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Downwind Load Model for Rigs of modern Sailing Yachts for Use in FEA

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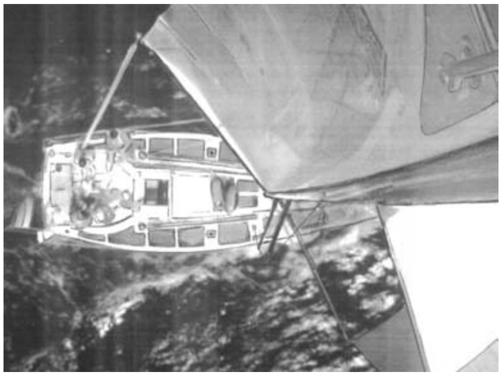
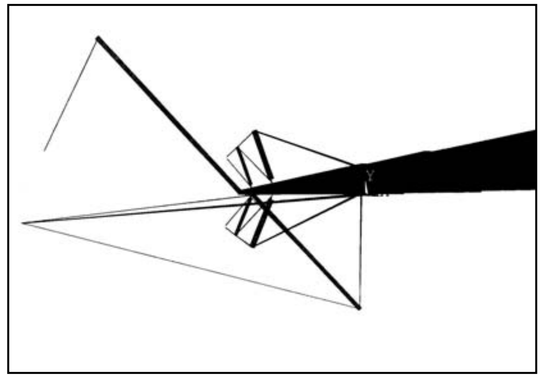




ABSTRACT

Standard approaches to define loads for a rig start with the righting moment of a yacht at 30 degrees of heel. This is a quite good approach for defining maximum lateral forces of the sails on upwind courses. For downwind courses this procedure may be questioned because the forces from the sails are no longer limited by the righting moment. In this paper the loading for rigs of modern sail yachts in the downwind sailing condition is discussed. A load model based on sail areas and apparent wind speeds for application in FEA is developed. The load model will be evaluated by comparing real size rig measurements performed on the Technical University of Berlin's research sailing yacht "DYNA" with a finite element analysis of her rig.

NOTATION

AWA	apparent wind angle
AWA	apparent wind speed
FEA	finite element analysis
CFD	computer fluid dynamics
CL	lift coefficient
CD	drag coefficient
P_{air}	density air
A_m	area main
A_{sp}	area spinnaker

Forces main sail:

L_m	lift main
D_m	drag main
L_{lm}	lift leech main
D_{lm}	drag leech main
L_{fm}	lift foot main
D_{fm}	drag foot main
L_{spr}	lift spreader tip main
D_{spr}	drag spreader tip main
M_l	membrane leech main
M_f	membrane foot main
V	vang
DL_l	drag and lift on leech perpendicular to plane of main sail
DL_f	drag and lift on foot perpendicular to plane of main sail

Forces spinnaker:

L_{sp}	lift spinnaker
D_{sp}	drag spinnaker
L_{tsp}	lift tack spinnaker
D_{tsp}	drag tack spinnaker
V_{tsp}	vertical tack spinnaker
L_{hsp}	lift head spinnaker
D_{hsp}	drag head spinnaker
V_{hsp}	vertical head spinnaker
H_{sp}	halyard spinnaker
H_{vsp}	halyard vertical spinnaker

Forces rig frame:

Fx	forward
Fy	athwart to port side

1. INTRODUCTION

With FEA performed on yacht rigs it is possible to determine tensions in all parts of the rig and to predict deformations of the mast and the standing rigging including the sag of the fore stay. With modern tools like FEA the structure of a sail yacht rig can be simulated with great accuracy. All important facts like the

- three dimensional several times static over destined structure
- pre-tensioned standing rigging
- shrouds, that can fall slack on the leeward side (non linear elements)
- geometrically non linear behaviour, that leads to increased loads when the rig deforms,
- buckling of the whole rig

can be considered today.

But defining loads on the rig for FEA is still a big problem. Without the right loads even the best simulation of the rig structure is worthless. There are many different loads on a sailing rig. Pretension, also referred to as "dock tuning", is one load case. Sail loads as a function of wind velocity, apparent wind angle and sail combinations are a second case. A third case is inertial forces when the yacht is moving with all six degrees of freedom and big accelerations in waves (e.g. a rapid deceleration when nose diving). A fourth case is the weight of the rig itself which has to be considered with large rigs. Finally there are also the extreme load cases, when the main sail is flogging violently in a gust causing the whole rig to vibrate, or when the yacht has broached or capsized.

In rig dimensioning procedures it is a common practice to take the righting moment of the sailing yacht as a base to compute the compression forces in the mast tube and the tension forces in the standing rigging. The procedures are described in "Principles of Yacht Design" (Larsson & Eliasson, 2000) and "Guidelines for Design and Construction of Large Modern Yacht Rigs" (Germanischer Lloyd, 2002).

Taking the righting moment of the yacht for designing cross sections of a rig is a good idea for the rig can't be loaded more than the hull is able to hold the mast up against the wind. That is true for apparent wind angles from a close hauled to a tight reach. But the righting moment of the yacht does no longer limit the loading of the rig when the yacht bears away to a broad reach, a run and a dead run.

The goal of the paper is to analyze downwind loadings of rigs and to describe a procedure how to perform computations for downwind, steady-state load cases with FEA. The results of the FEA are evaluated with real size measurements.

General aspects of rig loadings for downwind sailing are described in section 2. A load model is developed in section 3. The load model is verified in section 4. Calculated loads of the load model for three different AWA's are applied on a FEA model of the rig from the "DYNA". The results of the computations are compared with measurements. Conclusions are given in section 5.

2. RIG LOADS DOWNWIND

Figure 1 shows the popular photo from the Volvo Ocean Race boat "Amer Sport 1" after broaching with a heeling angle of about 80 degrees. She is being pulled sideways at the topmast by her gennaker. That looks very critical for the rig on first inspection. However, loading of the rig was highest before. The curve of the righting moment of the yacht has at about 60 degrees heel its maximum. How high were the rig loads before the broaching? This can't be estimated by the righting moment of the yacht. The yacht did not heel much when sailing downwind. The loads from the sails (especially from the big gennaker) are large. Quantifying these loads is crucial to for FEA of rigs.

