THE USE OF COMPUTATIONAL MODELLING IN A STUDY OF DOWNWIND SAIL

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PHOENICS VERSION 3.2.

Abstract

The wind flow around a mainsail and a spinnaker is modelled by using a body fitted grid that is fitted to the sail shapes provided by a sail design programme. In modelling the real situation the velocities solved are the components of the apparent wind velocity, which varies in both speed and direction with height. In this situation the sea surface is moving at minus the boat velocity. A simpler straight flow situation is used to investigate the flow interactions between the sails. It is found that while under some situations this interaction is significant, under normal sailing situations the interaction is quite small. It is also shown that the thrust and side force coefficients with twisted flow are similar to those with straight flow if referenced to the masthead apparent wind speed and direction.

1. Introduction

It is widely recognised by the wind engineering community that in order to generate realistic results from model tests it is necessary to accurately model both the object being studied and the characteristics of the wind effecting it. For this reason wind tunnel studies of buildings etc. are almost always conducted in boundary layer wind tunnels which model both the velocity profile and the turbulence of the wind. In studying the wind loads on moving objects, such as yachts, the situation is more complicated since the relative air movement is a combination of the reversed boat velocity and the wind velocity. The vector addition of the components results in a relative wind profile that varies in both speed and direction (twist) with height. This phenomenon is not very significant when sailing upwind but is quite marked when sailing downwind. This has been recognised at the University of Auckland in the development of a twisted flow wind tunnel [1] that has been extensively used by the New Zealand America’s Cup syndicate in their downwind sail development. This facility has also been used for more fundamental studies of downwind sail aerodynamics including tests designed to investigate the interaction between the mainsail and spinnaker as illustrated in Figure 1. This figure shows the pair of sails attached to a 2m high mast, which is itself supported on a six-component force balance. The tunnel is 6m wide and 3m high and has vanes just upstream of the model, which twist the flow.

Figure 1. Model mainsail and spinnaker sails under test in the University of Auckland Twisted Flow Wind Tunnel.

A complimentary series of computational studies has been conducted to help understand the complex three-dimensional flows. In the most complex cases the onset wind is modelled by using twisted flow inlet conditions and a moving floor to produce an accurate model of the wind relative to the sails at all heights. However when studying aspects such as sail interaction the inclusion of twisted flow introduces too much complexity to the situation and would make interpretation of result very difficult, as a result a simple wind profile has been used in these cases. The sail geometry is generally extracted from a sail design programme and a body fitted grid generated around these sail shapes. The sail forces are calculated by differential pressure integration and can be compared with wind tunnel data.

2. General model features

The flow around a pair of downwind sails has been modelled in PHOENICS version 3.2 by using a body fitted grid. The grid geometry was created in a separate Fortran program, which used as its input information the sail shapes that were created by a sail design program. The Fortran program shaped the grid so that cell faces were located on the surface of the sails. The triangular shape of the sails and the fact that the sails are well separated at the foot of the sails but are very close together at the head meant that the grid was very bunched at the head of the mast. In order to minimise this effect the sails are slightly clipped at their head but the area removed is only a small fraction of the total sail area. Nevertheless some of the cells are highly non-orthogonal and so both NONORT and SYMBFC are set to true. The boundaries of the solution domain were placed about eight mast heights from the sails in all directions. The foot of the mainsail was placed 3m above the sea surface. The grid was imported into the satellite program by using the READCO PIL command.

Although there was no attempt to model the hull of the yacht, the alignment of its centreline was specified in the Q1 file (THETAB) so that the direction of the boat velocity was defined. In situations where the fully twisting flow was simulated the boat velocity was specified as a fraction of the masthead true wind speed. The true wind speed at masthead, the mast height above the sea surface and the air density were used as reference parameters and the problem solved in non-dimensional form. In all cases the true wind profile was assumed to fit a simple log law with a surface roughness length $z_0 = 0.001$ m.

$$V_T = u_* \ln(z/z_0+1.0)/K \qquad (1)$$

where K = von Karman's constant ($K = 0.4$)

u_* = friction velocity

z = height above sea surface

z_0 = surface roughness length

The particular form of equation (1) is used in order to give a zero velocity at the $z=0$ plane, which represents the mean sea surface. Over open water z_0 varies between 0.1 mm and 10 mm, and so for this study a value corresponding to moderate wind speeds has been used.

The true wind angle was set in the Q1 file and varied from 90° to 180° (spinnaker and mainsail almost perpendicular to the wind). Some of these angles are physically impossible with real sails since the spinnaker would collapse. Inlets were provided on two sides of the domain and outlets on two sides. The type of outlet boundary condition was varied depending on the dominant flow direction. At the primary downstream boundary a zero pressure was specified but at the secondary boundary a fixed mass flux sink equal in magnitude to the inlet mass source on the opposite face was used.

The k-ε turbulence model was used with the boundary conditions specified in the manner recommended by Richards and Hoxey [2]. As a result the inlet turbulence property profiles were:

$$k = 3.33\, u_*^2 \qquad (2)$$

$$\varepsilon = u_*^3/K(z+z_0) \qquad (3)$$

A shear stress equal to ρu_*^2 was applied to the top of the domain in order to minimise the pressure gradient through the domain.

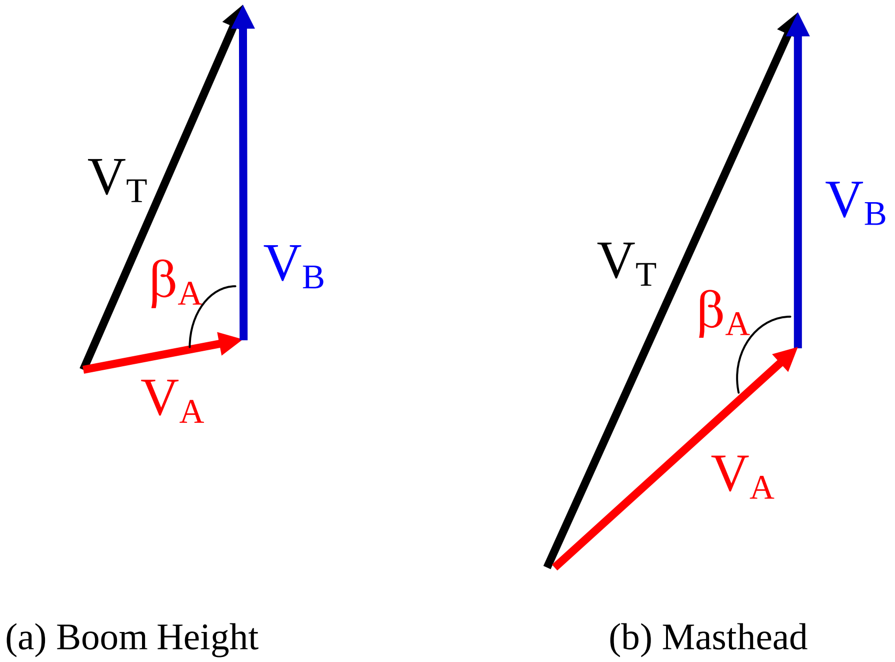
The sails used in this model were based on a pair of sails designed by North Sails (NZ) Ltd. for the Whitbread 60 round the world yacht Winston. The mainsail boom (bottom of the mainsail) was set at an angle of 55° to the boat centreline in all cases.

