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Strenght aspects of the design of highly skewed propellers

SUMMARY

The paper discusses problems related to design of highly skewed propellers. These propellers require application of special methods both in hydrodynamics and in strength analysis. Their blades are influenced by the phenomenon known as hydroelasticity. Namely, the geometry of the blades may change considerably under loading, leading to meaningful changes in hydrodynamic characteristics.
This phenomenon should be taken into account in the design procedures of highly skewed propellers.

The paper presented at International Conference on Problems of Marine Propulsion HYDRONAV'95, Gdańsk, November 1995

INTRODUCTION

The design methods of highly skewed propellers differ markedly from the design of standard propellers, because of the way of selecting the skewback distribution and because of high elasticity of the skewed blades.

Firstly, when designing highly skewed propellers one should have the possibility of arbitrary selection of the blade outline, especially the magnitude and distribution of skewback.

Secondly, appropriate selection of the skewback distribution requires alternate application of design procedures and hydrodynamic analysis procedures calculating the bearing forces, pressure pulses induced on the hull or the generated acoustic pressure.

Thirdly, high elasticity of skewed propellers strongly influences their design methods. The magnitude and distribution of skewback affect the values and location of maximum stresses in the blade. Consequently, the hydrodynamic design procedure should interact with an appropriate strength analysis procedure, which should be capable of calculation of stresses in an arbitrary point of the blade and determination of deformation of all blade sections. Even at the design loading distribution the blade deformation may influence markedly the blade pitch and mean line camber of the blade sections.

The hydroelasticity problem plays an important role in the design of highly skewed propellers.

CHARACTERISTICS OF THE PROPELLER BLADE SKEWBACK

The most characteristic feature of highly skewed propellers is their blade outline (Fig..1). This specific shape is applied first of all in order to improve propeller operation in the circumferentially non-uniform velocity field which is characterized by regions of strong variation of direction or magnitude of the inflow velocity vector. In these cases the clue of shaping the blade outline lies in creating an appropriate time shift between the instants at which different blade sections enter such regions.

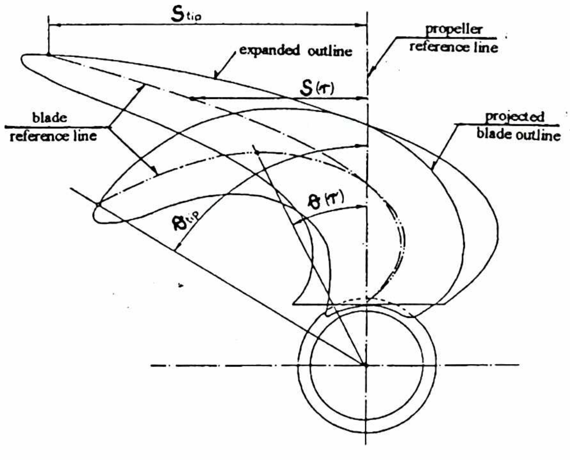

Fig. 1. Propeller blade outline and skewback definition

$$S_{tip} = \Theta_{tip} / \cos\Phi$$

Propeller blade skewback is a displacement of the blade reference line from the generator line along the helical line of the respective blade section. This displacement is shown in Fig.1 on the expanded blade outline. The measure of this displacement is the arc length of the helical line marked as S(r). The angle (r) shown in Fig.1 may also be used as a measure of the blade skewback.There is a strict relation between these quantities:

$$S(r) = \Theta(r)\, r / \cos[\Phi(r)] \tag{1}$$

Generally speaking, the distribution of S(r) may be more or less complicated. For example, when reduction of the blade spindle torque in a controllable pitch propeller is desired, then application of negative skewback near the propeller hub is necessary. Also for fixed pitch propellers negative skewback near the hub may be applied on the basis of the details of the inflow velocity field. In view of different radial distributions of skewback, its value on the blade tip should not be regarded as a general measure of skewback. The tip skewback may serve as measure of skewback only for a given series of propellers having a defined radial distribution of skewback.

In certain situations, for example in comparative analysis of experimental results from different research establishments or in numerical optimization analysis it is desirable to characterize univocally different skewback distributions using minimum possible number of parameters. One way of fulfilling this requirement may be the assumption that the curve S(r) is a second order parabola defined by the values of local skewback at the hub, at the tip and in the middle between these two locations.

In this case, as the skewback on the hub is by definition zero, two parameters are enough to characterize the skewback distribution: skewback on the tip, related to the propeller diameter S_{tip}/D and the ratio of local skewback at the middle radius to the tip value:

$$A_S = S(R_m)/S_{tip}$$

The values of skewback at intermediate radii may then be determined as

$$S(r) = S_{tip}\left\{a\left(\frac{r}{R}\right)^2 + b\left(\frac{r}{R}\right) + c\right\} \tag{2}$$

where: a,b,c - coefficients of the parabola based on the three above mentioned points.

Very different skewback distributions may be obtained by varying the parameter A_S, from a straight line (A_S =0,5), to the distributions with negative skewback near the hub. The propeller shown in Fig.1 has the distribution of S(r) characterized by A_S=0 The distributions of NSRDC highly skewed propeller series for pitch P/D=1,0 correspond practically to A_S=0,3231. Both the magnitude and shape of skewback are equally important. The shape of the blade outline must be individually selected for every non-uniform velocity field.

STRENGTH ASPECTS OF THE DESIGN OF HIGHLY SKEWED PROPELLERS

In a design calculation the shape of blade section profiles, which should be attained under prescribed design loading, is determined . In the case of meaningful changes in blade geometry under loading, when these changes influence visibly the hydrodynamic characteristics, the propeller blade geometry without loading should be known, because this geometry is the basis for manufacturing documentation. If the distortion is limited and stresses in the blade do not reach the level of plastic deformation, the determination of blade geometery without loading is relatively simple. The changes in blade geometry are determined on the basis of blade shape under loading taken from the design calculation. The direction of loading is then reversed (including the centrifugal forces) and the displacements normal to chords of all blade sections are calculated. These displacements influence the propeller hydrodynamic characteristics only if they lead to change of blade pitch or blade section mean lines.

