Computational methods for investigating sail forces — A case study

Patrick Couser[1]
Australian Maritime Engineering Cooperative Research Centre
Perth Core, Curtin University of Technology

1. Introduction

Computational methods for calculating the flow of the wind over a yacht's sails have been developed over many years. Amongst the pioneers in this field were Milgram (1968), Thrasher (1979) and Register (1983). These methods are under continuous development and refinement, for example Fiddes (1996).

This paper presents the results of a case study using such a computational model. In this study the upwind performance of the International Mirror Class dinghy is investigated, with particular regard to the interaction between the jib and main sail and the effects of raking the mast aft. The latter point was of particular interest since the British sailors had adopted this rig set-up in preference to a vertical mast and were able to dominate the racing, particularly in lighter winds.

The work presented here is part the Australian Maritime Engineering Cooperative Research Centre's (AME CRC) Yacht Technology Research Program. This program involves the development of computational techniques for predicting yacht performance. Two of the principal tools are the velocity prediction program (VPP) and a vortex lattice model which is used to compute sail forces. After a presentation on the Yacht Technology Research Program at the recent Sailing Science Conference in Hobart, Tasmania (Couser 1997), the author was approached by Norm Deane[2] and Steve Walker[3] with the aim of using computational methods to investigate the aforementioned phenomenon. This work was undertaken since it contributed to the ongoing validation and improvement of these numerical methods and provided an ideal opportunity to apply theoretical sail analysis methods to a practical problem.

1.1 International Mirror Class dinghy

First introduced in England in 1963, the Mirror quickly became the most popular one-design dinghy class in the world. Since its introduction, nearly 70,000 Mirrors have been built around the world. In 1990 the Mirror dinghy became an international class recognised by the International Sailing Federation. The main dimensions of the Mirror dinghy are given in Table 1. The dinghy is shown sailing upwind in Figure 1.

---

[1] Research Associate, AME CRC, Perth Core, Curtin University of Technology, GPO Box U1987, Perth, W.A. 6845, Australia. Tel: +61 (0)8 9266 3955; Fax: +61 (0)8 9266 2377; Email: p.couser@amecrc.curtin.edu.au.

[2] Vice President of the International Mirror Class Association and Australian Manager / Coach for the Mirror Class.

[3] Steve Walker Sails Pty. Ltd.

Table 1: International Mirror Class dinghy dimensions.

P'mouth Ydstk	1382 (1362 Single-handed)
LOA	3.3m
Beam	1.4m
Draft	0.1m, board raised
Mast Height	4.9m, mast and gaff from deck
Mast Length	3.3m
Gaff Length	2.8m
Boom Length	2.3m
Sail Area	6.5m^2
Main	4.6m^2
Jib	1.9m^2
Spinnaker	4.4m^2
Rig	Gunter with optional spinnaker
Dinghy weight	Complete 61.4kg + crew of two

Figure 1: International Mirror Class dinghy.

1.2 Computational methods: Vortex lattice method

The computational method commonly used to predict the flow over sails is the vortex lattice method. The form of the method used in this investigation is based on the work of Greeley and Kerwin (1982) and Greeley et al. (1989). This code is under development at AME CRC under its Yacht Technology Research Program.

The current vortex lattice method is capable only of predicting the potential fluid flow over the sails; i.e. the effects of fluid viscosity are ignored. This is a reasonable approach for predicting upwind sail performance provided that separation is restricted to small areas in the vicinity of the mast. If the sails are operated near their maximum lift coefficient it is possible that separation may occur from the leeward side of the sail. This will result in a much greater drag than that predicted by the potential flow model. Where significant separation does not occur the skin friction of the sails and the drag of the mast may be approximated by empirical equations and experimental data (Milgram 1978).

Although the predicted forces obtained by this method may not be precisely accurate in absolute terms, such computational techniques are very valuable for comparative studies and flow visualisation since they may be carried out more cost effectively than wind tunnel test and under more controlled conditions than on-the-water testing.

2. Objective

As has been briefly stated in the introduction, the aim of this research was to determine the interaction characteristics between the main sail and the jib, particularly the influence of raking the mast aft. The motivation for this investigation came after the World Titles in Kingston, Canada where the British fleet used rigs with masts raked aft by approximately 4°. The Australian fleet, which up to that point had been dominating the international scene for a number of years, was significantly slower with upright masts, particularly in light airs.

3. Computational model

Six models were used for the analysis. Two rig set-ups were tested: mast upright and mast raked. For each of the set-ups three sail sets were used: both sails set, main sail only and jib only. Each sail was represented by 20 spanwise panels and 16 chordwise panels. Previous experience has shown this panel density to be sufficient from a convergence point of view. A typical panel arrangement is shown in Figure 2, and may be compared with the actual rig in the upright condition, Figure 3.

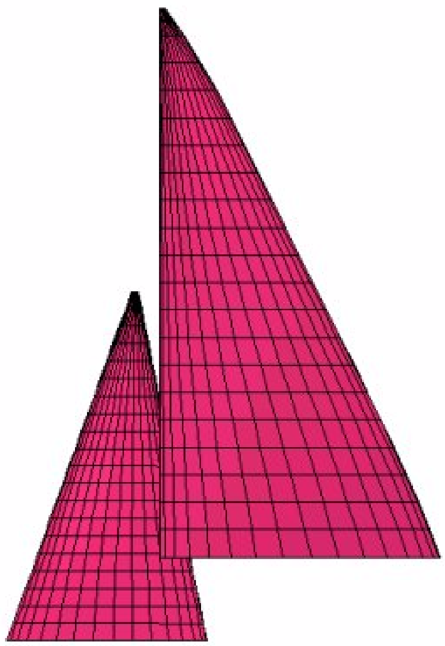

Figure 2: Typical panel layout.

Figure 3: The real thing!

The sail sections were computed using AME CRC's Sail Visualisation[4] software which is capable of tracing the camber stripes on the sail and computing the section draught, camber, entrance angle, exit angle, front and back and relative twist. Examples of the computational model and the actual sail are given in Figure 4 and Figure 5.