3. Twisted Flow

In modelling the flow around yacht sails the grid is fixed to the yacht and the flow computed is the flow relative to the yacht, the apparent wind $\mathbf{V_A}$. This relative flow results from the combinations of the yacht's motion $\mathbf{V_B}$ and the air's motion, the true wind $\mathbf{V_T}$. These are related by the vector equation (4):

$$\mathbf{V_A} = \mathbf{V_T} - \mathbf{V_B} \tag{4}$$

Twisted onset flow occurs because the true wind speed varies with height whereas the yacht's velocity is a fixed quantity. Figure 2 illustrates this situation where the true wind speed at the masthead is greater in magnitude than that at boom height (bottom of the mainsail), but with the same direction, and as a result the two apparent wind velocities differ in both magnitude and direction. It may be noted that the apparent wind angle (β_A) is greater at the masthead than it is at boom height.



(a) Boom Height

(b) Masthead

Figure 2. Velocity triangles at Boom Height and Masthead

Calculations of the inlet velocities, turbulence properties and mass fluxes resulting from these vector additions were programmed into the GROUND file. With twisted flow the sea surface was treated as a moving rough wall with a velocity $-\mathbf{V}_B$. The combination of twisted inlet conditions, a moving sea surface and the shear stress on the top of the domain resulted in a flow which in the absence of any sails was almost in equilibrium and hence the outlet conditions were almost identical to the inlet conditions. Figure 3 shows the velocity vectors at the mast in the absence of the sails. Although the mainsail is shown in this figure the cell faces were not blocked in this run. The variation in both apparent wind speed and direction is quite clear.

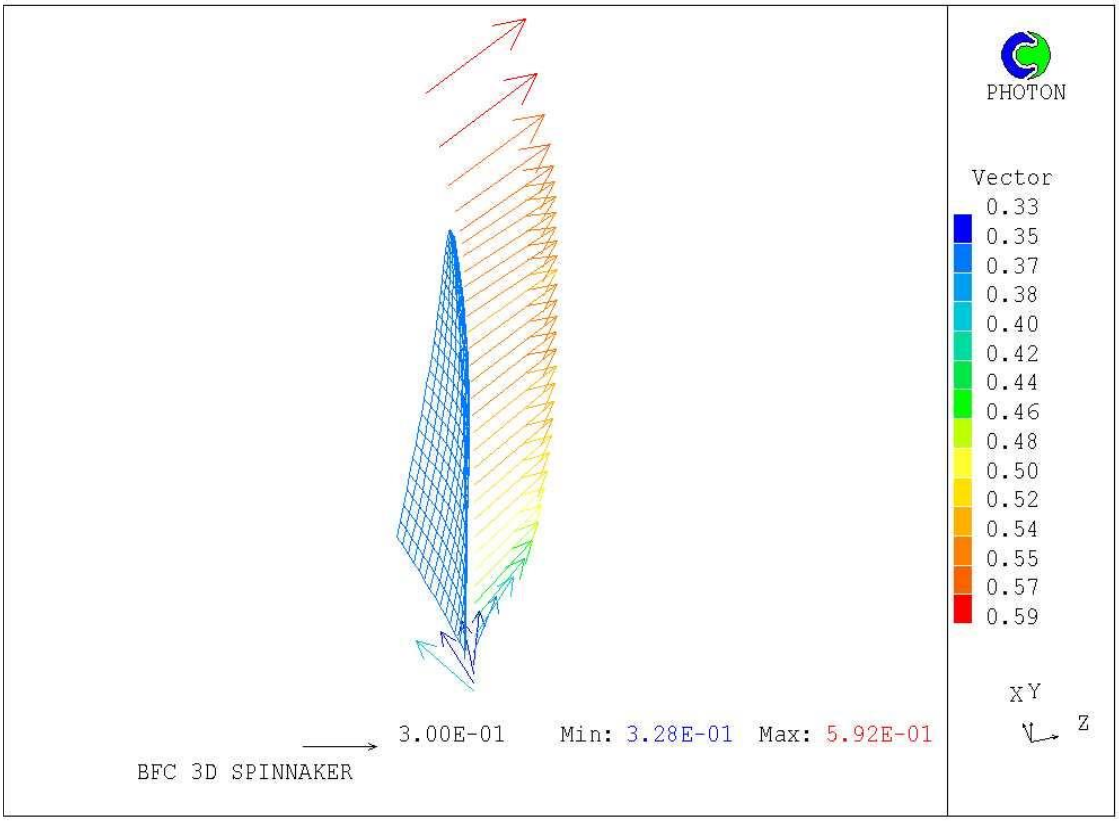


Figure 3. Apparent wind velocities at the mast in the absence of blocked sails.

4. Force calculations

The pressure forces acting on the sails have been calculated by determining the area vector for each cell face that makes up part of the two sails. This vector is multiplied by the difference in pressure across the particular face and the resulting components summed over each sail. The coding associated with this routine was inserted into GROUND as an attachment to the wall friction calculations for the sails, and the resulting forces written to the RESULT file. At the same time the total surface area of the sails is integrated so that it can be used in the calculation of force coefficients.

5. Sail interaction study

Studies, by undergraduate students [3,4], in two of the University of Auckland wind tunnels have shown surprisingly little interaction between the mainsail and spinnaker. France and Erceg [3] did find some reduction in the lift produced by the mainsail at low apparent wind angles (90° to 120°) when they tested a 0.75m mast model in uniform wind, but found very little interaction at larger angles. Johnson and Stanton [4] tested the model shown in Figure 1 in both straight and twisted flow. In this study the sail forces were measured with each sail flown independently and with both sails up. In each test the trim of the sails was adjusted so that the spinnaker pole (located between the mast and the windward lower corner of the spinnaker) was almost perpendicular to the apparent wind and the mainsail boom (the beam attached to the mainsails lower edge) positioned to give maximum thrust. The results showed that the thrust measured with the two sails together was only about 5% smaller than the thrust obtained by summing the forces measured when the sails were flown separately. That is, the interaction between the two sails was causing a 5% reduction in the thrust. Similar reductions were observed with both straight and twisted flows. In addition it was observed that the maximum thrust occurred with twisted flow at a masthead apparent wind angle that was about 10° larger than for straight flow. This is not surprising since the apparent wind angle at lower heights, where the majority of the sail area exists, will experience a lower apparent wind angle.