The change of blade pitch angle is determined by subtracting displacement at the trailing edge y_t from the displacement at the leading edge y_n and dividing the result by the chord length L:

$$\Delta\Phi \approx \arctan\left(\frac{y_n - y_t}{L}\right) \approx \frac{y_n - y_t}{L} \tag{3}$$

The changes in mean line geometry are determined by relating the local normal displacements to the new chord length (defined by displacement of the leading and trailing edge):

$$\Delta F = y(x) - y_n + x\tan(\Delta\Phi) \tag{4}$$

Examples of such calculation by using a special computer program [11] are presented in Figs. 2 to 7. This program is based in its hydrodynamic part on the lifting surface model, and in its strength analysis part it is based on finite element model. It seems that the variation of local pitch and mean line shape is influenced first of all by the local skewback *S(r)* and that such a shape exists there which is described by formula developed by NSRDC [2,10] for which even at large total skewback values the blade distortion under loading is negligible. For other shapes of skewback the problem of change in hydrodynamic characteristics under loading plays an important role. Figs.8 to 11 show the lines of constant displacement normal to the blade section chords drawn against the blade outline (the width scale is different in different figures). The presented results concern propellers having different magnitude and distribution of skewback. Consequently, despite having been designed for identical design condition, they differ in blade pitch line and mean line camber.

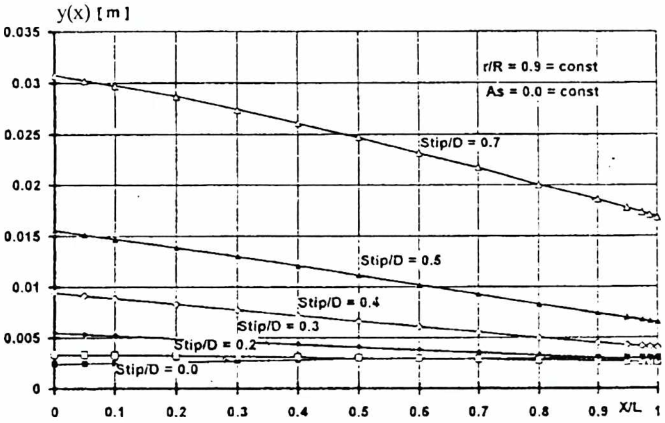

Fig. 2. Deformation of the blade section at radius r/R=0,9 for different tip skewback and A_S=0=const.

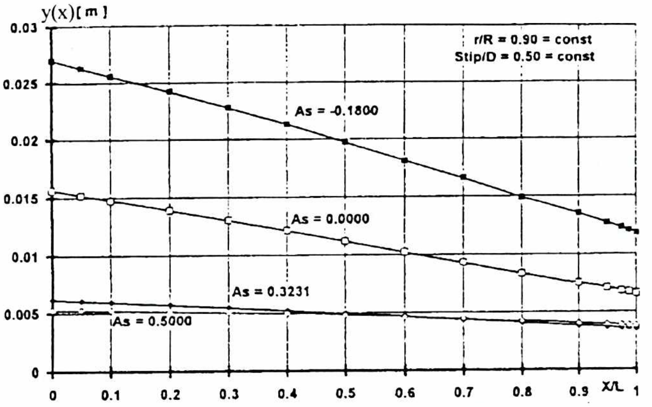

Fig. 3. Deformation of the blade section at radius r/R=0,9 for different skewback distribution and S_{tip}/D=0,5=const.

The blade width and thickness distribution are kept constant. Also the radial and chordwise loading distribution is the same for all cases.

Analysing the above mentioned figures it may be concluded that there is a strong influence of the magnitude and shape of skewback on the blade displacements. It is best visible in Figs.2 and 3 in which the normal displacements y at the cylindrical section *r/R = 0,90* are presented. In Fig.3 the propellers have the same tip skewback $S_{tip}/D = 0,5$ and they differ in local skewback $S(r)$ defined by the parameter A_S. In Fig.2 the propellers have the same value of $A_S = 0$ and they differ in the tip skewback S_{tip}/D. In Figs. 4 to 7 the influences of these displacements on the blade pitch and section mean lines is presented. Fig.4 shows the change in pitch coefficient P/D at different cylindrical section $r/R = const.$ for propellers having the same tip skewback $S_{tip}/D = 0,5$ and different distributions of local skewback $S(r)$ characterized by the parameter A_S. Minus sign denotes the reduction of pitch under loading. Similarly, Fig.5 presents changes in the blade section mean line camber F/L. In this case negative sign denotes reduction of camber under loading. Figs.6 and 7 show the changes in pitch P/D and in mean line camber m/c for propellers having constant parameter $A_S=0$ and differing in the tip skewback S_{tip}/D. It may be noticed that a symmetrical propeller of $S_{tip}/D=0$ having chordwise loading distribution NACA a = 0,8 experiences an increase of pitch and camber under loading. A small skewback annihilates this increase and meaningful changes in blade geometry start from $S_{tip}/D = 0,4$ for $A_S = 0$ (they result in changes of about 2 per cent in the hydrodynamic characteristics). It is difficult to establish limiting values of S_{tip}/D and A_S above which the hydroelasticity problem becomes important in propeller design, because the blade deformation is proportional to $(nD)^2$, which may be different for different propellers.

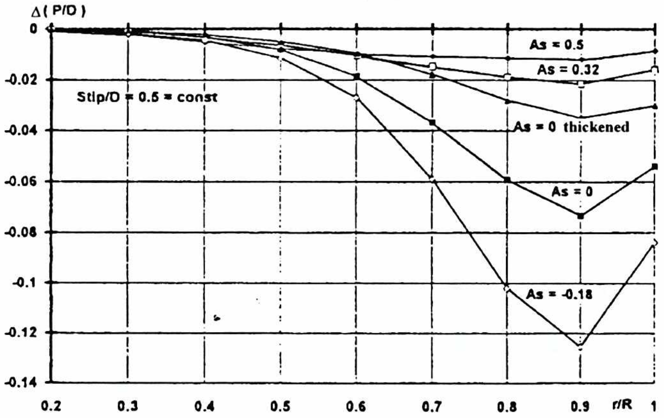

Fig. 4. Changes of pitch for propellers with different skewback distributions A_S for $S_{tip}/D=0,5=const.$

