POLISH MARITIME RESEARCH 4(67) 2010 Vol 17; pp. 17-25
10.2478/v10012-010-0031-2

A complete design of tandem co-rotating propellers using the new computer system

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ABSTRACT

The computer system for the complete design of the tandem co-rotating propellers, presented in this article, has several common blocks and procedures with the computer system for the design of conventional single propellers, presented in detail in Polish Maritime Research No. 1 Vol. 16 (2009). In this article only these blocks and procedures are described, which are different in both systems. The comparative analysis of the designed tandem propeller and a conventional propeller is also included.

Keywords: ship propellers; tandem co-rotating propellers; design methods; computational fluid dynamics

INTRODUCTION

The tandem co-rotating propeller consists in fact of two propellers, usually of the same diameter and the same number of blades, mounted on the same shaft with certain angular shift between them (cf. Fig. 1). Application of such propellers may be advantageous when a very high power must be absorbed by a single shaft propeller having a limited diameter. Design of such propellers requires taking into account the mutual hydrodynamic interaction effects between the forward and aft propeller. The design of tandem co-rotating propellers is based on the same requirements and assumptions which are employed in the design of conventional single propellers [1, 3]. Apart from that, the design of tandem propellers requires the following new requirements:

a) determination of the division of the hydrodynamic loading between the forward and aft propellers,
b) determination of the mutually induced velocity field, i.e. the field induced by the forward propeller at the aft one and vice versa. This field must be taken into account not only in the design, but also in the analysis of the tandem propeller operation in the non-uniform inflow velocity field behind the ship hull.

Similarly as in the design of the conventional single propellers, the computer system for the complete design of the tandem propellers must include three interacting programs (blocks of procedures):

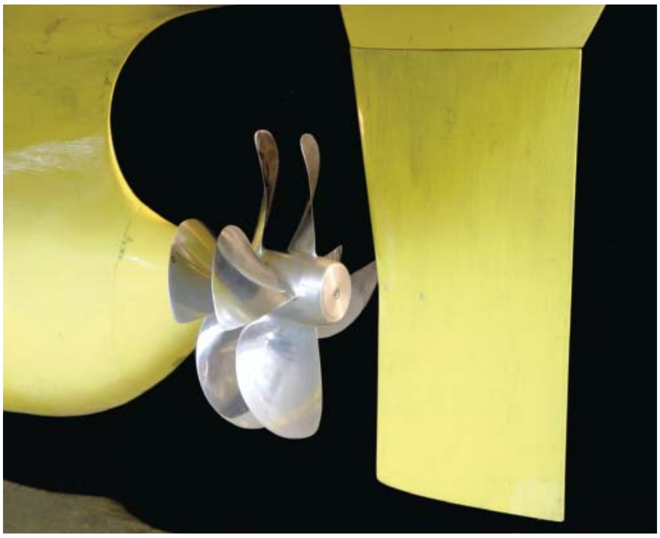

Fig. 1. *A typical tandem co-rotating propeller (Model tests in the Ship Hydromechanics Division of CTO SA)*

1) the programs for determination of the design velocity field for both propellers,
2) the program for the propeller design,
3) the program for the analysis of the tandem propeller operation in the non-uniform velocity field behind the ship hull, taking into account the mutual hydrodynamic interaction between both propellers.

