SAILING YACHT PERFORMANCE : THE EFFECTS OF HEEL ANGLE AND LEEWAY ANGLE ON RESISTANCE AND SIDEFORCE

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ABSTRACT

A racing yacht sails in perfect balance of aerodynamic, hydrodynamic and hydrostatic forces with a leeway angle and a heel angle. The balance of forces and moments must be solved to obtain sailing leeway and heel angles and predict the speed of the yacht. In this paper, an approach based on towing tank tests and aerodynamic sail data is presented to solve this task.

An elementary background theory of aerodynamic and hydrodynamic forces and moments due to sail and the hull is given to present the balance equations. Aerodynamic forces are introduced by sail lift and drag coefficients. Hydrodynamic forces are derived from towing tank tests for several heel and leeway angles by use of a dedicated experimental system based on a six component balance dynamometer. A PC based data acquisition system is utilised to collect tank data. A typical sailing yacht model at l/8 scale is used for towing tank tests. Towing tank tests are analyzed to investigate the effects of heel angle and leeway angle on the resistance and sideforce generated by the hull. And finally, a VPP analysis is carried out to derive the performance curves.

NOMENCLATURE

$B_{0,2,3}$	: Constant
$C_{0,2,3}$	: Constant
CLR	: Centre of lateral resistance
COE	: Centre of effort
C_H	: Aerodynamic heeling force coefficient
C_F	: Skin friction coefficient
C_R	: Aerodynamic driving force coefficient
C_I	: Induced resistance coefficient
D	: Drag
F_H	: Aerodynamic heeling force
F_{LAT}	: Horizontal aerodynamic force
F_R	: Aerodynamic driving force
FN	: Froude number
F_S	: Hydrodynamic side force
F_{S-HOR}	: Hydrodynamic side force
F_V	: Vertical aerodynamic force
F_{VW}	: Vertical hydrodynamic force
k	: Form coefficient
L	: Lift
LWL	: Load waterline
M_H	: Heeling moment
M_{PA}	: Air trimming moment
M_{PW}	: Water trimming moment
M_R	: Righting moment
M_{YL}	: Water yawing moment
M_{YW}	: Air yawing moment
R	: Hydrodynamic resistance
RA	: Righting arm
Re	: Reynolds number
R_F	: Frictional resistance
R_H	: Resistance due to heel
R_I	: Induced resistance
R_T	: Total resistance
R_V	: Viscous resistance
R_W	: Wave resistance
S_A	: Sail area
V_A	: Apparent wind speed
V_{MG}	: Speed made good
V_S	: Boat speed
V_T	: True wind speed
WSA	: Wetted surface area
β	: Apparent wind angle
ε_A	: Aerodynamic efficiency angle
ε_H	: Hydrodynamic efficiency angle
A	: Displacement
γ	: True wind angle
λ	: Leeway or yaw angle
ν(nu)	: Kinematic viscosity
ρ_A(rho)	: Mass density of air
θ	: Angle of heel

INTRODUCTION

There has been recently some interest in sailing yacht racing in Turkey. A study of sailing yacht performance in the design stage has been started Istanbul Technical University, and first stage of this study is presented in this paper.

Performance prediction of sailing yachts is of a complex nature, and differs from conventional ship performance prediction due to presence of leeway angle, hence the sideforce associated with it. The resistance and side force prediction of a yacht is a complicated hydrodynamic problem because of asymmetrical flow about the hull. Experimental methods are being utilised widely for performance predictions.

An experimental approach (Dayi 1991) has been developed to measure the resistance, side force, yawing moment, heeling moment, sinkage and trim angle of a yacht sailing in fixed heel angle and leeway angle at a certain speed in ITU., Ata Nutku Ship Model Testing Laboratory (ANSMTL). The approach has been verified by experiments on a sailing yacht model at l/8 scale with five different keels. The variation of total resistance and sideforce have been investigated by changing the heel angle, leeway angle, speed and keel characteristics. Hydrodynamic efficiency of the hull (sideforce/resistance) is demonstrated.

Based on aerodynamic data and towing tank data, a velocity prediction program has been developed to predict the yacht speed at any arbitrary true wind angle and true wind speed (Helvacioglu and Insel 1994).