Figure 1 Broaching of a Volvo Ocean Racer (photo Rick Tomlinson)

Rig loads are limited by righting moment when sailing close-hauled or on a tight reach. But the loading of the rig can become larger when the yacht bears away to a broad reach or run because the direction of the sail forces is now aligned more in the longitudinal plane with an associated increase in restoring force. The loading of the rig sailing steadily on a dead run is a function of the size of the sails and apparent wind speed. The loading of the rig can rise with the apparent wind speed as long as the helmsman is able to keep the yacht on her course. A loss of control like nose diving, crash-gybing or broaching stops the steady-state loading and causes large spikes in rig loads

Computing the rig loads for the steady-state sailing under control requires knowledge of the different sail configurations and their associated wind ranges. Defining the maximum wind speed for any given sail configuration is difficult.

Simply assigning limits based on sailing experience or seamanlike behavior may prove erroneous. E.g. it is not uncommon for a racing yacht to be sailing at her limit and experience a sudden gust that increases the apparent wind speed by 50%. Since sail force scales as the square of the wind speed, a 50% increase in AWS (a factor of 1.5) equates to a 125% increase (a factor of 2.25) of the sail force.

There are a number of cases that must be considered when determining rig loads sailing downwind. The sudden gust is only one case. Another case is that of rapid deceleration often caused by slamming into waves which results in increased inertial loading.

A third case involved is increased apparent wind speed as a function of changed boat speed. A deceleration on a dead run caused by a nose dive can enlarge the apparent wind speed up to the amount of the former boat speed. Or take a Volvo boat that is beam reaching on a plane under gennaker. In this condition the apparent wind may reach well over 25 knots and the spinnaker pole can cause extreme perpendicular loads on the mast. This type of load will cause heavy mast bending and torsion moments.

Another extreme load condition, again out of control, could occur when the mast or pole is dipped in the water while traveling at high speeds. The Volvo 60 “SEB” experienced a similar situation during a gybe that led to their dismasting in the Southern Ocean several thousand miles offshore.

The rig of a sailing yacht can’t be designed for every conceivable loading. The rig would become too heavy and the performance of the yacht would suffer too much even for a cruising yacht.

Defining sound loadings and safety factors for the design of yacht rigs is beyond the scope of this paper. This paper only investigates loads from the sails in steady-state conditions, with a mainsail/spinnaker combination considered.

Sailing downwind, sail forces primarily act in the longitudinal direction. The spinnaker or gennaker pulls the mast forward. The aft rigging (backstays, runners, checkstays) is highly loaded to counter the sail forces. Fortunately the staying base of the aft rigging is often (but not always) much greater than the staying base of the arthwartship rigging. These loads are usually manageable and significant less. Figure 2 shows different aft staying bases depending on the type of the rig.

Experience has shown that standard dimensioning procedures based on the righting moment work well for rigs with good aft rigging. This assumes that the yacht is not drastically pushed downwind, as a VOR 60 in the Southern Ocean. A more rigorous computation is necessary for rigs without a sufficient aft rigging and for rigs of racing yachts sailing at their limits.

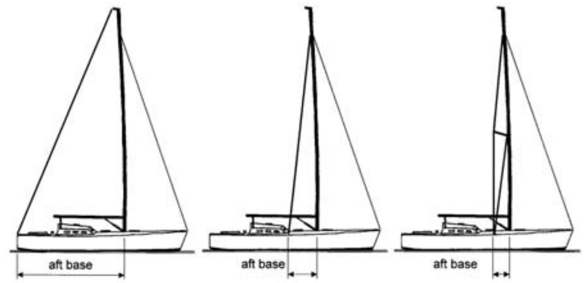


Figure 2 Aft staying bases depending on rig types

Mast compression results from the tensions in the rigging and in the halyards. The halyard tensions depend on the trim of the sails for different apparent wind angles and speeds. Mast compression remains relatively unchanged as long as none of the standing rigging becomes slack. Then the tensions in the standing rigging only shift from one side to the other. If one part of the standing rigging (sailing upwind the lee shrouds, sailing downwind the head stay) is falling slack, then the mast compression rises steadily with the wind loading. In this condition the stiffness of the rig is halved. Adequate pretension levels must be maintained to avoid this situation.

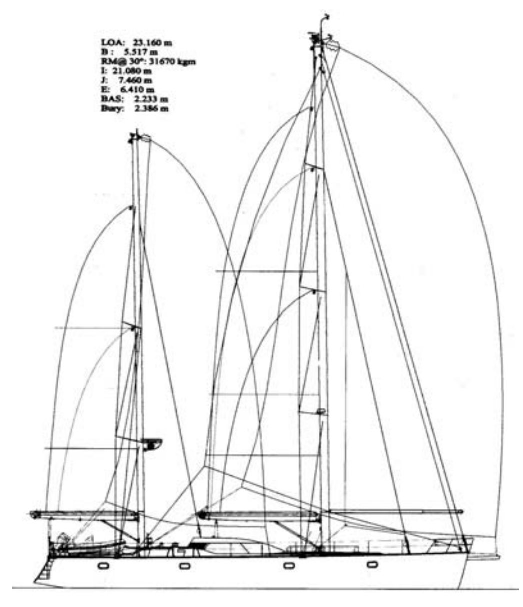


Figure 3 76’ ketch without aft rigging (Tripp Design)

Some cruising yachts have favored rigs without backstays or running backstays. Figure 3 shows a new 76’ ketch without aft rigging. This type of rig has the advantages of simplified sail handling and the ability to use a mainsail with a much larger roach. The spreaders in this type of rig are raked aft 30 or 35 degrees.