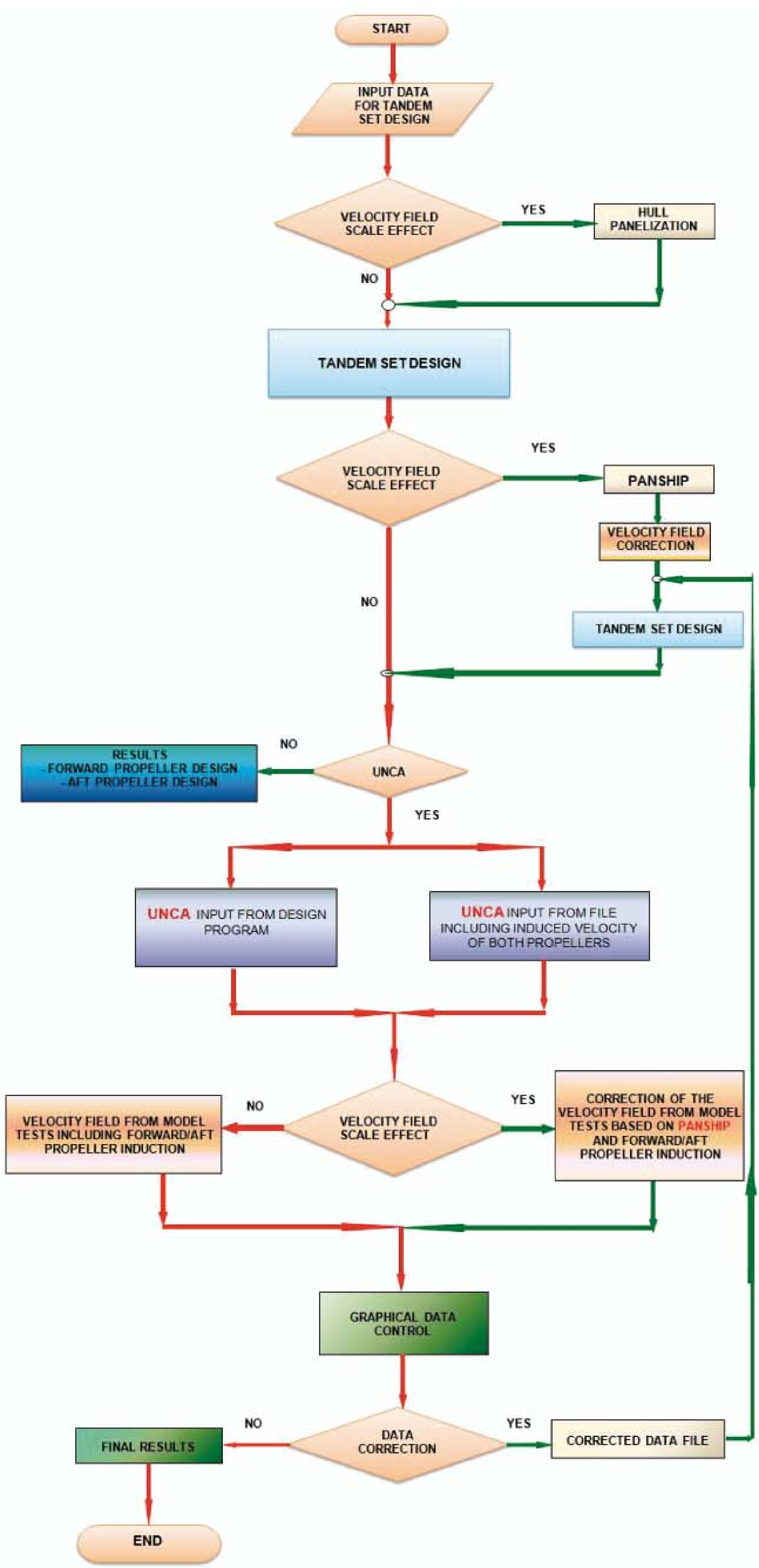

Fig. 2. *The block diagram of the computer system for the complete design of the tandem co-rotating propellers*

