18th Australasian Fluid Mechanics Conference
Launceston, Australia
3-7 December 2012

On the Road to Establishing Ventilation Probability for Moth Sailing Dinghies

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Abstract

Ventilated cavity formation mechanisms are investigated for a surface piercing T-foil. Theoretical and experimental data were reviewed, identifying the most probable development process of cavity inception. A numerical analysis was then conducted for a surface-piercing International Moth T-foil over a range of realistic operating conditions using a commercial RANS code. This enabled an identification of the particular sailing conditions of increased ventilation probability. The analysis results are presented as a series of polar plots indicating the ventilation inception potential of a T-foil at a given wind speed over a full spectrum of true wind angles.

Nomenclature

A_{CF}	Centre T-foil characteristic area
A_{RF}	Rudder T-foil characteristic area
$C_{hLoss_{CF}}$	Centre T-foil submergence depth coefficient representing the reduction in lift with proximity to a free surface
$C_{hLoss_{RF}}$	Rudder T-foil submergence depth coefficient
$C_{L_{CF}}$	Centre T-foil lift coefficient
$C_{L_{RF}}$	Rudder T-foil lift coefficient
g	Gravitational acceleration
h	Submergence depth
P	Local minimum pressure on the foil
P_{atm}	Atmospheric pressure
U	Free stream velocity
V_B	Vessel velocity
α	Foil angle of attack
Δ	Vessel mass
ρ	Density
σ_v	Ventilation number

Introduction

The development of hydrofoiling sailing craft has introduced a new dynamic into both leisure and competitive yachting; hydrofoil use comes with low drag and a significant speed advantage. The International Moth is one such class of a relatively new breed of sailing dinghies that utilises ‘T-foil’ hydrofoils to drastically increase its maximum speed. However, as with any near-surface device utilising a pressure differential to generate lift, the potential exists for the inception of both cavitated and ventilated cavities. Cavity formation generally results in an undesirable and rapid loss in lift if it occurs on the foil or a loss in side force and transverse stability if it occurs on the strut.

The International Moth, shown in figure 1, is a 3.4 metre single handed sailing dinghy typically fitted with two T-foils which, in addition to performing the roles of a centreboard and rudder, are capable of generating lift sufficient to raise the hull out of the water. When fully foil-borne it is quite typical for a Moth to achieve speeds in excess of 25 knots.

Figure 1: A typical T-foil borne International Moth [12]

The wand, shown in figure 1 piercing the water at the bow of the dinghy, is a proportional control device which adjusts the angle of attack on the centre T-foil’s lift flap via a mechanical linkage. The force exerted by the water on the wand varies with vessel ride-height and speed, altering the angle of attack in order to maintain an equilibrium condition, which is expressible as:

$$g\Delta = \frac{1}{2}U^2\rho(C_{L_{RF}}A_{RF}C_{hLoss_{RF}}+C_{L_{CF}}A_{CF}C_{hLoss_{CF}}) \qquad (1)$$

Ventilation

Natural ventilation can be defined as the phenomenon of air entering a region of sub-atmospheric pressure on an immersed body where it displaces the local fluid to create an air filled cavity that is open to the atmosphere. A review of published data [2] [4] [6] [8] [9] [14] [15] [16] suggests four criteria that must be met for ventilation to occur; a region of sub-atmospheric pressure, a concurrent region of flow separation or cavitation, proximity to a free surface and a path of low impedance to air flow that stretches from the atmosphere to the region of sub-atmospheric pressure.

The region of low pressure along the top of the foil and along the side of the yawed strut is, as is readily apparent from figure 1, in close proximity to the atmosphere. The existence of the large pressure differential between these regions has two notable effects in relation to ventilation. The first is the deformation of the free surface, wherein the resultant local region of downwardly accelerating fluid provides the appropriate conditions for the formation of free surface filament vortices [13]. The second effect is that, provided that the other ventilation criteria are met; the differential will draw air from the atmosphere onto the submerged T-foil, displacing the local fluid and creating a ventilated cavity [4]. In practice this generally means that as a foil generates more lift, the pressure differential will increase and the foil will become more likely to ventilate. Numerous authors [6] [9] [14] [15] indicate a region of cavitation or separation as a requirement for a ventilated cavity to fully develop. The low relative flow velocity present in these regions prevents entrained air from being swept downstream before a ventilated cavity can fully develop.

