High Performance Yacht Design Conference
Auckland, 4-6 December, 2002

THE RIG OF THE RESEARCH SAILING YACHT "DYNA" MEASUREMENTS OF FORCES AND FEA

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Abstract. The "DYNA" is a research sailing yacht of the TU-Berlin, also called the "Sail-Force-Dynamometer". She is an entire measuring device for aerodynamic and hydrodynamic forces. The focus in the paper is on measured and computed forces in the standing rigging and in the mastfoot. The aim of the work is to better predict loads and deformations of rigs from high performance yachts for design purposes. The forces in the rig are measured with 20 separate force transducers for mast compression, all shrouds, stays and sheets. A global FEA model of the rig is built up. Geometrical non linear computations for the load cases dock pretensions and sailing upwind with 30° heel are performed. Results are internal forces and deformations of the rig. The loads from the sails are calculated by a load model based on the righting moment of the "DYNA" and the sag angles of the sails. The results of the measurements and the computations are compared with each other.

1. INTRODUCTION

Force measurements and FEA computations for the rig of a 33 feet sailing yacht are performed and compared with each other. One aim is to see how well FEA computations correspond with the real world of a rig. An other aim is to improve FEA for rigs. For the design of light but also safe rigs it is very important to be able to predict as exactly as possible the internal loadings and the deformations of rigs. That is even more necessary for big rigs than for small rigs.

2. THE RESEARCH SAILING YACHT "DYNA" AND HER RIG

The "DYNA" is the research sailing yacht of the TU-Berlin. The hull is identical with a "*Dehler 33*" designed by judel/vrolijk & co (Germany). Everything else is custom made for research purposes. The main dimensions are:

length overall:	9.99 m
beam:	2.98 m
depth:	2.05 m
displacement:	4,160 kg
sail area:	55.9 m²

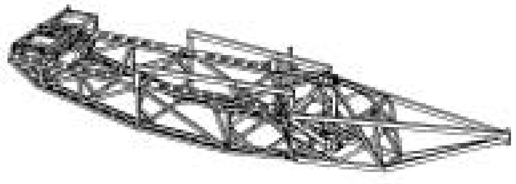

Figure 1. Aluminium frame inside the hull

She is specially designed and constructed as an entire measuring device. Aerodynamic and hydrodynamic forces can be separately measured during actual sailing conditions.

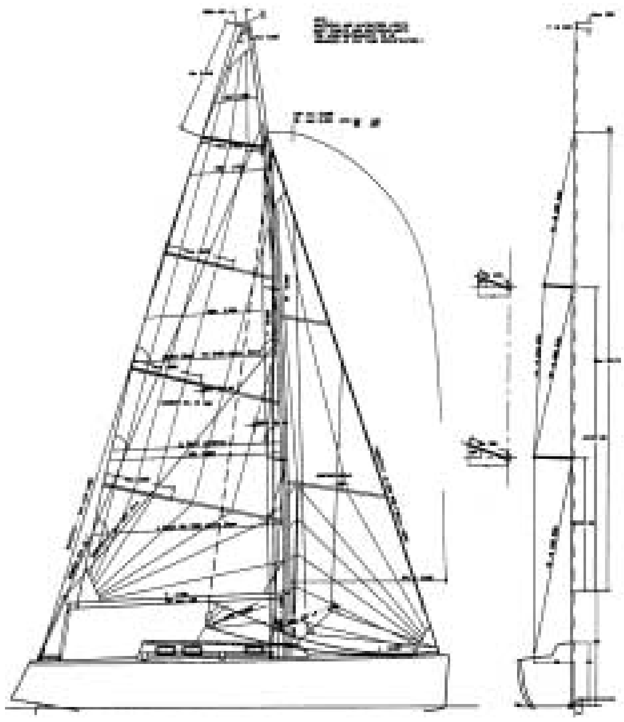

Figure 2. Sailplan

A rigid aluminium frame is installed within the hull (figure 1). All parts of the rigging are mounted on the frame. The frame itself is connected to the hull through a 6-component balance. All forces on the keel, the rudder and in every part of the rigging are measured separately. In order to correlate these readings with current values

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for apparent wind speed and direction as well as boat speed, heeling angle, heading and position of the yacht are taken. For detailed information see [1, 2].