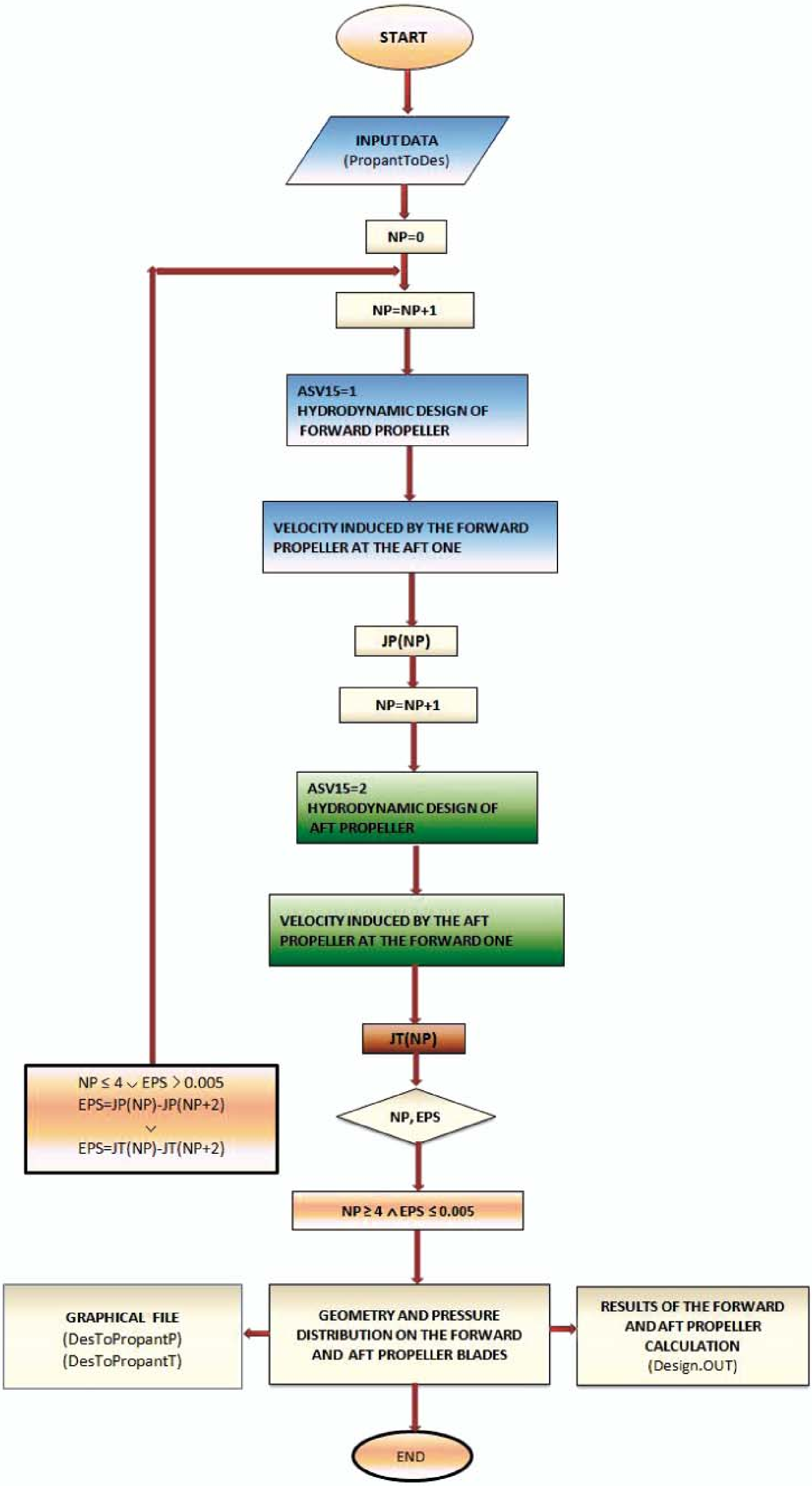

Fig. 3. The block diagram of the design procedure for the tandem co-rotating propellers

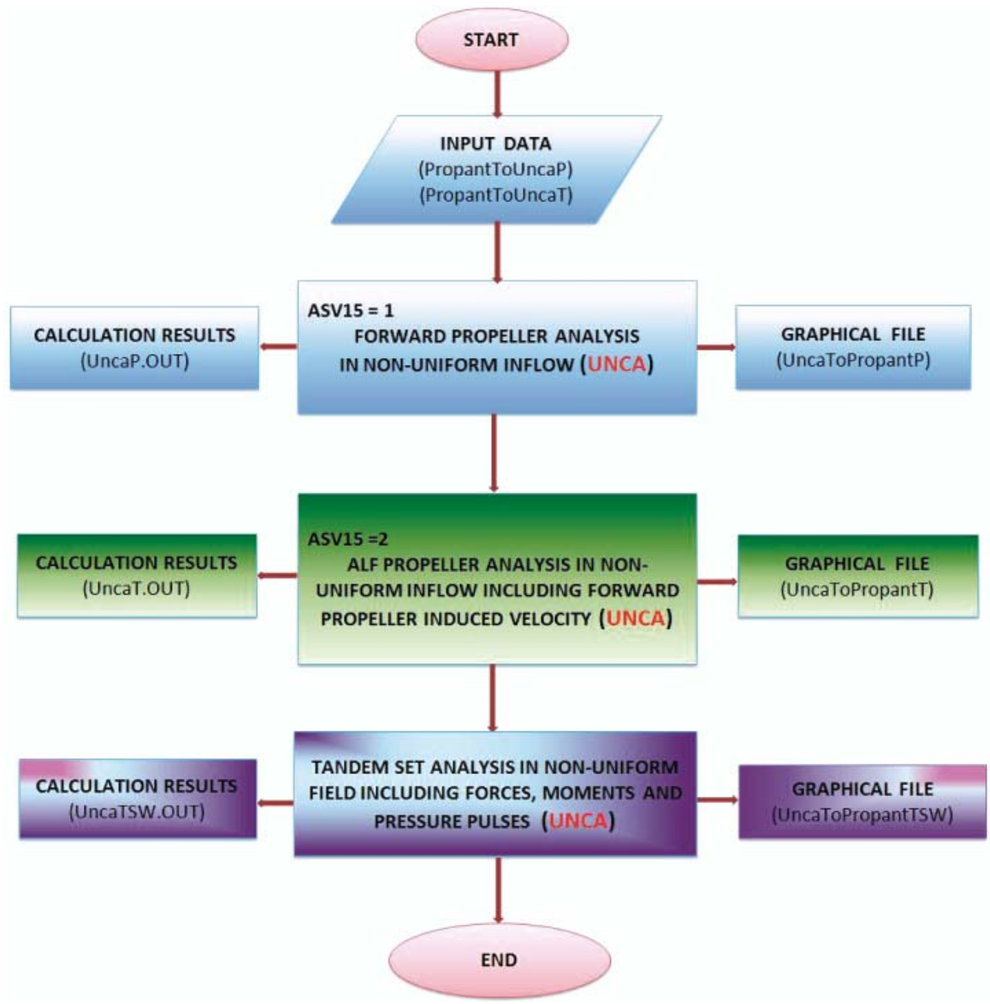

Fig. 4. *The block diagram for the program for analysis of the tandem propeller operation*

With respect to the design system for conventional single propellers, the system for tandem propellers differs by the following elements:

a) the procedures for the graphical presentation of the geometry of both propellers independently,
b) the procedures for determination of the design velocity field for both propellers, taking into account their mutual interaction,
c) the procedure for modification of the non-uniform velocity field used in the analysis of the propeller operation by the program UNCA,
d) the procedures for determination of the pressure pulses induced by both propellers separately and by the entire tandem propeller set,
e) the procedures for determination of the shaft bearing forces for both propellers separately and for the entire tandem set.

The appropriate interaction between all programs and procedures ensures the correct design of the tandem co-rotating propellers. The computer system integrates all necessary components and the process of tandem propellers design may be controlled directly from the computer screen, without the necessity for preparation of the separate input data files for the respective computer programs. Moreover, the system is equipped with the necessary graphical procedures for the control of input data and of the intermediate results, as well as for the convenient modification of the geometry of the designed propellers in the course of the design calculations. The block diagram of the computer system for design of tandem propellers differs from the block diagram of the system for conventional propeller design [1]. The basic block diagram (cf. Fig. 2) is supplemented with the block diagram of the program for design of the tandem propellers (cf. Fig. 3) and with the block diagram of the program for analysis of the tandem propeller operation (cf. Fig. 4).