There are primarily two obstacles which prevent air entrainment into a region of sub-atmospheric pressure. The first is the region of water that exists between the atmosphere and the region of sub-atmospheric pressure that is at a greater pressure than atmospheric pressure. The second obstacle is the attached free surface boundary layer [11]. For air to enter the water and form a ventilated cavity both of these barriers must be overcome; the free surface boundary layer must be breached and a path of low relative pressure, and hence low impedance to air flow, must exist through the water to the sub-atmospheric region. Experimentation [6] [9] [14] [15] suggests that this air flow path can be provided by either; free surface filament vortices onto a strut or by foil tip vortices onto a foil. T-foil ventilation has therefore been categorised into one of these two ventilation modes.

Foil Tip Vortex Ventilation

Given a high enough pressure gradient over the foil, foil tip vortices are of a sufficient magnitude to extend to and pierce the free surface downstream of the foil. The low relative pressure within the vortex cores allows air to enter and propagate along them. An ingested air pocket is consequently able to travel along these flow path 'tubes' to reach a sub-atmospheric trailing region of separation on the foil, if it exists, where it will form a ventilated cavity. The following series of figures demonstrates the development process of a tip vortex ventilated cavity for a Moth T-foil.

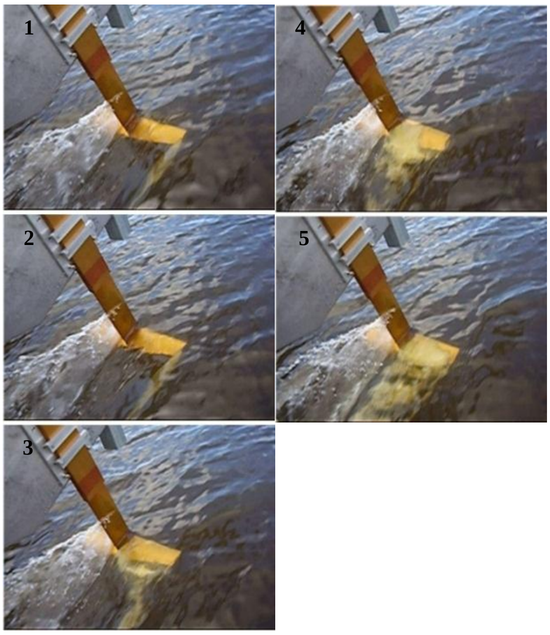

Figure 2: Tip vortex ventilation mode inception process [3]

The air ingestion mechanism for this ventilation mode is illustrated in figure 3.

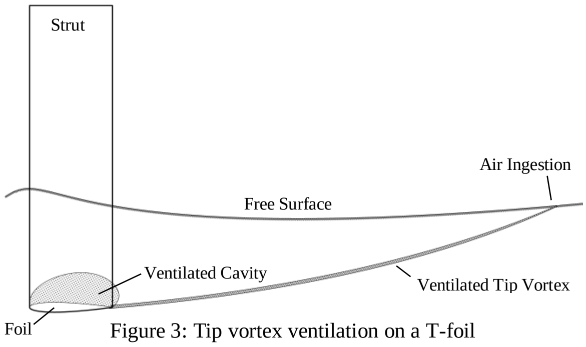

Figure 3: Tip vortex ventilation on a T-foil

Although a ventilated cavity can appear qualitatively similar to cavitation, it can be easily distinguished by observation of the cavity formation mechanism and noting the presence of air, not water vapour, within the cavity.

Strut Free Surface Filament Vortex Ventilation

Surface deformation, caused by the regions of low relative pressure on the T-foil, provides the appropriate conditions for the formation of surface perturbations through the disturbance amplifying effect of the Rayleigh-Taylor instability present in the locally accelerating free surface [7] [13] [14]. Possible causes of the initial surface disturbances include surface debris and vorticity introduced into the free surface as a result of flow separation on the T-foil itself or from the aforementioned wand. As the magnitude of the free surface curvature, and hence the local fluid acceleration, reduces, the perturbations will collapse to form free surface vortices [7]. Although these vortex filaments are comparatively short, it is only required that they pierce the thin surface boundary layer in order for strut ventilation to occur.

The inception process of the free surface filament vortex mode of ventilation is indicated below. In this series of figures a probe performs the role of creating the initial surface disturbance to form the filament vortex which feeds the ventilated cavity.