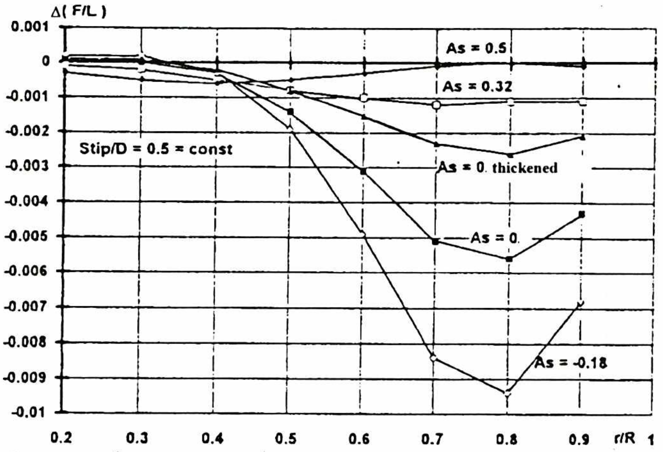

Fig. 5. Changes of blade section mean line camber for propellers with different skewback distribution A_S for $S_{tip}/D=0,5=const$

The above presented results concerning influence of skewback on the hydrodynamic characteristics were obtained numerically, but they have been confirmed by experiment [5,7,9]. Figs.12 and 13 present the results of experiments with highly skewed propeller models. The propeller in Fig.12 has the tip skewback $S_{tip}/D = 0,5$ and the distribution of skewback is characterized by $A_S = 0$ (the expanded blade outline of this propeller is shown in Fig.1.) Three pairs of curves $K_T = K_T(J)$, $K_Q = K_Q(J)$ obtained in model experiments at different number of revolutions are presented. Decisively larger changes could be detected for a propeller with $S_{tip}/D = 0,7$ and $A_S = 0$, which results are presented in Fig.13. In the course of experiments with this propeller at 40 revs per second and $J = 0,55$ the plastic stress limit was exceeded and the blades were permanently deformed (the tests were started from high J values). At 50 revs per second the propeller was already deformed and it underwent further deformation as the velocity was reduced. Generally, satisfactory correlation between experimental and calculated results was obtained as long as plastic deformation was absent.

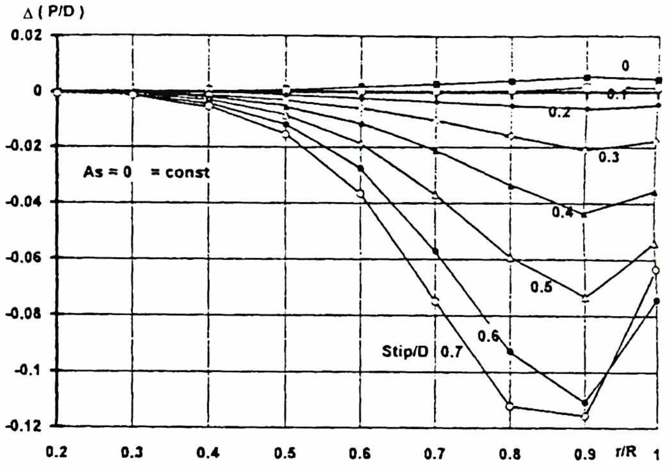

Fig. 6. Changes of pitch for propellers with different skewback S_{tip}/D for $A_S=0=const.$

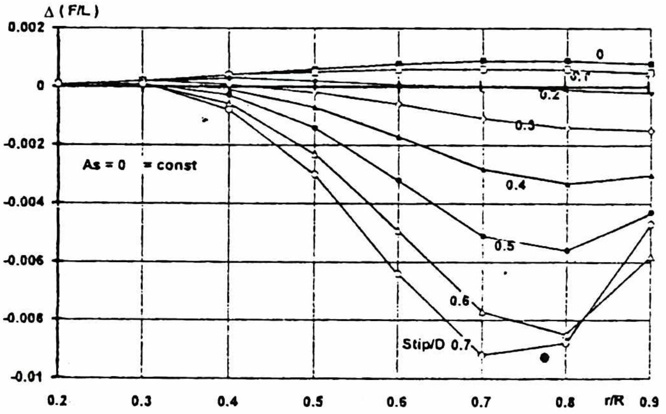

Fig. 7. Changes of blade section mean line camber for propellers with different skewback S_{tip}/D for $A_S=0=const.$

Another problem, which should be solved in the design process of highly skewed propeller, concerns the changes of magnitude and location of maximum blade stress connected with changes in blade skewback. The problem of hydroelasticity is relatively new and the necessity of its analysis is not universally ackowledged. For example, in the series of highly skewed propellers tested at NSRDC [2,10] having $A_S = 0,32$, the problem of influence of skewback on the hydrodynamic characteristics may be disregarded in practice. It is quite opposite with propellers having A_S close to zero or in particular with propellers having negative A_S, which exhibit very favourable effects in reduction of fluctuating bearing forces and pressure pulses. The example presented in the preceding section shows that a similar reduction of fluctating bearing forces and pressure pulses may be obtained with $S_{tip}/D = 0,5$ and $A_S = 0,3231$ and with $A_S = 0$ and $S_{tip}/D = 0,25$. From Fig.3 it follows that in the second case the pitch and mean line distortion under loading is negligible, so by proper manoeuvring with skewback distribution the same results may be obtained at half the total skewback and without necessity to analyze hydroelastic effects

The design of highly skewed propellers becomes more complicated when the requirement of a very low level of fluctuating bearing forces and/or pressure pulses enforces application of a very high tip skewback in conjunction with low values of A_S. In view of the above presented examples it would be interesting to decide which of the two parameters should be preferred in search for the optimum blade outline of a propeller operating in a particular velocity field.

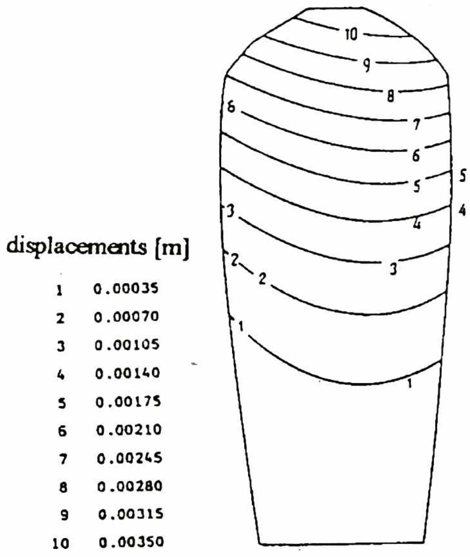

Fig. 8. Constant displacement lines for a propeller with symmetrical blades.