The rig of the “DYNA” (figure 2) is fractional with two aft swept spreaders (20°), one backstay, two runners and two checkstays. The mast is 15.4 m long and has a rake of 3°. The chain plate base is 910 mm. The rig is designed by AES (Applied Engineering Services, New Zealand) and fabricated by Hall Spars (USA). The mast tube, the spreaders and the main boom are made out of standard modulus carbon. The standing rigging for the shrouds and the headstay is out of rod. The backstay and the runners are out of kevlar and the checkstays out of 1x19 wire.

3. MEASUREMENT OF RIG FORCES

Publications of measured rig forces are relatively scarce [3, 4, 5]. The reasons for this are that the measurements are costly and often secret. This chapter describes the measuring method and the results for the “DYNA“ rig. Forces are listed for dock tuning and an upwind load case.

3.1 Force transducers

In the rig there are 20 force transducers. Table 1 lists the position of the force transducers, the nominal force and the accuracy.

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

All force transducers are manufactured by HBM (Hottinger Baldwin Messtechnik, Germany). They are of the type U9B for tension (standing rigging and sheets) and C9 for compression (mastfoot). Figure 3 shows a typical arrangement of the force transducers in the shrouds.

3.2 Results

Forces in the rig are measured for the dock tuning alone and sailing loadcases. Table 2 lists the measured forces for the dock tuning and one representative upwind case with an apparent wind speed of 10.3 m/s and an heeling angle of 30° sailing on port side with the wind coming from starboard side. The sails are unreefed mainsail and genoa III. The measured heeling moment is 17,930 Nm.

Table 2. Measured rigging forces

load cells	dock tuning force [N]	upwind 30° heel force [N]
D1 starb.	4,980	7,520
D1 port	4,770	30
D2 starb.	2,380	3,600
D2 port	2,450	30
V1 starb.	11,220	13,670
V1 port	11,260	5,170
V2 starb.	8,780	10,090
V2 port	8,830	5,030
headstay	4,800	12,200
backstay	----	520
runner starb.	----	3,200
runner port	----	----
checkstay starb.	----	940
checkstay port	----	----
halyard main	----	2,440
halyard genoa	----	1,890
main sheet	----	1,780
genoa sheet port	----	2,970
genoa sheet starb.	----	----
mastfoot	-38,500	-56,020

Figure 3. Force transducers at the first spreader tip

The forces under sailing conditions depend on the tuning of the aft rigging (backstay, runners and checkstays). A big tension in the runner and the backstay leads to big forces and a small sag in the headstay but reduces also the pretension in the shrouds for the spreaders are swept aft.

4. FINITE ELEMENT ANALYSIS

4.1 Reasons for FEA

To dimension rigs of sailing yachts there are traditional and simple procedures like that of Skene [6] and S&S [7]. More detailed classification rules come from Bureau Veritas [8] and the Nordic Boat Standard [9] based on Norske Veritas. Spar fabricators often use their own dimension procedures. They are based on the above rules and extended by their own experience.
All these dimensioning procedures work with the righting moment at 30° heel of the hull to predict compression forces in the mast. Pretensions in the standing rigging are neglected assuming the shrouds on the leeward side fall slack. To define the moments of inertia for the mast cross sections the Euler buckling formula for columns is applied. Reserve factors found by experience take into account the different clamping of the masts in different rig types. This procedure makes it difficult to design rigs with new geometries of spreader arrangements and standing rigging (for example rigs with no runners and no backstay or rotating rigs). The necessary reserve factors for new rig types are not yet known. For the rigs of racing yachts with experienced and trained crew the reserve factors can be reduced some way to make them lighter. Only experience shows how much the standard reserve factors can be reduced without risking loseing a rig which means the same as to lose the race.
The procedures are also limited by the size of the rigs. For example the Nordic Boat Standard is only intended for sailing yachts up to 15 m length. But the rigs become bigger and bigger. 60 m long masts are quite usual now and new projects go up to 90 m long masts. There are new effects that has to be considered. For example the weight of the rig becomes more and more important with the rig size and the part of the own weight may reach up to 30 % of the total loading.
With the above procedures it is not possible to compute deformations of the rigs like the mast bending when loaded by the sail forces or the trim equipment. But this information is very important for the design of the sails.