PRESENTATION OF THE SELECTED BLOCKS OF THE DESIGN SYSTEM

The computer system for the design of tandem propellers set has many common blocks with the system for the design of conventional single propellers. Below only new elements, specific for the case of tandem propellers, are presented in detail. The elements common for tandem and conventional propellers are only briefly mentioned.

The input data

The input data include all magnitudes necessary for performing optionally four versions of the design calculation, similarly as in the case of the conventional single propellers [1]. The input data may be introduced directly from the computer screen or in the form of the file prepared earlier.

The input parameter characteristic for the tandem co-rotating propellers is the distance between the generator lines of the forward and aft propellers. Another characteristic parameter of the tandem propellers is the angular shift between the forward and aft propeller, which is determined in the course of the design calculation in the program.

The program enables graphical control and, if necessary – easy modification of the input data. For example, the points defining radial distribution of the geometrical parameters of the propeller such as blade outline, blade thickness or blade rake and skew, may be easily moved on the computer screen to their correct positions. An example of such correction in case of the blade skewback is shown in Fig. 5.

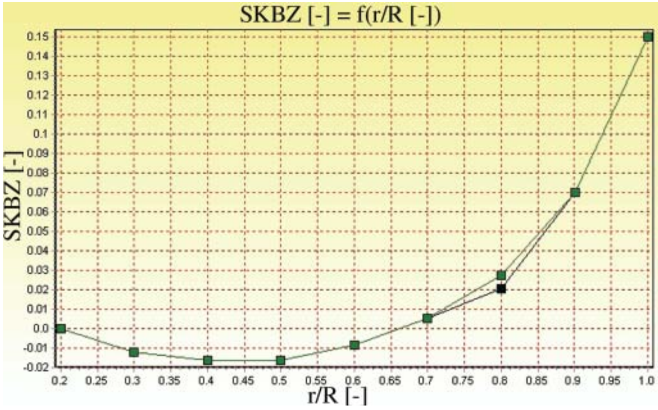

Fig. 5. *The control display of the propeller blade skewback, showing the correction of the erroneous data at radius 0.8*

The design program

The algorithm of the design program for the tandem co-rotating propellers differs significantly from the algorithm for design of the conventional single propeller presented in [1]. The main differences are:

a) the design calculations is performed only for the given total thrust of the tandem propeller set,
b) the program automatically defines the optimum division of the total thrust between the forward and aft propeller,
c) the velocities induced by each of the propellers at the location of the other one must be computed and taken into account in the design. This is achieved in an iterative process.

The design calculation is performed in the same way for all four possible design tasks (analogically as in the case of conventional single propellers). The design calculation ends with the results which are available in the form of numerical files and they may be also presented graphically on the computer screen. An example of the graphical presentation of the designed tandem propeller set may be seen in Fig. 6. The set of propellers shown on the screen may be rotated and viewed from an arbitrary angle. All graphical presentations may be directly printed out or stored in special files.

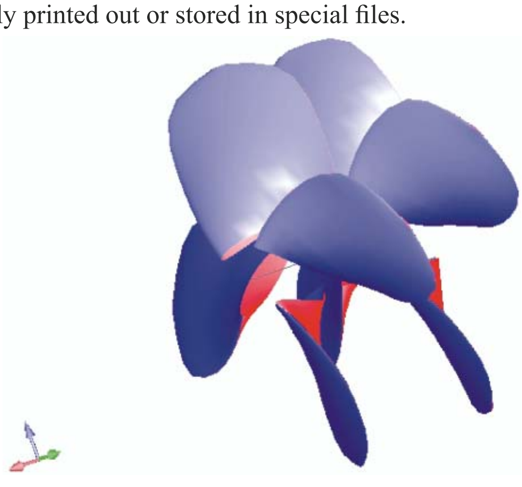

Fig. 6. *The rendered view of the designed tandem propeller*

As it has been mentioned above, the new and indispensable element of the tandem propellers design procedure is the determination of the velocity induced by the system of bound vortices representing the propeller blades and by the systems of trailing, free vortices shed from these blades. As may be seen in the block diagram shown in Fig. 3, this determination has the form of an iterative process based on calculation of the mutual interaction of both propellers of the tandem set.

The induced velocity field

In the design calculation based on the vortex theory the system of bound and trailing vortices representing the propeller is determined in a simplified way, in which the trailing vortices form the helical surfaces. This approach is sufficiently accurate for calculation of the velocity induced on the propeller blades, leading to the definition of the blade geometry. In the case where the induced velocity in front and behind the blades must be determined, this simplified model is no longer sufficient.

In the physical reality the system of trailing vortices behind the propeller blades undergoes contraction and deformation, in which the processes of vortex concentration and dissipation of vorticity play an important role. As a result, the concentrated tip vortices are formed behind each blade and a concentrated hub vortex is formed along the propeller axis. Such a system of vortices induces a specific velocity field in the near vicinity of the propeller, as shown in Figs 7-11.