THE BALANCE OF AERODYNAMIC AND HYDRODYNAMIC FORCES

The aerodynamic forces acting on a sail and hydrodynamic-hydrostatic forces acting on a hull must be balanced for a sailing yacht. The forces and their relative positions, hence the moments, are given in Figure 1. Aerodynamic forces are generated by the wind with a true wind speed (V_T) at a true wind angle of (γ). However wind forces act on the sail relative to the yacht, that is at apparent wind angle (β) and at apparent wind speed (V,). Figure 1d is called aerodynamic wind triangle. It may be observed that speed against wind direction, or speed made good, can be calculated as $V_{MG}=V_S \text{ Cos}(\gamma)$. This speed is the most important feature in yacht racing. The six force-moment balance equations for a yacht can be written as :

1. $F_R=R$		4. $M_{PA}=M_P$		
2. $F_H=F_S$	FORCES	5. $M_H=M_R$	MOMENTS	(1)
3. $F_V=F_{VW}$		6. $M_{YW}=M_{YL}$		

a) **<u>Horizontal plane</u>** : If the forces on the horizontal plane are considered (Figure lc), aerodynamic driving force (F_R) acting on the sail at the centre of effort (COE) is balanced by the hydrodynamic resistance force (R) acting on the hull at the centre of lateral resistance (CLR).
The horizontal aerodynamic force (F_{LAT}) must be balanced by a hydrodynamic side force ($F_{S\text{-}HOR}$). Such a side force can only be generated by giving the hull a leeway angle (λ) for a symmetric yacht form. Increasing the speed of the yacht increases the aerodynamic force, hence the leeway angle must be increased to balance the yacht. But this also causes an increase in the resistance, consequently reduction in yacht speed. The moment generated due to the distance between CLR_X and COE, must be compensated by rudder moments, which in turn increases the resistance. In a well balanced yacht design, CLR must correspond to COE for optimum performance.

b) **Cross Sectional Plane :** The aerodynamic heeling force (F_H) and hydrodynamic force (F,) creates a heeling moment which is balanced by mainly hydrostatic righting moment of A RA (Figure 1b). Such a balance necessitates a heel angle under sailing conditions. As the aerodynamic lateral force increases by the yacht speed, the heel angle must also increase. The aerodynamic force in the vertical direction is at a smaller magnitude, and balanced by the increase of hull draft (sinkage).

c) LogitudinalPlane : The longitudinal and vertical forces (Figure la) are balanced as given in the previous planes. The trimming moment (M_{PA}) is caused by the difference of aerodynamic and hydrodynamic force acting points in vertical direction **(COE_Z-CLR_Z)**, and balanced by trim angle change.

AERODYNAMIC FORCES

The sails behave like thin aerofoil at an angle of attack. The shape of the aerofoil is depend on the flat, or reef, given by the yachtsmen. Aerodynamic drag and lift components are generated at the same direction of apparent wind and normal to apparent wind respectively (Figure 2). The angle between lift and total aerodynamic force represents aerodynamic efficiency (Cot ε_A=L/D). These forces can also be represented in the axis system defined by yacht course, which can be expressed as driving force and heeling force.

$$F_R = L \sin\beta - D \cos\beta = 0.5\, C_R\, \rho_A\, S_A\, V_A^2 \qquad (2)$$
$$F_H = L \cos\beta + D \sin\beta = 0.5\, C_H\, \rho_A\, S_A\, V_A^2$$

Assuming maximum lift efficiency is obtained for the sail, driving force, heeling force can be obtained as a function of apparent wind angle (β). An example of such case is given in Figure 3a and 3b.

Although aerodynamic driving force and heeling force are not effected by the leeway angle, they are highly effected by the heel angle. As the heel angle increase both driving and heeling forces are reduced with increasing heel angle (Kerwin 1976), which can be assumed to be linear.

$$C_R = C_{R0}\,(1\text{-}a\,\theta) \qquad (3)$$
$$C_H = C_{H0}\,(1\text{-}b\,9)$$

Driving force and heeling forces for a particular sail rig can be determined by :

a) Aerodynamic theory, by use of lifting line/lifting surface calculations (Milgram 1970)
b) Wind Tunnel tests (Marchaj 1990)
c) Full Scale Trials (Davidson 1936)

HYDRODYNAMIC FORCES

The flow about hull at a heel and a leeway angle is quite complex due to both asymmetry and the interface between water and air. Hence assumptions must be introduced to simplify the force-moment balance. Firstly resistance force can be assumed to be made up of a viscous component associated with skin friction and form drag, and a pressure component associated with wavemaking. Resistance change by the heel and leeway is assumed to consist of only pressure component which can be scaled from model tests to yacht scale by Froude' method and have no influence on viscous resistance.

