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Tin Matulja, Ph.D.
E-mail: tin.matulja@riteh.hr
Albert Zamarin, Ph.D.
E-mail: zamarin@riteh.hr
University of Rijeka, Faculty of Engineering, Vukovarska 58, 51000 Rijeka
Robin Matulja, dipl. ing.
E-mail: robin@fly.hr
Flymar d.o.o., M. Tita 32, 51410 Opatija

Boat Equipment Design Methodology Based on *QFD* and *FEA*

Abstract

Defining the potential buyers' needs and requirements should precede any concept design. Most usually, such needs and requirements are defined through statistical analyses. Due to various buyer profiles, there are also as many various market niches laying down the relevant equipment features. In this accordance, market analysis for sailing boats has been suggested with the objective of determining differently featured boat equipments. To that purpose, the Quality function deployment technique (*QFD*) is suggested as the first phase of the methodology. In that way, systematic identification and validation of potential buyers' needs and requirements were enabled, leading through a precisely determined procedure to the basic parameters for defining the targeted equipment configuration. In the second phase, the Finite element analysis (*FEA*) is suggested for the global strength analysis and optimization of the previously selected equipment configuration. In the paper, the suggested methodology was used in the case study dealing with the racing sail boat keel selection and design. Furthermore, the design approach was presented on the selection of the keel body and bulb parameters and on calculations such as the geometry, mass and centre of gravity.

Key words: boat equipment, design methodology, *QFD* technique, *FEA*

1. Introduction

The Quality Function Deployment technique (*QFD*), [9], is a structured approach in defining customer needs or requirements and translating them into specific plans to produce products to meet those needs. The customer needs/requirements are captured in a variety of ways, directly or indirectly, [10]. This understanding of the customer needs is then summarized in a product planning matrix. These matrices are used to translate a higher level of needs into a lower level of product requirements, or technical characteristics. In such a manner, using this technique, the boat equipment general features can be determined as the premises toward generating the equipment concept design, [11]. Fig 1 presents the suggested process flow chart with customer requirements taken into consideration.

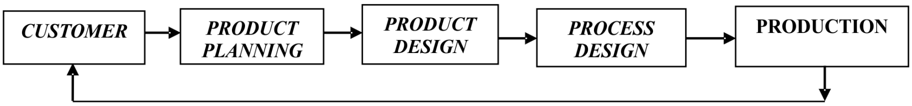

Fig. 1 The suggested process flow chart

Customer requirements may be diverse. Consumer markets are abundant in a variety of different needs. Once the customer needs have been collected, they have to be organized. The whole mass of interview notes, requirements and market researches needs to be distilled into a handful of statements expressing the customer key needs. Affinity diagramming is a useful tool to assist in this effort. Brief statements capturing customer key requirements are transcribed onto cards. These cards are organized into logical groupings or related needs, [8], [12].

Gathering of customer requirements was made directly by means of interviews and the analysis of market research data published in relevant magazines, [5]. In this paper, the market analysis was focused on different sailing boat ballast keel configurations. In order for a successful market analysis to be obtained, the equipment design parameters should be reviewed, [6].

Keel is the part of the sailing boat hull of critical importance for achieving sailing performances. Its shape should be optimal for creating the hydrodynamic forces and minimizing the hydrodynamic resistance, [7]. At the same time, its weight must create the momentum to balance the stability reversing moment generated from wind in the sails. In designing the keel, attention is given to the following design parameters: the basic geometry that is associated with the hydrodynamic characteristics, surface A_K, weight G_K, draft T_K, slenderness, taper ratio C_1/C_2, sweep angle, fig. 2, [14]. Depending on the purpose of sailing, the geometry of the keel can vary significantly. Cruising sailing boats have a long keel with smaller draft, thus providing greater comfort of navigation, less draft and simpler structural design. Racing sailing boats require better hydrodynamic characteristics in order to reduce the resistance of the underwater part and respond to the larger hydrodynamic forces generated by the boat keel. Such keels require the volume of the ballast to be set as low as possible, usually in the bulb, [15].