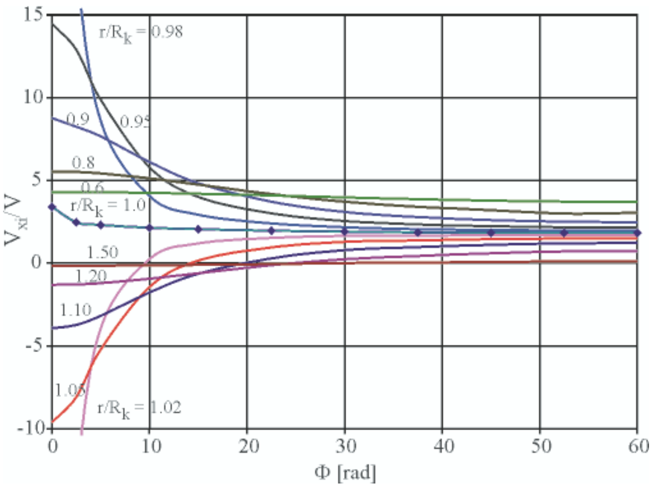

Fig. 7. *The axial component of the velocity induced behind the three-bladed propeller as the function of the angular co-ordinate Φ*

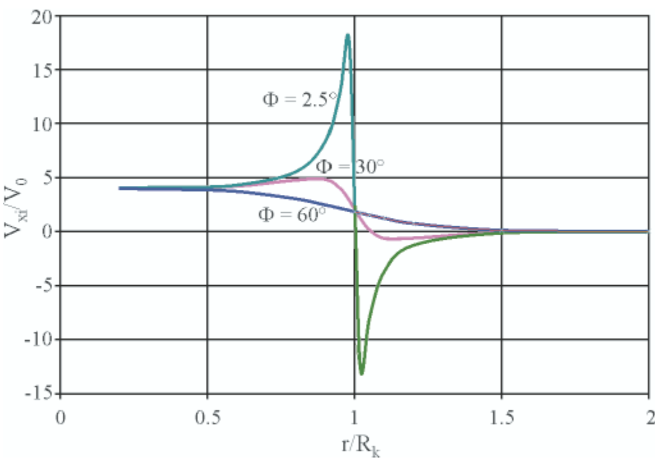

Fig. 8. *The axial component of the velocity induced behind the three-bladed propeller for selected sections Φ = const*

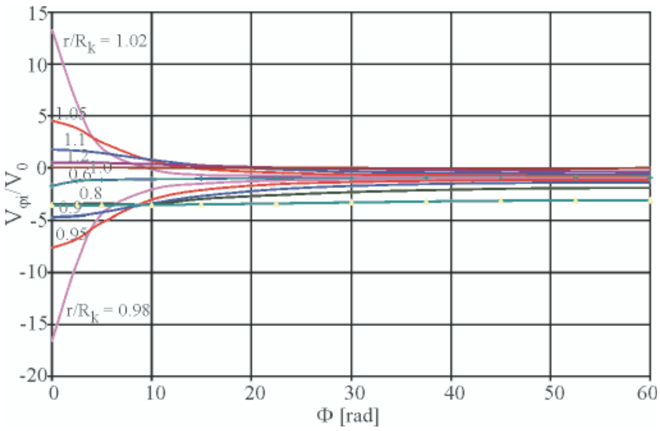

Fig. 9. *The tangential component of the velocity induced behind the three-bladed propeller as the function of the angular co-ordinate Φ*

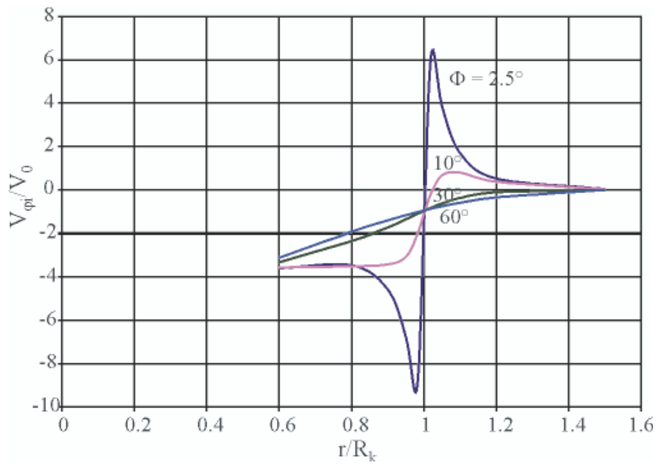

Fig. 10. *The tangential component of the velocity induced behind the three-bladed propeller for selected sections Φ = const*

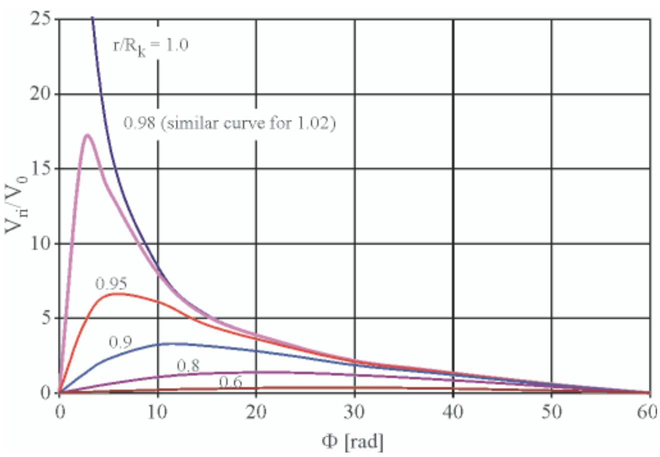

Fig. 11. *The radial component of the velocity induced behind the three-bladed propeller as the function of the angular co-ordinate Φ*