$$R_T = R_V + R_W + R_H + R_I \qquad (4)$$

a) **Viscous Resistance (R_V=(1+k) R_F)** : Viscous resistance originates from the energy lost in frictional loses and creating vortices, turbulence. Frictional resistance can be estimated from

$$R_F=C_F\ 0.5\ \rho\ WSA\ V_S \quad (5)$$

where C_F is skin frictional line which can be obtained from ITTC 1957 or Schoenherr lines;

$$C_F=0.075/(\log Re -2)^2 \quad (6)$$

where Re is calculated by an effective length for the hull typically 0.7 L_{WL}, i.e.

$$Re=0.7\ V_S\ L_{WL}/\upsilon \quad (7)$$

Form drag is due to three dimensional effects of viscous flow, and can be assumed to be equal to kR_F. form coefficient can be obtained from Prohaska method following ITTC recommendations, a typical example is given in Figure 4. Frictional drag of hull, keel and rudder must be calculated separately,

b) **Wave Resistance (R_W)** : Wave resistance is assumed to be the difference between total resistance and viscous resistance in upright condition, i.e. zero heel angle and zero leeway angle, mainly consists of energy lost in creating waves. Prediction of wave resistance of a yacht is difficult due to the shape of the hull. Delft yacht series (Gerritsma et al 1991) forms the main data source in the literature. In practice towing tank test are used as the most reliable method available.

c) Resistance due to Heel (R_H) : Resistance change between the heeled case and upright condition is called resistance due to heel. The resistance change due to heel at zero side force is governed by the hull shape. A narrow yacht with circular sections would experience practically no change in resistance with heel at small angles, a reduction may also be possible. Meanwhile a yacht with large beam at the midship and fine ends would experience significant change. Heel resistance is expressed by Gerritsma et al (1992) as :

$$R_H=0.5\ \rho\ WSA\ V_S^2\ \theta\ Fn^2\ C_H \quad (8)$$

d) **Induced Resistance (R_I)** : As the hull sails with leeway, lift is generated which in turn causes an increase in the resistance, called induced drag. The induced drag is principally function of the effective aspect ratio of hull-keel combination and square of the sideforce coefficient.

$$R_I=0.5\ \rho\ WSA\ V_S^2\ C_I\ (F_S/0.5\ \rho\ WSA\ V^2)^2 \quad (9)$$

where C, depends on the shape of the keel, Froude number and heel angle, and can be expressed as

$$C_I=C_0+C_2\ \theta+C_3\ Fn \quad (10)$$

In addition to the resistance, the hull experiences a lift force with increasing leeway angle. In a racing yacht lift is mainly due to keel (up to 80 %). The hull and rudder contributes 20-50 % of the lift. Gerritsma et al (1993) gave the horizontal component of side force as a function of leeway angle, and froude number :

$$\lambda=F_S\ \cos\theta\ (B_0+B_2\ \theta^2)\ /\ 0.5\ \rho\ WSA\ V_S^2 +\ B_3\ \theta^2\ Fn \quad (11)$$

A hydrodynamic efficiency (cot $\varepsilon_H=F_S/R$) can be defined similar to the sail case. As aerodynamic and hydrodynamic forces are balanced, the angle of apperant wind must be equal to summation of aerodynamic and hydrodynamic efficiency angles $\beta=\varepsilon_A+\varepsilon_H$ (Figure 2).

TOWING TANK TEST TO DETERMINE HYDRODYNAMIC FORCES

Since Davidson (1936) introduced the principles of yacht testing, towing tanks have been utilised in performance prediction. The development of Australia II led to a combination of tank testing and velocity prediction programs for accurate speed predictions, such as required by

Americas Cup designs.

Analytical methods are also introduced as an alternative to the tank testing. However the accuracy of such methods are still limited, and their use are usually restricted to preliminary investigation of design alternatives, to reduce the tank testing expenses. Two types of model experiments have been utilised by the experimental tanks (Larsson 1990). Free to heel approach simulates the aerodynamic forces at the centre of effort (COE) and model is free to trim, heel, and yaw. Hence all the aerodynamic forces must be determined before the experiments and different set of experiment must be conducted for any change of sail configuration. The second approach fixes the heel angle and leeway angle. Resistance, and sideforce are measured for a set of heel angles and a set of leeway angles. An iterative technique can be applied to find a balance position from this data for a given sail configuration. This approach has been utilised for the current work.

A series of yacht tests have been conducted in ITU Ata Nutku Ship Model Testing Laboratory (ANSMTL). The towing tank is 160 m long, 6 m wide, and 3.4 m deep. A typical yacht model at l/8 scale has been used in the tests (see Table 1). Model and five keels with sections of NACA 63A0 15 were built from wood and turbulence studs at 25 % behind the leading edge were used on both hull and keels. In all tests the model was free to trim and sinkage, but fixed to heel, yaw and sway.