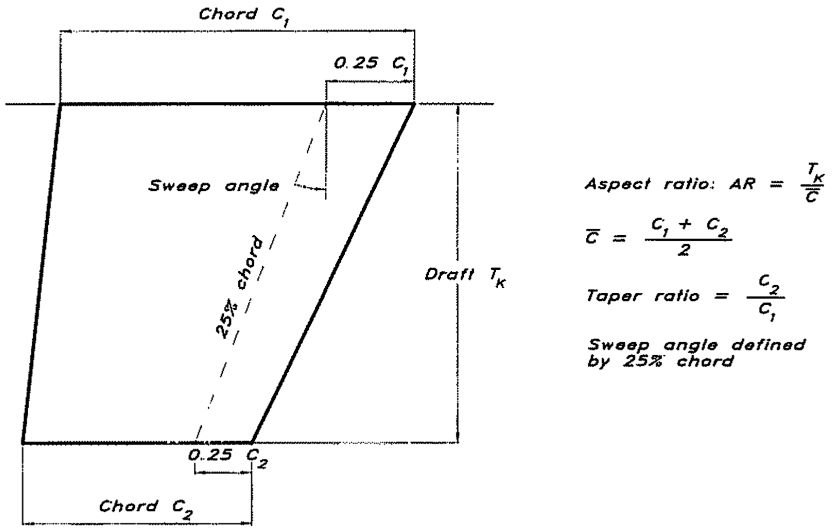

Fig. 2 Keel main characteristics, [14]

The ballast mounted in the keel varies in dependence on the type and requirements of the sailing boat. Ballast weight depends on the length of the boat and is expressed as a percentage of the boat weight total. This value is around 45% of the total weight. In racing boats, the percentage is often higher, over 55%, while in cruising boats it is lower, 35%.

The ratio between the boat length on the waterline and the draft (L_{WL}/T) increases with the waterline length. Draft can be expressed as a function of the maximum breadth $B_{max} = 1.6\ T$. Higher draft is better for racing boats because it allows for greater slenderness of the keel which has a positive impact on sailing performances; on the other hand, smaller draft allows for safer manoeuvring in harbours and shallow bays. The keel draft T_k is calculated by subtracting the hull draft T_c from the total draft T. The ratio between the keel draft and the keel medium-cord length represents the slenderness of the keel $AR = T_K/C$, Fig. 2. While sailing, the value of the effective slenderness of the keel equals twice the slenderness of the keel. This is because the hull, to which the keel gives the effect, increases efficiency and prevents the formation of vortices. Fig. 3 shows the results of the tests with different keel slenderness values and their impact on the lift coefficient C_L and the drag coefficient C_D. Where the angle of the inflow of around 5° is concerned, which is the approximate angle of water inflow to the keel while sailing because of the leeway angle, the keel of $AR = 1$ generates almost twice as little lift C_L then the keel of $AR= 3$. The value of the drag coefficient C_D slightly decreases with the increasing slenderness of the keel, but the ratio between the lift and drag forces increases, whereby the efficiency of the keel increases as well, and ultimately reduces the roll angle sailing by more than half the angle of the keel with lower slenderness.

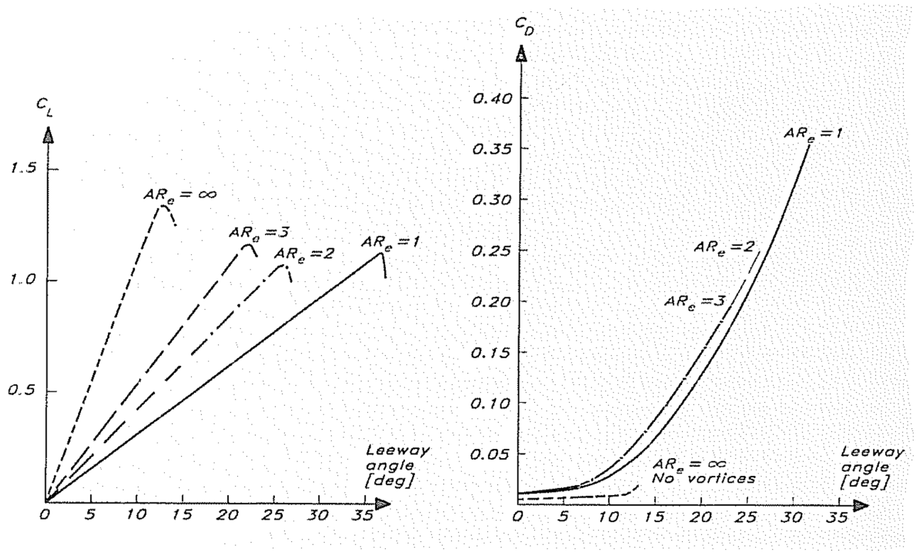

Fig. 3 Aspect ratio influence on lift and drag coefficients [14]