On such rigs the shrouds must take the longitudinal loads in addition to the side loads. Without backstays, the aft staying base is very small and is indeed much smaller than the arthwartship staying base. Therefore, the pretension has to be much greater as compared with a conventional rig to avoid the headstay from falling slack sailing downwind.

Dinghies and multi-hulls are well-suited for rigs without backstays and runners. The majority of these boats have rigs with no more than one set of spreaders, and in some cases, no spreaders. The ones with spreaders often have a sweep of between 20 and 35 degrees and the staying base is relatively large. Spreaders reduce the staying base assuming the same shroud to mast angle. Larger yachts with up to five pairs of spreaders swept 30 degrees aft have a very small staying base in relation to the height of the mast (compare Figure 2).

3. LOAD MODEL

A load model is developed for sailing yachts with a mainsail and spinnaker sailing at apparent wind angles from about 90 to 180 degrees (a reach to a dead run). The model is intentionally made simple by applying the dynamic pressure formula to compute the forces of the sails. It can easily be programmed in a spreadsheet and yields to quick results. A much more costly alternative would be to use CFD calculations for the pressure distribution on each sail surface, and to then perform FEA membrane calculations with the sails to get the forces acting on the rig. Additionally, the results of this FEA could be combined with CFD for further optimization of the sails as is commonly done within the more sophisticated sailmaking companies. However, numerical solutions for downwind sail configurations with separated flows are still difficult, and model tests are still necessary to validate the computations.

Drag and lift forces of the sails are computed in the load model individual by using the dynamic pressure formula. The sail areas have to be known, and the wind speed and the coefficients for lift and drag have to be defined.

$$L_m = C_{Lm} \cdot 0{,}5 \cdot \rho_{air} \cdot AWS^2 \cdot A_m$$
$$L_{sp} = C_{Lsp} \cdot 0{,}5 \cdot \rho_{air} \cdot AWS^2 \cdot A_{sp}$$

$$D_m = C_{Dm} \cdot 0{,}5 \cdot \rho_{air} \cdot AWS^2 \cdot A_m$$
$$D_{sp} = C_{Dsp} \cdot 0{,}5 \cdot \rho_{air} \cdot AWS^2 \cdot A_{sp}$$

Defining the correct lift and drag coefficients for downwind sailing may be difficult. Individual coefficients for the mainsail and the spinnaker are rare in literature. “Principles of Yacht Design” (Larsson & Eliasson, 2000) make casual reference to these coefficients for use in velocity prediction programs. Lift and Drag coefficients can also be found in “Sail performance – Theory and Practice” (Marchaj, 1996) and “The Symmetry of Sailing” (Garret, 1996).

The individual drag and lift forces of both sails are separately defined at specific places in the rig. First the procedure for the mainsail will be described, then the procedure for the spinnaker.

3.1 Mainsail Load Model

The drag and lift forces of the main sail are divided respectively into three parts. The three parts are applied on the leech, the foot and the spreader tips (Figure 4). All forces act in a Cartesian co-ordinate system with u, v and w. The apparent wind and the drag forces act in the v direction. The lift forces act in the u direction. The fractions of the drag and lift forces of the mainsail depend on the sizes of their respective areas shown in Figure 5.

The magnitude of the spreader forces is, in large part, dependent on how much the mainsail compress into the leeward rigging. The further the mainsail is eased, the more it will compress on the spreaders. For a given boom length (and associated girths up the span of the mainsail), the larger the spreaders, the greater the force applied on them by the mainsail. Likewise, spreaders with more aft sweep will encounter greater forces imparted by the mainsail. Another factor to consider is twist of the mainsail as controlled by the vang. Larger vang forces reduce leech twist and thus reduce mainsail force on the spreaders, especially on the upper spreaders. All of these factors must be considered when applying the spreader tip forces in the FEA model.

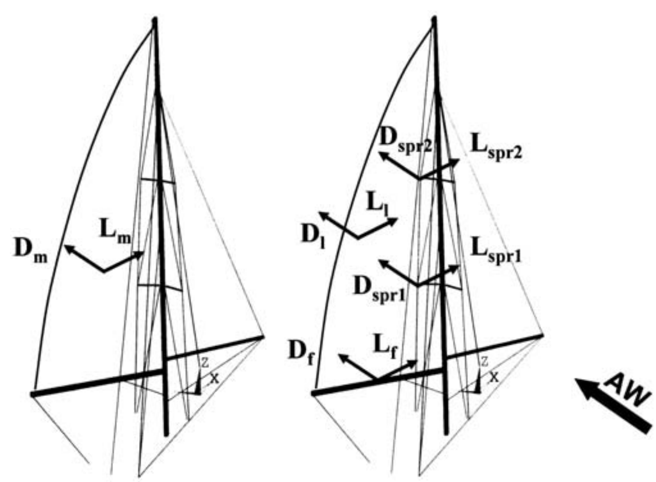


Figure 4 Applying drag and lift forces from the main on the rig

The remaining lift and drag components for the leech and the foot result from their corresponding areas. The part for the leech is generally bigger than the part for the foot.

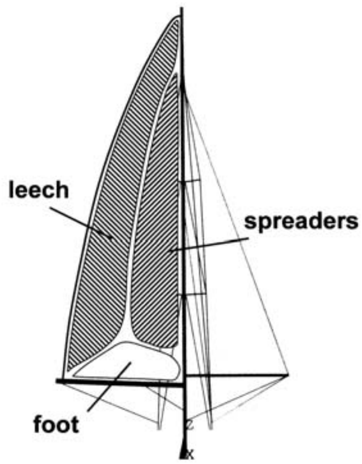


Figure 5 Sizes of areas from the mainsail corresponding with parts of the mainsail force

The mainsail forces are dissected further as shown in Figure 6. The forces on the leech and the foot are halved and re-positioned. The leech forces now act at the head and the clew, and the foot forces are moved to the tack and the clew. The apparent wind angle changes over the height of the mast. With the simple halving of the leech and foot forces, the change of the apparent wind angle is neglected.