M199			Model	Yacht
Waterline Length	L_{WL}	m	2.000	16.000
Beam	B	m	0.656	5.248
Draft	T	m	0.125	1.000
Depth	D	m	0.250	2.000
Block Coefficient	C_B		0.343	0.343
Midship Section Coefficient	C_M		0.532	0.532
Prismatic Coefficient	C_P		0.656	0.656
Longitudinal Centre of Buoyancy	LCB	m	0.137	0.137
Wetted Surface Area	WSA	m^2	0.890	56.96
Displacement	Δ	kg	56.252	29521

Table 1: Model and yacht characteristics

Keel	Max Keel Length / Model Length	Depth (m)	Aspect Ratio	Keel Projection Area (m^2)	Sweptback Angle
B	0.1326	0.265	1.0	0.0703	20.0
C	0.1875	0.187	0.5	0.0703	20.0
D	0.1075	0.325	1.5	0.0703	20.0
F	0.1279	0.375	1.0	0.0703	15.5
H	0.1268	0.375	1.0	0.0703	15.5

Table 2: Keel characteristics

Measurement system consisted of a six component balance to measure resistance, side force, heeling **moment,** and **yaw moment. An** LVDT and a rotary **potentiometer have used for** sinkage and trim angle measurements. Bridge balance-amplifier system has been used in combination with six component balance to amplify signals. All measurement were recorded by a PC based data acquisition system and averaged (Dayi 1991).

The following procedure has been followed in the experiments :

a) Upright condition is tested (θ=0°, λ=0°) for 11 speeds
bl) Model set for a heel angle (θ=0°, 5°, 10°, 20°)
b2) Model set for a leeway angle (λ=-12°,-8°,-4°,0°,4°,8°,12°)
b3) Model tested for four speeds

THE EFFECT OF HEEL ANGLE AND LEEWAY ANGLE ON RESISTANCE AND SIDEFORCE

The effect of heel on resistance is generally to increase resistance (Figure 8). However some of the tank results show resistance decrease with heel angle increase. This is attributed to the wetted surface area decrease in heeled conditions.

If the hull-keel-rudder combination is considered as an symmetric aerofoil, the lift, i.e.sideforce, and resistance is increased by increase of angle of attack, leeway angle. The increase in resistance, i.e. induced drag (Figure 9), is proportional to the square of the sideforce. This can easily be seen from Figure 12 and 13.

The effect of leeway angle on sideforce is demonstrated in Figure 10. Sideforce is proportional to the leeway angle. At the highest speed tested (10 knots) and at high leeway angles (above 8 degrees), a decrease in sideforce was observed. This is resulted from the separation at high angle of attack similar aircraft stall. A nondimensional plot of leeway angle **vs** sideforce is given in Figure 11, displaying speed independence of sideforce coefficient as long as separation is avoided.

Typical sideforce square vs resistance curves are drawn in Figure 12 and 13 for two keel aspect ratios. In general the curves are almost linear, indicating induced drag is proportional to the sideforce square. As the speed increases the slope of the lines are decreases, hence a Froude number dependence in induced drag can be expected.

A comparison of two figures reveals that the high aspect keel is more efficient to generate side force with least drag penalty, which is expected from fundamental aerodynamics theory. Such conclusions are also supported by polar performance plots.

CALCULATION OF A YACHT PERFORMANCE

Prediction of yacht speed for a given true wind angle and wind speed can be calculated by an iterative calculation procedure called velocity prediction program (VPP). Such a program has been developed in ITU (Helvacioglu and Insel I994). The method utilises the towing test data and aerodynamic data consisting of lift and drag coefficients of a specific sail rig. In the current work Gimcrack data by Davidson (1939) is utilised as a benchmark (Marchaj 1990).

Firstly two equations are defined from velocity triangle (Figure lc) as:

$$V_S+V_T \cos\gamma=V_A \cos \beta \tag{12}$$
$$V_T \sin \gamma= V_A \sin \beta \tag{13}$$

Secondly the balance equations are simplified by assuming vertical forces are negligible, CLR and COE are coincident on the horizontal plane, hence yaw moments are negligible and pitching moment is compensated by the trim angle. The balance equations are reduced down to three for a balanced yacht

$$\begin{aligned} &F_R=R \\ &F_{LAT}=F_{S\text{-}HOR} \\ &F_H(COE_Z-CLR_Z)=RA\ A \end{aligned} \tag{14}$$

The iterative method does iterate V_S, leeway angle, heel angle in turn to satisfy all five equations for a true wind angle and wind speed. By changing wind angle from 0 to 360 degrees and wind speed within a suitable range all performance values can be determined. A polar performance diagram can be derived. This diagram is the most suitable way to compare two alternative designs such as keel variations. The effect of keel aspect ratio and sweptback angle is demonstrated in Figures 14 and 15 respectively by means of performance plots.

