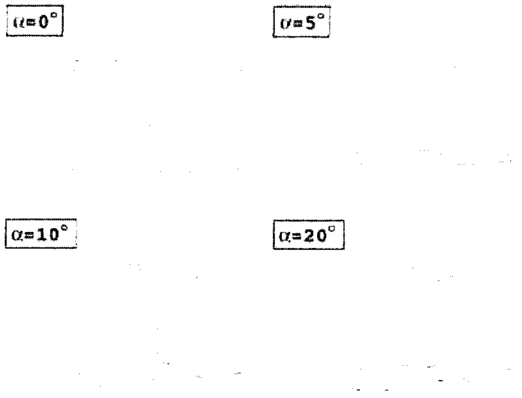


Figure 3: The trailing wake geometries of a flapped rudder for four angles of attack

A three-component load cell is manufactured and inserted inside of center segments to measure hydrodynamic force components. The static calibration of the load cell has been done for each component to test the reliability of sensor itself. After the assembly of the Coanda rudder model, calibrations of the whole system are carried out also and the results show good linearity, negligible hysteresis and reasonably small interferences between force components.

The water for jet flow generation is supplied through a non-contact type Labyrinth connector and the flow rate has been kept at a constant rate using a pressurized chamber. The air in the chamber has to be also compressed to suppress fluctuations during the water supply. In the present experiments, production of uniform jet flow along the vertical span of the flap requires a specially designed regulator for adjustment of flow rate to overcome the gravitational force. The flap has a circular nose with its center on the rotating axis to keep the gap constant irrespective of the flap angle. However, the flow rate of the jet can be adjusted by varying gap width or pressure level of regulator.

The magnitude of the jet is usually expressed with the non-dimensionalized jet momentum coefficient, C_μ defined as

$$C_\mu = \frac{\dot{m} V_j}{\frac{1}{2}\rho V_\infty^2 c} \tag{1}$$

Where $\dot{m}$ is mass flow rate of jet, V_j is average velocity of the jet at the slot and ρ_∞ and V_∞ is free stream density and velocity, respectively.

2.2 Numerical method

A potential-based panel method was applied to compute the flow around the Coanda Rudder in which rudder surface is discretized using the hyperboloidal panels as shown in Figure 2. Half cosine spacing was used in the vicinity of the leading and trailing edge of the main foil and the flap to capture the rapid changes of the flow characteristics. If the angle of attack increases, numerical errors will increase also due to the misalignment of the wake sheet at the trailing edge of the foil. The vortex roll-up model (Pyo et al 1999) was adopted to minimize the numerical errors. The resulting geometries of trailing wakes for different angles of attack are shown in Figure 3.

A gap flow model is adopted to consider the dominant viscous effect inside the gap. The flow at the surface of the foil accelerates from point 0 to point 1 shown in Figure 4. In the method, the gap flow is assumed as an equivalent Couette flow and the mean velocity are found to include the viscous effect. More details of the numerical methods can be found in Pyo et al (1999).

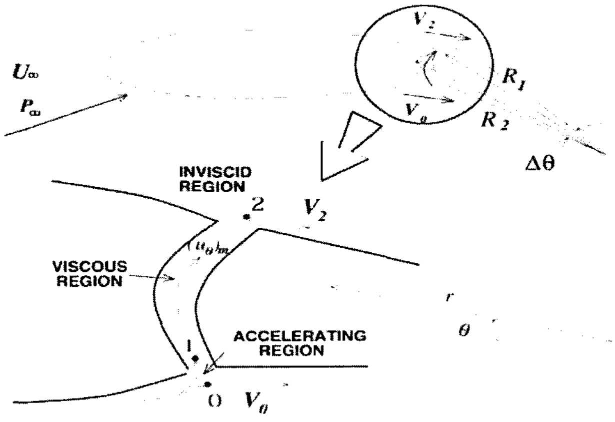


Figure 4: The sketch of the gap flow

2.3 Comparison of the results

Figure 5 shows the effect of the gap flow model on the lift when the jet is not present. The width of the gap for the case is $s/600$, where s is span of the rudder, and the angle of the flap is 40^o.

