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DESIGN OF SHIP-ENGINE-PROPELLER SIMULTANEOUS MATCHING AND DEVELOPMENT OF A PROPELLER AND ENGINE SELECTING SYSTEM

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Abstract. A process to design ship-engine-propeller simultaneous matching is proposed in this paper. The design process treats the whole system as an assembly of the ship-propeller subsystem and the engine-propeller subsystem in which relationships between rotational speed of the propeller and advancing speed of the ship are found and expressed as *N-V* curves. Furthermore, databases of propellers and engines are established and connected to self developed user interface to calculate simultaneous matching conditions in loops and the matching points are collected to form a selection pool where user can conduct selection. An example to select a propeller and an engine for a 25,000t bulk carrier using the developed selecting system is described and the outputs are listed and analyzed. The selected pair of the propeller and the engine is efficient and comprehensive compared with other instances in the databases.

1 INTRODUCTION

Design of ship-engine-propeller matching condition is decisive to ship performance and economy in sailings. For example, life fuel consumption of KCS SIMMAN container ship was successfully decreased by 10.36% through a successful design by Nelson [1]. On the other hand, the 053H frigate in the 91287 troop of the China Navy increased propeller diameter without corresponding matching design, and as a result, surges and winds overloaded the engine as well as damaged the shafts in a military exercise [2].

The traditional matching design follows a step-by-step match-check process. In the first step, propeller diameter and pitch ratio are determined according to force balance between the ship resistance and the propeller thrust. Hence the rotational speed and input power of the propeller is obtained. In the next step, usually as a check step, the rotational speed is compared with that of the engine and input power is compared with the engine output power. If these two key factors are matched up, the simultaneous matching design process would be finished. Otherwise, the diameter and pitch ratio have to be adjusted and the whole process has to be performed again. The traditional propeller design with series charts is mainly based upon this approach [3]. Referring to this process, many softwares to design propellers and engines are developed, including the ENGINE 78, a part of the HYDROCOMP and the online interface of the Mercury Marine company [4,5]. However, according to Nelson [1], in actual sailings, this step-by-step design results would sometimes be too idealized to achieve, thus may be inefficient in harsh sea conditions.

In this paper, a simultaneous ship-engine-propeller matching design process is proposed. This process preserves the match step regarding the ship and the propeller while substituting the check step by a parallel match step concerning the propeller and the engine. To be more specific, the whole ship is treated as a combination of a ship-propeller subsystem where force balance has to be obtained and an engine-propeller subsystem in which power conservation should be followed simultaneously. Different from the match-check process, whose aim is to design propellers or engines, the proposed process is to predict simultaneous matching conditions with known engines and propellers.

Based upon the proposed design process, matching conditions of multiple pairs of engines and propellers can be predicted. Therefore, if there are enough pairs, abundant matching conditions are calculated for designers to select. The propeller and engine selecting system is developed to achieve this goal. First, databases of propeller and engines are constructed and the proposed process is applied on these data. Matching conditions are predicted and stored in the selection pool which users can choose matching conditions from. Finally, the corresponding information is exported to the selection database where each instance is under ship-engine-propeller simultaneous matching condition.

2 SHIP-ENGINE-PROPELLER SIMULTANEOUS MATCHING DESIGN PROCESS

The force balance and power conservation in the ship-engine-propeller system are illustrated in figure 1.

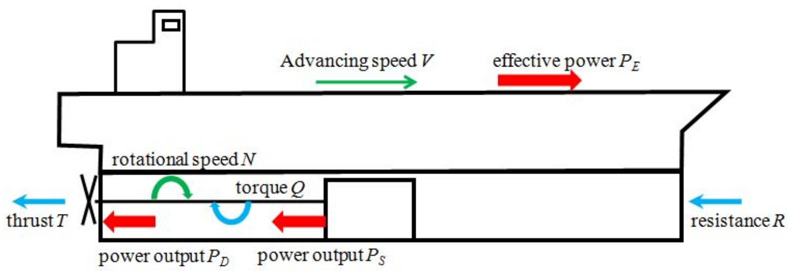

Figure 1: Forces and powers in ship-engine-propeller system

It can be generalized that, at the same advancing speed, the resistance acting on the ship hull is equal to the thrust generated by the propeller and that at the same rotational speed, the power input of the propeller is equal to the power output of the engine. Following these basic laws, predictions of matching conditions are conducted as follows.