Because the sail model could only operate with sails defined by horizontal camber lines, including the sail foot and head board, some compromise of the modelled geometry had to be made. This was particularly true for the jib which has quite an angled foot (i.e. the clew is higher than the tack). The idealised sail geometries and the camber stripes used to define the sails are shown in Figure 6.

In all cases the sail forces were calculated for zero heel angle, in air of density 1.206kg/m^3, and the wind speed and direction were kept constant with height; i.e. no wind gradient was used. The sailing conditions for the calculations are summarised in Table 2.

A trailing vortex wake was shed from the trailing edge of each sail. The shape of this wake was iterated so that there was no pressure jump across the wake.

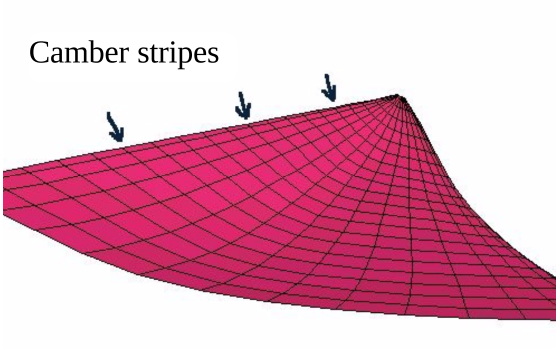

Figure 4: Idealised sail.

Figure 5: Sail with camber stripes.

Table 2: Sailing conditions.

Boat speed	4.1kts	Main sail area	4.7m^2
True wind speed	8.7kts	Jib area	2.0 m^2
Apparent wind speed	12kts	I	3.324m
True wind angle	45°	BAS	0.798m
Apparent wind angle	31°	J	1.190m
Main sail sheeting angle	6° to centre line		
Heel angle	0°		
Jib sheeting angle	14° to centre line		

---

[4] Developed by Andrew Woods of the Centre for Marine Science and Technology, Curtin University of Technology.

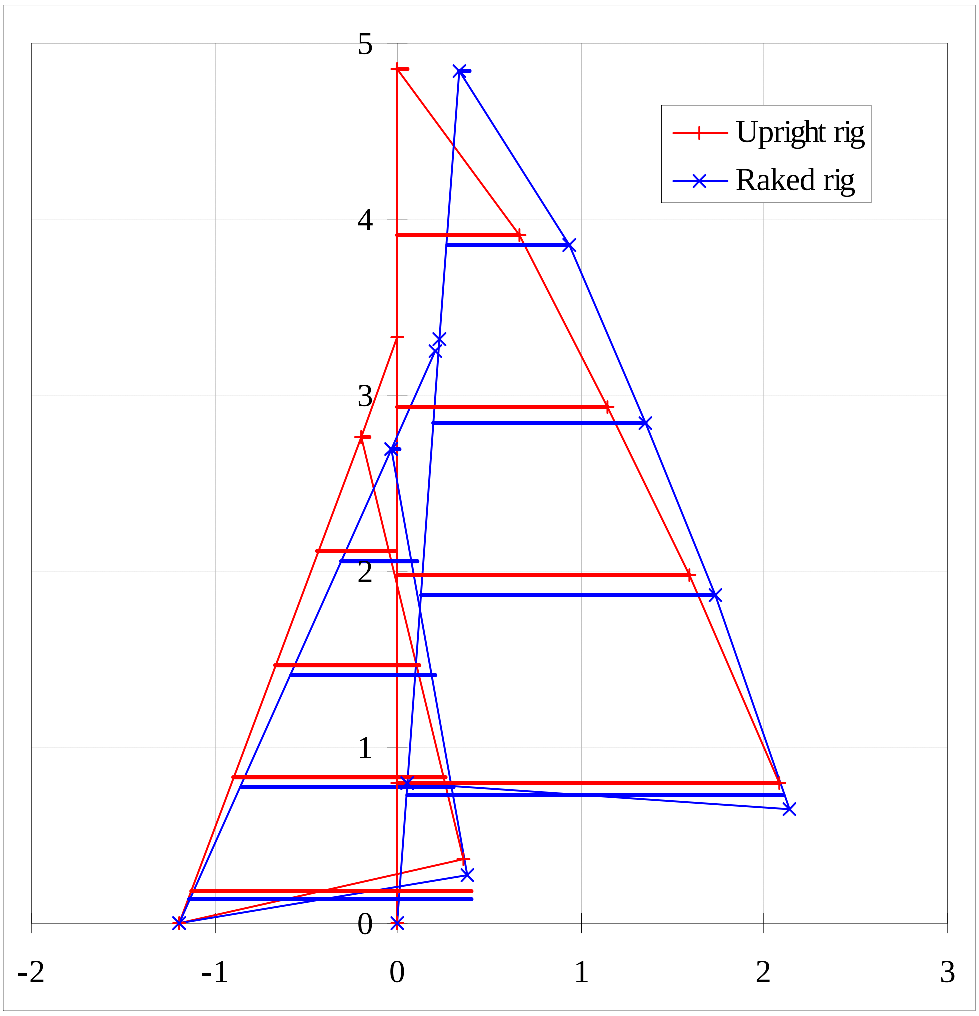

Figure 6: Idealised rig geometry.

Despite the approximations of the idealised sail geometries illustrated in Figure 6, there were negligible differences in the sail areas of the main sail and jib for the upright and raked conditions.

4. Results and discussion

The results of the investigations are presented in Tables 3 to 6 and Figures 8 to 13. As has been discussed above, two rig configurations were tested: the first with the mast upright; and the second with the mast raked aft 4°, this caused the forestay to be rotated by 3.5° and to increase in length by 0.08m. Figures 14 and 15 show the computed loading (vorticity distribution) of the sails for the upright and raked configurations. In these figures, the upper picture shows the loading for the sails rigged together and the lower pictures show the loading for the sails in isolation.