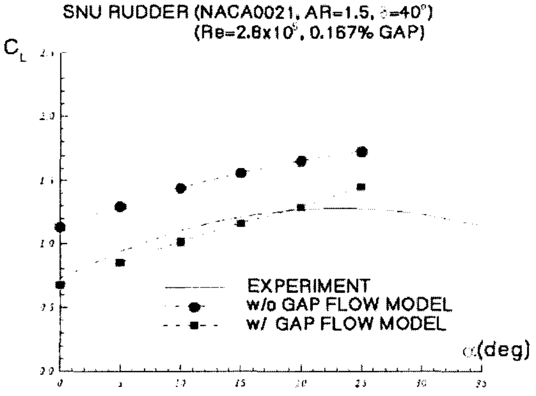


Figure 5: Effect of the gap flow model on the lift (without jet blowing)

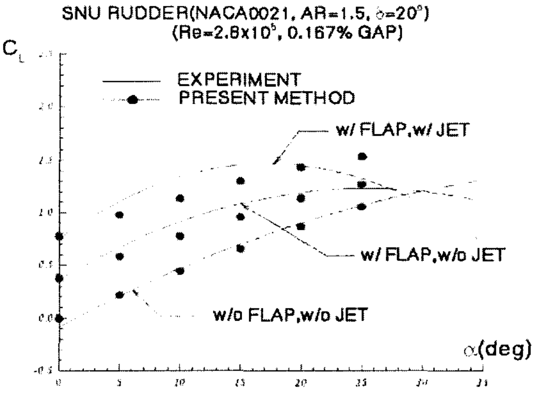


Figure 6: Effect of the jet flow on the lift of a flapped rudder (flap angle=20^o)

It is shown in the figure that the effect of the gap flow model on the lift is significant. It is clear in the figure, the numerical results adopting the gap flow model shows relatively good coincidence with the experimental ones.

Figure 6 and 7 show the lift characteristics of the Coanda rudder for various angles of attack with and without a flap. The momentum coefficient C_μ defined by (1) is fixed at the value of 0.04 and the flap angles δ are 20^o and 40^o, respectively.

Figure 6 shows the changes in the lifts when the flap angle is fixed at 20^o. It is apparent that the lifts of the rudder increase when the flap is present and jet is injected if the angles of attack do not exceed 20^o. However, if angles of attack become larger and stall occurs the trend completely reversed as shown in the figure. The worst is the stall seems to occur at the lower angles of attack if flap is present or jet is supplied. In general, the computed results coincide well to the experimental findings but failed to predict the stall and related behavior.

Figure 7 shows the change in the lift coefficient of the Coanda rudder when the flap angle is 40^o. In this case, the lift of the flapped rudder increases further if jet is applied as before. The results of the experiments and numerical computations show that the lift coefficient of the Coanda rudder increases in the normal operational ranges of the rudder angles. Hence, it may be concluded that the Coanda foil can be implemented to the marine control surfaces. However, the experiments have been conducted with the jet momentum coefficient C_μ of 0.04 only and the general trend of the lift of a flapped rudder due to jet momentum should be known before conclusions.

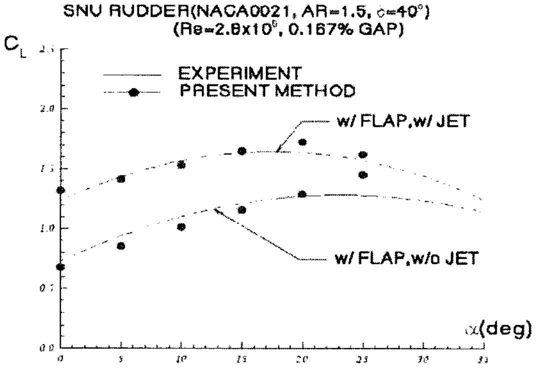


Figure 7: Effect of the jet flow on the lift of a flapped rudder (flap angle=40^o)