The velocity field shown in these Figures has been determined at the distance of one radius behind the propeller. All dimensions are related to the radius of the location of the tip trailing vortex centre R_k. The computational model of the free vortex system is composed of the strongly concentrated tip vortices and the hub vortex [4,6]. The computations for vortices of different degree of concentration have shown that the induced velocity field in the region between the tip vortices is independent from the degree of concentration of vortices, assuming that the location of their centres is correct. On the contrary, there are large differences in the vicinity of the free vortices (for the values of the angular co-ordinate Φ close to zero). In the case of lower concentration of vorticity the extreme values of velocity are smaller.

The aft propeller achieves the best performance and the lowest risk of cavitation when its blades are located in places, where the velocity induced by the front propeller is the lowest and the radial gradient of this velocity is small (cf. Figs. 7 and 9). This condition is fulfilled exactly in the middle between the free vortices shed from the front propeller blades (in the case of three-bladed propellers, as shown in Figs. 7-11, this corresponds to the angular co-ordinate value Φ = 60 [deg]. Consequently, the determination of the mutual angular position of the forward and aft propellers of the tandem set is very important in the design process.

The velocity induced by the aft propeller at the forward propeller is several times smaller and more uniformly distributed in space. The mutual angular position of the forward and aft propeller is determined in the design program by means of the theoretical-empirical relation, described in detail in [4-9]. The value of the angular shift between the forward and aft propeller is given in the results.

The results for each propeller of the tandem set are presented in the same format as for the conventional single propeller (see [1]). Additionally, the values of total thrust, torque and power for the entire tandem set are included.

The program for the analysis of the tandem propeller operation in the non-uniform velocity field

The computer program UNCA for the analysis of the propeller operation in the non-uniform velocity field is an important component of the propeller design process. The main part of the algorithm of this program is the determination of the extent of different forms of unsteady cavitation on the propeller blades. The original computational model integrates the unsteady vortex lifting surface theory with the time-dependent sheet cavity. This algorithm is described in detail in [10-12].

In the case of the analysis of tandem propellers the mutually induced velocities of the forward and aft propeller should be taken into account. This is achieved by an additional procedure inserted into UNCA, which calculates the propeller induced velocity in the arbitrary points in front and behind the propeller. This induced velocity field is superimposed on the non-uniform velocity field generated by the ship hull. Such a modified velocity field enables the analysis of the forward and aft propeller of the tandem set.

Both newly designed propellers of the tandem set are analyzed by the program UNCA from the point of view of:
a) detection of the different forms of cavitation in a number of selected angular positions of the propeller blades in the non-uniform velocity field,
b) calculation of the pressure pulsations induced by each of the propellers separately and by the entire tandem set on the hull surface or in the surrounding space,
c) calculation of the fluctuating bearing forces and moments on each of the propellers separately and by the entire tandem set.

After analyzing the results from the program UNCA the design calculation may be repeated, introducing modifications of the propeller geometry with purpose of achieving better propeller performance in the non-uniform velocity field. For example, the following parameters may be modified:
a) the values and character of the radial distribution of the blade skewback,
b) the values and character of the radial distribution of the blade profile chord lengths,
c) the values and character of the radial distribution of the blade thickness,

d) the type of chord-wise blade thickness distribution,
e) the type of chord-wise mean line camber distribution,
f) the radial distribution of the hydrodynamic loading,
g) the number of propeller blades,
h) the division of the hydrodynamic loading between the forward and aft propeller of the tandem set.

The analysis of the tandem set operation in the non-uniform inflow velocity field is performed only for the design condition, because any change in the propeller advance velocity or the rate of rotation leads to changes in the induced velocity field of the forward and aft propeller of the tandem set.

An example of the calculation results of the tandem co-rotating propeller set is included in the next section of the article, devoted to the comparative analysis of the conventional propeller and the tandem propeller set, both designed for the same conditions.

COMPARATIVE ANALYSIS OF THE RESULTS

Many years of experience and practice show that in most cases the single fixed and controllable pitch propellers fulfil the most demanding requirements concerning efficiency, cavitation performance, fluctuating bearing forces, pressure pulsations generated on the hull, and hydro-acoustic emission. However, some specific field of application may be found, in which the tandem co-rotating propeller sets are likely to be better.