The directions of the forces and moments given in the tables is presented in Figure 7.

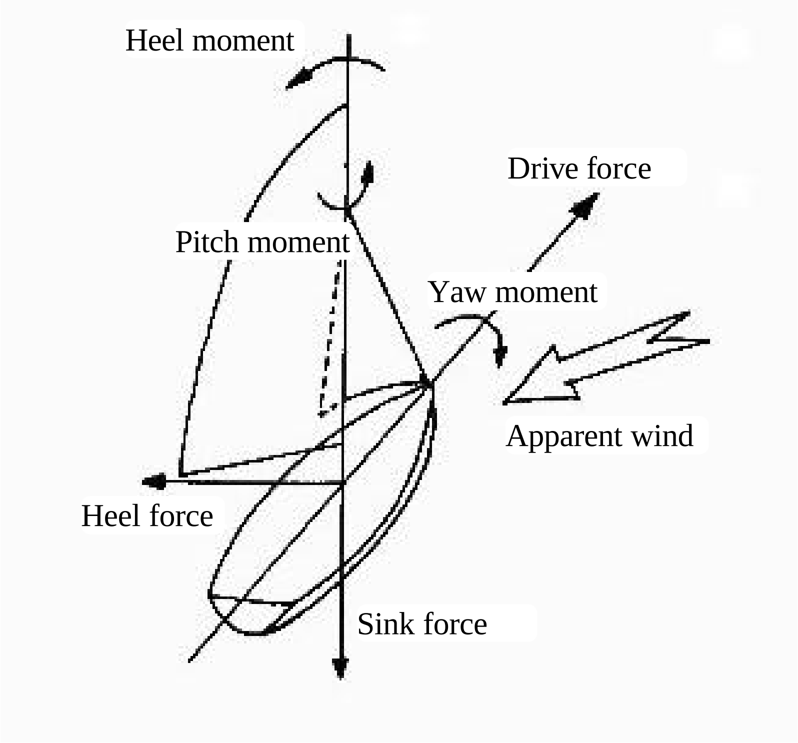

Figure 7: Force and moment direction and orientation

In Tables 3 to 6, for both rig configurations, the results are presented for the combined sails rigged together (normal sailing configuration), this result is then separated into the components contributed by the main sail and jib, finally the results for the main sail and jib rigged in isolation are given.

Table 3 gives the results for the three components of the force and three components of the moment generated by the sails. The directions of the positive force or moment are also specified. It may be seen that in all cases the sails rigged in isolation produce significantly different forces compared with the forces generated by each sail when they are rigged together: the main sail generates greater forces in isolation and the jib produces lower forces. This is not necessarily true for the moments, indicating that the centre of pressure of the sails change. These results are to be expected since, when rigged together, the jib operates in the upwash of the main resulting in greater forces, and the main operates in the downwash of the jib resulting in lower forces. The effect on the main is less pronounced since the rig is fractional and the jib only influences the flow over the lower part of the main sail.

Table 3: Forces and moments. Complete rig; main and jib contributions; and main and jib in isolation. For upright and raked rigs.

	Drive F +ve fwd N	Heel F +ve leeward N	Sink F +ve down N	Heel M +ve leeward Nm	Pitch M +ve bow up Nm	Yaw M +ve weather helm Nm
Upright rig	82.4	197.5	-15.1	398.6	-175.1	45.3
Main	42.4	115.3	3.2	290.9	-124.2	74.1
Jib	40.0	82.2	-18.2	107.7	-50.8	-28.8
Main alone	54.4	128.2	3.6	304.2	-136.9	71.0
Jib alone	28.2	65.0	-13.1	84.5	-34.2	-23.2
Raked rig	83.7	198.9	-20.8	391.6	-177.1	72.0
Main	44.0	117.3	0.1	289.5	-128.5	94.6
Jib	39.7	81.6	-20.9	102.1	-48.6	-22.6
Main alone	55.9	130.7	-0.2	303.5	-140.2	93.0
Jib alone	28.4	65.1	-15.1	80.8	-33.2	-18.5

When comparing the forces generated by the main sail in isolation and when operating behind the jib, it is important to consider the influence of the boundary layer. The vortex lattice method assumes potential flow and boundary layer separation is not modelled, however these effects should be born in mind when interpreting the results. If the main is operating in isolation at high lift coefficient (e.g. travelling upwind with the main sheeted hard) then it is possible for the flow to separate from the leeward side of the main causing the drag to increase significantly and a reduction in lift, i.e. the sail stalls. When the main is operating behind the jib it is less likely that this separation will occur; the presence of the jib may delay the onset of stall of the main sail if it is able to influence the main sail boundary layer. Hence it is probable that the main in isolation would not develop forces as large as those predicted by the vortex lattice method since it could not be sheeted so hard without causing the sail to stall.

It is interesting to note that the total drive and heel forces, and heel and pitch moments remain approximately constant for both upright and raked rigs. This is true also when the sum of the forces / moments of the individual sails in isolation are compared with the total forces / moments of the sails rigged together. This indicates that the loss in forces on the main is almost exactly matched by the increase in forces on the jib. (See Figure 8, 9, 11 and 12.)

Differences in the upright and raked rigs is most apparent in the sink force (Figure 10) and yaw moment (Figure 13). The differences in yaw moment are primarily due to the centres of effort of the main and jib moving aft as the mast is raked back. The yaw moments generated by the sails in isolation are slightly reduced when compared with the sails rigged together. The effect of rake is seen in the sink force generated: the force vector is rotated so that a larger portion acts in the vertical direction. The jib, which even in the upright rig has a raked forestay produces a relatively large upward force, whereas the main produces a small downward force, mainly due to twist producing a downward component of the normal vector of the sail's surface. When the rig is raked aft, the jib produces a slightly greater upward force, but the vertical force generated by the main sail is reduced to virtually zero.