CONCLUSIONS

Sailing yacht balances aerodynamic and hydrodynamic forces. Such a balance is primarily based on the leeway angle and heel angle, Performance prediction of this type craft can be based on towing tank experiments with resistance and sideforce measurements. Future improvements are planned by inclusion of yaw moment for the inclusion of rudder angle in the performance predictions. Test with bulbous and winged keels are underway in ITU to demonstrate their capabilities.

The effect of heel is generally to increase the resistance, but no conclusions on the behaviour of resistance increase could be drawn from current experiments.

Sideforce is proportional to the leeway angle, Decrease of sideforce can be observed if separation is encountered. Induced resistance is proportional to leeway angle, or square of the sideforce.

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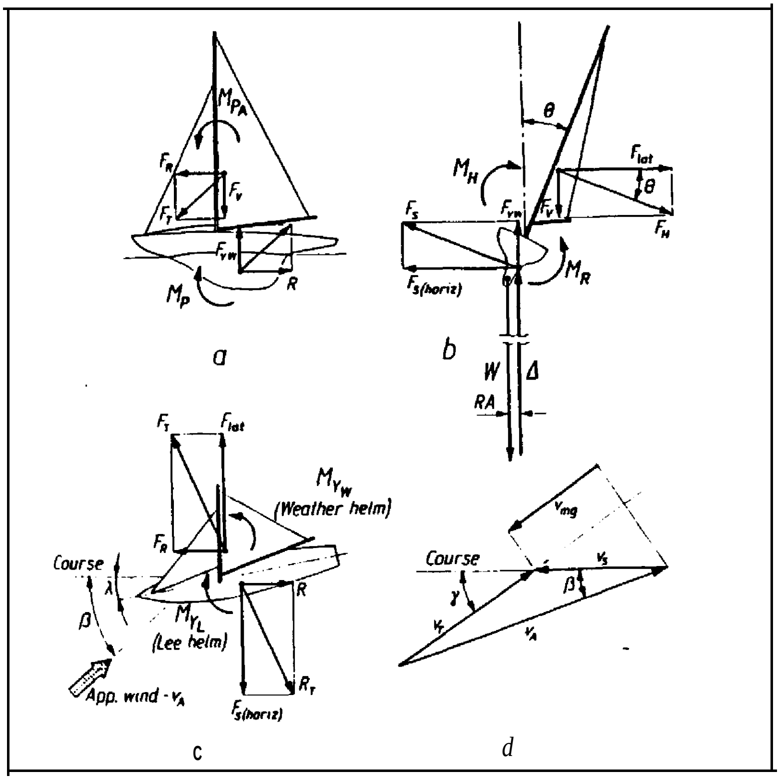

Figure 1: Balance of aerodynamic, hydrodynamic **and** hydrostatic forces and moments for a sailing hull