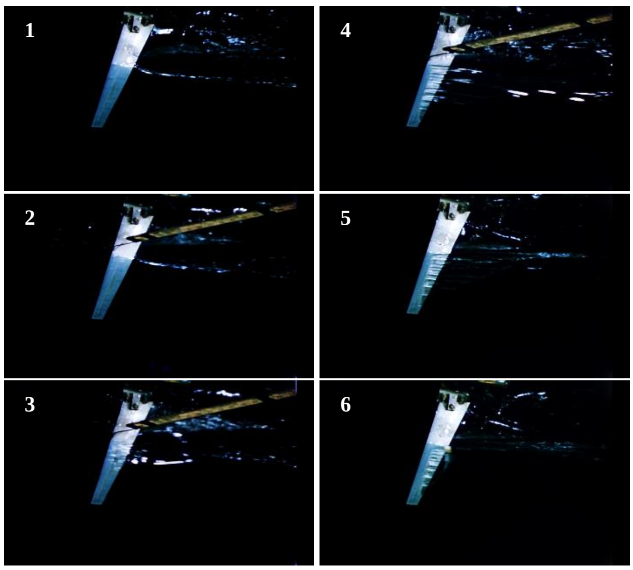

Figure 4: Filament vortex ventilation mode inception process [10]

The ingestion mechanism for the filament vortex ventilation mode is illustrated below.

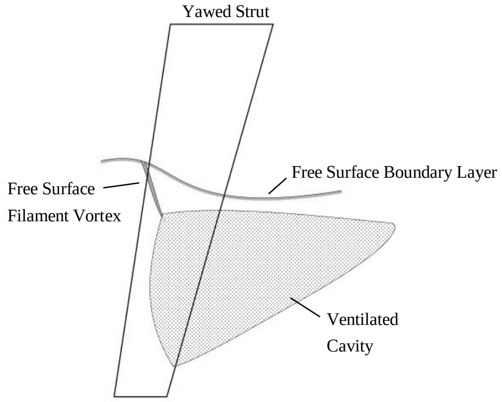

Figure 5: Free surface vortex ventilation of the trailing edge

Investigated Conditions

The investigated input conditions for the numerical analysis were determined using Hull's (2011) FS-Equilibrium module for an International Moth [5]. FS-Equilibrium uses a set of empirical and semi-empirical formula to calculate the hydrodynamic equilibrium condition of a vessel given a set of input data including hull offsets, weight distribution, foil characteristics and sail characteristics. The lift and drag data for the T-foil was obtained from a previous experimental investigation [1]. A data set of Moth leeway angles, hull speeds, foil immersion depths and lifting foil angles of attack were produced using this module for a set of ten vessel speeds and sixteen true wind angles. It is surmised that this data represents a range of realistic operating conditions for an International Moth; an assumption that is, in general, supported by Hull's (2011) validation study [5].

Numerical Analysis

The numerical investigation was carried out using the computational fluid dynamics software package ANSYS V13-CFX. The investigated three-dimensional T-foil domain was discretised using unstructured tetrahedral volumes. The investigated geometry was the Moth centre T-foil shown in figure 2 which consists of a NACA 0015 strut and a NACA 0012 foil.

Numerical Models

The RANS equations were used to model flow behaviour within the domain, solved using the finite volume method. Viscous behaviour was modelled using the Shear Stress Transport model. The volume of fluid method was used to track the free surface(s) with an implemented surface tension model. Interphase momentum transfer was modelled using the inhomogeneous Eulerian-Eulerian particle model with air having a dispersed morphology.

Grid Independence

Result sensitivity to discretisation was assessed by undertaking a grid independence study. Figure 6 is an example for the 8m/s wind speed and 40 degree true wind angle sailing condition, which corresponds to an investigated 5 degree foil angle of attack, 0.395m foil submergence depth and 7.6 m/s hull velocity condition. The relative error to the available experimental data is also plotted.