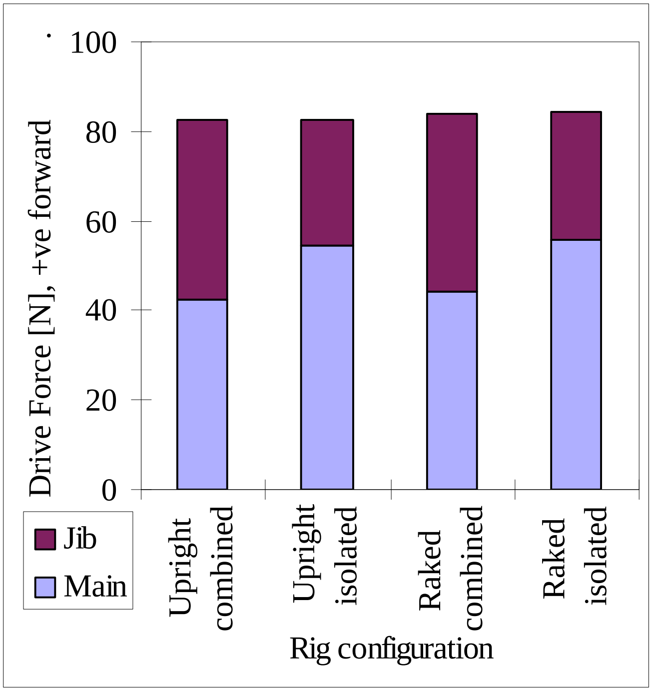

Figure 8: Individual sail contributions to drive force, for different rig configurations.

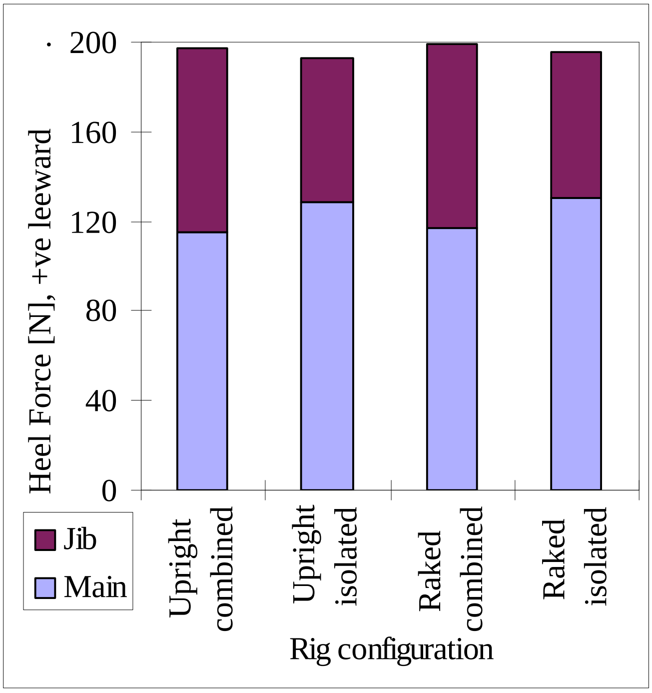

Figure 9: Individual sail contributions to heel force, for different rig configurations.

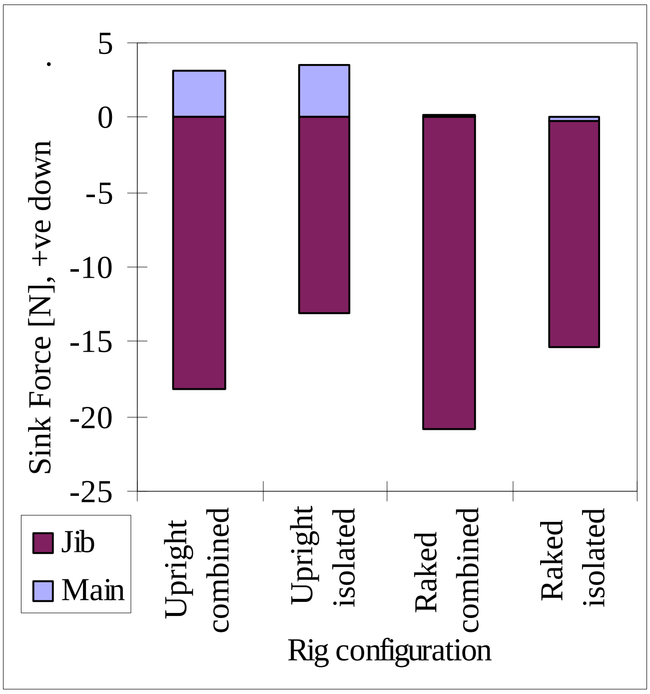

Figure 10: Individual sail contributions to sink force, for different rig configurations.

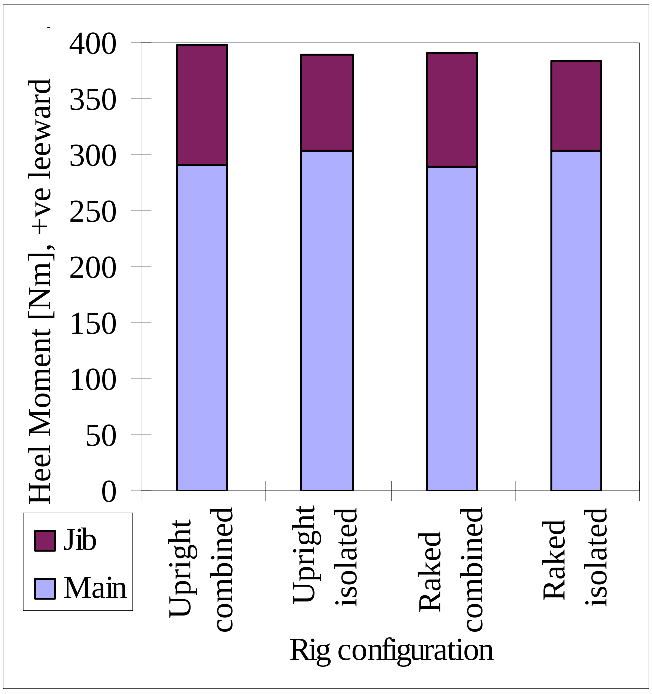

Figure 11: Individual sail contributions to heel moment force, for different rig configurations.