In order to shed further light on this subject a CFD study, similar to the wind tunnel study of Johnson and Stanton [4], has been conducted. In this study the mainsail and spinnaker were modelled in straight flow both independently (Main Only and Spinnaker Only) and together (Both). The resulting lift and drag coefficients are shown in Figure 4(a) and 4(b). In these figures the apparent wind angle has been measured relative to the Z axis shown in Figure 5 and the reference areas used are the areas of the particular sails.

It may be observed in Figure 4(a) that the presence of the mainsail causes a slight increase in the lift provided by the spinnaker and a significant reduction in the drag on the spinnaker at high apparent wind angles. The cause of these effects can be seen in Figure 5 which shows the pressure contours and flow vectors for $\beta_A = 180°$. In this situation the mainsail is shielding about half of the spinnaker from the wind and so the pressures on the inner surface of the spinnaker are both weaker and asymmetric. The asymmetry of these pressures then drives flow through the slot between the sails and hence generates the lift force.

In contrast the effects of the spinnaker on the mainsail forces are much more noticeable, as illustrated in Figure 4(b). Both the reductions in lift and drag on the mainsail can be associated with an increase in the pressure on the leeward side of the sail, which is created by the spinnaker.

Although the lift and drag forces are important, it is the thrust provided to the yacht that is of primary interest. In order to calculate the thrust and side force coefficients it has been assumed that the boom is at an angle of 55° to the hull centreline. This places the centreline on a line that passes through the mast and lies 30° clockwise from the Z-axis. The resulting thrust and side force coefficients are shown in Figure 4(c) and Figure 6. In these figures the reference area used is the total sail area in all cases. Hence the thrust coefficient for the mainsail may be added to that for the spinnaker in order to give the total thrust coefficient.

From Figure 4(c) it can be seen that the spinnaker is the major contributor to both the thrust and sideforce. This is primarily due to its larger area, which is typically of the order of twice the mainsail area. It may also be observed that the maximum thrust is obtained at an apparent wind angle of 110°. This is exactly perpendicular to the spinnaker pole, which in Figure 5 lies 50° clockwise from the Z-axis and hence 20° clockwise from the yacht centreline. Whidden [5] comments: “When the wind is aft of 120°, the pole should generally be squared, at right angles, to the apparent wind. This right-angle rule provides the maximum separation between the spinnaker and the mainsail, which is desirable. With the wind ahead of 120°, the pole should be oversquared – or closer than 90° to the wind.”

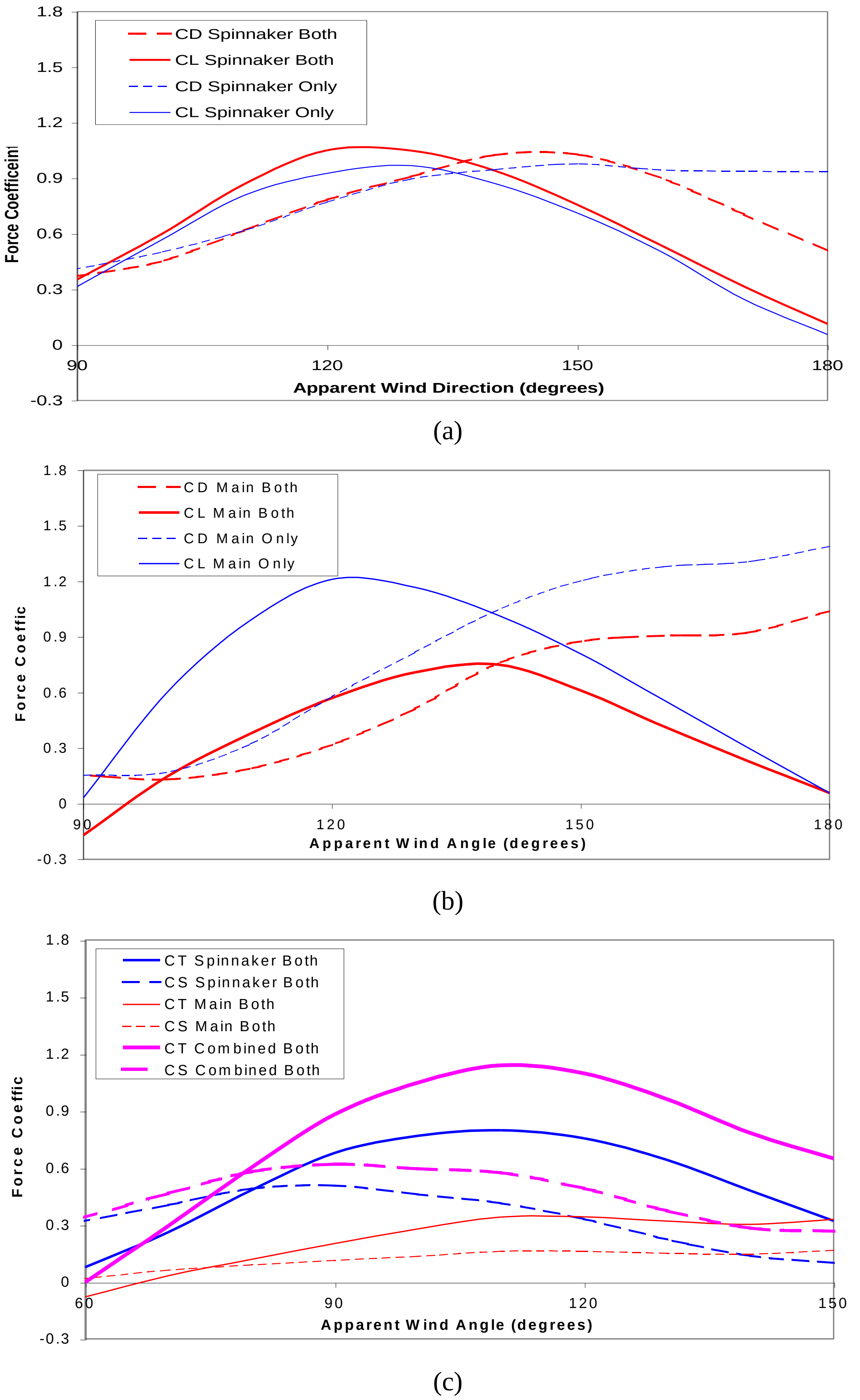


Figure 4. Force coefficients from the sail interaction study (a) Lift and Drag forces on the spinnaker, (b) Lift and drag forces on the mainsail and (c) Thrust and side forces.