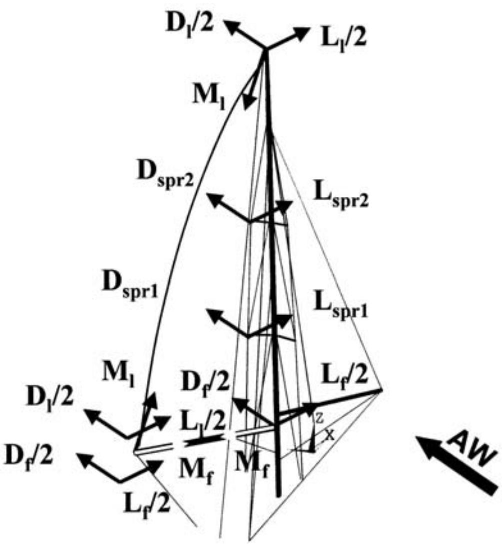
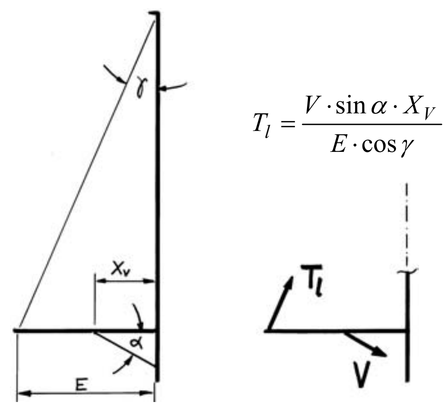


Figure 6 All single forces of the load model for the main sail acting on the rig

The forces on the leech and the foot cause tension forces along the leech and the foot depending on the corresponding sags. This membrane forces has to be applied at the tack and the clew for the foot and at the head and the clew for the leech.

Leech tension, or corresponding twist, sailing downwind is primarily controlled with the boom vang, and to a lesser degree, the mainsheet. In the model, the vang force is considered to balance the leech force. Because the vang attaches to the boom only part-way down it's length, the vang lever arm is much smaller than that of the leech. The vang force can be calculated considering the geometry illustrated in Figure 7. The leech tension force is much smaller than the vang force.



$$T_l = \frac{V \cdot \sin\alpha \cdot X_V}{E \cdot \cos\gamma}$$

Figure 7 Leech and vang force

The main sheet has only a small vertical component when the boom sweep angle is large (mainsail eased), and therefore it is neglected. If the vang force is known like in the measurements on the "DYNA", then the leech tension can be computed. If the vang is tensioned with hydraulics, the force can be adjusted with a gauge. The vang force can be limited with a hydraulic overload relief valve.

The leech tension force (membrane force M_l) can also be computed by assuming defined sag for the leech. The size of the leech sag (camber) can be estimated with photos taken into the direction of the boom. The common catenary formula (Figure 8) is used to compute the tension force in the leech. This assumes a constant uniform load calculated by dividing the drag and lift force on the leech perpendicular to the plane of the mainsail through the leech length.

$$M_l = \frac{DL_l \cdot l}{8 \cdot s}$$

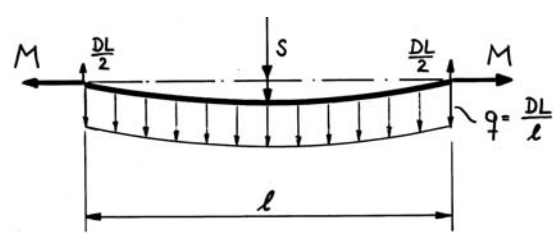


Figure 8 Tension force in the leech or foot

The computation of the tension force in the foot is performed analogically assuming a sag (camber) in the foot. The mainsail on the "DYNA" is loose footed (attached at tack and clew only). But even if the foot would be fixed on the boom this makes little difference in the computation.

The sags of the leech and the foot depend on the trim of the mainsail. Typical values for the leech sag are in the range from 15 to 25 % of the leech length sailing from a reach to a dead run. Racing boats may have smaller values while cruising boats may have larger ones. The sag of the foot is about 5 to 10 % of the foot length.

The sags are defined to be perpendicular to the plane given by the three corners of the mainsail, the head, the clew and the tack. The drag forces on the leech and the foot act only perpendicular to this plane when the boom is vertical to the apparent wind. Usually that is not the case. Then the drag and lift forces of the leech and the foot have to be divided into two components, one perpendicular and one parallel to the plane. The sum of the perpendicular components is then used for the catenary formula to compute the membrane forces.

3.2 Spinnaker Load Model

The lift and drag forces of the spinnaker are divided to the three corners of the spinnaker: the head, the tack and the clew (Figure 9). The forces depend on the cut and trim of the spinnaker in combination with the mainsail, and the apparent wind angle. At first, the forces can be assumed to be one third for each corner. This may be a good assumption while sailing on a dead run. However on a reach the tack will have a larger force than the clew, and the head force may be larger still.