The ratio between the chord length at the bottom of the keel section and the one at the junction with the hull C_2/C_1 describes the shape of the keel. Higher values indicate an approximately rectangular shape of the keel, while smaller values indicate tapering of the keel bottom.

The sweep angle of keels is calculated as the angle between the Z-axis and the line at 25% of the length of the leading edge of the keel. This is so because of the application of the force of buoyancy on the current cross-sections at approximately 25% of the length of the leading edge. The sweep angle of the keel normally varies between 20-30°, yet in racing boats it is smaller and could be 0°.

2. Equipment configuration selection using QFD technique

The keel configuration selection can be performed by using consumer requirements related to keel design parameters. The basic *Quality Function Deployment* technique involves four phases that occur over the course of the product development process. During each phase, one or more matrices are prepared to help plan and communicate critical product and process planning and design information. The *QFD* approach is represented in table 1.

Table 1 Phases of QFD approach

PHASE 1	PHASE 2	PHASE 3	PHASE 4
PRODUCT PLANNING	ASSEMBLY/ PART PRODUCT DEPLOYMENT	PROCESS PLANNING	PROCESS QUALITY CONTROL
- define and prioritize consumers needs - analyze competitive opportunities - plan a product to respond to needs and opportunities - establish critical characteristic target values	- identify critical parts and assemblies - make a note of critical product characteristics - translate into critical part/ assembly characteristics and target values	- determine critical processes and process flow - develop production equipment requirements - establish critical process parameters	- determine critical part and process characteristics - establish process control methods and parameters - establish inspection and test methods and parameters

Once the product planning has been completed, a more detailed technical specification can be prepared. The product requirements or technical characteristics and the product specification serve as the basis for developing product concepts. Product benchmarking, brainstorming, and research and development are sources for new product concepts. Once the concepts have been developed, they are analyzed and evaluated, and cost studies are performed. Then, the product concept selection matrix is used to help the evaluation process. In the concept selection matrix, as presented in table 2, product requirements or technical characteristics are listed down the left column of the matrix, [12].

Table 2 The keel concept selection matrix

Criteria	*Importance*	A *Long keel*	B *Fin keel*	C *L bulb keel*	D *T bulb keel*
Positive hydrodynamic characteristics	5	□ / 5	●/ 25	●/ 25	●/ 25
Displacement	5	□/ 5	○/ 15	●/ 25	●/ 25
Draft	3	□/ 3	○/ 9	●/ 15	●/ 15
Stability	5	○/ 15	○/ 15	○/ 15	●/ 25
Influence on sailing speed	5	□/ 5	○/ 15	●/ 25	●/ 25
Price	3	○/ 9	○/ 9	○/ 9	○/ 9
Maintenance	3	○/ 9	○/ 9	○/ 9	○/ 9
	Total:	51	97	123	133

●	*strong interaction*, **5**
○	*medium interaction*, **3**
□	*weak interaction*, **1**

Keel concepts are listed across the top. The various concepts are evaluated against the degree to which they satisfy each one of the criteria in the left column, using the *QFD* symbols for strong, medium or weak, with accompanying *QFD* symbol weights: 5, 3 or 1. If the product concept does not satisfy the criteria, the column is left blank. The symbol weights (5-3-1) are multiplied by the importance rating for each criterion. These weighted factors are then added for each column. The best preferred concept will have the highest total. The product concept is represented with block diagrams or a design layout. Criticality is determined in terms of effect on performance, reliability and quality. By implementing the presented technique, it is possible for any other equipment characteristics to be defined.

According to table 2, the T bulb keel concept satisfies the criteria in the best way and is suggested for further development through the next phase.