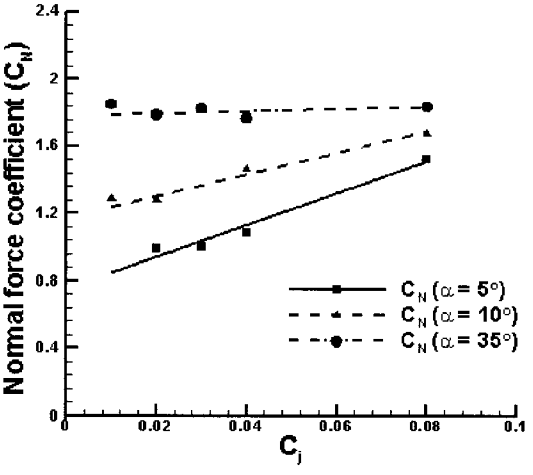


Figure 8: Effect of the jet momentum on the normal force

Figure 8 shows the experimental results when the angles of attack and jet momentums are systematically varied but flap angle is fixed at 20^o. It is shown in the figure that increase of jet momentum improves generation of lift force.

3 Cavitation tunnel experiments

3.1 Model experiments

Experiments on the two dimensional Coanda hydrofoil have been also carried out in the cavitation tunnel of RIMSE. The geometry of hydrofoil section is identical to the center segment of the rudder model: NACA 0021 section, and a flap occupies a quarter of the chord length. The height of the jet slot is maintained to be $0.0088c$ for all flap angles. The jet blowing system and measuring devices are installed inside the model as in the towing tests.

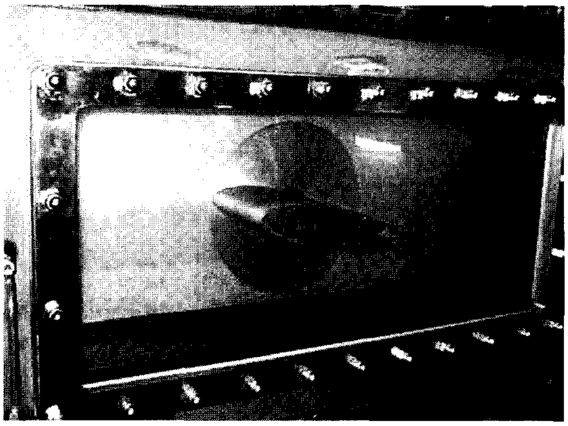


Figure 9: Experimental setup in the cavitation tunnel

Figure 9 shows the model installed in the test section of the cavitation tunnel. A total of 28 pressure holes are placed on the foil surface with a cosine spacing to measure surface pressure distributions. Pressure taps are connected to the Scanni-valves by vinyl tubes and pressure transducers are used to measure the total head corresponding to the surface pressure. In general, it is evident from the experiments that the Coanda effect increases the lift since the result show considerable decrease in the surface pressure on the suction side.

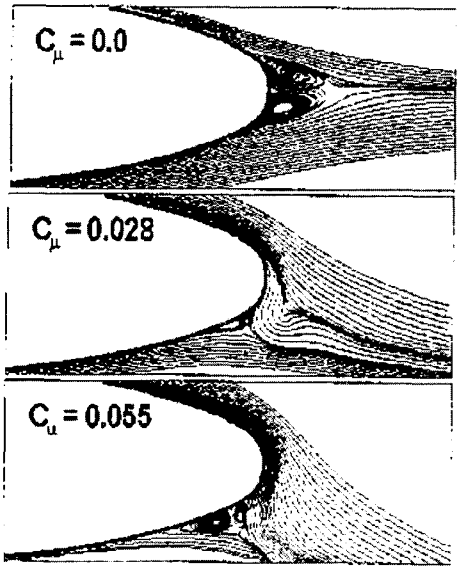


Figure 10: Change in Streamlines with different C_μ's ($Re = 7.5 \times 10^5$)

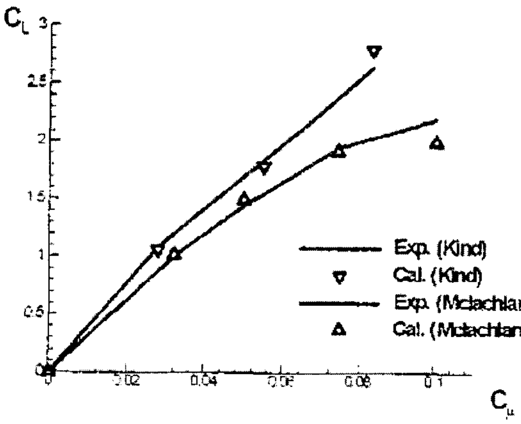


Figure 11: Changes in Lift with Jet Momentum (experiments: solid lines, computation for Kind et al $\bigtriangledown$, McLachlan $\triangle$)