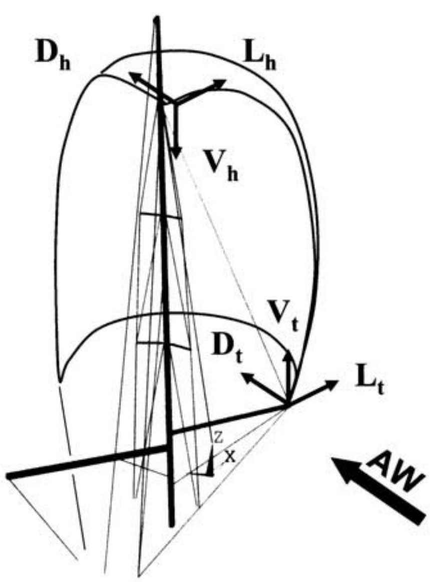


Fig. 9 Applying forces of the spinnaker on the rig

The halyard of the spinnaker between the halyard sheave and the head of the spinnacker has an angle of about β = 30° downward from the horizontal. The exact angle depends on the cut and trim of the sail. The vertical component of the halyard can be computed by the halyard angle and the horizontal lift and drag forces (Figure 10) of the spinnaker head.

$$H_{vsp} = \sqrt{D_{hsp}^{\;2} + L_{hsp}^{\;2}} \cdot \sin \beta$$

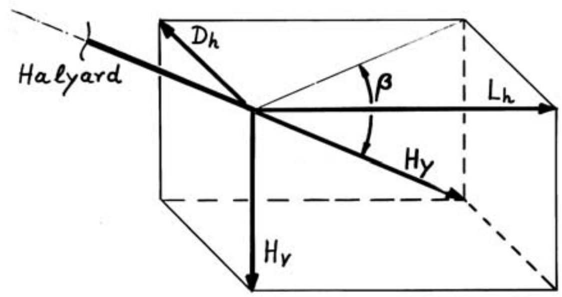


Figure 10 Forces at the spinnaker head

The halyard force itself can be calculated with the three components. On the "DYNA" it can be compared with the size of the measured value.

$$H_{sp} = \sqrt{D_{hsp}^{\;2} + L_{hsp}^{\;2} + H_{vsp}^{\;2}}$$

A spinnaker may be able to produce not only a lift and a drag force but also a vertical force like kites or parawings. This vertical component is neglected in the load model. Accordingly the vertical force component at the head of the spinnaker acting downward has to be counteracted at the tack and the clew acting upward. The sum of the vertical forces has to be zero. In this way, the vertical forces at the tack and the clew are calculated.

In addition to these forces there are membrane forces in the foot. They act in the line between tack and clew and they depend on the sag (camber) of the foot. The forces could again be computed using the catenary formula like for the mainsail. The sag of the spinnaker foot is very big in comparison to the sag of the mainsail foot while sailing on a run. The sag of the spinnaker foot becomes smaller when sailing on a reach but it is still relatively big. The foot membrane forces are neglected in the load model.

The force of the spinnaker acts on the rig at the halyard sheave and the spinnaker pole tip. The force of the sheet acts on the hull and is not relevant to the rig.

The halyard forces from the mainsail and the spinnaker act on the sheaves in the mast. The halyards are often redirected at their sheaves. The forces to be applied at the sheave axles in the vertical direction are the sum of the halyard forces itself and the vertical components of the halyard forces. Figure 11 shows how the halyard forces have to be applied at the sheave.

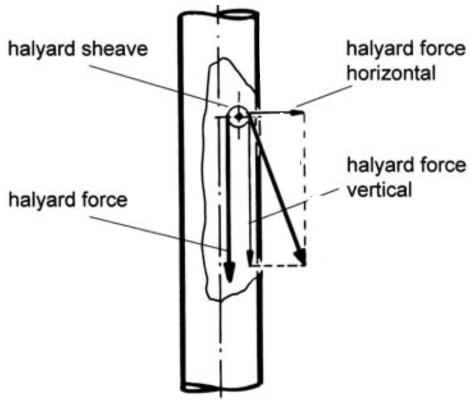


Figure 11 Halyard forces applied at sheaves

When the halyards are not redirected but locked at the mast, the halyard forces have to be applied directly with the vertical and horizontal components only. The halyard forces may also act on winches or cleats at the mast like it is at the "DYNA" rig.

The halyard forces are measured on the "DYNA" and can be compared with the computed values. The measured halyard force of the mainsail is much larger than the computed halyard force. In the computed halyard force only leech tension is considered. The difference results from the pretension in the luff.

The u, v, w force components have to be transformed to the x-, y-, z-coordinate system of the rig (x ship centre line forward, y athwartships to port, z vertical upward) to easily apply the forces in the FEA model.

4. VERIFICATION OF THE LOAD MODEL

FEA and real size measurements are performed to see how well the developed load model works for downwind load cases. The computations and the measurements were carried out for the rig of the "DYNA". The "DYNA" is a 10 m long research sailing yacht owned by the TU-Berlin. She is based on the type "Dehler 33" and is described in "Full Scale Hydrodynamic Force Measurement on the Berlin Sail-Force-Dynamometer" (Hochkirch & Brandt, 1999). She has a fractional rig as shown in Figure 12. The mast tube is made of carbon, and the standing rigging is primarily stainless rod (backstay is Kevlar, check stays are cable 1x19). FEA of her rig and a comparison to measurements for an upwind load case are performed in "The Rig of the Research Yacht "DYNA" – Measurement of Forces and FEA" (Grabe, 20002). This reference details the measurements and FEA computations for an upwind load case and will not be repeated here in full length. Only a short description of the rig measurements and the FEA model is given. However, changes and extensions for the download cases are explained in detail.

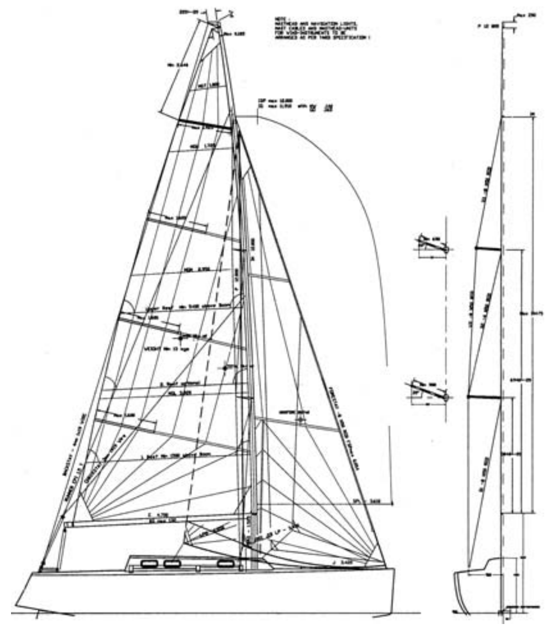


Figure 12 The rig of the "DYNA"

Twenty-one force transducers are mounted in the rig and listed in Table 1. A force transducer for the vang, which is not normally used for upwind measurements, is added here. The vang transducer is important in the downwind cases because the vang pulls the main boom downwards in contrast to the upwind load case where the mainsheet performs this function to large degree. Figure 13 shows the mounting of the force transducer between the vang and the main boom.