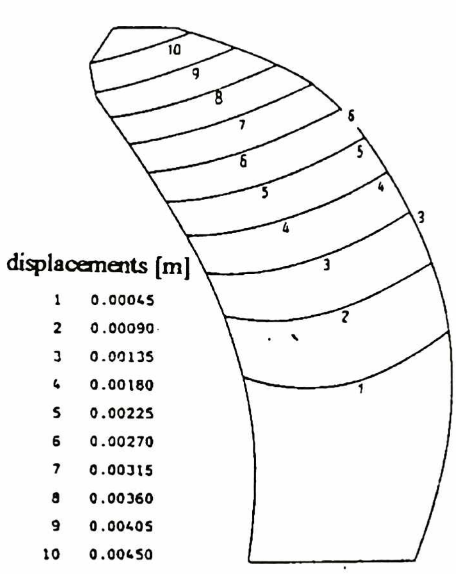

Fig. 9. Constant displacement lines for a skewed propeller with $S_{np}/D=0,2$, $A_s=0$

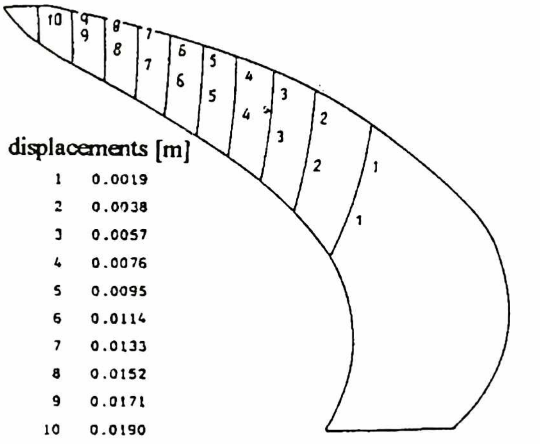

Fig. 10. Constant displacement lines for a skewed propeller with $S_{np}/D=0,5$, $A_s=0$

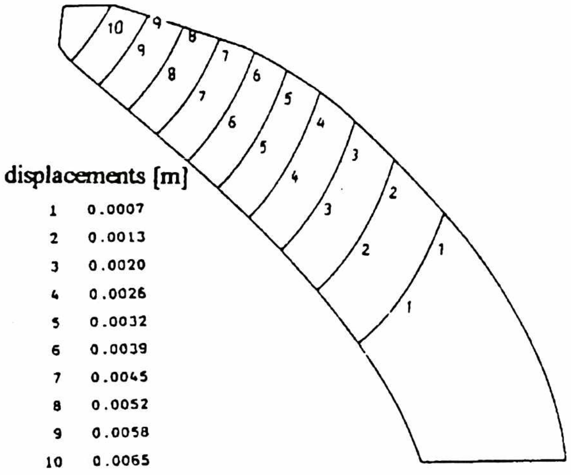

Fig. 11. Constant displacement lines for a skewed propeller with $S_{np}/D=0,5$, $A_s=0,5$

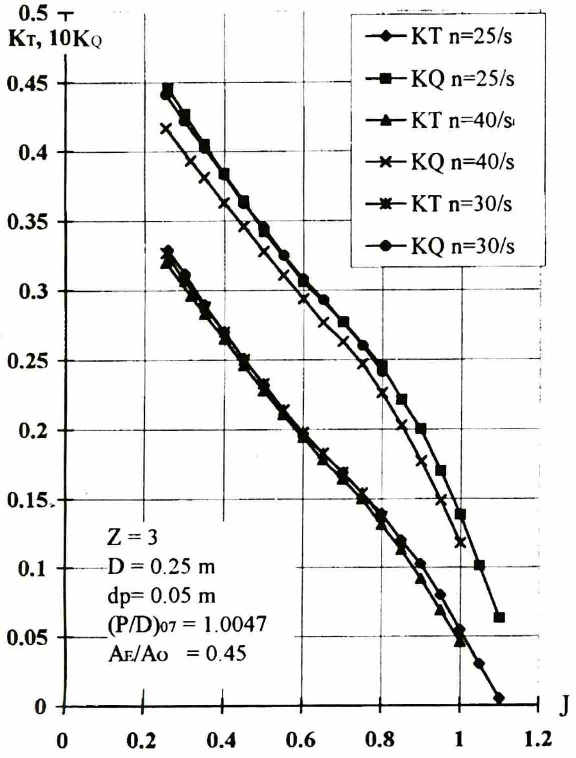

Fig.12. Hydrodynamic characteristics from model tests at different revolutions,. $S_{np}/D=0,5$, $A_s=0$

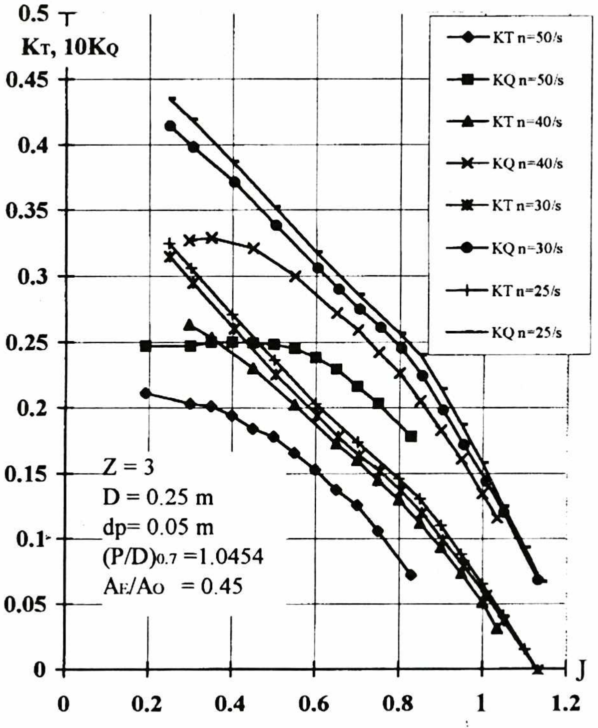

Fig.13. Hydrodynamic characteristics from model tests at different revolutions, $S_{np}/D=0,7$, $A_s=0$