3.2 Numerical method

The authors reported numerical solutions on the viscous flow fields around a two-dimensional Coanda in Park and Lee (2000), Kind and Maull (1968). The numerical studies use the Reynolds averaged Navier-Stokes equations discretized by a finite-volume method and appropriate turbulence models including Boldwin-Lomax, $k - \omega$ and Reynolds stress transport models are used to approximate the Reynolds stresses.

In an earlier paper (Park and Lee 2000) solution around an elliptic Coanda foils are simulated to compare the experiments of Kind and Maull (1968) and McLachlan (1989). Figure 10 compares computed streamlines for C_μ's of 0.0, 0.028 and 0.055 and the Reynolds number of 7.5×10^5. It is apparent in the figure that injection of jet flow near the foil surface increases flow momentum inside the boundary layer and so makes the separation delay and enhances the lift considerably as shown in Figure 11, in which computed results show good agreement to the experimental ones.

The flow field around the Coanda flapped rudder has been computed recently to compare to the present experimental results and the details are reported in Rhee et al (2002). A commercial code has been used for the computations and angles of attack α's are taken as 0 and 10 degrees, and jet momentum coefficients C_μ's as 0, 0.16 and 0.64, with flap angle fixed at 20 degrees. Computational conditions are indicated by combinations of numbers for α, δ and C_μ and hereafter, e.g., (10, 20, 0.64) indicates that α = 10 degrees, δ = 20 degrees and C_μ = 0.64. Re based on the original chord length, 0.25 m, is 1.91×10^5. Two non-zero C_μ's corresponding to the chord length can be reproduced with $\dot{m}$ of 6.6 kg/s and 13.2 kg/s at the end of the plenum, and V_∞ = 1 m/s is imposed on the front and side boundaries. The computational mesh shown in Figure 12 is for (10, 20, 0.64) case and consists of 198,892 quadrilateral and triangle cells. Boundary layers are placed around the solid surface with the first cell spacing equal to approximately 1 in terms of wall y^+.

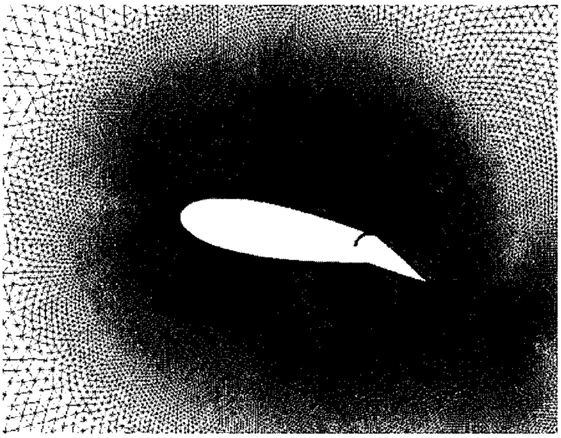


Figure 12: Computational mesh for (10, 20, 0.64) case

3.3 Comparison of the results

C_p comparisons on the hydrofoil surface are presented in Figures 13 through 16. Suction side pressure peaks and the overall pressure difference between suction and pressure side are smaller in the measured data. The differences between measured and computed C_p's increase consistently