Table 1 Force transducers

Position	Nominal force [kN]	Accuracy [+/-N]
D1's	10	50
D2's	20	100
V1's	20	100
V2's, (D3's)	20	100
headstay	50	250
backstay	10	50
runners	10	50
checkstays	5	25
main sheet	5	25
genoa sheets	10	50
halyards	5	25
mastfoot	50	250
vang	10	50

A global FEA model of the rig is constructed with beam elements for the mast tube, the spreaders, the boom and the spinnaker pole. Nonlinear link elements with the ability to fall slack are chosen for the standing rigging. Geometrical nonlinear computations consider large deformation effects. A spinnaker pole and its running rigging are added to the upwind model for the downwind load case. The FEA code used is ANSYS 6.1.

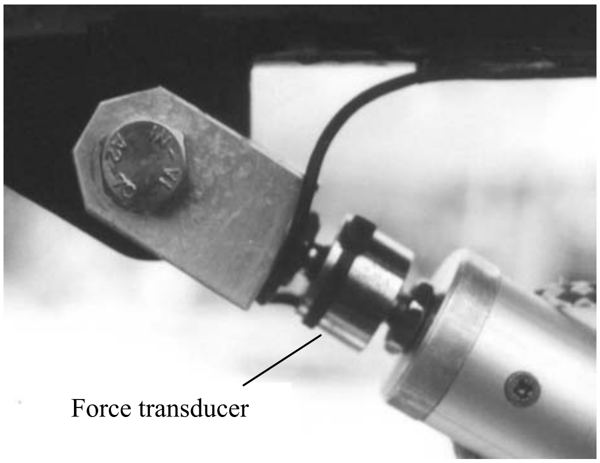


Figure 13 Force transducer in the vang

Three downwind load cases with different AWA's are computed. The AWA's are 90° (reach), 135° (broad reach) and 180° (dead run) with the yacht on starboard tack in each condition. Three FEA models with different sheeting angles for the boom and the spinnaker pole (as measured from the yacht centerline) corresponding to each AWA are constructed (Table 2). Figure 14 shows the three different geometries looking in the direction of the apparent wind.

Table 2 Sweep angles

AWA	90°	135°	180°
Main boom	35°	45°	65°
Spinnaker pole	5°	45°	90°

The main boom has a sheet and a vang. The spinnaker pole has a topping lift, a guy and a downhaul. The downhaul runs in an unusual arrangement from the pole end to the mast collar and not to the bow. The guy goes to different points on the deck depending on the AWA. With an AWA of 90° the lead block of the guy is just aft of the shrouds chainplate. Sailing with an AWA of 135° and 180° the guy block is moved to the stern near the running backstay chainplate. The reason for the two different arrangements of the guy and the unusual arrangement of the downhaul is that all forces of the rig of the "DYNA" have to be applied directly on the rig frame and not on the hull to be accurately measured. At an AWA of 90° the guy would press on the windward shrouds if the lead block is fixed further aft near the runners. To avoid this without using a reaching strut the guy block is set in the more forward and more outboard position at an apparent wind angle of 90°.

The three FEA models are loaded through pretensions and sail loads. The pretensions are the same as for the upwind load case. They are applied as initial strains for the single parts of the standing rigging. The sizes of the initial strains are adjusted to get pretensions in conformity as good as possible with the measured forces (Table 3).

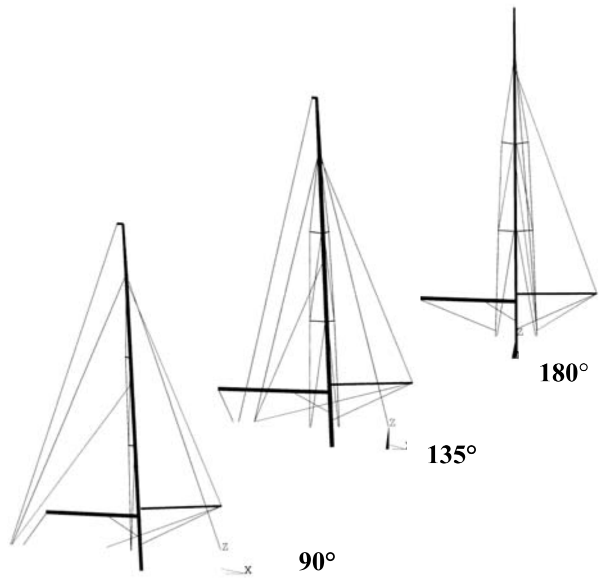


Figure 14 Geometries of the FEA models, three AWA's

Table 3 Rigging pretensions

rigging	measured mean [N]	simulated [N]	difference [N]	difference [%]
D1's	4,875	4,872	-3	-0.1
D2's	2,415	2,481	66	2.7
D3's	8,805	9,708	903	9.3
V1's	11,240	12,400	1,160	9.4
V2's	8,805	9,882	1,077	10.9
headstay	4,800	3,851	-949	-24.6
mastfoot	-38,500	-38,133	367	-1.0

Table 4 lists the computed sail forces from the load model for the three different apparent wind angles with three different measured apparent wind speeds. The sail configuration was always full main sail (35.4 m²) and spinnaker (47 m²). The wind speeds for the load model are chosen accordingly to match the measured wind speeds. The measurements were all performed on the same day, and the true wind speed was nearly constant. The apparent wind speed tends to be inversely proportional to the apparent wind angle, increasing as the "DYNA" is pointed closer to the wind.