FEA has been used for the simulation of rigs [10, 11, 12] for the last 10-15 years. With the FEA it is possible to design new rig types, geometries and also big rig sizes. The three dimensional geometry and effects like pretensions and self weight are considered. Germanischer Lloyd is the first classification society that demands a FEA in the 'Guidelines for Design and Construction of Large Modern Yacht Rigs' for the certification of rigs [13]. For the global stability analysis the three dimensional structure of the rig has to be simulated and reserve factors are given for an evaluation according to the Euler Eigenmode method.
With the FEA not only the forces and stresses in all parts of the rig but also the deformations and specially the bending of the mast tube can be simulated.
In contrast to the above procedures the FEA yields not directly to the cross section properties of the mast panels and the standing rigging. The right cross section properties have to be found in an iterative process until the reserve factors for the global buckling are big enough.
The FEA becomes more and more important for the design of the rigs of racing yachts and the ever growing rigs of performance yachts. FEA is becoming easier to handle and less expensive which is enabling it to be applied to more and also smaller rigs with lower budgets.
Comparisons of FEA computations with full-scale measurements of rigs show the potential limitations for the dimensioning of rigs but also give confidence for the computations.

4.1 FEA model of the "DYNA" rig

The rig of the "DYNA" is built up as a global model. The whole rig with mast tube, spreaders, main boom, vang and standing rigging is simulated. The FEA model ends at the connections to the hull. The hull of the "DYNA" is not reproduced but the bending stiffness of the hull is considered with a spring at the lower end of the headstay.

The element types used are line elements supplemented by bearing and spring elements:

- three dimensional beam elements for mast tube, spreaders, main boom and headstay
- non linear link elements with the ability to fall slack when compressed for the standing rigging
- linear link element for the vang
- spring element to represent the hull stiffness
- bearing element for the goose neck.

The reason to take line elements and not shell, plate or volume elements is to keep the model simple for fast computations and easy changes in geometry and cross section properties. The chosen elements yield good results for the global model. But to get exact tensions in fittings, local models have to be built up with shell, plate and/or volume elements.

The FEA carried out includes geometrical non linearity. That is very important for the loading of compressed structures like rigs with the ability to buckle. The geometric non linear computations take into account effects of large deformations. That means, that the internal loading depends on the deformation of the rig. Unfortunately the internal loading rises with deformation in compressed structures like rigs. With a geometric non linear FEA it is possible to compute the rising deformations and stresses in the rig until it buckles. Geometric non linear computations take a lot more time than linear computations and sometimes there may be convergence problems.

To generate the geometry of the rig a lot of key points have to be computed to define the position of the mast panels, the spreader tips and so on. All three co-ordinates of a Cartesian co-ordinate system are necessary. A computation sheet helps to reduce the work time. Additional nodes are generated between the key points by meshing with beam elements. Figures 4 and 5 show the geometry of the "DYNA" rig in the FEA model.

The mast tube is simulated with beam elements representing only a line at the neutral axis. To connect spreaders and standing rigging at the real geometric points, very stiff "helping beams" are introduced. They go from the neutral axis to the actual attachment points. The same procedure is performed for the halyard sheave axles, the goose neck and so on. The helping beams are important for a realistic attack of the forces at the mast tube and to get the right bending moments. Even though the beam elements are only lines it is possible to render them in the right shape.
The headstay is simulated with a beam and not with a link element to be able to apply a pressure load from the genoa luff. That is not possible with link elements. To get the influence of the sagging headstay and to make it visible the beam elements are also necessary.
The FEA model also needs a lot of cross section and material properties that can't be listed here. So a summery of the material properties is given. The carbon mast of the "DYNA" has an axial modulus of 80 GPa. The rod has an axial modulus of 175 GPa. Note that this value is smaller than the previously accepted value of 193 Gpa and results from new test data obtained by Navtec.
The FEA program used is ANSYS 5.7. The FEA model has 68 keypoints and 230 nodes. A geometrical non linear computation takes about 25 seconds on a PC (Pentium IV, 1.5 GHz).

4.2 Load model

Defining the right loading for the rig is still a big problem when performing FEA for rigs. There are a lot of loads acting on the rig:

- sail loads
- pretension loads
- inertia loads.

Inertia loads are self weight and acceleration forces in a sea way. Self weight is an important load for rigs of sailing yachts with a length of more than about 60 feet. The "DYNA" with her 33 feet is relatively small. Computations with the influence of the self weight showed that it can be neglected for the "DYNA". Accelerations in a seaway like pitch, roll and heave are important loads. The measurements on the "DYNA" are performed mostly in sheltered waters and mean values are computed for periods of 8 to 16 seconds. So the influence of accelerations in a sea way is not taken into account for the FEA computations.