3. Developing the selected equipment concept

The methodology was tested on the real sailing boat with the following main features:

Overall length, LOA	12.49	m
Width, B	3.99	m
Length on waterline, LWL	10.74	m
Hull draft Tc	0.42	m

Displacement, D	5660	kg
Sail area, SA	94.86	m^2

According to [13], [3] a boat can be analysed by the $SA / (D)^{2/3}$ ratio. In slow sailing boats these values are around 17, while in racing boats they are above 22. For the selected sailboat the ratio is $SA / (D)^{2/3} = 29.86$. The configuration of the selected T-bulb keel is presented in Fig. 4.

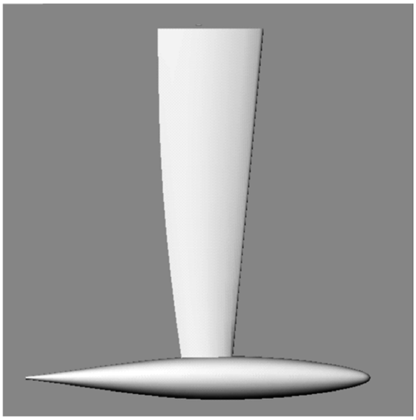

Fig. 4 Computer image of the selected T-bulb keel [4]

The geometry and the internal structure of a T-bulb keel are shown in Fig. 5. The lateral surface of the selected keel is 1.91 m2, which is 2.02% of the total sail area and represents the lover limit for this type of the boat. The keel sweep angle is 3.2°. For a better arrangement of volumes and better load distribution, the chosen ratio is $C_2 / C_1 = 0.49$, which does not affect significantly the hydrodynamic resistance. The total keel draft with a bulb is 2.64 m. The keel is shaped using different *NACA* sections.

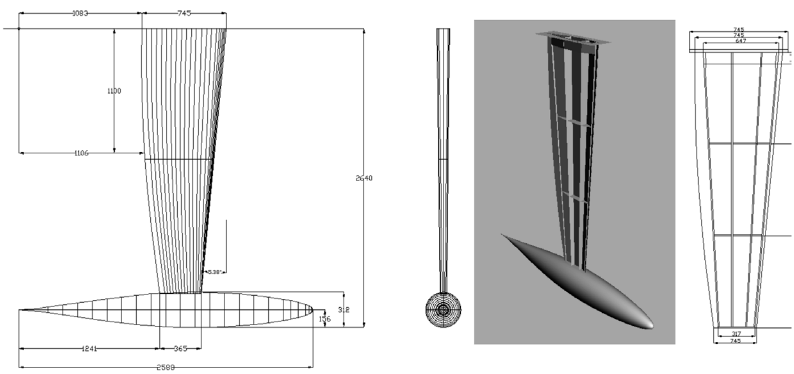

Fig. 5 Main dimensions and internal structure of a T-bulb keel

Strength calculation has to satisfy the requirements of *ISO* standards 12215, [1]. They include the calculation of:

- estimated weight,
- center of gravity,
- design bending moments,
- modulus of the cross-sectional area,
- stresses at critical parts of the structure, and
- keel and hull connection, i.e. flange and associated screws dimensions.

The results of strength calculation are shown in table 3.

Table 3 Design parameters calculation

Design parameter	**Mark**	**Unit**	**T-bulb keel**
Bulb area	S_b	m^2	1,595
Bulb volume	V_b	m^3	0,101
Keel area (without bulb)	S_s	m^2	2,302
Bulb weight	Q_b	kg	1134
Keel weight (without bulb)	$Q_{plašta}$	kg	191
Internal structure weight	Q_{is}	kg	29
Flange weight	Q_{fl}	kg	26
Keel internal ballast (without bulb)	Q_{bal}	kg	345
Filler weight	Q_{kit}	kg	207
Total weight	Q	kg	1932
Center of gravity	x_T, z_T	mm	1430, 1912
Bending moment	M_{qd}	kNm	66,492
Cross-sectional moment of inertia	SM_{qx} SM_{qy}	cm^3 cm^3	456 2407
Normal stress	σ	MPa	146
Shear stress	τ	MPa	20
Total stress	σ_T	MPa	150
Permissible stress, Normal, σ_d=0,9 σ_y Shear, τ_d=0,9 σ_d Contact, σ_{bd}=1,8 σ_d		MPa	MS / HTS AH36 211 / 320 118 / 178 380 / 575
Flange dimensions		mm	847 x 236
Screw dimensions	d_{nom} d_{neck}	mm mm	16 13,55