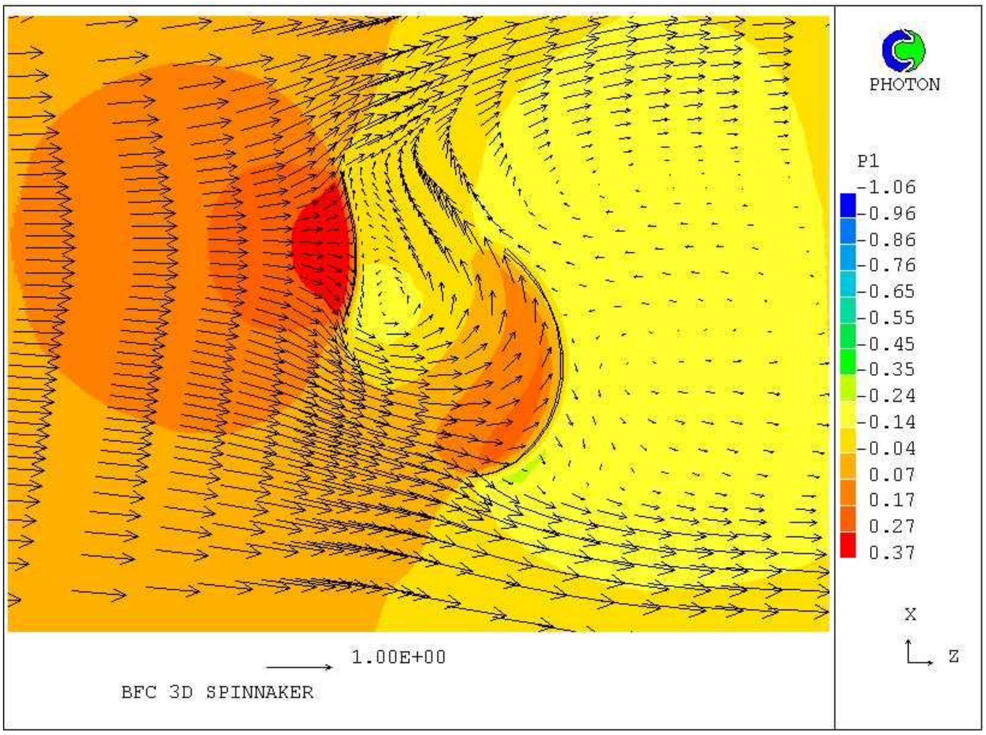


Figure 5. **Pressure contours and velocity vectors at about 1/3 mast height for apparent wind angle 180°.**

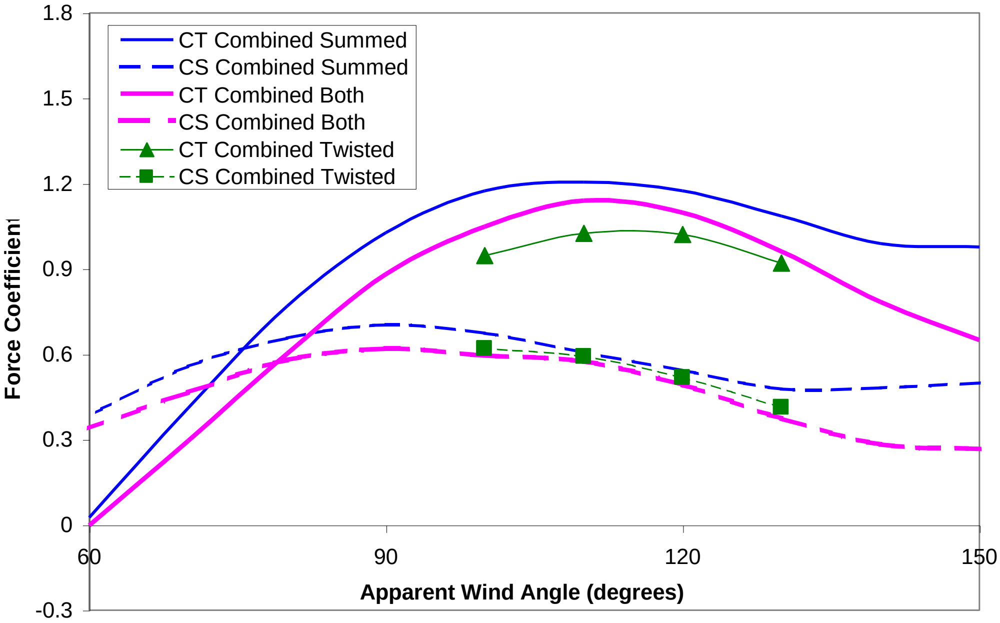


Figure 6. Thrust and side force coefficients

Figure 6 shows the difference between the thrust and side forces obtain by summing the two individual sail tests in comparison with those obtained when the sails were modelled together. It is interesting to note that while significant differences occur at some angles, the two curves are closest around the point of maximum thrust. In this region the summed values are about 5% larger. This is consistent with the wind tunnel results discussed earlier since in those tests the sails were trimmed at each point of sail in order to maintain maximum thrust. It may therefore be concluded that while in some situations there may be significant interaction between a mainsail and spinnaker, near the normal operating point this interaction is small. Further, in these situations, where the spinnaker is the primary provider of driving force, the spinnaker is less affected by the mainsail than the mainsail is by the spinnaker.

6. The effects of twisted flow.

Also shown in Figure 6 is the thrust and side force calculated with twisted flow for a limited range of angle. The results presented are those obtained with unity apparent wind speed at the masthead and plotted against the apparent wind direction at the masthead. The boat velocity has been taken as 60% of the true wind speed and the corresponding true wind speed and direction calculated. In the case of a 130° apparent wind angle, the required true wind speed is double the apparent wind speed and the true wind direction is 157.4°. It can be seen that while the side force coefficients are similar to the straight flow situation, the thrust coefficients are slightly smaller and peak at an apparent wind angle that is about 5° larger than with straight flow. This latter affect is associated with the lower apparent wind angles experienced by the lower parts of the sails.

7. Conclusions

The wind flow around a mainsail and a spinnaker has been modelled by using a body fitted grid. In modelling the real situation the velocities solved are the components of the apparent wind velocity, which varies in both speed and direction with height. In this situation the sea surface is moving at minus the boat velocity. A simpler straight flow situation has been used to investigate the flow interactions between the sails. It is found that while under some situations this interaction is significant, under normal sailing situations the interaction is quite small. It is shown that the thrust and side force coefficients with twisted flow are similar to those with straight flow if referenced to the masthead apparent wind speed and direction.

References

1. R. G. J. Flay, N. J. Locke and G. D. Mallinson, *New Zealand development of a twisted flow for testing yacht sails*, 9th International Conference on Wind Engineering, New Delhi, 1995.

2. P. J. Richards and R. P. Hoxey, Appropriate *boundary conditions for computational wind engineering models using the k - ε turbulence model, J.* Wind Eng. Ind. Aerodyn. 46, 145-153, 1993.