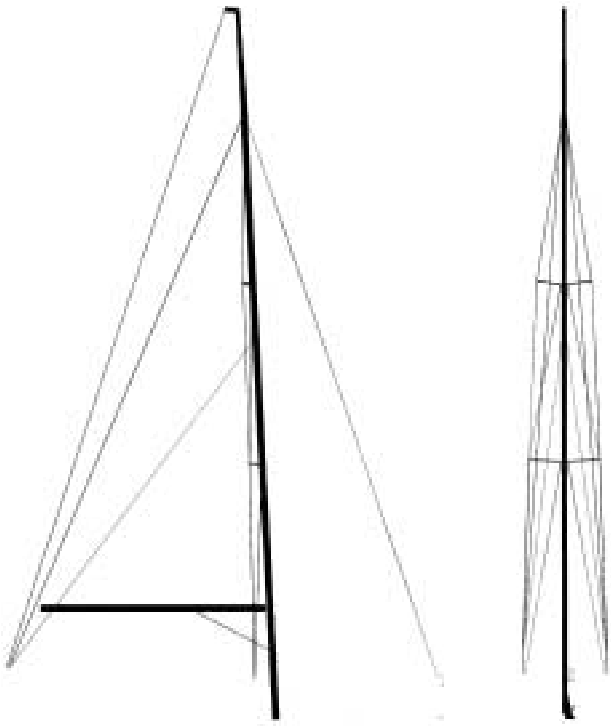

Figure 4. Geometry of the FEA model, side and front view

Figure 5. Geometry, left photo, right FEA model

The pretensioning of the "DYNA" rig is performed with a mast jack. It was not possible to achieve the necessary pretensions computed by AES using turnbuckles only. It is very important to pretension the rig in the FEA model like in the real rig. Otherwise the measured forces can't be the same as the computed ones.
The measured pretensions of the standing rigging are simulated in the FEA by individual initial strains (equivalent in reality to tightening the turnbuckles) for the D1's, D2's, V1's, V2's (D3's) and the headstay. It

takes some time to find the right initial strains for the single shrouds and stays because they interact with each other in the aft swept spreader rig of the “DYNA“in the longitudinal and athwartship directions.
The pretensions in the FEA are applied stepwise as if using the mast jack. First step: the outer shrouds (V1’s, V2’s and D3’s) and the headstay are tensioned with the D1’s and the D2’s staying slack. The spreaders push the mast below the headstay fitting forwards and the masthead bends aft. The mast is allowed to move freely forward in the deck, so that it bends from the mastfoot to the headstay fitting. Second step: the mast is clamped in that position in the deck and the D1’s are tensioned. Third step: the D2’s are tensioned. When tensioning the D’s, the mast bend is reduced. The mast should still have a little forward bend. The tensions for each step are right when the 3 mast compressions for the 3 steps, that are computed for the mast jack, are reached. Fine tuning of the pretensions in the rigging and in the clamping position of the mast in the deck is necessary to get aproximately the same pretensions that are measured before the “DYNA“ sets sail.
The measured pretensions in the shrouds are not absolutely symmetrical. The differences for port and starboard shrouds are up to 500 N or 7 % in spite of a straight looking mast. Without an exact measurement this would not be obvious. The reason for the differences is, that the turnbuckles only allow turn angles of 180° for the securing by cotter pins. In the FEA model the pretensions are simulated to be symmetrical with the mean value of port and starboard side.
The achieved pretensions in the shrouds of the FEA model differ less than 11 % from the measured mean values from port and starboard (see table 3). V1, V2 and D3 are 10 % too big in spite of the headstay with a force too small by –24.6 %. The differences would be smaller when applying self weight, for the mast rake is 3° and the aft rigging - even not pretensioned - pulls aft with its self weight.

Table 3. Pretensions

position	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

The sail loads predominate in the total loading of the rig. The pressure distribution on the sail surfaces caused by the stream of the air is transmitted through the sailcloth acting as a membrane to the rig. The sail membrane acts with pressure loads along the luffs on the mast tube and the headstay and single forces are acting at the corners of the sails in halyards, outhaul and cunningham. The halyard forces act twice on the sheave axles in top of the mast. The corner forces and the pressure loads are effective in three dimensions. They depend on the apparent wind angle, the wind speed, the shape and trim of the sails and the bending of the mast.