The selected keel is defined with a bonding steel flange and screws classified according to the ISO 898-1 standard, (8.8 *ISO*). Flange dimensions and screw positions are presented in fig. 6. Mechanical properties of selected bolts are: σ_u = 800 Nmm^{-2}, σ_y = 640 Nmm^{-2} Nmm^{-2}, σ_d = 400 Nmm^{-2}.

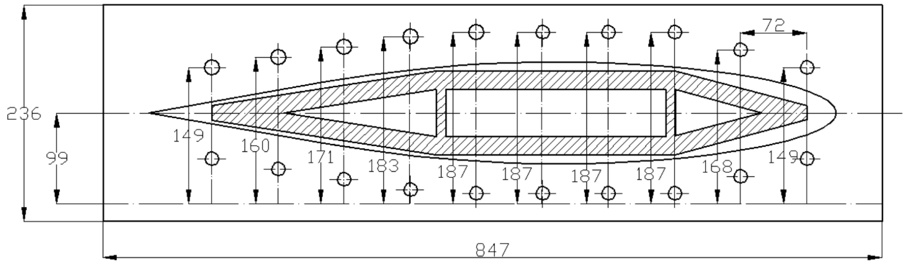

Fig. 6 Cross section of the keel and flange dimension and screw positions

4. Finite element analysis

The first step to the structural analysis using *FEM* is the generation of keel computational models using adequate 3D software. The models are then transferred to the FEMAP NX Nastran [2], where the finite element mesh is created, fig.7, as well as the material and boundary conditions, fig.8, and design loads. The linear static analysis was conducted for the state of the maximum load that occurs at the moment the keel is in a horizontal position, or the boat is tilted by 90°.

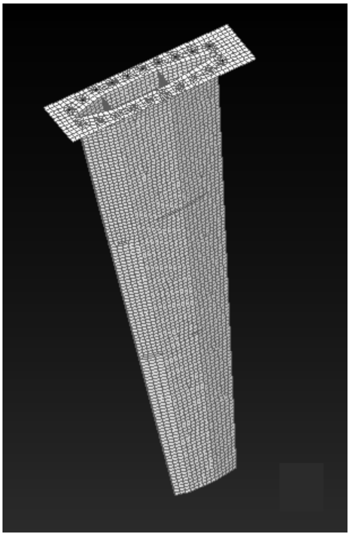

Fig. 7 Model mesh

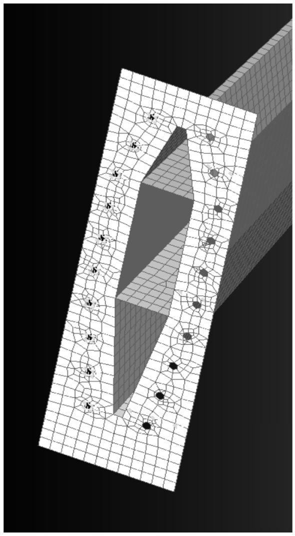

Fig. 8 Model constraint

When the selected keel with T-bulb is loaded to bending, there occurs a displacement of the peak leaf steel structure of about 48 mm, Fig. 9. The torsion angle of such a T-bulb keel is about 0.1° at the fore end, which does not produce any significant impact on the sailing performance.