3. C. Erceg and J. France, *Flow interaction of downwind sails*. University of Auckland, Department of Mechanical Eng. Project Report PME98.25&26, 1998

4. A. Johnson and A. Stanton, *The Flow Interaction of Downwind Sails for America's Cup Class Yacht's,* University of Auckland, Department of Mechanical Eng. Project Report, 1999.

5. T. Whidden and M Levitt, *The art and science of sails: A guide to modern materials, construction, aerodynamics, upkeep, and use,* St Martins Pr. ISBN 0312044178, 1990.

Appendix A. Q1 File

```
TALK=F;RUN( 1, 1);VDU=X11-TERM
    GROUP 1. Run title and other preliminaries
TEXT(BFC 3D SPINNAKER)
REAL(USTAR,HZ0,DZ0,MULT,HLEN,DIREC,VG,VREF)
REAL(ZED0,ZED02,UP,UPD,TOP,TPD,SD,SDD,AKE0,HZ01,AK)
REAL(BH,MH,MS,THETAB,VB,VBX,VBZ)
INTEGER(NXB1,NXB2,NYB1,NYB2,NZB1,NZB2)
INTEGER(NZUP,NBL,NYTP,NXSD,NZHW,NXMID,NZDN)
INTEGER(NXBOX,NYBOX,NYBOOM,NZBOX,NXM1,NXM2,NYM1,NYM2)
INTEGER(NXS1,NXS2,NYS1,NYS2,NXEX,NZMS,NZEX,NZM,NZS)
  The MAST height of 30.0m is used as the reference length.  The ground
  roughness is now set to 0.001m.
MH=1.0;HZ0=30000;ZED0=MH/HZ0;AK=0.41;HZ01=HZ0+1.0
   Mast height and boom height
MH=1.0;BH=MH/10;MS=0.2
VREF=1.6
USTAR=VREF*AK/LOG(HZ01)
AKE0=USTAR*USTAR/SQRT(0.09)
DIREC=6.0*3.14159/180.0
THETAB=-30.0*3.14159/180.0
VB=0.6*VREF;VBX=VB*SIN(THETAB);VBZ=VB*COS(THETAB)
  The MAST height MH, main to spinnaker distance MS
  and half length HLEN are all a ratioed to the mast height.
HLEN=0.25*MH
  The domain has boudaries 8*MH away from the sails and is 8*MH high.
UP=7.0*MH+0.5*MS;UPD=UP-0.5*MS-0.5*MH;TOP=8.0*MH;TPD=TOP-1.5*MH
SD=7.0*MH+HLEN;SDD=SD-HLEN-0.5*MH
DZ0=TOP/ZED0+1.0;VG=USTAR*LOG(DZ0)/AK
  Surface roughness other than ground is set to 0.0001m.
ZED02=0.0001/30.0
  The number of cells in each region are set as follows.
NXEX=6;NZEX=6;NZMS=6
NYBOOM=4;NYBOX=25;NXBOX=26+2*NXEX;NZBOX=NZMS+NZEX
NZUP=14;NBL=6;NYTP=14;NXSD=12;NZDN=12
NZHW=1;NXMID=0
NXB1=NXSD+1;NXB2=NXSD+NXBOX;NYB1=NYBOOM+1
NYB2=NYBOOM+NYBOX
NZB1=NZUP+1;NZB2=NZUP+NZBOX
NXM1=NXB1+12+NXEX;NXM2=NXB1+25+NXEX;NYM1=NYB1;NYM2=NYB2
NXS1=NXB1+NXEX;NXS2=NXB1+12+NXEX;NYS1=NYB1;NYS2=NYB2-5
NZM=NZB1;NZS=NZB1+NZMS
    GROUP 2. Transience; time-step specification
    GROUP 3. X-direction grid specification
NX=2*NXSD+NXBOX
XULAST=2*SD
    GROUP 4. Y-direction grid specification
NY=NYBOOM+NYBOX+NBL+NYTP
YVLAST=TOP;DZ0=TOP/ZED0
    GROUP 5. Z-direction grid specification
NZ=NZUP+NBL+NZBOX+NZDN
ZWLAST=2*UP
    GROUP 6. Body-fitted coordinates or grid distortion
BFC=T;NONORT=T;MULT=2**0.5
UUP=T;VUP=T
NCRT=1;SYMBFC=T
READCO(grid)
      GROUP 7. Variables stored, solved & named
SOLVE(P1,U1,V1,W1,KE,EP)
SOLUTN(P1,Y,Y,Y,N,N,N)
STORE(UCRT,VCRT,WCRT)
```

```
    GROUP 8. Terms (in differential equations) & devices
DIFCUT=0.0
    GROUP 9. Properties of the medium (or media)
ENUL=5.1E-7;RHO1=1.0;ENUT=GRND3;EL1=GRND4
    GROUP 10. Inter-phase-transfer processes and properties
    GROUP 11. Initialization of variable or porosity fields
INIADD=F
PATCH(START,INIVAL,1,NX,1,NY,1,NZ,1,1)
INIT(START,P1,0.0,1E-3);INIT(START,U1,0.0,GRND)
INIT(START,V1,0.0,0.0);INIT(START,W1,0.0,GRND)
INIT(START,KE,0.0,GRND);INIT(START,EP,0.0,GRND)
  RESTRT(ALL)
    GROUP 12. Unused
    GROUP 13. Boundary conditions and special sources
PATCH(TOP,NORTH,1,NX,NY,NY,1,NZ,1,1)
COVAL(TOP,U1,GRND8,GRND8);COVAL(TOP,W1,GRND8,GRND8)
COVAL(TOP,KE,GRND8,GRND8);COVAL(TOP,EP,GRND8,GRND8)

CONPOR(MAIN,0.0,LOW,NXM1,NXM2,NYM1,NYM2,NZM,NZM)
CONPOR(SPINAK,0.0,LOW,NXS1,NXS2,NYS1,NYS2,NZS,NZS)

PATCH(KESO1,PHASEM,1,NX,2,NY,1,NZ,1,1)