A good way to compute the loads from the sails is to perform

- CFD computations to get a pressure distribution on the sails
- to apply this on a membrane model of the sails to get the line loads and corner forces and
- to apply them on the FEA model of the rig.

But when the sails and the rig are both loaded both will be deformed. That changes the shape of the sails and the procedure starts again with a CFD computation. With a costly (and hopefully converging) iteration procedure the problem can be solved like big sail making companies show (unfortunately the programs are not for sale). But in spite of the expenditure there are limitations in accuracy and in the size of the apparent wind angles. To this day, CFD computations for downwind courses have their problems and model tests in wind tunnels are still necessary.

Instead of the procedure described above the sail loads for the FEA model of the “DYNA“ rig are computed with the input of the heeling stability of the hull compared with the measured overturning moment and the sag angles of the leeches. Even so this sounds to be crude compared with the above procedure it leads to good results for upwind courses and is much easier to handle with a simple computation sheet.
The overturning moment of the sails has to be the same as the righting moment. So the total athwartship forces of the main and the foresail can be computed with the knowledge of the righting moment at a given heeling angle, the height of the centres of efforts of the sails and by taking into account different lift factors for the sails (bigger one for the foresail). Based on the total sail forces the wind speed can be back-calculated by using the dynamic pressure formula and therefore controlled.
The total athwartship forces of the main and the genoa are divided on the three sides of the sails. Depending on the sag angles of the leeches at the corners of the sails the forces are computed with the catenarian formula.
The computed sail loads are listed in table 4. They are computed for the measured upwind load case on port side at a wind speed of 10.3 m/s, a heeling angle of 30° and a righting moment of 17,930 Nm. The direction of the forces and pressures are indicated by the indices of the co-ordinate system used (x ship centre line forward, y athwartships to port, z vertical upward).
There are a lot of adjustments to be set in the load model depending on the sail shape. These adjustments are controlled by the measured halyard and main sheet forces and also by the apparent wind speed. This values must be about the same measured and computed.

Table 4. Sail loads for upwind case, forces and pressures

position of force	main [N]	genoa [N]
halyard sheave x	-560	240
halyard sheave y	170	190
halyard sheave z	-4,760	-3,710
halyard on winch z (meas.)	-2,440	-1,890
boom sheave x	1,090	----
boom sheave y	420	----
boom sheave z	1,810	----
main sheet z (measured)	1,780	----
goose neck x	-140	----
goose neck y	50	----
goose neck z	90	----

mast tube / headstay	main [N/m]	genoa [N/m]
const. pressure x	-90	-130
const. pressure y	50	60

The forces of the main halyard in x and y are not applied directly at the sheave axle. Better results are achieved by applying them at a height half way between the masttop and the mast fittings of the D3's. That takes into account, that the membrane forces of the leech are distributed over a length on the mast top and not at the sheave axle alone. The z-component is applied in the sheave axle for it realy acts there.
After loading the FEA model according to table 4 the backstay, runner and the checkstay are tensioned by initial strains according to the measured values.

4.3 Results

Forces and deformations are important results of the FEA computations.

Figure 6 shows the deformations of the rig as vector plots with views from starboard and from behind. The biggest deformation is 0.16 m in the mast top. That is a small value for the 30° heel upwind load case. The bending curve of the mast in the for/aft direction shows a small counter bend in the height of the checkstay. In figure 7 the deformations can be seen from above in real size and as a vector plot. Figure 8 is a view from above on starboard side looking forward. It demonstrates the sag of the headstay. The sag of the headstay is 0.12 m corresponding to 1 % of the headstay length. This is a very good value for the effectiveness of the genoa.

Figures 9 and 10 show the tension and compression forces in the mast and in the rigging. The forces are made visible with contours. The width of the contour is proportional to the force. The contour is right of the elements in the case of compression and left in the case of tension. Note the steps in the mast compression at every attachement of the D's. In figure 10 looking from port side one can see the tensions of the shrouds on the windward and on the leeward side. The shrouds on the windward (starboard) side are tensioned more.