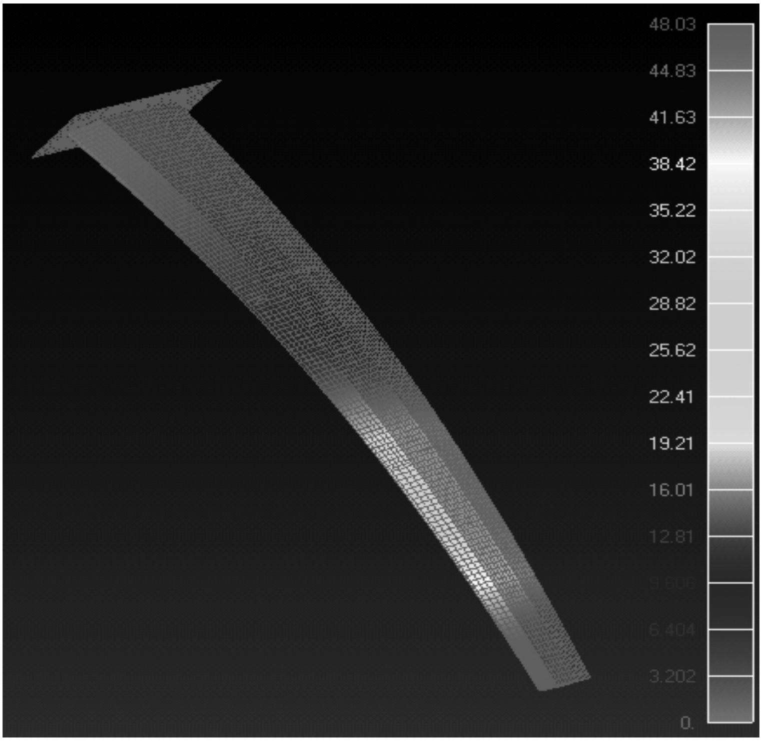

Fig. 9 T-bulb keel deformation; bending and torsion

Stress distribution in MPa for a T-bulb keel is presented on the left part of Fig. 10. Stresses are highest at the lateral surfaces of the steel girder, rising towards the flange. The global stress is about 230 MPa, while local stresses reach up to 278 MPa. Therefore, the selected material is AH36 steel of 20 mm in thickness. In this way, the greatest stress does not exceed 87% of the allowable stress for high strength steel AH36. At the junction of the structure where 10 mm and 20 mm steel plates are welded together, the maximum stress is 203 MPa, which does not exceed the permissible stress for normal shipbuilding steel, Fig. 10, right part. On the flange of the keel with T-bulb, the stress appears to reach 134 MPa and does not exceed 42% of the allowable stress for high strength steel. Large stresses arise at the edges of screw holes, where they significantly exceed the allowable stress of 320 MPa. Since it is about a local stress, a separate analysis should be carried out on the contact model.

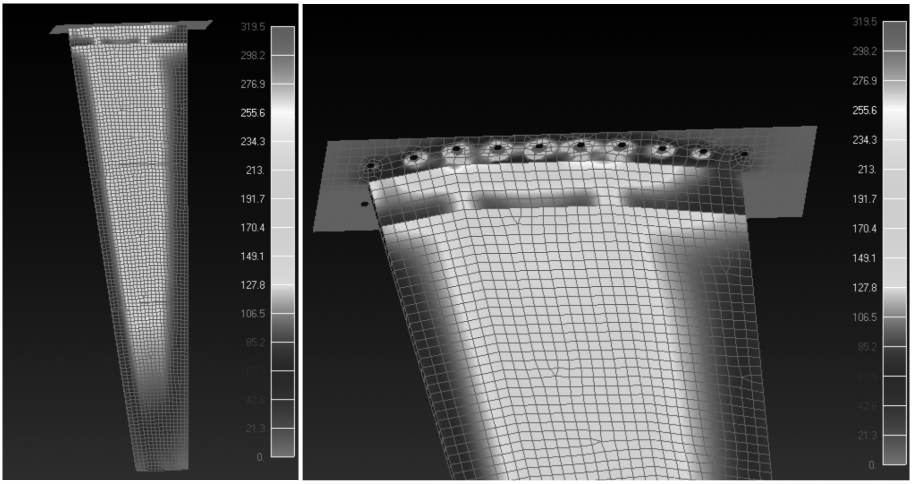

Fig. 10 Stress distribution along the keel structure and on the flange to the keel joint