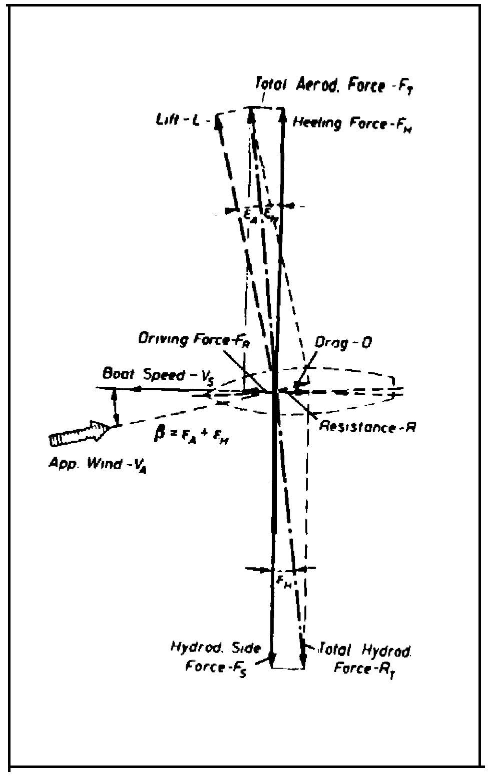

Figure 2: Aerodynamic and hydrodynamic forces on horizontal plane

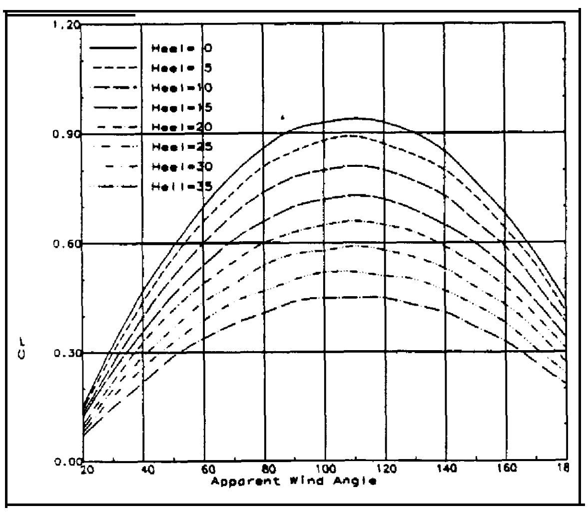

Figure 3a: Typical sail driving force coefficient curves

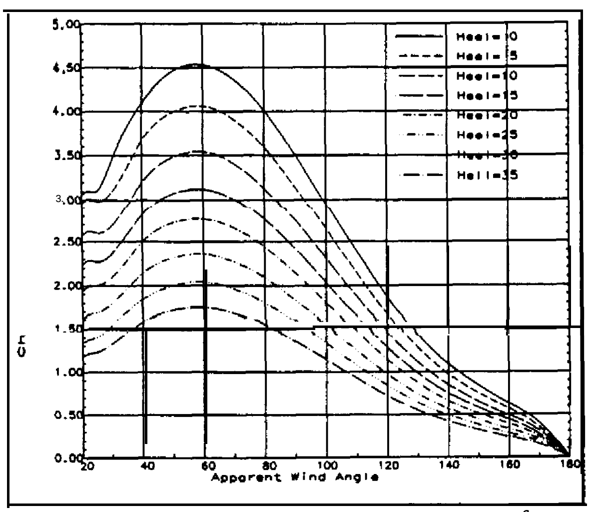

Figure 3b: Typical sail heeling force coefficient curves

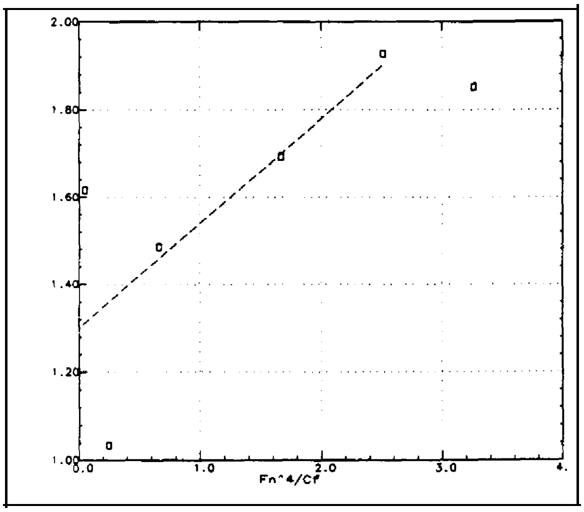

Figure 4: Prohaska analysis of form factor

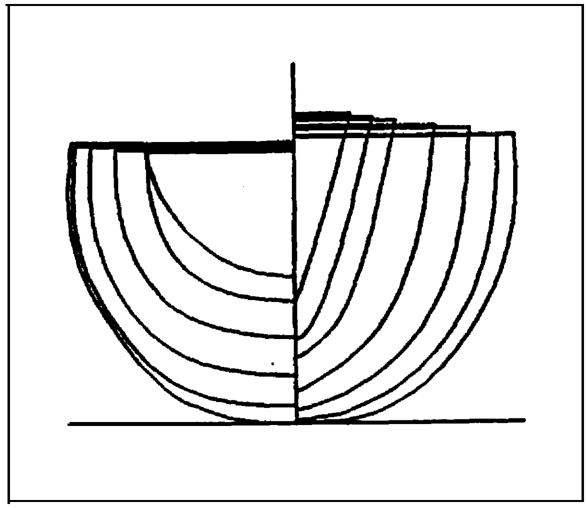

Figure 5: Yacht form used in experiments (Ml 99)