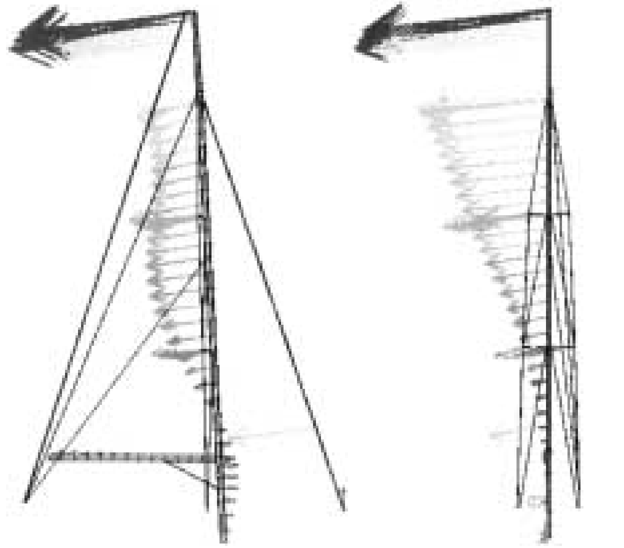

Figure 6. Deformations, view from starboard, from behind

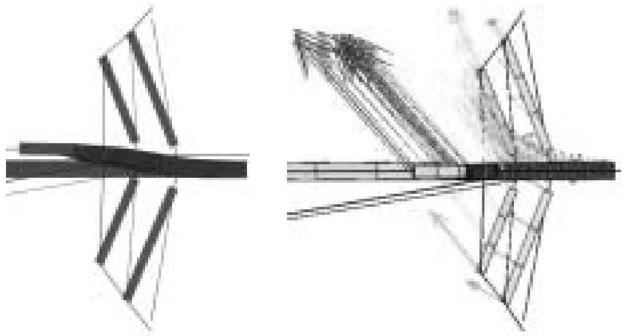

Figure 7. Deformations, view from top, real size, vector plot

Figure 8. Deformations, sag of the headstay

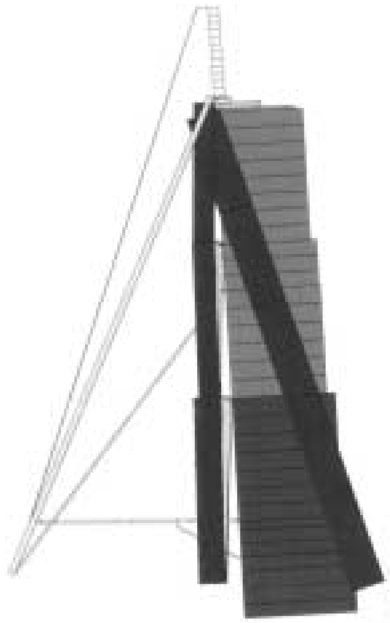

Figure 9. Tension and compression forces, view from starboard

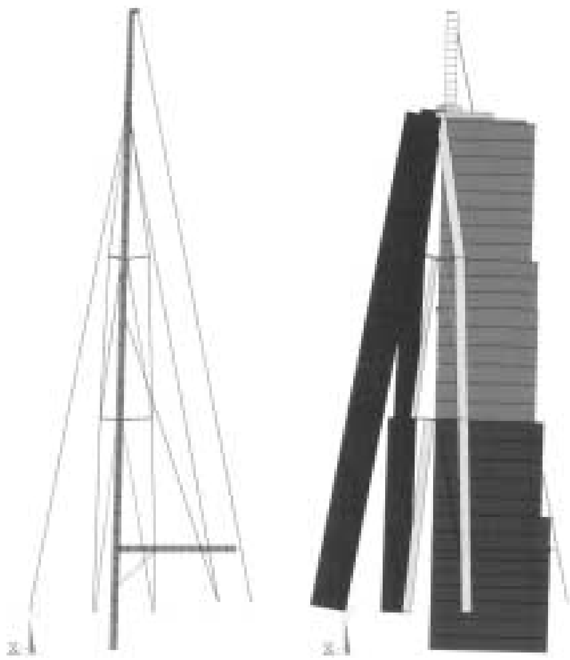

Figure 10. Geometry and forces, same views from port side looking aft

On the leeward side the D2 is slack and the D1 still has a little tension (not visible in the picture). The V’s are still tensioned quite well as in the measurements (see also table 5).