Table 4 Sail forces computed by the load model

AWA [°]	90	135	180
AWS [m/s]	6.6	5.8	4.4
Main	**[N]**	**[N]**	**[N]**
halyard sheave x	127	84	44
halyard sheave y	179	125	56
halyard sheave z	-2,164	-2,503	-2,196
halyard on winch z	1,092	1,259	1,103
goose neck x	-593	-171	-30
goose neck y	549	247	139
goose neck z	750	1,003	949
boom tip x	1,136	486	185
boom tip y	-393	-201	-171
boom tip z	321	241	144
spreader tip 1 x	0	53	53
spreader tip 1 y	0	23	7
spreader tip 2 x	74	80	79
spreader tip 2 y	37	34	10
Spinnaker	**[N]**	**[N]**	**[N]**
halyard sheave x	395	283	220
halyard sheave y	222	148	0
halyard sheave z	-785	-554	-380
halyard on winch z	524	369	254
pole x	395	283	220
pole y	222	148	0
pole z	175	123	85

The true wind speed was about 15 knots. The steerage was at the limit sailing with the AWA of 90 degrees. Flow separation starts to occur at the rudder. In these wind conditions, steerage on a broad reach and a run was not a problem. The calculated forces for the downwind load cases are smaller than for the upwind load case in spite of the big sail area of the spinnaker.

Measured forces are listed in Table 5. The forces are from the load cells of the rig and from the rig frame. Fx and Fy are forces from the rig frame. Fx is the total force of the sails in the forward direction of the "DYNA" and Fy is the total force in athwart direction to port. The drag and lift coefficients of the sails in the load model are computed using these two forces. Normally these values are not measured, and the coefficients have to be estimated for the load model.

Both check stays and the port runner were slack while sailing. The starboard runner was without intention more tensioned sailing with the AWA of 135 degrees than sailing with the AWA's of 90 and 180 degrees.

The mast compression while sailing was only slightly above the pretension level of 38,500 N. The mast compression reached a maximum at an AWA of 135 degrees caused by increased runner tension. For comparison, the mast compression sailing close hauled at 10 m/s AWA was 65,020 N.

Table 5 Measured forces

AWA	90°	135°	180°
AWS [m/s]	**6.6**	**5.8**	**4.4**
Force	**[N]**	**[N]**	**[N]**
Fx	1,713	1,248	874
Fy	905	582	35
D1 starb.	5,657	4,417	4,475
D1 port.	2,419	2,572	3,869
D2 starb.	3,676	2,429	2,041
D2 port.	1,399	2,060	2,996
V1 starb.	14,075	12,440	11,584
V1 port.	8,382	9,789	11,571
V2 starb.	10,374	9,984	9,525
V2 port.	7,049	7,654	8,531
headstay	3,692	4,651	3,127
backstay	117	21	107
runner starb.	1,595	2,107	306
runner port.	0	0	0
checkstay starb.	0	0	0
checkstay port.	0	0	0
vang	1,125	1,053	784
mastfoot	-41,029	-41,391	-40,202

Table 6 Computed forces, FEA

AWA	90°	135°	180°
Force	**[N]**	**[N]**	**[N]**
D1 starb.	5,448	5,392	5,415
D1 port.	4,562	4,718	5,460
D2 starb.	2,718	2,373	2,523
D2 port.	1,753	1,974	2,399
D3 starb.	10,706	9,620	9,647
D3 port.	7,826	8,229	9,073
V1 starb.	13,679	12,249	12,468
V1 port.	9,849	10,481	11,782
V2 starb.	10,887	9,804	9,859
V2 port.	8,051	8,444	9,315
headstay	4,605	5,877	3,831
backstay	113	22	106
runner starb.	1,594	2,102	308
checkstay starb.	0	0	0
vang	992	1,053	784
mastfoot	-40,051	-40,646	-39,199

The results of the FEA can be found in Table 6. All forces of the rig for the three models according to the three apparent wind angles are listed. The tensions of the aft rigging (backstay, runner and checkstay) in the FEA models are adjusted by initial strains to the size of the measured forces.

Figure 15 shows the computed tension and compression forces in the rig for the apparent wind angle of 135 degrees. The forces are made visible with contours. The width of the contour is proportional to the force. The contour points to the right of the elements in the case of compression and to the left in the case of tension.

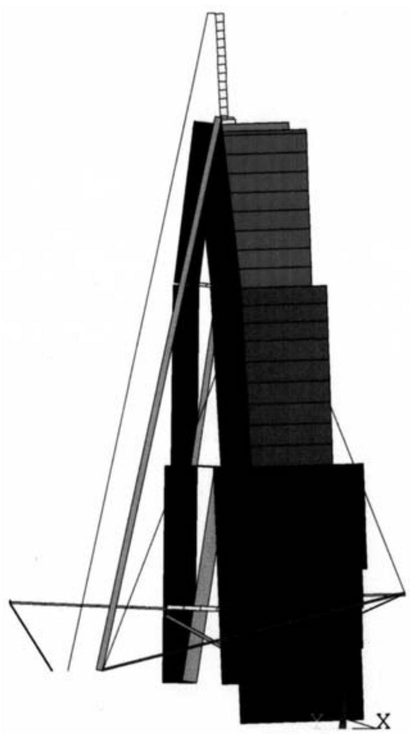


Figure 15 Tension and compression forces in the rig, FEA, AWA 135

Figure 16 shows moments of torsion in the “DYNA” rig. They are greatest in the lowest mast panel (panel 1) and reduce stepwise at the spreaders. The main boom and the spinnaker pole push into panel 1. Both cause big torques in the same turning direction (see Figure 15). The forces applied at the spreader tips yield a torque in the opposite direction. The size of the torque for the apparent wind angle of 135 degrees is 135.7 Nm. The size of the torque itself is no problem for the “DYNA” mast. The closed hollow cross section of panel 1 is very strong with a big part of fiber orientation in +/- 45°. But open mast tubes for furling of the mainsail should get special consideration. Additionally, holes in the mast tube for halyards increase the danger for a buckling mode of combined compression, bending and torque.