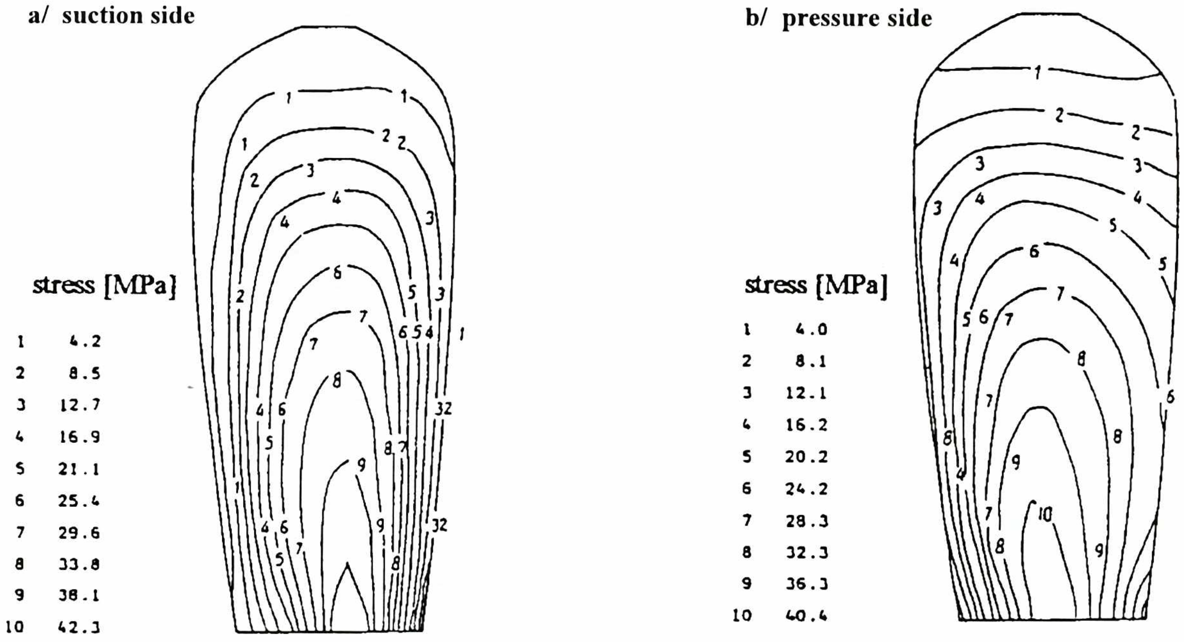

Fig. 14. Constant stress lines for a propeller with symmetrical outline.

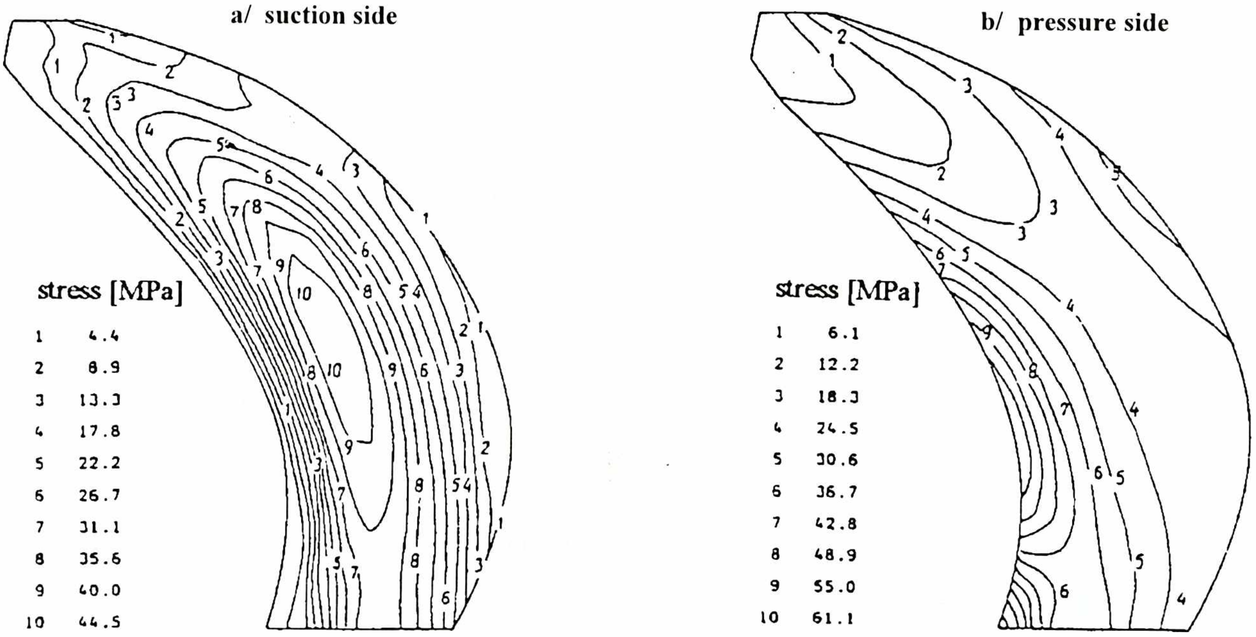

Fig. 15. Constant stress lines for a skewed propeller with $S_{tip}/D=0,3$, $A_S=0$

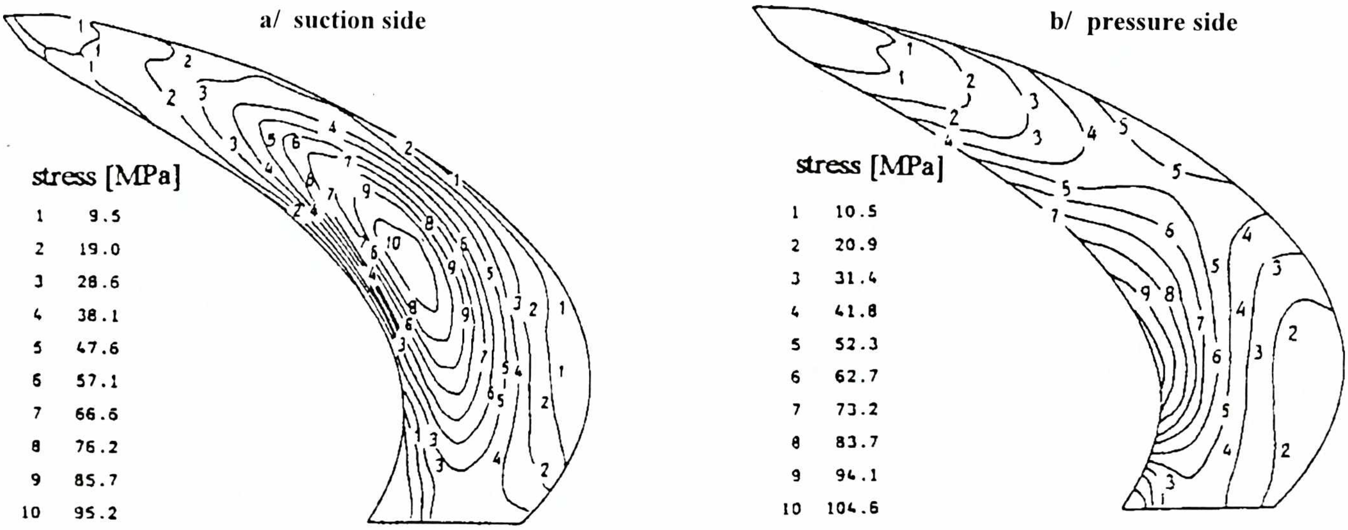

Fig. 16. Constant stress lines for a skewed propeller with $S_{tip}/D=0,5$, $A_S=0$