5. COMPARISON OF MEASURED AND COMPUTATED FORCES

In table 5 measured and computed forces are listed in columns 1 and 2. The differences are listed in column 3. The differences are divided by the individual single measured forces and by the maximal measured force in the mastfoot. This values are listed in per cent in columns 4 and 5. Of course column 5 has only small values compared to column 4. But it shows that in the range of the force measurements up to 56,020 N the computed forces are quite good. Comparing percentage differences on much smaller force levels over emphasises the differences not taking into account the accuracy and zero setting of the force trancducers combined with the neglected self weight.

Table 5. Measured and computed forces, upwind load case

position	**meas. force [N]**	**comp. force [N]**	**abs. diff. [N]**	**diff./ meas. force [%]**	**diff./ max. force [%]**
column	**1**	**2**	**3**	**4**	**5**
D1 starb.	7,520	3,860	-3,660	-48.7	-6.5
D1 port	30	230	200	666.7	0.4
D2 starb.	3,600	2,460	-1,140	-31.7	-2.0
D2 port	30	0	-30	-100.0	-0.1
D3 starb.	10,090	9,470	-620	-6.1	-1.1
D3 port	5,030	4,650	-380	-7.6	-0.7
V1 starb.	13,670	12,190	-1,480	-10.8	-2.6
V1 port	5,170	4,450	-720	-13.9	-1.3
V2 starb.	10,090	9,760	-330	-3.3	-0.6
V2 port	5,030	4,590	-440	-8.7	-0.8
headstay	12,200	15,620	3,420	28.0	6.1
backstay	520	240	-280	-53.8	-0.5
runner starb.	3,200	2,860	-340	-10.6	-0.6
checkstay st.	940	810	-130	-13.8	-0.2
mastfoot	-56,020	-51,900	-4,120	7.4	7.4

The greatest absolute differences between measured and calculated forces are in the mastfoot with 4,120 N followed by the D1 on the starboard side with 3,660 N and the headstay tension with 3,420 N. The computed forces for the mastfoot and the D1 on starboard side are too small. The computed headstay tension is too big. If the D1 on the starboard side were bigger, that would also increase the mast compression. One possible reason for the differences could be the neglecting of either the hull stiffness or the rig frame stiffness.

The biggest percentage difference is in the D1 on port side with 666.7 %. Only a very small tension value is measured. At 30 N it is much smaller than the accuracy of the force transducer, which is +/-50 N. As a result this percentage is meaningless. At least the D2 on portside computed to have no force is the first to fall slack which can be seen when sailing upwind at high degrees of heel.

Even with the same apparent wind speed, apparent wind angle and heel angle there is a bandwidth in the measured forces. The bandwidth depends on the trim of the rigging and the sails – and last but not least on the helmsman.

6. CONCLUSIONS

Force measurements and FEA computations of the rig of the “DYNA“ are performed. There are differences in the measured and computed values of up to only 7.4 % with reference to the maximal measured force in the mastfoot. That sounds good. But the absolute differences are up to 4,120 N. On one hand that is a lot. On the other hand the 30° heel load case is much more diffcult to simulate than a load case with less heel such as 20°. That is caused by the much bigger sail loads in the 30° heel condition in relation to the pretensions. The leeward shrouds fall loose and the pretensions in the rigging are changed dramatically. To aggravate the situation the shifting of the pretensions in the “DYNA“ rig are not only in athwartship direction but also in the fore-aft direction since the spreaders are swept aft. An inline spreader rig is easier to compute.

Other reasons for the differences between the measured and calculated forces may be the simple load model, the symmetrical simulated pretensions in the shrouds neglecting the measured differences but also the accuracy of the measurements. Measurements on a full size sailing boat are not easy to perform and they are not comparable with measurements in an air-conditioned laboratory.

The load model should be improved. With comparisons between measured and computed forces for angles of heel from 10 to 30 degrees it is possible to get the best adjustments in the load model.

The upwind load case leads without doubt to high loads in the rig. But there may be other load cases like sailing downwind (reaching/running) with a gennaker or spinnaker that yields still bigger loads. These loads are no longer limited by the righting moment of the sailing yacht. Only the apparent wind speed and the set sails define the loading of the rig by the sails. For downwind courses new load models have to be developed.

The comparison of the measured and the computed forces shows how well the forces in a rig of a sailing yacht sailing upwind can be computed and predicted by applying the FEA for rigs. To design a rig also other loadings than the sail loads alone have to be considered like the self weight for big rigs and the accelerations in a sea way.

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