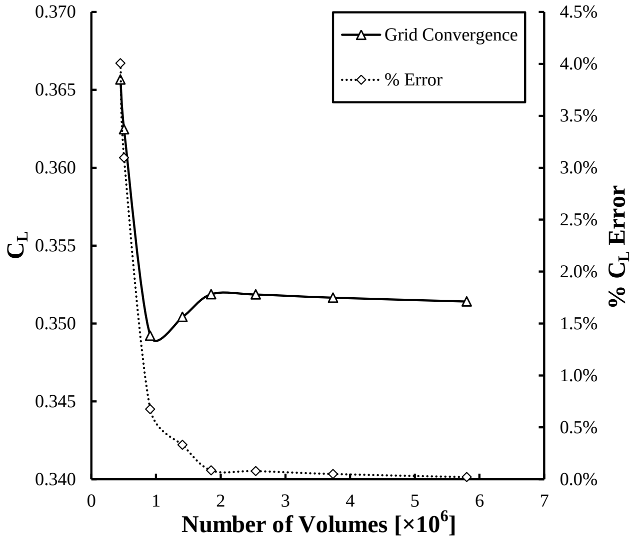

Figure 6: Grid independence study

Validation Against Experimental Data

A set of simulations recreating the experiments conducted on the physical T-foil by Binns (2008) [1] were used to validate the simulation arrangement, the results of which are as follows;

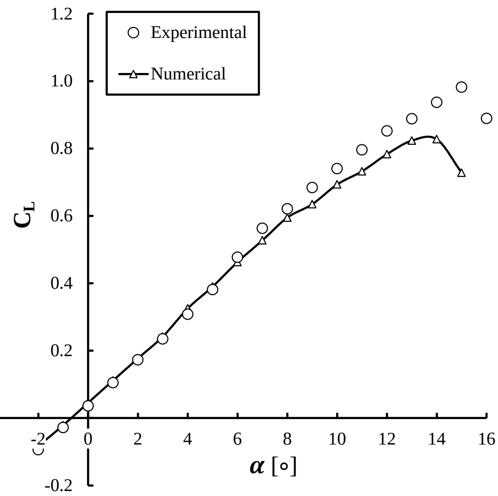

Figure 7: Validation study

The simulation shows good agreement with experimental results for angles under approximately eight degrees, an acceptable limit given that the analysed sailing conditions have a foil angle of attack no greater than 7.5 degrees.

Results

Ventilation probability is assessed using the following formula:

$$\sigma_v = \frac{P - P_{atm}}{\frac{1}{2}\rho U^2} \qquad (2)$$

Similar to cavitation number, it expresses the relative probability of ventilation inception as a relationship between the local pressure differential between the atmosphere and the low pressure region on the T-foil, and the kinetic energy in the flow. The local pressure was determined from the numerical analysis and an atmospheric pressure of 101.325kPa was used. The results for each case were plotted as a series of polar plots; an example for the 12m/s wind speed condition is given in figure 8, the relative T-foil submergence depth for this condition is given in figure 9.

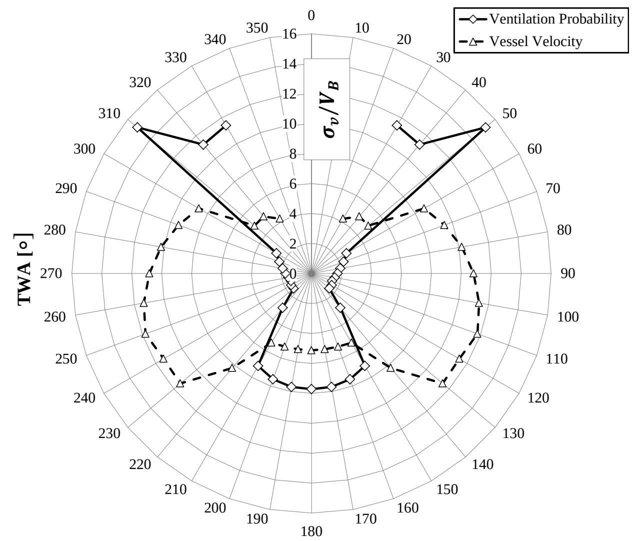

Figure 8: T-foil ventilation probability and vessel velocity at 12m/s wind speed against true wind angle