Table 4 shows the magnitude of total resultant force and moment vectors generated by the sails in the different conditions. Also presented are the lift and drag coefficients and lift:drag ratio of the sails. It may be seen that the overall magnitudes are very similar (1% difference for the force and 0.4% for the moment). However, the lift:drag ratio of the raked rig shows an improvement of 3% over that of the upright rig and this seems to be mainly due to an improved lift:drag ratio of the main sail in the raked condition. The change in lift:drag ratio of the jib shows no significant change. The improvement of the main sail's performance appears to be due to both improved main / jib interaction and improved performance of the main sail in isolation. When compared with the upright case, the raked main sail shows a 2% increase in lift:drag ratio in isolation and a 4% increase with both sails rigged. This indicates that, for the raked condition, the force vector has been rotated to a more beneficial direction.

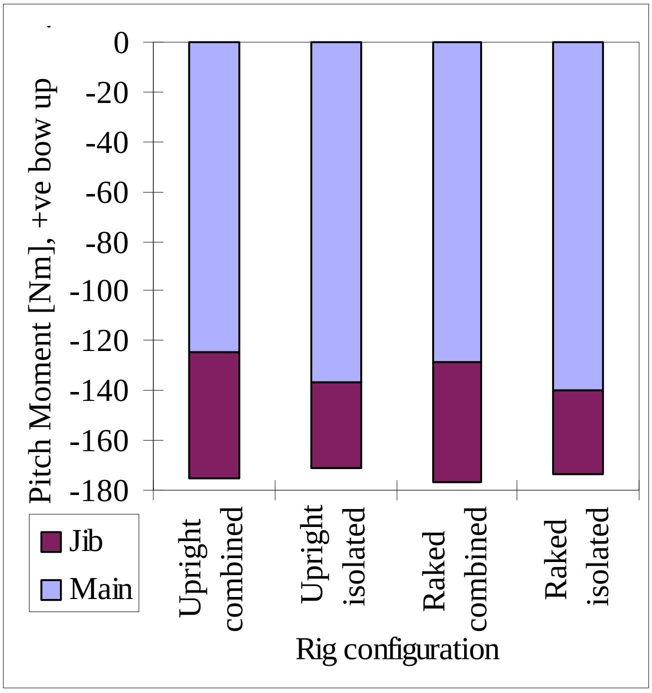

Figure 12: Individual sail contributions to pitch moment, for different rig configurations.

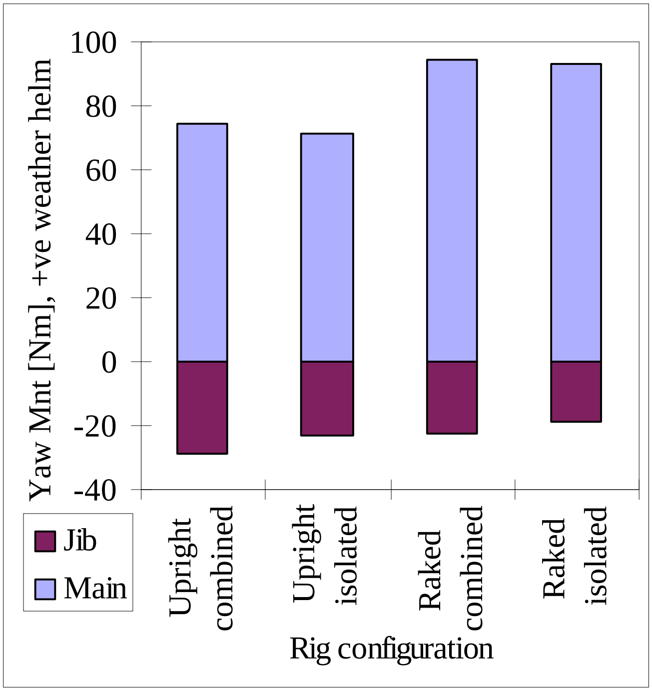

Figure 13: Individual sail contributions to yaw moment, for different rig configurations.

Table 4: Total force and moment, and lift and drag coefficients. Complete rig; main and jib contributions; and main and jib in isolation. For upright and raked rigs.

	Total Force N	Total Moment Nm	C_L	C_D	C_L/C_D	% increase over upright
Upright rig	214.6	437.7	1.346	0.199	6.769	
Main	122.9	324.9	1.106	0.211	5.242	
Jib	93.2	122.5	1.932	0.171	11.311	
Main alone	139.4	341.1	1.264	0.178	7.102	
Jib alone	72.0	94.1	1.490	0.197	7.568	
Raked rig	216.8	435.8	1.365	0.196	6.969	+3%
Main	125.3	330.5	1.127	0.207	5.442	+4%
Jib	93.1	115.3	1.917	0.170	11.298	-
Main alone	142.1	347.0	1.287	0.177	7.257	+2%
Jib alone	72.6	89.3	1.494	0.195	7.664	+1%

Table 5: Forces and moments as percentage of total force / moment, and sink force as percentage of drive force. Complete rig; main and jib contributions; and main and jib in isolation. For upright and raked rigs.