The tandem co-rotating sets are characterized by a large number of blades. There can be Z = 4 + 4 = 8, Z = 5 + 5 = 10, and even Z = 6 + 6 = 12 blades. Placing of such a large number of blades in one propeller disc leads to a significant reduction of efficiency and may cause serious manufacturing problems. The harmonic amplitudes of the fluctuating bearing forces and propeller-generated pressure pulsations are related to the number of propeller blades – lower values are usually obtained for a larger number of blades. Moreover, in the case of tandem co-rotating propellers it is easier to avoid cavitation – the combined expanded blade area ratio of the forward and aft propellers may be well over 1.0

In order to illustrate the above statements, the comparative design calculations of a single propeller and an equivalent tandem co-rotating propeller set are presented below. A large and fast ship has been selected as the test example. The design ship speed is V = 25.3 knots, with the required propeller thrust equal to T = 3750 kN. The design rate of propeller rotation was n = 100 rpm.

For the single propeller the following results were obtained:

The optimum diameter: D_{opt} = 8.25 m.
The expanded blade area ratio: Ae/Ao = 0.92.
The power delivered to propeller: P_d = 43989 kW.
The mass of the blades: G = 40640 kg,
The propeller moment of inertia: GD^2 = 1154566 kGm^2.

In the same design condition the following results were obtained for the tandem co-rotating set:

The optimum diameter: D_{opt} = 7.40 m
The expanded blade area ratio: Ae/Ao = (0.65 + 0.65) = 1.3.
The power delivered to propeller: P_d = 42880 kW.
The combined mass of blades: G = (23630 + 21955) kG = = 45585 kg,
The combined propeller moment of inertia: GD^2 = (506735 + + 465040) kGm^2 = 971775 kGm^2.

For both propellers operating in the same velocity field behind the hull wake, the harmonic amplitudes of the unsteady bearing forces and of the pressure pulsations generated in the same points on the hull were calculated and they are presented in Figs. 12-15.

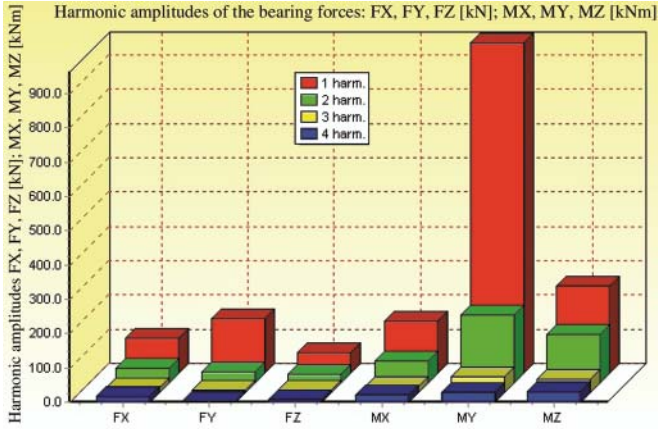

Fig. 12. Harmonic amplitudes of the bearing forces for the single propeller

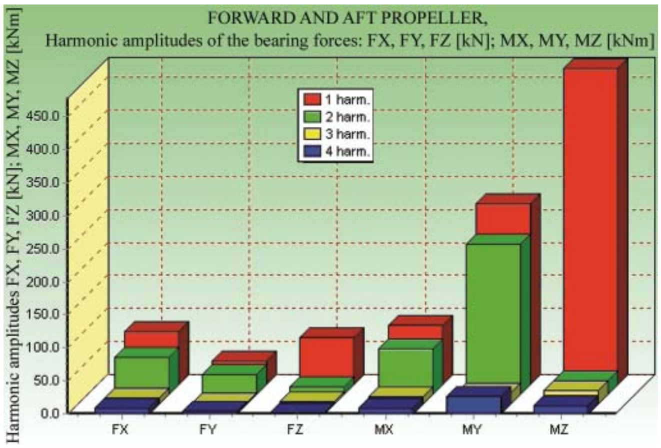

Fig. 13. Harmonic amplitudes of the bearing forces for the tandem propeller set

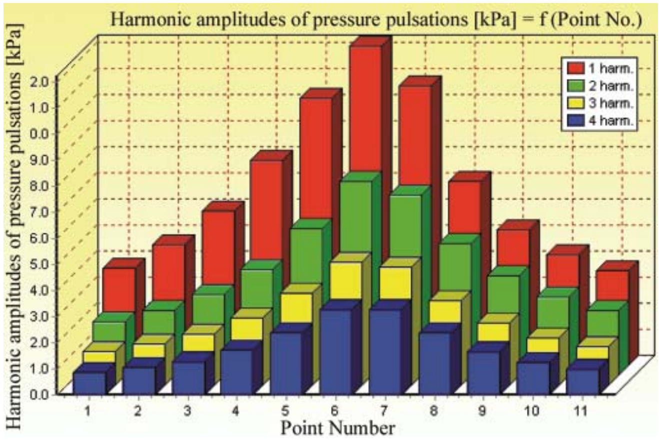

Fig. 14. Harmonic amplitudes of the pressure pulsations induced on the hull by the single propeller

The above presented results demonstrate the significant advantage of the tandem propeller set over the conventional single propeller. This is not a general rule, but the presented example has been selected in such a way that this advantage can be demonstrated in certain specific operating conditions. In this example the tandem propeller set can be characterized by the following results:

- the lower delivered power than for the single propeller,
- the lower harmonic amplitudes of the unsteady bearing forces,
- the lower harmonic amplitudes of the pressure pulsations induced on the hull,
- the cavitation phenomena similar to those on the single propeller.