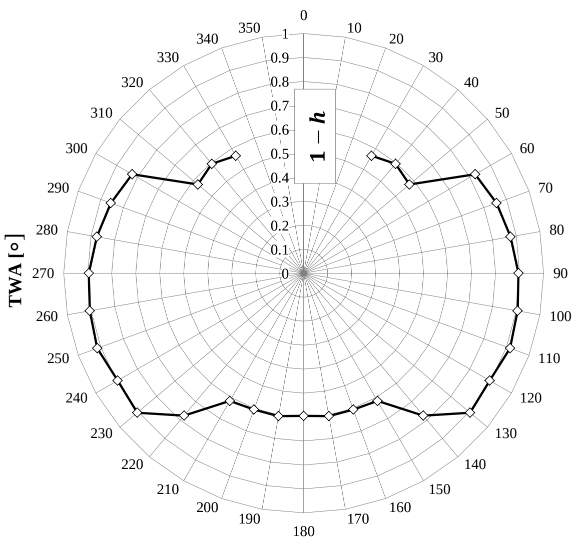

Figure 9: Relative submergence depth against true wind angle

The true wind angle at which the highest probability of ventilation inception occurs, in this case 50 degrees, corresponds to the highest angle of T-foil yaw. Somewhat counter-intuitively this is at one of the deepest foil submergence depths and lowest vessel speeds. Conversely, the 70 – 120 range of true wind angles correspond to a fully foiling condition; very low submergence depths, but very low angles of yaw and low ventilation probability.

Conclusions

The results indicate that yaw appears to have a more significant influence on ventilation probability than free surface proximity or vessel speed, a conclusion which is supported by all 160 investigated conditions. This is attributed to two phenomena:

- The superposition of the regions of low pressure on the foil and strut, increasing the magnitude of ventilation inducing pressure differential.
- The closer proximity of the region of low pressure on a yawed strut to the free surface compared to the foil.

It is concluded from these results that future assessments of Moth ventilation probability could utilise yaw angle as an indication of a T-foil's likelihood to ventilate.

It is unlikely that, given the complex nature of the generation process of free surface filament vortices, a quantification of this mode of ventilation is feasible since identifying the magnitude of surface disturbances caused by semi-random encounters of surface debris, along with the effects of other surface disturbers such as the wand, presents a significant obstacle. As with the approach taken by this paper, a probabilistic analysis appears to represent the most likely method of describing this mode of ventilation inception. On the other hand, the tip vortex mode of ventilation is more amenable to a direct analysis given the relatively high degree of certainty to which tip vortex structure can be resolved using modern computational methods.

References

[1] Jonathan R Binns, Paul A Bradner, and Julien Plouhinec, "The effect of heel angle and free surface proximity on the performance and strut wake of a moth sailing dinghy rudder T-foil," in *Performance Yacht Design Conference*, Auckland, 2008.

[2] J Breslin and R Skalak, "Exploratory Study of Ventilated Flows about Yawed Surface-Piercing Struts," Washington, 1959.

[3] Jonathan A. Emonson, "An Investigation into the Effect of Froude, Weber and Cavitation numbers on Ventilation of Surface-piercing T-Foils," Launceston, 2009.

[4] Gerald Fridsma, "Ventilation Inception on a Surface Piercing Dihedral Hydrofoil with Plane-face Wedge," 1963.

[5] Dane Hull, "Speed Sailing Design and Velocity Prediction Program," Launceston, 2011.

[6] V Johnson and P Eisenburg, "Environmental and Body Conditions Governing the Inception and Development of Natural and Ventilated Cavities," *ITTC Vol. 11*, pp. 171-181, 1968.

[7] Thomas Lundgren and Petros Koumoutsakos, "On the Genertaion of Vorticity at a Free Surface," *Journal of Fluid Mechanics*, pp. 351-366, 1999.

[8] W.B. Morgan, "Surface Piercing Struts (Strut Ventilation)," *Cavitation Session*, pp. 377-381.

[9] W.B. Morgan, "The Testing of Hydrofoils and Propellers for Fully-Cavitating or Ventilated Operation," *Cavitation Session*, pp. 202-218.

[10] National Advisory Comittee for Aeronautics. Development of Ventilation on a Surface Piercing Hydrofoil Serial L-371. Film.

[11] V. C. Patel, L. Landweber, and C.J. Tang, "Free Surface Boundary Layer and the Origin of Bow Vorticies," Iowa, 1984.

[12] Mark Robinson. Sunday Flying!.

[13] Turgut Sarpkaya, "Vorticity, Free Surface and Surfactants," *Annual Review Fluid Mechanics*, pp. 83-128, 1996.

[14] P Swales, A Wright, R McGregor, and R Rothblum, "The Mechanism of Ventilation Inception on Surface Piercing Foils," *Journal of Mechanical Engineering Science*, pp. 18-24, 1974.

[15] Kenneth Wadlin, "Ventilated Flows With Hydrofoils," Berkeley, 1959.

[16] Robert Waid, "Experimental Investigation of the Ventilation of Vertical Surface-Piercing Struts in the Presence of Cavitation," Sunnyvale, 1968.