COVAL(KESO1,KE,GRND4,GRND4);COVAL(KESO1,EP,GRND4,GRND4)

PATCH(INLETZ,LOW,1,NX,1,NY,1,1,1,1)
COVAL(INLETZ,P1,FIXFLU,GRND2);COVAL(INLETZ,U1,ONLYMS,GRND2)
COVAL(INLETZ,V1,ONLYMS,0.0);COVAL(INLETZ,W1,ONLYMS,GRND2)
COVAL(INLETZ,KE,ONLYMS,GRND2);COVAL(INLETZ,EP,ONLYMS,GRND2)

PATCH(OUTLETZ,HIGH,1,NX,1,NY,NZ,NZ,1,1)
COVAL(OUTLETZ,P1,FIXFLU,GRND2);COVAL(OUTLETZ,U1,ONLYMS,GRND2)
COVAL(OUTLETZ,V1,ONLYMS,0.0);COVAL(OUTLETZ,W1,ONLYMS,GRND2)
COVAL(OUTLETZ,KE,ONLYMS,GRND2);COVAL(OUTLETZ,EP,ONLYMS,GRND2)

  PATCH(OUTLETZ,HIGH,1,NX,1,NY,NZ,NZ,1,1)
  COVAL(OUTLETZ,P1,FIXVAL,0.0);COVAL(OUTLETZ,U1,FIXVAL,GRND2)
  COVAL(OUTLETZ,V1,ONLYMS,SAME);COVAL(OUTLETZ,W1,ONLYMS,SAME)
  COVAL(OUTLETZ,KE,ONLYMS,SAME);COVAL(OUTLETZ,EP,ONLYMS,SAME)

PATCH(INLETX,WEST,1,1,1,NY,1,NZ,1,1)
COVAL(INLETX,P1,FIXFLU,GRND1);COVAL(INLETX,U1,ONLYMS,GRND1)
COVAL(INLETX,V1,ONLYMS,0.0);COVAL(INLETX,W1,ONLYMS,GRND1)
COVAL(INLETX,KE,ONLYMS,GRND1);COVAL(INLETX,EP,ONLYMS,GRND1)

  PATCH(OUTLETX,EAST,NX,NX,1,NY,1,NZ,1,1)
  COVAL(OUTLETX,P1,FIXFLU,GRND1);COVAL(OUTLETX,U1,ONLYMS,GRND1)
  COVAL(OUTLETX,V1,ONLYMS,0.0);COVAL(OUTLETX,W1,ONLYMS,GRND1)
  COVAL(OUTLETX,KE,ONLYMS,GRND1);COVAL(OUTLETX,EP,ONLYMS,GRND1)

PATCH(OUTLETX,EAST,NX,NX,1,NY,1,NZ,1,1)
COVAL(OUTLETX,P1,FIXVAL,0.0);COVAL(OUTLETX,U1,ONLYMS,SAME)
COVAL(OUTLETX,V1,ONLYMS,SAME);COVAL(OUTLETX,W1,FIXVAL,GRND1)
COVAL(OUTLETX,KE,ONLYMS,SAME);COVAL(OUTLETX,EP,ONLYMS,SAME)

PATCH(GROUND,SOUTH,1,NX,1,1,1,NZ,1,1)
COVAL(GROUND,U1,GRND6,-VBX);COVAL(GROUND,W1,GRND6,-VBZ)
COVAL(GROUND,KE,GRND6,GRND6);COVAL(GROUND,EP,GRND6,GRND6)

PATCH(WINW1,HIGH,NXM1,NXM2,NYM1,NYM2,NZM-1,NZM-1,1,1)
COVAL(WINW1,U1,GRND7,0.0);COVAL(WINW1,V1,GRND7,0.0)
COVAL(WINW1,W1,FIXVAL,0.0)
COVAL(WINW1,KE,GRND7,GRND7);COVAL(WINW1,EP,GRND7,GRND7)
```

```
PATCH(LEEW1,LOW,NXM1,NXM2,NYM1,NYM2,NZM,NZM,1,1)
COVAL(LEEW1,U1,GRND7,0.0);COVAL(LEEW1,V1,GRND7,0.0)
COVAL(LEEW1,KE,GRND7,GRND7);COVAL(LEEW1,EP,GRND7,GRND7)

PATCH(WINW2,HIGH,NXS1,NXS2,NYS1,NYS2,NZS-1,NZS-1,1,1)
COVAL(WINW2,U1,GRND7,0.0);COVAL(WINW2,V1,GRND7,0.0)
COVAL(WINW2,W1,FIXVAL,0.0)
COVAL(WINW2,KE,GRND7,GRND7);COVAL(WINW2,EP,GRND7,GRND7)

PATCH(LEEW2,LOW,NXS1,NXS2,NYS1,NYS2,NZS,NZS,1,1)
COVAL(LEEW2,U1,GRND7,0.0);COVAL(LEEW2,V1,GRND7,0.0)
COVAL(LEEW2,KE,GRND7,GRND7);COVAL(LEEW2,EP,GRND7,GRND7)
    GROUP 14. Downstream pressure for PARAB=.TRUE.
    GROUP 15. Termination of sweeps
LSWEEP=200
    GROUP 16. Termination of iterations
RESREF(P1)=XULAST*YVLAST*1E-6;RESREF(U1)=XULAST*YVLAST*1E-6
RESREF(V1)=XULAST*YVLAST*1E-6;RESREF(W1)=XULAST*YVLAST*1E-6
RESREF(KE)=XULAST*YVLAST*1E-6*USTAR*USTAR*3.33
RESREF(EP)=XULAST*YVLAST*1E-6*(USTAR**3)*LOG(DZ0)
    GROUP 17. Under-relaxation devices
RELAX(U1,FALSDT,0.1);RELAX(V1,FALSDT,0.1)
RELAX(W1,FALSDT,0.1);RELAX(KE,LINRLX,0.5)
RELAX(EP,LINRLX,0.5);RELAX(P1,LINRLX,0.1)
KELIN=0
    GROUP 18. Limits on variables or increments to them
    GROUP 19. Data communicated by satellite to GROUND
GENK=T
RSG23=VBX;RSG24=VBZ;RSG15=DIREC;RSG16=VG
RSG26=USTAR;RSG28=ZED02;RSG25=ZED0;RSG27=RHO1
  LSG9 switch on sail force calculations
LSG9=T
ISG1=NXM1;ISG2=NXM2;ISG3=NYM1;ISG4=NYM2;ISG5=NZM
ISG6=NXS1;ISG7=NXS2;ISG8=NYS1;ISG9=NYS2;ISG10=NZS
    GROUP 20. Preliminary print-out
TSTSWP=-1;ECHO=T
    GROUP 21. Print-out of variables
INIFLD=F
    GROUP 22. Spot-value print-out
IXMON=NXM1+6;IYMON=NYM1+10;IZMON=NZS
    GROUP 23. Field print-out and plot control
IXPRF=1;IXPRL=NXB2+2;IYPRF=1;IYPRL=NYB2+2;IZPRF=NZM-2;IZPRL=NZB2+2
YZPR=F;NXPRIN=1;NYPRIN=1;NZPRIN=1;ITABL=2
    GROUP 24.
AUTOPS=F
SAVE=T
STOP
```