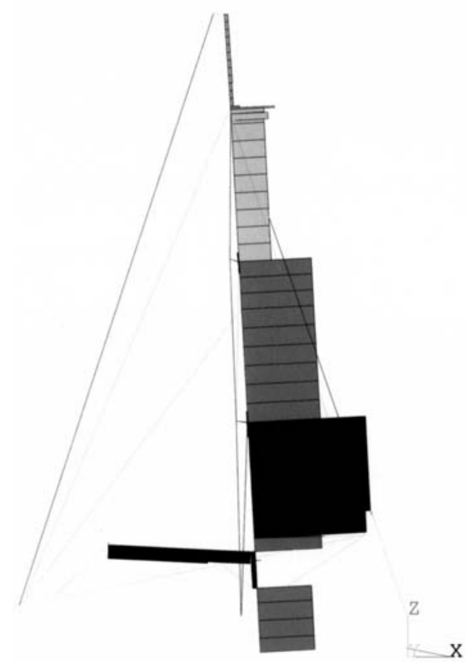


Figure 16 Torque in the rig, AWA 135

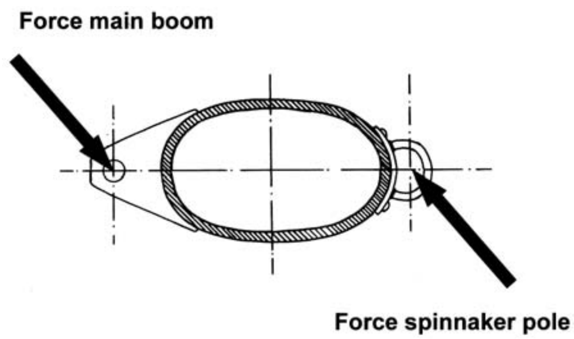


Figure 17 Initiating torque in mast panel 1

The measured and computed values from Table 5 and Table 6 are compared in Table 7. Absolute and percentage values are listed. A big absolute difference is in the D1 port side. The D1 differences are also big in the upwind load case. That may be caused by the clamping of the mast in the mast collar in the deck. The mast is clamped in the x and y direction in the deck in the FEA model, which may be an over-simplification. But the D1’s are also very sensitive to the forces of the main boom and the spinnaker pole.

The force differences are related to the maximum mast compression forces. The percentage differences are with a maximum value of 4 % small. They are even smaller than in the upwind load case where the biggest value was 7.4 %. One reason for this is that in the downwind cases there is much less shifting of pretensions. Also no part of the standing rigging falls slack.

Table 7 Comparison of measured and computed forces.

AWA	90°		135°		180°	
	abs. diff. [N]	diff./ max force [%]	abs. diff. [N]	diff./ max force [%]	abs. diff. [N]	diff./ max force [%]
D1 starb.	209	0,5	-975	-2,4	-940	-2,3
D1 port.	-2,143	-5,2	-2,146	-5,2	-1,591	-4,0
D2 starb.	958	2,3	56	0,1	-482	-1,2
D2 port.	-354	-0,9	86	0,2	597	1,5
D3 starb.	-332	-0,8	364	0,9	-122	-0,3
D3 port.	-777	-1,9	-575	-1,4	-542	-1,3
V1 starb.	396	1,0	191	0,5	-884	-2,2
V1 port.	-1,467	-3,6	-692	-1,7	-211	-0,5
V2 starb.	-513	-1,3	180	0,4	-334	-0,8
V2 port.	-1,002	-2,4	-790	-1,9	-784	-2,0
headstay	-913	-2,2	-1,226	-3,0	-704	-1,8
backstay	4	0,0	-1	0,0	1	0,0
runn. stb.	1	0,0	5	0,0	-2	0,0
chst. stb.	0	0,0	0	0,0	0	0,0
vang	133	0.3	-42	-0.1	-149	-0.4
mastfoot	-978	-2,4	-745	-1,8	-1,003	-2,5

5. CONCLUSIONS

A load model for FEA of the rig of sailing yachts sailing downwind is developed. The load model is validated by a comparison of FEA results with real size measurements of forces in the rig of the “DYNA”. The differences between measured and computed values are with maximal 4 % in relation to the mast compression small. In spite of the intentionally made simple computations of the sail forces by applying the dynamic pressure formula and the catenary formula to compute the forces of the sails the load model simulates the sail loads very good.

It is necessary in the load model to define the wind speeds and the belonging sail configurations. That is a difficult task. It will cause “hot” discussions to define the right working load and extreme load cases for dimensioning the rig. The wind speed is in contrast to the righting moment of a sailing yacht no concrete number. A smaller problem (but still a problem) is to define the lift and drag coefficients for the mainsail and the spinnaker separately.

The measurements and the computations on the “DYNA” rig show, that the rig is loaded more (the mast compression is bigger) sailing close hauled than sailing downwind. But the “DYNA” rig has a good aft staying base and she was not pushed hard sailing downwind. The apparent wind speeds sailing downwind at apparent wind angles of 135 and 180 degrees could rise without loosing control of the yacht. The loading of the rig will then become greater.

The loading of the rig sailing downwind is different from sailing close hauled. The mast gets high compression forces sailing close hauled. Sailing downwind the mast compression may be smaller. But especially panel 1 gets a high torque and also bending moments caused by the compression forces of the main boom and the spinnaker pole. The buckling mode is different. It is a combined compression and torque mode. Buckling will happen at smaller mast compressions sailing downwind than sailing upwind.

Rigs without good aft rigging and rigs of racing yachts sailing at their limits downwind can be in danger when they are dimensioned only by the righting moment and the upwind load case. For these kinds of rigs it is recommended, to perform a FEA for downwind loading cases with the developed load model.

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