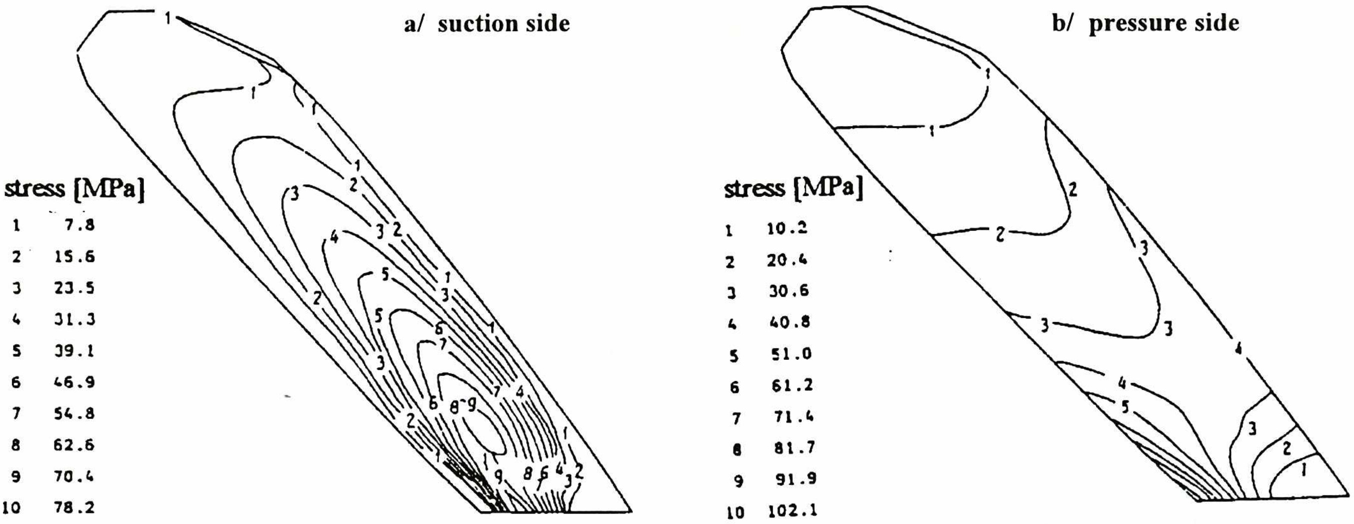

Fig. 17. Constant stress lines for. a skewed propeller with $S_{up}/D=0,5$, $A_s=0,5$.

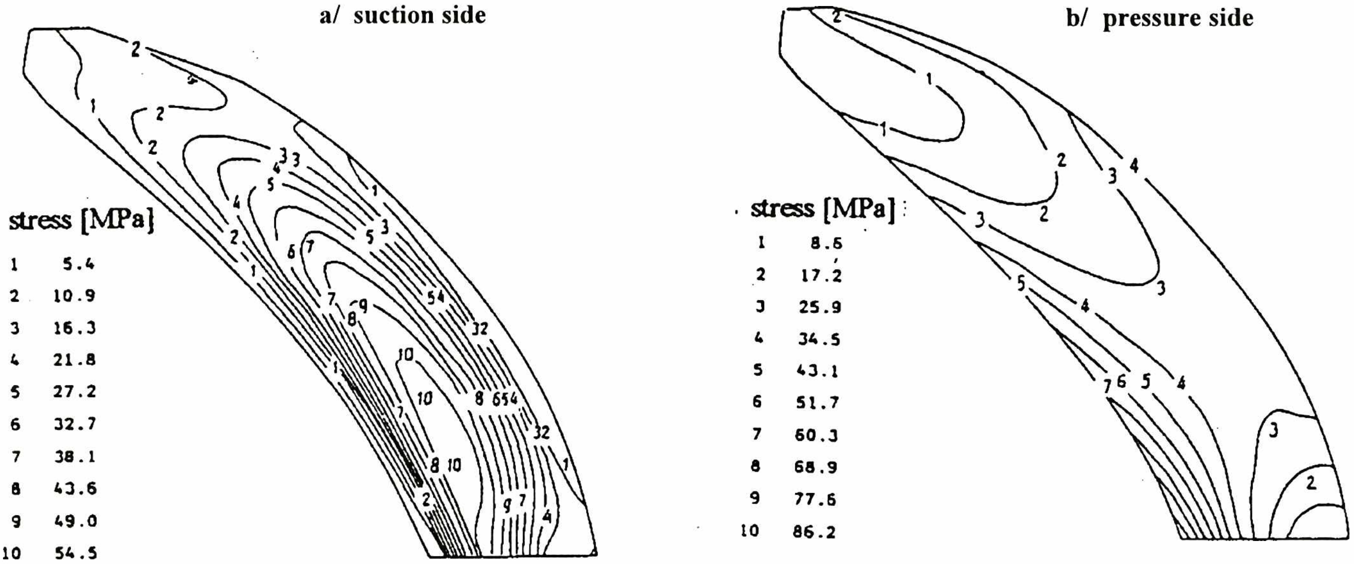

Fig. 18. Constant stress lines for a skewed propeller with $S_{up}/D=0,5$, $A_s=0,3231$.