Appendix B. Extracts from the GROUND file

```
C.... FILE NAME GROUND.FTN--------------------------------230597
      SUBROUTINE GROUND
*****************************************************************

C 2   User dimensions own arrays here, for example:
C      DIMENSION GUH(10,10),GUC(10,10),GUX(10,10),GUZ(10)
       DIMENSION CEN(140,120)
       DIMENSION PT1(3),PT2(3),PT3(3),PT4(3),VEC(3)
       DATA NXDIM,NYDIM/140,120
*****************************************************************

1      CALL WRYT40('GROUND file is GROUND.F   of: PJR26100 ')
C  Store for distance from the ground
      IF(.NOT.BFC) THEN
          CALL MAKE(YV2D)
          CALL MAKE(DYV2D)
       ENDIF
       CALL MAKE(YG2D)
*****************************************************************

C   A number of GRSP arrays are made for later use.
       RETURN
*****************************************************************

C--- GROUP 11. Initialization of variable or porosity fields
C                                                  Index VAL
11     CONTINUE
       CALL SUB3R(USTAR,RSG26,ZED,RSG25,DIREC,RSG15)
       IF (LSG9)CALL SUB2R(VBX,RSG23,VBZ,RSG24)
       IF(BFC)THEN
       CALL GTIZYX(69,IZ,CEN,NYDIM,NXDIM)
       CALL SETYX(GRSP2,CEN,NYDIM,NXDIM)
       ELSE
       CALL FN0(GRSP2,YG2D)
       ENDIF
       CALL FN2(GRSP2,GRSP2,ZED,1.0)
       CALL FN2(GRSP1,GRSP2,0.0,1.0/ZED)
       CALL FN43(GRSP1,GRSP1,1.0,0.0)
       CALL FN25(GRSP1,USTAR/AK)
       IF(INDVAR.EQ.U1)CALL FN2(VAL,GRSP1,0.0,SIN(DIREC))
       IF(INDVAR.EQ.U1.AND.LSG9)CALL FN33(VAL,-VBX)
       IF(INDVAR.EQ.W1)CALL FN2(VAL,GRSP1,0.0,COS(DIREC))
       IF(INDVAR.EQ.W1.AND.LSG9) CALL FN33(VAL,-VBZ)
       IF(INDVAR.EQ.KE) CALL FN1(VAL,USTAR*USTAR/SQRT(CMUCD))
       IF(INDVAR.EQ.EP) CALL FN28(VAL,GRSP2,USTAR*USTAR*USTAR/AK)
       RETURN
*****************************************************************
```