5. Conclusion

The equipment design methodology based on *QFD* and *FEA* is suggested in the paper. In the first phase, the *Quality Function Deployment* is used for determination of the basic equipment configuration. Market analysis was performed for evaluation of customer needs and requirements. The product concept was selected by using the *product concept selection matrix*, whereby different design requirements were evaluated and equipment technical characteristics were determined. Using such a systematic procedure, premises were defined for the basis of the boat equipment concept design, as a product that will optimally satisfy customer requirements. In the second phase, the design parameters affecting the sailing boat performances are described as the basis for further concept design and details. For the selected T-bulb keel, the internal structure was dimensioned and analyzed. For strength calculation, the weight, centre of gravity and bending moments were defined. Design loads are defined according to the ISO standard for the keel in horizontal position, i.e. the boat tilted by 90°. The vertical and horizontal loads on the keel and the stress in way of the keel and hull connection were verified. The connecting screws were also dimensioned. A keel 3D model was generated in Rhinoceros software and strength assessment was performed using the finite element method within the Femap NX Nastran software. In using such a method, the analysis showed that the area of greatest stress is located in the junction of the keel and the flange and that the maximum stress in the structure of the keel does not exceed the allowable material stress. In further analysis, local stresses in bolts area should be addressed. The application of the presented methodology leads toward the selection of the equipment concept that satisfies the customer needs in the first place and further allows for the requirements of the prescribed rules to be satisfied as well.

Acknowledgements

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List of symbols

QFD		-	Quality Function Deployment technique
FEA		-	Finite Elements Analysis
A_K	m^2	-	Keel surface
GK	kg	-	Keel weight
TK	m	-	Keel draft
$C_{1,2}$	m	-	Keel top and bottom chord length
C_1/C_2		-	Tapper ratio
€	m	-	Medium chord length
a	°	-	Keel sweep angle
AR		-	Keel aspect ratio
L_{WL}	m	-	Boat length on water line
T	m	-	Total draft
T_c	m	-	Hull draft (without keel)
B_{MAX}	m	-	Boats maximum width
C_L		-	Lift coefficient
C_D		-	Draft coefficient
D	kg	-	Displacement
SA	m^2	-	Sail area
S_b	m^2	-	Bulb area
V_b	m^3	-	Bulb volume
S_s	m^2	-	Keel area (without bulb)
Q_b	kg	-	Bulb weight
$Q_{plašta}$	kg	-	Keel weight (without bulb)
Q_{is}	kg	-	Internal structure weight
Q_{fl}	kg	-	Flange weight
Q_{bal}	kg	-	Keel internal ballast (without bulb)
Q_{kit}	kg	-	Filler weight
Q	kg	-	Total weight
x_T, z_T	mm	-	Centre of gravity
M_{qd}	kNm	-	Bending moment
SM_{qx}	cm^3	-	Cross-sectional moment of inertia
σ	MPa	-	Normal stress
τ	MPa	-	Shear stress
σ_T	MPa	-	Total stress
d_{nom}	mm	-	Screw dimensions

Tin Matulja, Albert Zamarin, Robin Matulja

Metodologija projektiranja opreme brodice temeljena na metodama *QFD* i *MKE*

Sažetak

Potrebe i zahtjevi potencijalnih kupaca trebaju se definirati prije izrade samog konceptualnog projekta. Uobičajeno je da se takve potrebe i zahtjevi definiraju kroz statističke analize. Zbog različitih profila kupaca, postoji isto toliko različitih tržišnih niša koje diktiraju karakteristike pojedine opreme. Stoga je u radu predložena analiza tržišta s ciljem utvrđivanja različite karakteristične opreme za jedrilice. U tu svrhu predlaže se tehnika evolucije kvalitete (*QFD*) kao prve faze metodologije. Na taj način obavljena je sustavna identifikacija i vrednovanje potreba i zahtjeva potencijalnih kupaca koja dovodi točno utvrđenom procedurom do osnovnih parametara ciljane konfiguracije opreme. U drugoj fazi predlaže se metoda konačnih elemenata (*MKE*) za analizu globalne čvrstoće i optimizaciju prethodno odabrane konfiguracije opreme. Predložena metodologija prikazana je na primjeru izbora i projektiranja balastne kobilice odabrane jedrilice. Nadalje, projektni pristup prikazan je na odabiru parametra struka i bulba kobilice te na definiranju geometrije, mase i težista mase sustava.

Ključne riječi: oprema brodice, metodologija projektiranja, *QFD* tehnika, *MKE*