2.1 Ship-propeller subsystem matching prediction

Resistance curve and propeller open water curves are used in the matching prediction in the ship-propeller subsystem. First, p rotational speed $N_1 \ldots N_p$ (r/min) are used, and so are q advancing speed $V_1 \ldots V_q$ (kn) for the prediction. With regard to each rotational speed N_i (i=1, p), calculation with each member of the advancing speed group is performed. Take N_1 for an example, advance coefficient is computed

$$J_{1,1\ldots q} = \frac{0.5144 \times (1-\omega) \times V_{1\ldots q}}{(N_1 / 60) \times D} \tag{1}$$

where ω is the wake fraction, D (m) is the diameter of the propeller. According to J, effective thrust of the propeller $T_{1,1\ldots q}$ (kgf) propeller is obtained in equation (2) with the help of the open water curves

$$T_{1,1\ldots q} = K_{T1,1\ldots q} \times \rho \times (\frac{N_1}{60})^2 \times D^4 \ \text{(kgf)} \tag{2}$$

in which K_T is the thrust coefficient, ρ (kgfs^2/m^4) is the density of water.

In the same manner, the rest of the rotational speed group are used for calculations and finally a group of thrust $T_{i,j}$(i=1, p; j=1, q) is acquired.

With advancing speed V used as x coordinates and thrust T used as y coordinates, p curves are drawn and each curve is labeled with a rotational speed N in figure 2. At the same time, ship resistance characteristic curve is overlapped on the same figure.

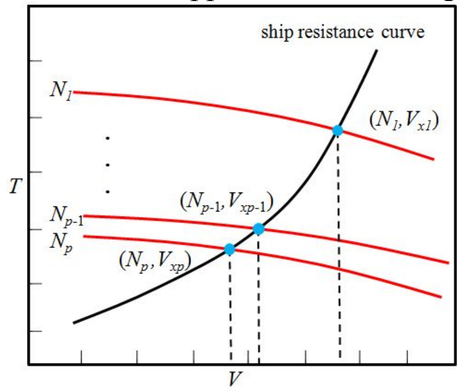

Figure 2: Force balance in the ship-propeller subsystem

It should be noted that V_{xi} represent x coordinate of the intersecting points where force balance is attained. Rearrange these points in ascending order with regard to rotational speed, the N-V curve of the ship-propeller subsystem is obtained, as shown in figure 3.

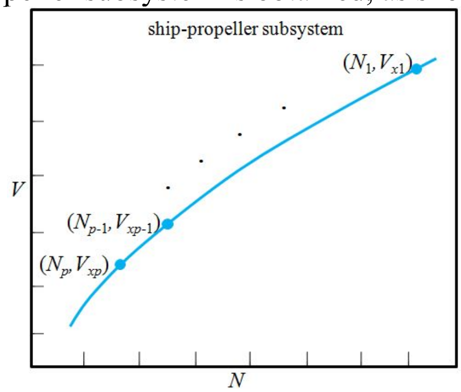

Figure 3: The N-V curve of the ship-propeller subsystem

Attention should be paid that every single point on the N-V curve follows the force balance law in the ship-propeller subsystem.

2.2 Engine-propeller subsystem matching

The matching prediction in the engine-propeller subsystem is in the same fashion as that in the ship-propeller subsystem. Referring to advancing velocity V_j (j=1, q), a computation is performed with every member of the rotational speed group. Also, aided by open water curves, the input power of the propeller is calculated

$$P_{S_{i,j}} = \frac{2\pi(\frac{N_i}{60}) \times K_{Q_{i,j}} \times \rho \times (\frac{N_i}{60})^2 \times D^5 / 75}{\eta_R \times \eta_S} \text{ (hp)} \tag{3}$$

where K_Q is the torque coefficient and η_R, η_S is the relative rotative efficiency and the shaft efficiency.

Use N as x coordinate and P_S as y coordinates, q curves are drawn while each of them is denoted by an advancing speed. Then superimpose the power characteristic curve of the engine on the same figure.

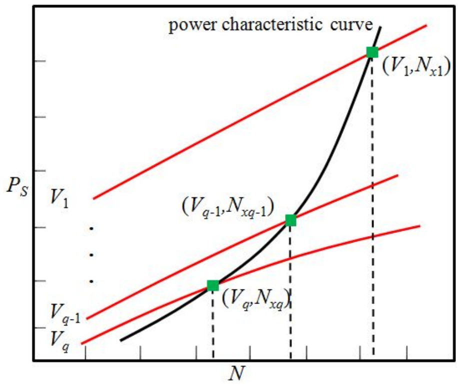

Figure 4: Power conservation in the engine-propeller subsystem

In figure 4, N_{xj} is read from every point of intersection and each of them satisfies the law of power conservation. Rearrange these points to obtain the N-V curve of the engine-propeller subsystem which is shown in figure 5.