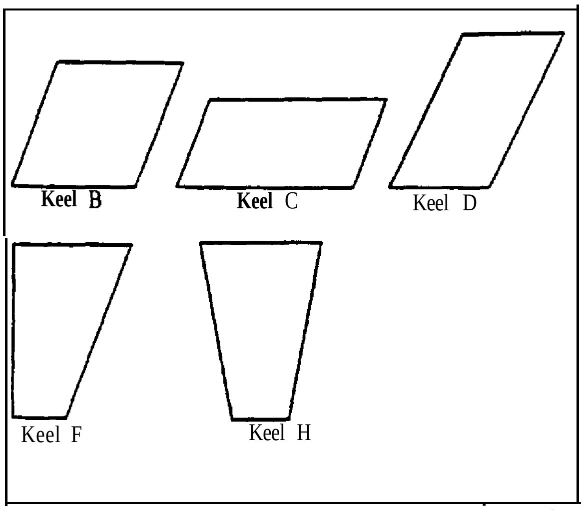

Figure 6: Keel forms used in the experiments

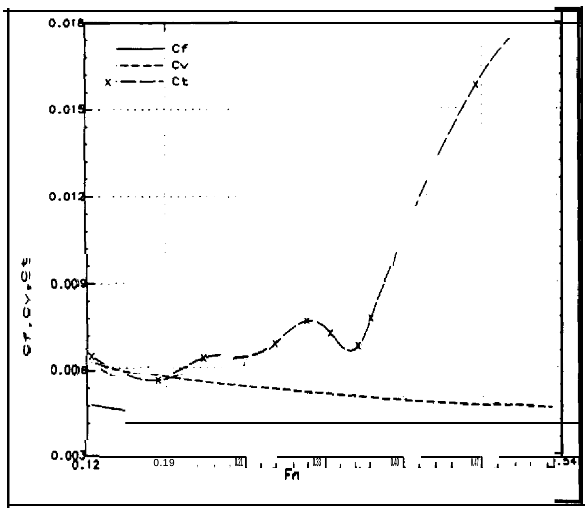

Figure 7: Upright resistance characteristics of model

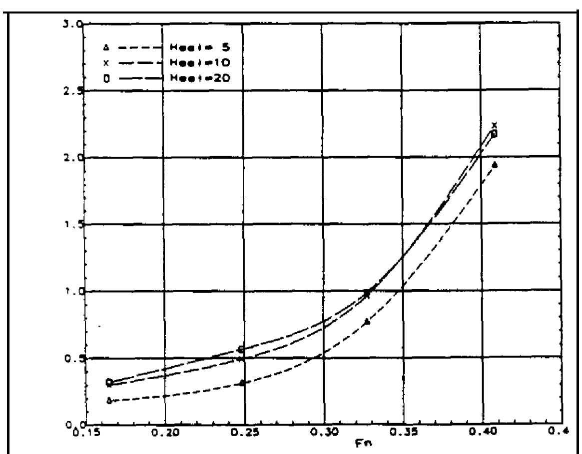

Figure 8: The effect of heel on resistance

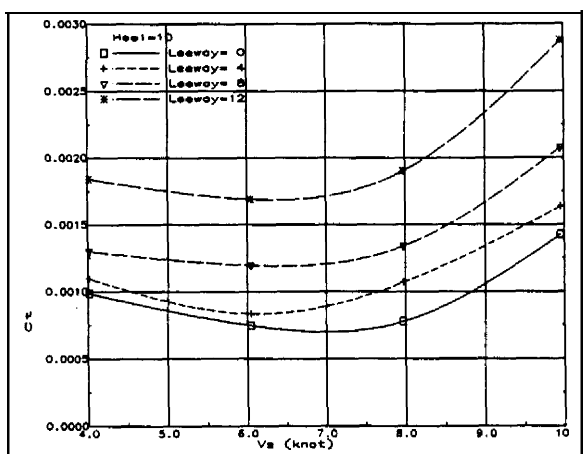

Figure 9: The effect of leeway angle on resistance

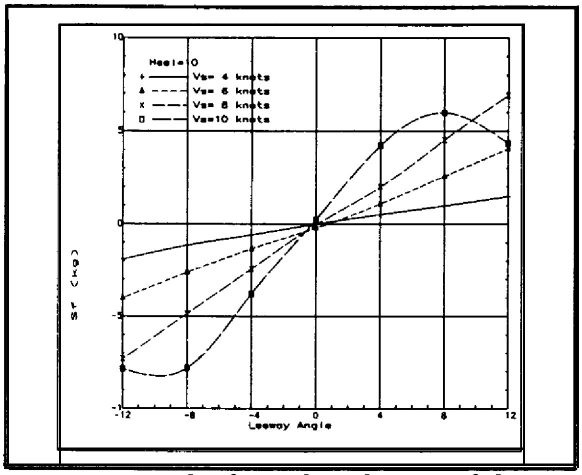

Figure 10: Side force by change of leeway angle and speed

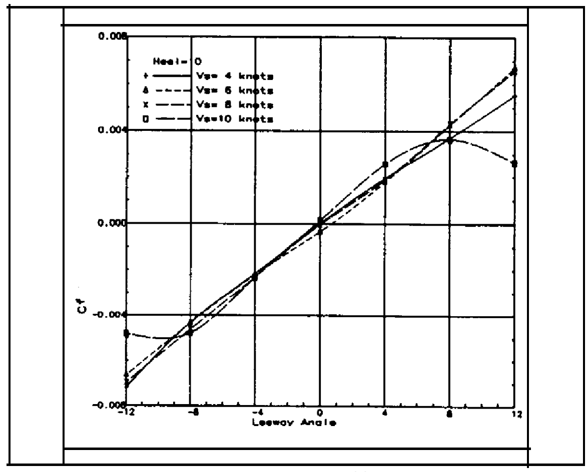