	Drive F / Tot F	Heel F / Tot F	Sink F / Tot F	Heel M / Tot M	Pitch M / Tot M	Yaw M / Tot M	Sink F / Drive F
Upright rig	38.4%	92.1%	-7.0%	91.1%	-40.0%	10.4%	-18.3%
Main	34.5%	93.8%	2.6%	89.5%	-38.2%	22.8%	7.4%
Jib	42.9%	88.2%	-19.6%	87.9%	-41.5%	-23.5%	-45.6%
Main alone	39.0%	92.0%	2.6%	89.2%	-40.1%	20.8%	6.6%
Jib alone	39.2%	90.2%	-18.1%	89.8%	-36.4%	-24.7%	-46.3%
Raked rig	38.6%	91.7%	-9.6%	89.9%	-40.6%	16.5%	-24.8%
Main	35.2%	93.6%	0.1%	87.6%	-38.9%	28.6%	0.3%
Jib	42.6%	87.6%	-22.4%	88.5%	-42.2%	-19.6%	-52.7%
Main alone	39.3%	91.9%	-0.1%	87.5%	-40.4%	26.8%	-0.3%
Jib alone	39.1%	89.6%	-20.8%	90.5%	-37.2%	-20.7%	-53.3%

Table 5 shows the component forces (drive, heel, sink) and moments (heel, pitch, yaw) as percentages of the total resultant force / moment for a particular configuration. In addition the sink force as a percentage of the drive force is also shown. It may be seen that the effect of raking the rig aft is small except for the sink force and yaw moment. The magnitude of sink force:drive force ratio is increased significantly when the rig is raked aft. The magnitude of the yaw moment:total moment ratio is also increased, since the centre of effort of the sails is moved further aft when the mast is raked.

Table 6: Forces and moments as percentage of upright rig forces / moments. Complete rig; main and jib contributions; and main and jib in isolation. For upright and raked rigs.

	Drive F	Heel F	Sink F	Heel M	Pitch M	Yaw M
Upright rig	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Main	51.5%	58.4%	-20.9%	73.0%	71.0%	163.5%
Jib	48.5%	41.6%	120.9%	27.0%	29.0%	-63.5%
Main alone	66.0%	64.9%	-23.7%	76.3%	78.2%	156.6%
Jib alone	34.2%	32.9%	86.6%	21.2%	19.6%	-51.2%
Raked rig	101.6%	100.7%	137.8%	98.3%	101.2%	158.8%
Main	53.4%	59.4%	-0.8%	72.6%	73.4%	208.7%
Jib	48.2%	41.3%	138.6%	25.6%	27.8%	-49.9%
Main alone	67.8%	66.2%	1.1%	76.2%	80.1%	205.2%
Jib alone	34.5%	33.0%	100.4%	20.3%	19.0%	-40.9%

Table 6 shows the forces and moments generated by the sails compared with the forces and moments generated by the upright rig (base condition). It may be seen that the main sail and jib rigged together each contribute approximately 50% of the drive force. In isolation the balance is shifted 66%:34%, with the larger portion generated by the main. It is of interest that the sail areas are in the ratio 70%:30% indicating that, for the isolated sails, the lift coefficient of the jib is slightly greater than that of the main sail (see also Table 4).

Table 6 indicates that the raked rig produces a 1.6% increase in drive force, marginal increase in heel force and a 37.8% increase in sink force which acts in the upward direction. Previous experience (Couser 1997) has shown that the increase in boat speed is approximately 20% of the increase in driving force, thus it might be expected that a boat with a raked mast would sail 0.3% faster that one with an upright rig. The effect of sink force may be estimated by assuming that the hull wave making resistance is proportional to displacement. Thus if the all-up weight of the hull and crew is 1730N and the increase in upward sink force is 5.7N, the wave making resistance might be reduced by 0.3%, given that the wave making resistance is approximately 50% of the total resistance, this might correspond to a total reduction of hull resistance of 0.15%, corresponding in turn to a 0.03% increase in speed. Although these differences in speed are small they are the margins by which yacht races are won and lost, 0.33% of a 100min race is 20sec.