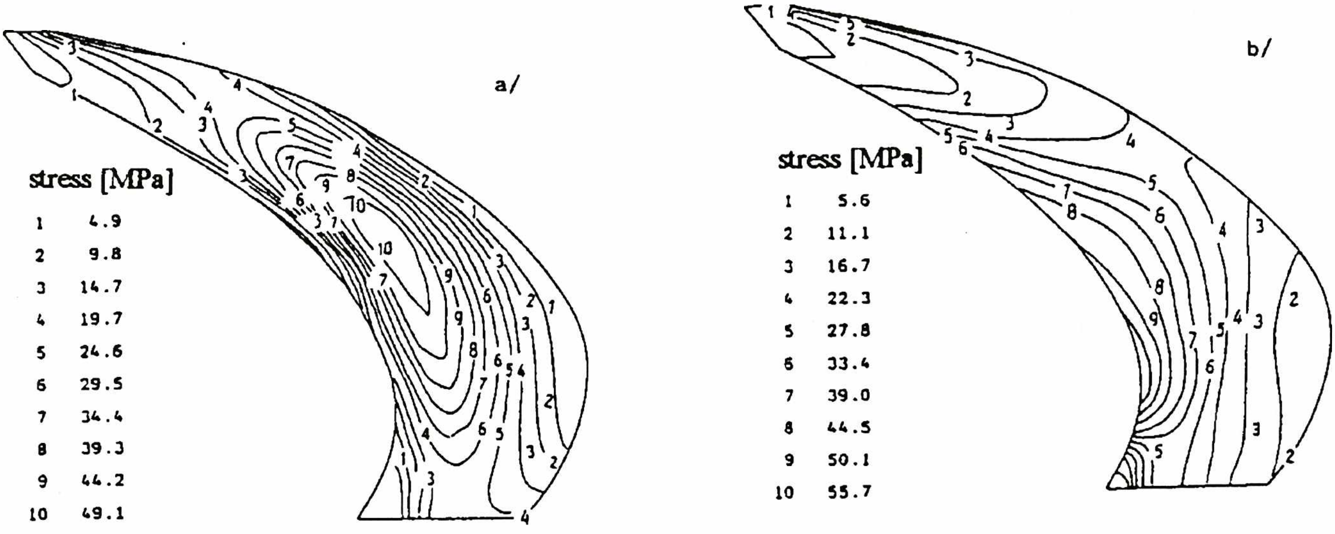

Fig. 19. Constant stress lines for a skewed propeller with $S_{up}/D=0,5$, $A_s=0$ and thickened blades.

At the moment it is not possible to answer this question univocally. The problem of hydroelasticity is relatively new and there is no sufficient experience accumulated yet. This is further complicated by the need to consider the overall blade strength simultaneously.

As it has been mentioned before, the blade skewback (both its magnitude and distribution), influences the values and distribution of the blade stresses. In Figs. 14 to 18 the results of calculation of stresses in the blades differing in S_{tip}/D and $S(r)$ are presented:

All propellers have been designed for the same design condition. The same blade outline and thickness distribution have been assumed. The values of blade pitch and mean line camber were changing with changes in skewback. Figs.14a and 14b show the results of calculation for the suction and pressure side of the blade in the form of equal stress lines for a propeller with symmetrical outline. The stresses shown in the figures are the reduced stresses according to the hypothesis of Huber, von Mises and Hencky .

The following figures show how the distribution and magnitude of stresses is changing with change in tip skewback and skewback distribution. Quite strong influence may be concluded when analysing Figs.14 to 16, showing propellers with constant A_S and varied S_{tip}/D, and Figs.16 to 18, showing propellers with constant S_{tip}/D and varied A_S . These examples demonstrate the importance of possessing a suitable method for strength analysis (possibly a computer program based on finite element method, cf. [8]). In view of the analysis of model test results and strength calculation of highly skewed propellers, the plastic stress limit for brass used for propeller manufacture is about σ_q = 120 MPa, and when a safety factor is included, σ_q = 60 MPa should be taken.

The stress distributions presented in the above figures exceed this value for higher blade skewbacks and a correction of blade thickness and chord lengths (because of cavitation) is necessary. It may be difficult to do because the finite element procedures are seldom included in the cavitation/strength iteration loops in design programs, as it is done with formulae developed by classification societies or with simple beam theory methods. It is more convenient to keep the finite element procedure as a separate program because of its size and execution time. Then the hydrodynamic design program produces the necessary information (complete propeller geometry and pressure distribution on the blade), while the finite element program calculates the stresses and deformations of the blade, supplemented if necessary with blade geometry without loading. This geometry may be necessary for preparation of the manufacturing drawings of the propeller experiencing meaningful distortion under stress.

The results presented in Figs.9 to 18 refer to a propeller having thickness distribution and blade outline determined according to the Polish Register of Shipping Rules and to the requirement of cavitation-free operation at the shock-free entry condition. At the moment all classification societies rules do not take into account the changes in location and magnitude of maximum stress due to blade skewback. An appropriate strength analysis shows that in the case of high tip skewback associated with low values of A_S very large changes in location and value of maximum stress do take place. Consequently, the thickness distribution determined according to the Rules for highly skewed propellers must be suitably corrected. For example, in order to reduce stresses in the blade characterized by $S_{tip}/D = 0{,}5$ and $A_S = 0$ (Figs.16a and 16b) to the permissible value *60 MPa*, the thickness and blade width had to be increased to the level presented in Fig.20. Figs.19a and 19b show the lines of constant stress after this correction. Such a correction influences markedly the blade distortion under loading. In Figs.4 and 5 the changes of pitch and mean line camber of the propeller after correction are presented. From these diagrams it may be concluded that for skewback of $S_{tip}/D = 0{,}5$ after reduction of maximum stress to *60 MPa* the influence of blade distortion under loading on the hydrodynamic characteristics is significantly reduced (before correction the changes in K_T and K_Q were of the order of *4* to *6* per cent, after correction they are of the order of *1,5* to *2,5* per cent). The necessity of such correction is much more visible for higher tip skewbacks. For example for a propeller having $S_{tip}/D = 0{,}7$ and $A_S = 0$ a five-fold increase in maximum blade stress is obtained in relation to the propeller with symmetrical blade outline.

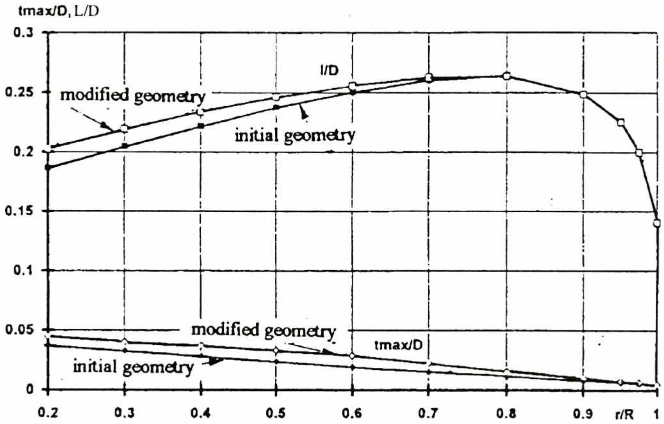

Fig.20. Modification of the blade section geometry in order to achieve permissible level of stresses

Reduction of this stress to the permissible level requires more serious changes of the blade geometry. This follows from the fact that the shape of the leading edge is decisive in reduction of fluctuating bearing forces and pressure pulses due to skewback. Consequently, every change in blade section length without changing the blade leading edge affects the local skewback. This additionally complicates the design based on systematic changes of magnitude and distribution of skewback.