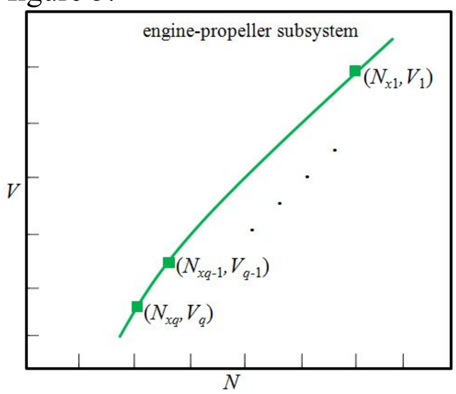

Figure 5: The N-V curve of the engine-propeller subsystem

2.3 Assembly of the subsystems

The force balance and power conservation relationship of the two subsystems are expressed by the *N*-*V* curves. Draw the two curves illustrated in figure 4 and figure 5 in figure 6.

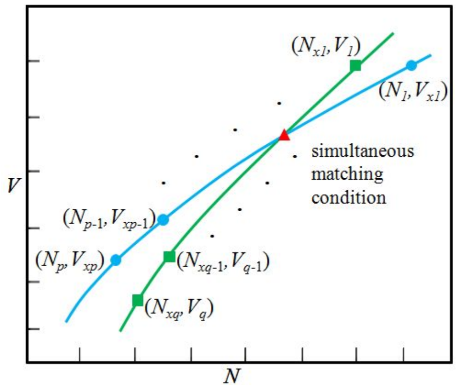

Figure 6: The simultaneous matching condition

Special attention should paid that every point on the *N*-*V* curve of the ship-propeller subsystem is force-balanced and that on the *N*-*V* curve of the engine-propeller subsystem is power-conserved. The intersecting point of the two curves should be both force-balanced and power-conserved, which is the very meaning of ship-engine-propeller simultaneous matching.

The whole process of this proposed ship-engine-propeller simultaneous matching design process is generalized in figure 7, from which the simultaneity and symmetry can be seen.

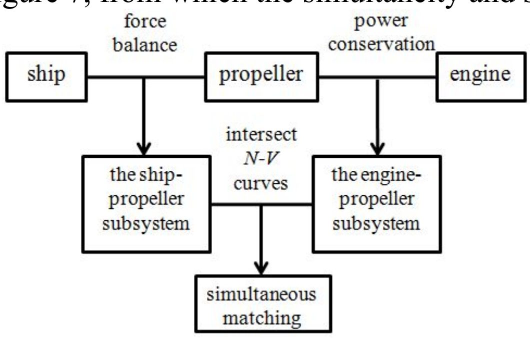

Figure 7: The simultaneous matching design process

3 THE PROPELLER AND ENGINE SELECTING SYSTEM

On the basis of the previous section, ship-engine-propeller simultaneous matching condition can be predicted using the proposed process. In order to fully practice this process, The engine and propeller databases are established and every instance in the database are read into a loop to carry out the process cyclically until each of the instance in the two databases is computed. In each loop, a matching point, if the simultaneous matching condition exists, would be generated. After the running of the whole program, several matching points regarding different pairs of engines and propellers would be calculated. To ease the selection of the users, the concept of the selection pool is proposed which is made up with all those available matching points. Users can choose satisfying matching conditions in the selection pool and relevant information including diameter and pitch ratio of the propeller as well as rated power and rotational speed of the engine are rearranged and exported. The program process is illustrated in figure 8. The user interface is shown in figure 9.