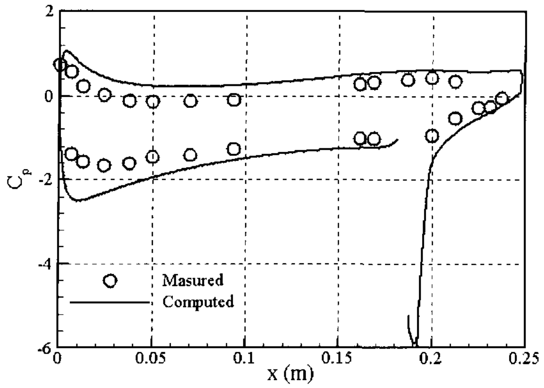


Figure 13: Surface pressure coefficients for (0, 20, 0.16) case

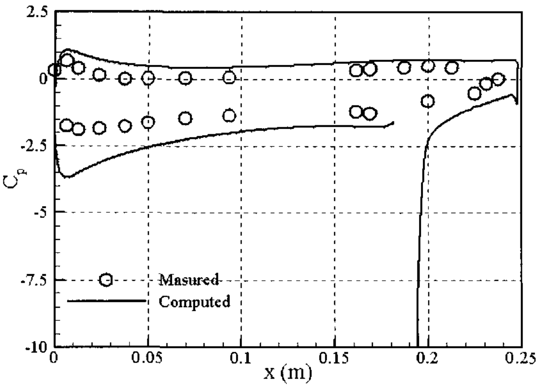


Figure 14: Surface pressure coefficients for (0, 20, 0.64) case

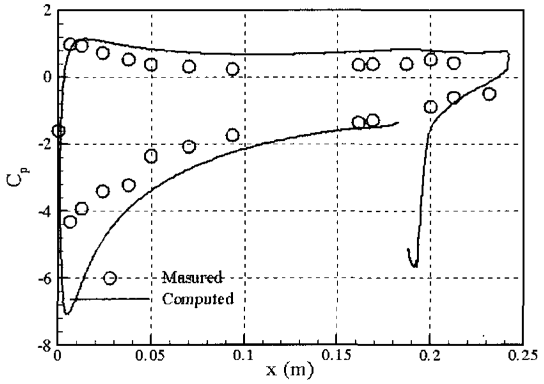


Figure 15: Surface pressure coefficients for (10, 20, 0.16) case

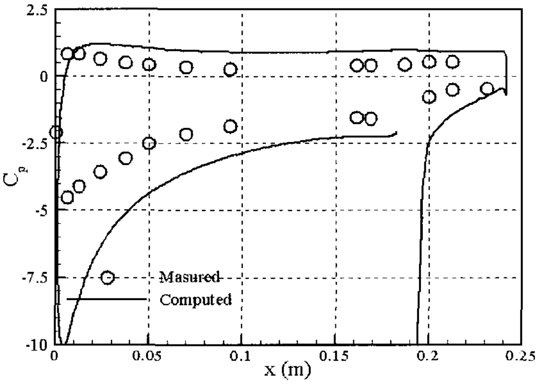
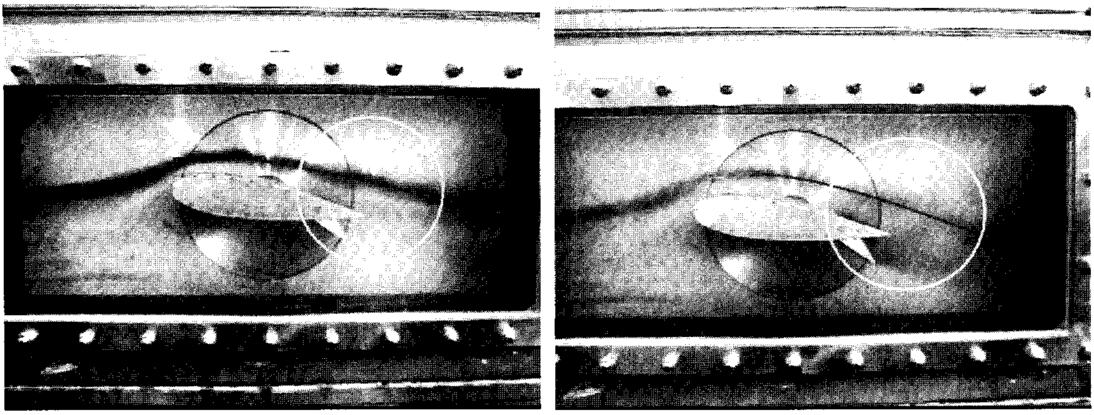


Figure 16: Surface pressure coefficients for (10, 20, 0.64) case

with increasing α and C_μ. There appears to be non-negligible amount of uncertainties and errors in the measurements, especially in the jet ejection system. More enhancement of the measurement system and enforcement of two-dimensionality are necessary but the numerical method needs improvement as well.