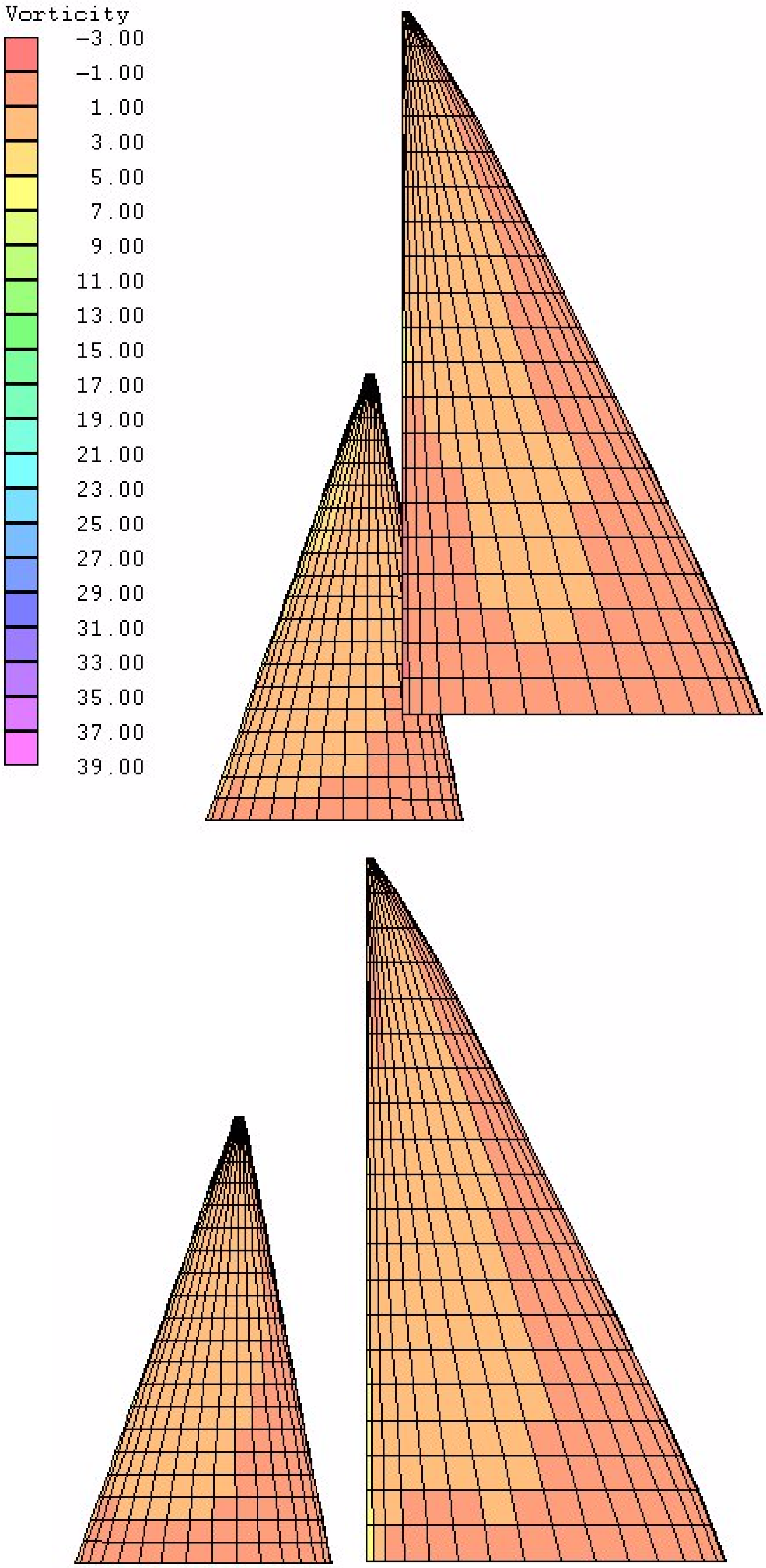

Figure 14: Upright rig, sail loading, combined and isolated.

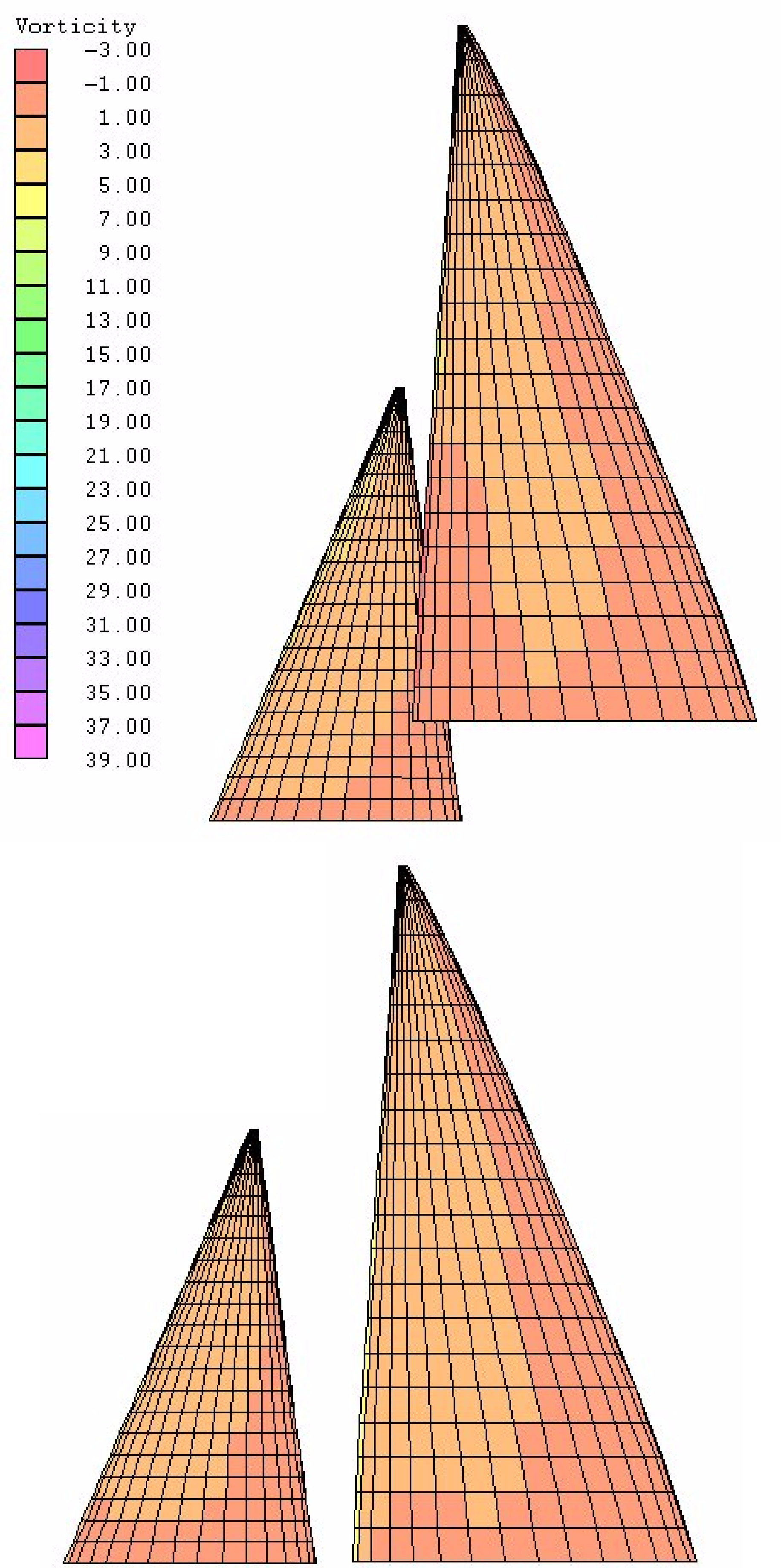

Figure 15: Raked rig, sail loading, combined and isolated.

Figures 14 and 15 show the loading on the sails for the upright and raked conditions respectively. In each figure the loading of the sails operating together is given above the loading when the sails operate in isolation. It is difficult to distinguish between the differences in loading due to mast rake. However, the differences in the loading characteristics of the combined and isolated sails are discernible. When the sails operate together the main operates in the downwash of the jib and the reduction in loading in the forward part of the main is evident. The influence of the jib is limited to an area immediately down stream; the part of the main above the head of the jib is largely unaffected, there is evidence of some *increase* in loading on the main just down stream of the jib's head, possibly caused by the tip vortex in this region.