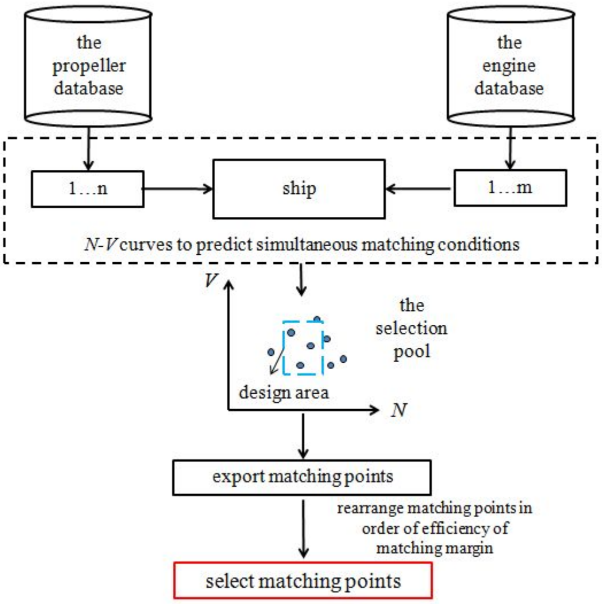

Figure 8: Process of the selecting system

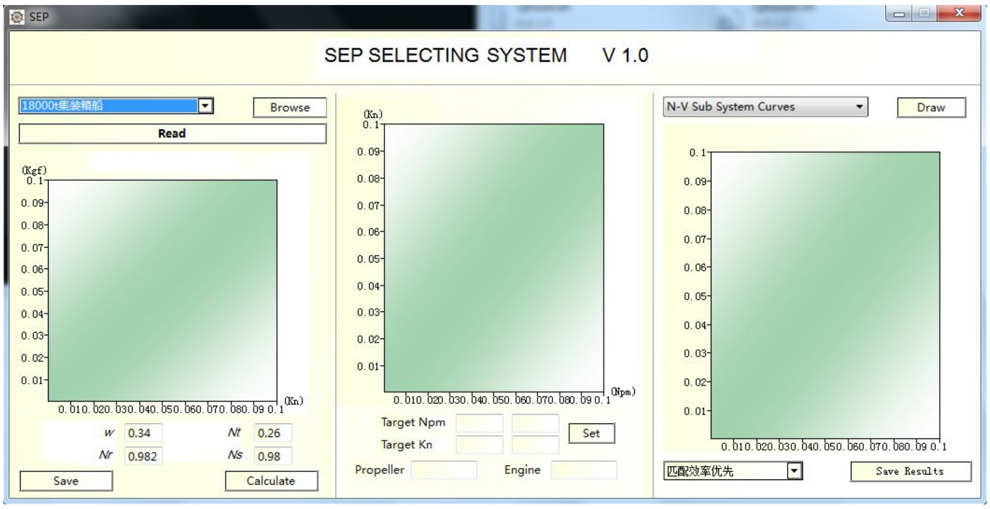

Figure 9: The user interface of the selecting system

The interface is made up with three parts. The left one is to input ship resistance data and set the hydrodynamic parameters. The middle part of the interface is to demonstrate the selection pool for users to conduct selection. Target rotational speed and advancing speed are set to help selection. The right part is used to show the open water curves, the engine power curves and the *N*-*V* curves of the subsystems and to output matching data.

4 EXAMPLES

The propeller and engine selecting system is used for a 25,000t bulk carrier whose parameters of the interface are well-known [6]. The instances in the databases are listed in table 1 and table 2. The interface during the usage is shown in figure 10.

Table 1: The engine database

engine	rate rotational speed (r/min)	rate power (hp)
Sulzer RD	159	29000
Sulzer 6RLB56	118.5	12000
Mercury 400	140	20580
Mercury 414	130	15379
Hamilton 318	140	17840
Hamilton 362	160	32770

Table 2: The propeller database

propeller	pitch ratio	diameter (m)
AU5-65	0.782	5.75
AU5-65	0.782	5.9
AU5-65	0.782	6
MAU4-55	0.7	4.77
MAU4-55	0.7	4.82
MAU4-70	1.2	4.7
MAU4-70	1.2	4.76
MAU4-70	1.2	4.8