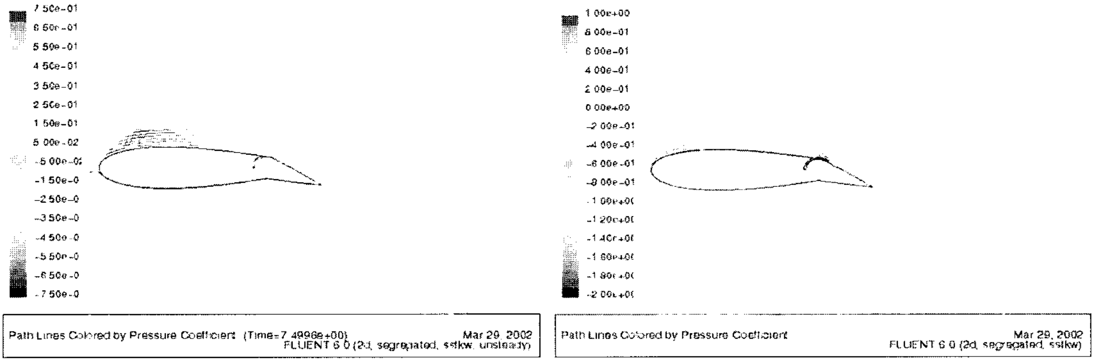
Flow field alteration is another advantage of employing Coanda hydrofoil using a blown flap. As an example, streamlines near the upper surface of the Coanda model for (10, 40, 0) and (10, 40, 0.16) cases are shown in Figure 17. The streamlines are not taken at the same location but it is evident in the photos that the streamline for jet blowing case is more parallel to the surface. The fact may be confirmed by the fact that measured lift of the case is increased by 360 % of that of none blowing case.

Figures 18 show the pathlines colored by C_p around the hydrofoil for (0, 10, 0) and (0, 10, 0.16) case, the different situations with the measurements and direct comparison in between will not be possible. However, it is apparent from the figures that the undulated and recirculating flow field due to the 10 degrees deflected flap is removed by the jet of C_μ = 0.16. Increasing circulation evidenced by shifting down jet flow in the wake and larger difference in suction and pressure side C_p's, indicating augmentation of the lift, is apparent. This may help straighten up of the wake



(a) Without jet blowing (b) With jet blowing

Figure 17: Streamlines with and without jet blowing for (10, 40, 0.16) case



(a) Pathlines for (0, 10, 0) case (b) Pathlines for (0, 10, 0.16) case

Figure 18: Pathlines with and without jet blowing for (0, 10, 0.16) case

flow and eventually reduce noise and signature. The lift force has been increased about 560 % and we believed this tendency was maintained along with the increasing momentum coefficient of jet ejection.

4 Concluding remarks

A Coanda foil with a flap has been subjected to experimental and numerical investigation to seek the feasibility of marine application.

For the purpose, model experiments are carried out both in a towing tank and cavitation tunnel and surface pressure distributions, forces and moments acting on the foil are measured at the various angles of attack and flap angles. Numerical codes for both the panel and the RANS method have been also applied to the problem for the purpose of replicating the experimental results at least in qualitative sense.

The experimental results show that significant increase in lift is also possible for the marine control surfaces, such as a flapped rudder and a hydrofoil, with the injection of jet by shifting the separation point downstream, even to the pressure side and so increasing the circulation. However, further improvement of the experimental setup and the measurement system seem to be needed to provide uniform and accurate jet injection and to ensure the two dimensionality if experimental results are directly compared to the numerical ones.

The numerical results show good coincidence with the experimental ones in general. The numerical methods, especially the RANS codes have to be improved further to simulate the problems more accurately and generally, for examples, enhancing turbulence models, inclusion of free surface effects or expanding to the three dimension may provide the more efficient tool for understanding of the Coanda effects. The numerical methods also have to be developed to cope with the larger angles of attack and flap angles as dealt in the experiments.

The present study succeeded in demonstrating the practical applicability of the Coanda foil to the design of ship control surfaces in some extent. The results of the present study also indicate that the Coanda foil with a flap can be utilized as a high-lifting device for marine applications as efficiently as in aerospace industries. In addition, substantial amount of knowledge's have been accumulated in the course of both the experimental and numerical studies, which would improve the forth-coming research for the practical application of the Coanda foils.

Acknowledgements

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