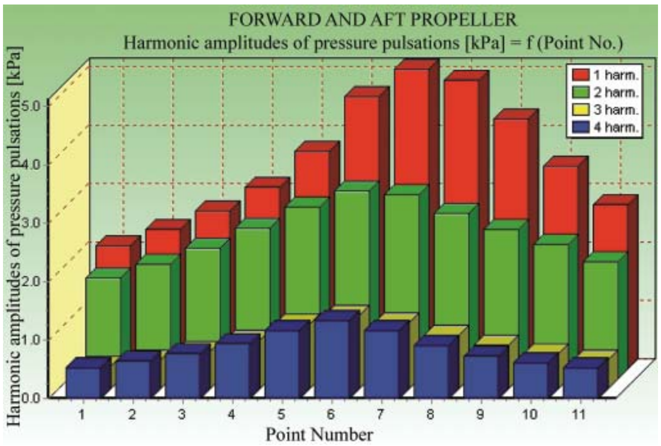

Fig. 15. Harmonic amplitudes of the pressure pulsations generated on the hull by the tandem propeller set

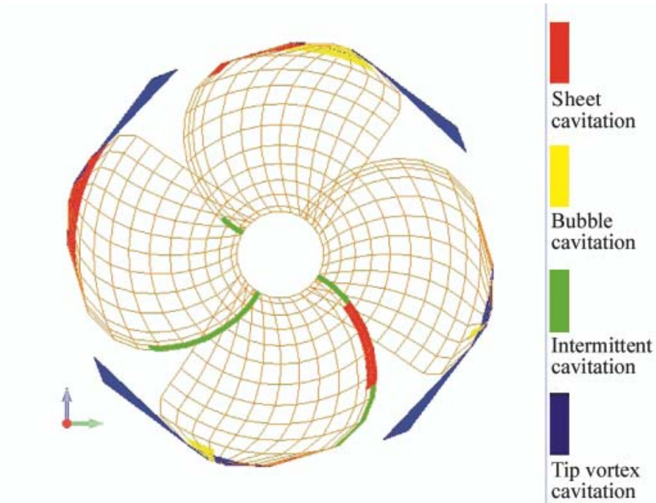

Fig. 16. Cavitation phenomena on the suction side of the single propeller

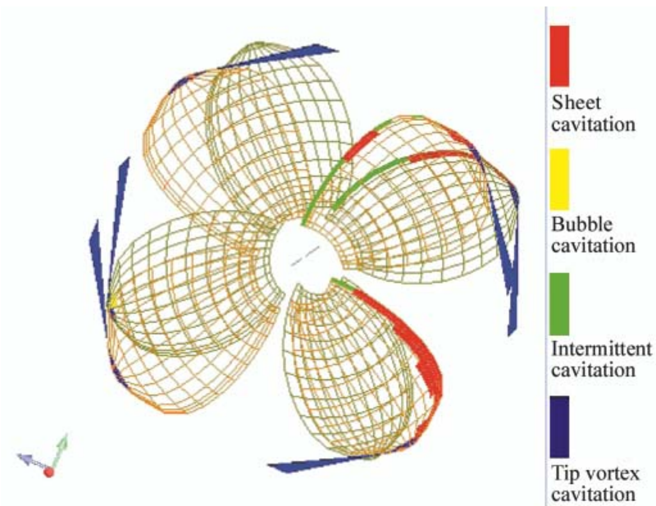

Fig. 17. Cavitation phenomena on the suction side of the tandem propeller set

The most controversial result is the lower delivered power for the tandem propeller set. This is mainly due to the higher value of the hull efficiency for the tandem propeller set. The hull efficiency depends strongly on the diameter of the propeller. In the analyzed example the optimum diameter for the single propeller is D = 8.25 m, while the optimum diameter of the tandem propeller set is equal to D = 7.4 m. In this case the hull efficiency was about 5 per cent higher for the smaller diameter.

The lower values of the harmonic amplitudes of the unsteady bearing forces result from the higher number of blades in the tandem propeller set, while the lower values of the pressure pulsations result both from the higher number of blades and the smaller diameter of this set.

FINAL REMARKS

The above presented computer system facilitates the process of design of the tandem co-rotating propellers. The system integrates all components necessary for the correct design of the tandem propellers. The design and analysis calculations themselves are performed very quickly and the graphical procedures enable an easy interpretation and analysis of the results. The short computation time allows an easy analysis of many variants of the design. For example the following parameters of the designed propeller may be varied without leaving the computer system:

- the number and shape of the propeller blades,
- the ship speed and the rate of propeller rotation,
- the division of thrust between the forward and aft propeller,
- the radial distribution of the hydrodynamic loading,
- the axial distance between the forward and aft propeller.

This enables an effective optimization of the tandem co-rotating propellers from the point of view of propulsive efficiency, cavitation, induced pressure pulsations, acoustic pressures and fluctuating bearing forces. The graphical presentation of all results makes this optimization process even easier.

The above presented example, as well as the results of computations presented in [2] for ducted propellers, demonstrate that propellers other than a conventional single propeller are worth considering in the design process of ships. The three propeller design systems [1, 2], based on the same basic elements of the design calculations, in which the preparation of the input data is almost identical, enable an easy comparative analysis and an appropriate selection of the optimum propeller type for any application.

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