The jib operates in a region of upwash generated by the main sail and this is evident in increased loading of the jib, particularly in the upper third of the sail.

4.1 Summary of effects of mast rake and sail interaction

There are several effects which may occur due to raking the mast aft. These are discussed below together with the degree to which they were observed in the numerical modelling:

- Enhanced endplate effects and reduced leakage under the foot of the sails. If the mast is raked aft the boom and foot of the jib will be closer to the deck, potentially this will increase the lift and reduce the induced drag of the sails. Past experience has shown that the benefits associated with a sealed off sail foot rapidly diminish as the gap between the sail foot and deck increase. It is unlikely that 4° of mast rake would lower the foot of the main sail to produce any discernible improvement. The case for the jib is not so clear since it is already quite close to the deck and further lowering the clew could be beneficial. The vortex lattice method did not show any large differences in the sail loading in the foot region of the sails due to mast rake. However, the calculations indicated that the lift:drag ratio of the main was increased by 4% when the mast was raked back, whilst the lift:drag ratio of the jib was virtually unchanged. The increase in lift:drag ratio of the main was attributed to improved lift:drag ratio of the isolated main and improved interaction between the main sail and jib.

- Reduction in span, hence reduced aspect ratio leading to greater induced drag and reduced lift. The reduction in span due to 4° of mast rake is likely to be insignificant (0.2%). No such effects were observed from the computations. In fact, as has been noted above, the lift:drag ratio of the main was improved and that of the jib remained virtually constant.

- Reduction of jib / main sail overlap. As may be seen in Figure 6, the difference of the overlapped area with and without mast rake is small. However, it does appear that the vertical extent over which the jib influences the main sail loading is reduced in the case where the mast is raked. The fact that the forestay length is increased and the head of the jib is further from the luff of the main, as in the case where the mast is raked, may be beneficial. There will be a more gradual transition from where the jib influences the main sail to where it does not. The reduction in overlap may reduce the maximum achievable lift coefficient of the main since stall may occur earlier.

- Increase in vertical component of sail force. This is achieved since the normal vectors of the sails' surfaces are rotated to produce a greater vertical force component. This is clearly predicted by the vortex lattice model. It is not immediately clear why a vertical force would improve the dinghy's performance, unless the Mirror is super critical to weight. In the raked condition the sails produce an extra 5.7N of vertical force (Table 3), this corresponds to only 0.3% of the dinghy's all-up weight (hull 602N, crew 1128N). It has been estimated that this reduction in displacement may increase the boat speed by 0.03%, which is virtually insignificant. The increase in boat speed due to increased drive was found to be an order of magnitude greater.

- Centre of effort moved aft. As might be expected, the centre of effort of the sails is moved aft when the mast is raked. This may improve the balance of the dinghy, hence improving its performance.

5. Conclusions

This case study has shown the value of the vortex lattice method for investigating the interaction between the sails and determining the relative effects of raking the mast aft. These types of computational tools allow detailed comparative investigations without the high cost of wind tunnel tests. As with wind tunnel tests the benefits of detailed flow visualisation are available.

A number of effects have been observed, particularly the increased vertical component of the sail force when the rig is raked and also the increase in yaw moment, some slight increase in thrust was also achieved by raking the mast. It appears that this was due, in equal parts, to improved lift:drag ratio of the main in isolation and improved interaction between the main and jib. From estimates of the gains in boat speed attributed to these phenomena it was found that the vertical force had a relatively insignificant effect. However, margins of around 20sec would be achieved over a 100min race due to the increase in thrust produced by raking the mast. There is scope for further investigation, in particular information relating to the hydrodynamic performance of the Mirror and its sensitivity to weight would allow a more complete analysis using a VPP to be performed.

6. Acknowledgements

The author would like to thank and recognise the support and contributions to this research made by Norm Deane, Vice President of the International Mirror Association and Australian Manager / Coach for the Mirror Class; and Steve Walker of Steve Walker Sails Pty. Ltd. who has been deeply involved in the design and construction of Mirror sails for many years as well as being the Australian Team Coach on two occasions.

The author would also like to thank Andrew Woods of the Centre for Marine Science and Technology, Curtin University of Technology, for the use of his Sail Visualisation software which was used to measure the sail shapes from photographs.

7. References

Couser, P. (1997). Prediction of aerodynamic sail forces for upwind yacht velocity prediction programs. *Proc. 1st Australian Sailing Science Conference*. Hobart, Tasmania, Australia. November.

Fiddes, S.P. and Gaydon, J.H. (1996). A new vortex lattice method for calculating the flow past yacht sails. *Journal of Wind Engineering and Industrial Aerodynamics*. 63 pp35-60.

Greeley, D.S., and Kerwin, J.E., (1982). Numerical methods for propeller design and analysis in steady flow. *Trans. Society of Naval Architects and Marine Engineers*. 90, pp415-453.

Greeley, D.S., Kirkman, K.L., Drew, A.L. and Cross-Whiter, J. (1989). Scientific sail shape design. *Proc. 9th SNAME Chesapeake Sailing Yacht Symposium*. Annapolis, Maryland, U.S.A.

Milgram, J.H. (1978). Effects of masts on the aerodynamics of sail sections. *Marine Technology*. 15, 1, pp35-42. January.

Milgram, J.H. (1968). The analytical design of yacht sails. *Trans. Society of Naval Architects and Marine Engineers*. 76, pp118-160.

Register, D.S. and Irey, R.K. (1983) Analysis of steady flow over interacting sails. *Proc. 6th SNAME Chesapeake Sailing Yacht Symposium*. Annapolis, Maryland, U.S.A.

Thrasher, D.F., Mook, D.T. and Nayfeh, A.H. (1979). A computer based method for analysing the flow over sails. *Proc. 4th SNAME Chesapeake Sailing Yacht Symposium*. Annapolis, Maryland, USA.