Figure 1 I: Side force coefficient by change of leeway angle

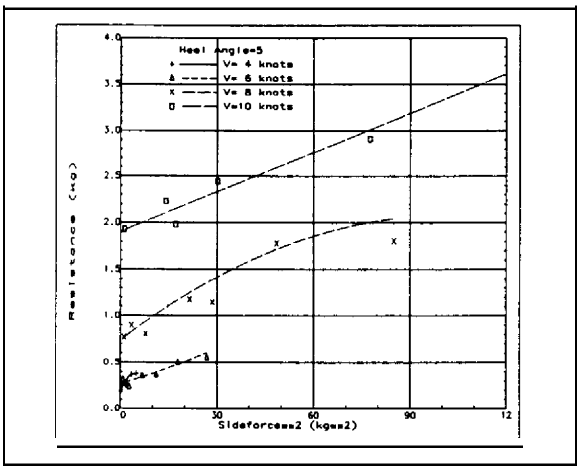

Figure 12: Resistance vs sideforce plot for keel aspect ratio 1.5

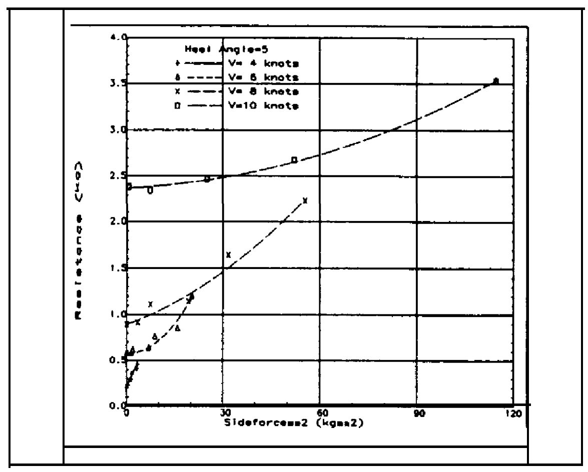

Figure 13: Resistance vs sideforce plot for keel aspect ratio of 1.0

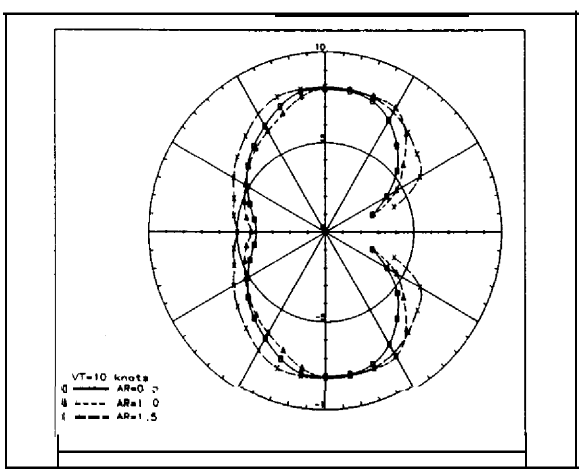

Figure 14: Polar performance plots with keel aspect ratio change

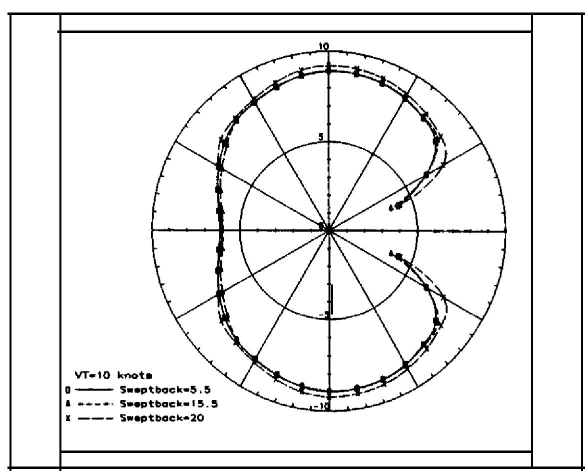

Figure 15: Polar performance plots with keel sweptback angle change