Wall function routines for X and Y plane walls are similar to those for the Z plane walls shown below, except that the Y plane walls change the roughness length to the rougher zed0 of the ground if the patch name begins with ‘GRO’.

```
*****************************************************************

137    CONTINUE
C------------------- SECTION  8 ------------- coefficient = GRND7
C   Wall functions for Z plane walls
C   GRSP3 initially is set to twice the normal distance of the node  from
C   the low and high  faces.  GRSP5 holds AK/ln(dist/zed+1.0)
       IF(BFC) THEN
          CALL GTIZYX(15,IZ,CEN,NYDIM,NXDIM)
          CALL SETYX(GRSP3,CEN,NYDIM,NXDIM)
```

```
       CALL FN2(GRSP3,GRSP3,0.0,2.0)
       ELSE
          CALL FN1(GRSP3,DZ)
       ENDIF
       ZED=RSG28
       RO1=RSG27
       CALL FN43(GRSP5,GRSP3,0.5/ZED,1.0)
       CALL FN28(GRSP5,GRSP5,AK)
C   The magnitude of the velocity parallel to the wall is put into GRSP4
       CALL FN29(GRSP4,1,3,IU,IV,IW)
       IF(INDVAR.LT.KE) THEN
          CALL FN55(CO,GRSP4,GRSP5,GRSP5,RO1)
       ELSE
          CALL FN2(GRSP6,GRSP3,1.0,1.0/ZED)
          CALL FN43(GRSP6,GRSP6,1.0,0.0)
          CALL FN55(CO,GRSP4,GRSP5,GRSP6,RO1*SQRT(CMUCD)/AK)
      ENDIF
      IF(LSG9) THEN
          NXM1=ISG1
          NXM2=ISG2
          NYM1=ISG3
          NYM2=ISG4
          NZM=ISG5
          NXS1=ISG6
          NXS2=ISG7
          NYS1=ISG8
          NYS2=ISG9
          NZSPIN=ISG10
       ENDIF
C  The following lines carry out the pressure integration on the mainsail.
      IF(LSG9 .AND. IZSTEP.EQ.NZM .AND. ISWEEP.EQ.LSWEEP-1) THEN
          CALL FNAV(EASP15,P1,'LOW')
          CALL FN34(EASP15,P1,-1.0)
          LFP1=L0F(EASP15)
          SUMMX=0.0
          SUMMY=0.0
          SUMMZ=0.0
          AMAIN=0.0
          AMAINZ=0.0
          DO 3335 II=NXM1,NXM2
          DO 3335 JJ=NYM1,NYM2
             PT1(1)=XC(II,JJ,IZ)
             PT1(2)=YC(II,JJ,IZ)
             PT1(3)=ZC(II,JJ,IZ)
             PT2(1)=XC(II+1,JJ,IZ)
             PT2(2)=YC(II+1,JJ,IZ)
             PT2(3)=ZC(II+1,JJ,IZ)
             PT3(1)=XC(II+1,JJ+1,IZ)
             PT3(2)=YC(II+1,JJ+1,IZ)
             PT3(3)=ZC(II+1,JJ+1,IZ)
             PT4(1)=XC(II,JJ+1,IZ)
             PT4(2)=YC(II,JJ+1,IZ)
             PT4(3)=ZC(II,JJ+1,IZ)
             CALL AREA4(PT1,PT2,PT3,PT4,AREA,VEC)
             AMAIN=AMAIN+AREA
             AMAINZ=AMAINZ+AREA*VEC(3)
             L1=LFP1+JJ+NY*(II-1)
             DELP=2.0*F(L1)
             SUMMX=SUMMX+DELP*AREA*VEC(1)
             SUMMY=SUMMY+DELP*AREA*VEC(2)
             SUMMZ=SUMMZ+DELP*AREA*VEC(3)
3335      CONTINUE
       ENDIF
```

```
*****************************************************************
C   A similar routine is used for pressure integration on the spinnaker.
*****************************************************************

       IF(LSG9 .AND. ISWEEP.EQ.LSWEEP-1) THEN
          WRITE(14,*)'/***AMAIN,AMAINZ,MAINFX,MAINFY,MAINFZ**/'
          WRITE(14,3333)AMAIN,AMAINZ,SUMMX,SUMMY,SUMMZ
          WRITE(14,*)'/***ASPIN,ASPINZ,SPINFX,SPINFY,SPINFZ**/'
          WRITE(14,3333)ASPIN,ASPINZ,SUMSX,SUMSY,SUMSZ
3333      FORMAT(5(F10.6))
       ENDIF
       RETURN
138    CONTINUE
C------------------- SECTION  9 ------------- coefficient = GRND8
C Coefficient for diffusion sources at the top of the domain
       CALL SUB3R(USTAR,RSG26,ZED,RSG25,DIREC,RSG15)
       IF(BFC)THEN
          CALL GTIZYX(13,IZ,CEN,NYDIM,NXDIM)
          CALL SETYX(GRSP1,CEN,NYDIM,NXDIM)
          CALL FN2(GRSP1,GRSP1,0.0,2.0)
       ELSE
          CALL FN10(GRSP1,YV2D,YG2D,0.0,2.0,-2.0)
       ENDIF
       CALL FN103(GRSP2,VIST,2)
       CALL FN10(CO,VIST,GRSP2,ENUL,1.0,-0.5)
       CALL FN27(CO,GRSP1)
       CALL FN25(CO,1.0/PRT(INDVAR))
       RETURN
139    CONTINUE
*****************************************************************

C------------------- SECTION 14 ------------------- value = GRND2
C      Inlet boundary conditions
       VALGRN=ISC-12
       CALL SUB4R(USTAR,RSG26,RO1,RSG27,ZED,RSG25,DIREC,RSG15)
       IF (LSG9) CALL SUB2R(VBX,RSG23,VBZ,RSG24)
       IF(BFC)THEN
          CALL GTIZYX(69,IZ,CEN,NYDIM,NXDIM)
          CALL SETYX(GRSP2,CEN,NYDIM,NXDIM)
       ELSE
          CALL FN0(GRSP2,YG2D)
       ENDIF
       CALL FN2(GRSP2,GRSP2,ZED,1.0)
       CALL FN43(GRSP1,GRSP2,1.0/ZED,0.0)
       CALL FN25(GRSP1,USTAR/AK)
       AKE0=USTAR*USTAR/SQRT(CMUCD)
       IF(VALGRN.EQ.1) THEN
          IF(INDVAR.EQ.P1) THEN
             CALL FN2(VAL,GRSP1,0.0,RO1*SIN(DIREC))
             IF(LSG9) CALL FN33(VAL,-VBX*RO1)
             IF(NPATCH(1:3).EQ.’OUT’)CALL FN2(VAL,VAL,0.0,-1.0)
          ENDIF
          IF(INDVAR.EQ.U1)CALL FN2(VAL,GRSP1,0.0,SIN(DIREC))
          IF(INDVAR.EQ.U1.AND.LSG9) CALL FN33(VAL,-VBX)
          IF(INDVAR.EQ.W1) CALL FN2(VAL,GRSP1,0.0,COS(DIREC))
          IF(INDVAR.EQ.W1.AND.LSG9) CALL FN33(VAL,-VBZ)
          IF(INDVAR.EQ.KE) CALL FN1(VAL,AKE0)
          IF(INDVAR.EQ.EP) CALL FN28(VAL,GRSP2,USTAR*USTAR*USTAR/AK)
       ELSE
          IF(INDVAR.EQ.P1) THEN
             CALL FN2(VAL,GRSP1,0.0,RO1*COS(DIREC))
             IF(LSG9) CALL FN33(VAL,-VBZ*RO1)
             IF(NPATCH(1:3).EQ.’OUT’)CALL FN2(VAL,VAL,0.0,-1.0)
```

```
          ENDIF
          IF(INDVAR.EQ.U1) CALL FN2(VAL,GRSP1,0.0,SIN(DIREC))
          IF(INDVAR.EQ.U1.AND.LSG9) CALL FN33(VAL,-VBX)
          IF(INDVAR.EQ.W1) CALL FN2(VAL,GRSP1,0.0,COS(DIREC))
          IF(INDVAR.EQ.W1.AND.LSG9) CALL FN33(VAL,-VBZ)
          IF(INDVAR.EQ.KE) CALL FN1(VAL,AKE0)
          IF(INDVAR.EQ.EP) CALL FN28(VAL,GRSP2,USTAR*USTAR*USTAR/AK)
       ENDIF
       RETURN
1314   CONTINUE
*****************************************************************

1318   CONTINUE
C------------------- SECTION 19 ------------------- value = GRND7
C   Wall functions for Z plane walls
C   The VALue for KE is set to USTAR**2/SQRT(CMUCD)
       IF(INDVAR.EQ.KE) THEN
          CALL FN21(VAL,GRSP4,GRSP5,0.0,1.0)
          CALL FN72(VAL,VAL,1.0/SQRT(CMUCD),2)
       ENDIF
C   The VALue of EP is set to SQRT(CMUCD)*KE*USTAR/(AK*(dist+ZED))
       IF(INDVAR.EQ.EP) THEN
          CALL FN2(GRSP3,GRSP3,ZED,0.5)
          CALL FN21(GRSP4,GRSP4,GRSP5,0.0,1.0)
          CALL FN56(VAL,GRSP4,KE,GRSP3,SQRT(CMUCD)/AK)
       ENDIF
       RETURN
1319   CONTINUE
C------------------- SECTION 20 ------------------- value = GRND8
C   The velocity half a cell above the top of the domain.
       CALL SUB3R(USTAR,RSG26,ZED,RSG25,DIREC,RSG15)
       IF (LSG9) CALL SUB2R(VBX,RSG23,VBZ,RSG24)
       IF(BFC)THEN
          CALL GTIZYX(69,IZ,CEN,NYDIM,NXDIM)
          CALL SETYX(GRSP2,CEN,NYDIM,NXDIM)
          CALL GTIZYX(13,IZ,CEN,NYDIM,NXDIM)
          CALL SETYX(GRSP1,CEN,NYDIM,NXDIM)
       ELSE
          CALL FN0(GRSP2,YG2D)
          CALL FN10(GRSP1,YV2D,YG2D,0.0,2.0,-2.0)
       ENDIF
       CALL FN10(GRSP1,GRSP2,GRSP1,ZED,1.0,1.0)
       IF(INDVAR.LT.KE) THEN
          CALL FN43(VAL,GRSP1,1.0/ZED,0.0)
          CALL FN25(VAL,USTAR/AK)
       IF(INDVAR.EQ.U1) THEN CALL FN25(VAL,SIN(DIREC))
       IF((INDVAR.EQ.U1AND.LSG9) THEN CALL FN33(VAL,-VBX)
       IF(INDVAR.EQ.W1)THEN CALL FN25(VAL,COS(DIREC))
       IF((INDVAR.EQ.W1.AND.LSG9) THEN
          CALL FN33(VAL,-VBZ)
       ELSEIF(INDVAR.EQ.KE) THEN
          CALL FN1(VAL,USTAR*USTAR/SQRT(CMUCD))
       ELSE
          CALL FN28(VAL,GRSP1,USTAR*USTAR*USTAR/AK)
       ENDIF
       RETURN
*****************************************************************
```