FINAL REMARKS

Summing up, it was demonstrated, that a suitable design program based on lifting surface theory (enabling calculation for an arbitrary blade outline) cooperating with a specialized strength analysis program (based on the finite element method and enabling calculation of stresses and displacements in arbitrary points of the blade) is indispensable in effective design of highly skewed propellers. Moreover, a computer program for analysis of operation of highly skewed propellers in non-uniform velocity field is necessary for determination of magnitude and distribution of skewback from the point of view of minimizing the fluctuating bearing forces, pressure pulses on the hull, and acoustic pressure. It is necessary because this is the primary reason for the application of high skewback in marine propellers.

NOMENCLATURE

a,b,c - coefficients of the parabola describing the skewback
dp - hub diameter
r - radius of blade section
t_{max} - maximum thickness of the blade sections
x - ordinate along chord
x/L - non-dimensional x - ordinate related to chord lenght
y_n, y_t - displacement respectively at the trailing and leading edge
y(x) - displacement normal to chord
Ae/Ao - expanded blade area ratio
A_S - parameter characterizing the skewback distribution
D - propeller diameter
F - mean line camber of blade section
F/L - non-dimensional mean line camber
J - advance coefficient
K_T - thrust coefficient
K_Q - torque coefficient
L - chord lenght
P/D - pitch coefficient
R - propeller radius
R_m - the middle radius of the propeller blade
S(r) - local skewback of the blade sections
$S(R_m)$ - local skewback at the middle radius
S_{tip} - skewback of the tip propeller blade
Z - number of blades

$\sigma(g)$ - reduced stresses
$\Theta(r)$ - skew angle of the blade sections
Θ_{tip} - skew angle at the tip
Φ - pitch angle
$\Phi(r)$ - pitch angle at the radius r
Φ_{tip} - pitch angle at the blade tip

BIBLIOGRAPHY

1.Atkinson P., Glover E.J.: „ Propeller Hydroelastic Effects ". Symposium Propellers' 88, Virginia Beach, 1988

2.Boswell R.G.: „Design, Cavitation Performance and Open Water Performance of a Series of Research Highly Skewed Propellers". DTNSRDC Report 3339, March 1971

3.Cumming R.A., Morgan W.B. Boswell R.G.: „Highly Skewed Propellers" Trans. SNAME Vol.80, 1972

4.Jarzyna H., Szantyr J., Koronowicz T.: „Screw Propeller Design" Bulletin of the Inst. of Fluid Flow Machinery No. 290/1171/89

5.Koronowicz T., Kaczorowski J.: „Hydroelastic Effects in Highly Skewed Propellers". Symp. on Practical Design of Ships and Mobile Units, Varna, 1989

6.Koronowicz T., Tuszkowska T.: „The Program CHDSK for Calculation of Propeller Characteristics Including Hydroelastic Effects". Report of the Inst. of Fluid Flow Machinery, No.161/90

7.Koronowicz T.: „Hydroelastic Problems in Design of Ship Hydromechanics". Symposium HYDRONAV'91, Gdańsk, 1991

8.Koronowicz T.: „Blade Strength in Computerized Design of Propellers". (in Polish), Bulletin of the Inst. of Fluid Flow Machinery, No. 372/1135/92

9.Koronowicz T., Kwapisz L.: „Hydroelastic Problems of Ship Propellers", 2nd Intern. Conference EAHE, Pilsen, 1994

10.Nelka J.J.: „ Experimental Evaluation of a Series of Skewed Propellers with Forward Rake". DTNSRDC Report 4113, 1974

11.Tuszkowska T.: „ Design of Ship Propellers with Arbitrary Skewback. Description of the Computer Program E15THPDSK". (in Polish), Report of the Inst. of Fluid Flow Machinery No.142/88

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Conferences

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CONFERENCE

SAFE SHIP

IS IT WORTH TO TAKE PART IN ?

On 31 January the 8-months period of collection papers for the Conference was terminated. The Organizers pose themselves a question: do the Conference topics draw sufficiently wide interest ?

Review of the titles and abstracts of the contributions offered and analysis of geographic distribution of the primary registration list, leads to a definitely positive response to the aforesaid question.

Why to attend the Conference ?

Some of the reasons are:

- Gain valuable insight from the assessment of the scope
- Learn about new developments in the branch
- Take advantage of the other participants experience
- Gain practical information from actual case studies
- Become more competitive by analyzing other approaches applied by other participants
- Assess the future
- Have your questions answered by other experts

Who should attend?

- ✧ Chief executives and members of management teams of shipyards and their suppliers
- ✧ Designers, R & D, and production staff, marketing executives
- ✧ Academic staff members
- ✧ Graduate students

Among the companies and institutions which have offered contributions, there are classification societies, whose representatives act in Poland, US Coast Guard, research centres, universities and marine equipment manufacturers from Australia. Germany, Italy, South Korea, Scandinavian Countries, Switzerland, UK and USA.

Polish shipyards, Maritime Administration and universities will be of course present either.

The actual registration list comprises over 100 names. The papers portfolio is full of very interesting contributions.

One of the basic assumptions concerning the Conference program has been to include some extra-technical aspects of the shipping safety, mainly an influence of the state economic policy, insurance system and the human factor in ship design, production and service.

The paper offered by US National Maritime Center, concerning presidential initiatives of supporting shipbuilding industry in USA, will match the above assumption and so will the paper of one of the insurance companies. The latter considers the influence of maritime insurance policy on the safety of shipping.

A presentation concerning evaluation of human factor impact on safety is also expected. The subject of extra-technical factors of ship design, construction and service will also be discussed in the papers delivered by Det Norske Veritas and the University of Plymouth.

Among the variety of papers concerning marine engineering problems, contribution of the Clemson University, South Carolina, USA, reviewing new ideas of lifesaving appliances, should be mentioned.

Significant number of papers concern such subjects like analysis of ship structure strength, damage stability, manoeuvrability, design procedures and marine equipment.

A number of presentations of computer software and some products aimed at to improve ship safety have also been offered.

Such variety of information presented in quiet and comfortable surrounding offered by the „Orle" Conference Centre on Sobieszewo island provides a response to question posed in the title of this note.

ZW