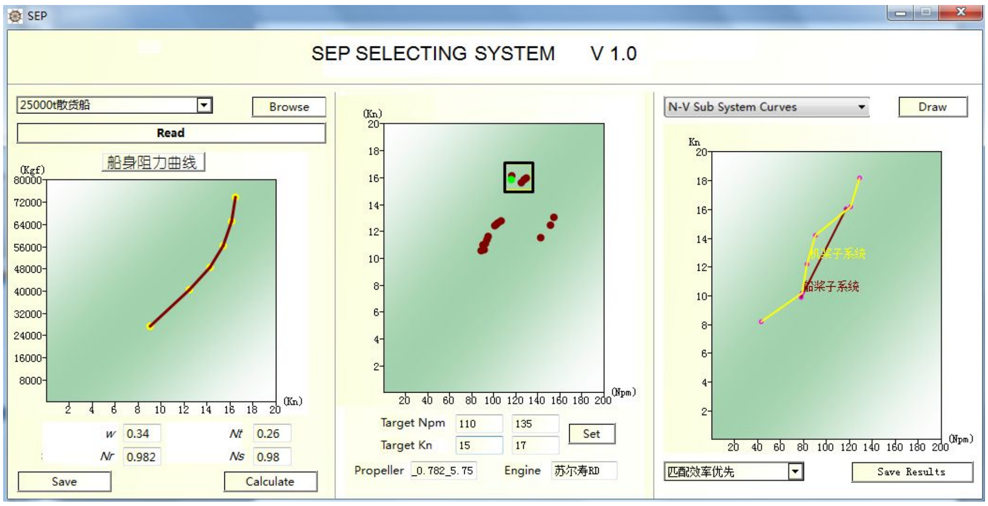

Figure 10: The user interface during usage

In this case, target rotational speed ranges from 110-135 r/min and advancing speed ranges from 15-17kn. There are 18 matching points in total in the selection pool where the highlighted point is the chosen one. Rearrange those points and list the top ten ones in table 3 and 4.

Table 3: The selection pool (in a descending order of the efficiency)

propeller	engine	rotational speed (r/min)	advancing speed (kn)	Open water efficiency
AU5-65_0.782_5.9	Sulzer RD	116.571	16.09	0.553442
AU5-65_0.782_5.75	Sulzer RD	116.088	15.8095	0.552805
AU5-65_0.782_6	Hamilton 318	102.566	12.4767	0.523005
AU5-65_0.782_6	Hamilton 318	94.04	11.3382	0.519016
MAU4-55_0.7_4.82	Sulzer 6RLB56	154.834	13.0015	0.481997
MAU4-55_0.7_4.77	Sulzer 6RLB56	151.733	12.416	0.475699
MAU4-55_0.7_4.77	Sulzer 6RLB56	142.849	11.4867	0.468679
MAU4-70_1.2_4.7	Hamilton 318	129.788	15.9245	0.465998
MAU4-70_1.2_4.76	Mercury_Marine414	127.771	15.8024	0.46415
MAU4-70_1.2_4.8	Mercury_Marine400	125.236	15.5749	0.463046

Table 4: The selection pool (in a descending order of the matching margin)

propeller	engine	rotational speed (r/min)	advancing speed (kn)	Open water efficiency
MAU4-70_1.2_4.8	Mercury_Marine 400	125.236	15.5749	0.463046
MAU4-70_1.2_4.76	Mercury_Marine 414	127.771	15.8024	0.46415
AU5-65_0.782_5.9	Sulzer RD	116.571	16.09	0.553442
AU5-65_0.782_5.75	Sulzer RD	116.088	15.8095	0.552805
MAU4-70_1.2_4.7	Hamilton 318	129.788	15.9245	0.465998
MAU4-70_1.2_4.7	Mercury_Marine 414	106.919	12.7343	0.454499
MAU4-70_1.2_4.76	Mercury_Marine 400	104.057	12.592	0.455722
AU5-65_0.782_6	Hamilton 318	102.566	12.4767	0.523005
MAU4-55_0.7_4.77	Sulzer 6RLB56	142.849	11.4867	0.468679
MAU4-70_1.2_4.8	Hamilton 362	101.152	12.3792	0.456835

The naming rule of the propeller is “type-blade area ratio_pitch ratio_diameter”. The chosen propeller is the AU5-65_0.782_5.75 and the engine is the Sulzer RD. At the simultaneous matching condition, the shaft rotational speed is 116.088r/min, advancing velocity is 15.8095kn and the open water efficiency of the propeller is 0.552805.

Attention should be paid that open water efficiency and matching margin are two of the most important factors to take into account. From table 3, the matching pair of the highest efficiency is not that of the greatest matching margin. Nonetheless, matching margin is decisive to ship overall performance, especially in harsh conditions [7]. As a matter of fact, these two parameters are not likely to be maximized in one design. In a comprehensive sense, the selected matching pair of the AU5-65_0.782_5.75 propeller and the Sulzer RD engine would be the second most efficient pair and the fourth most versatile pair.

5 CONCLUSIONS

- The proposed ship-engine-propeller simultaneous design process is to predict simultaneous matching conditions which is more versatile than the traditional step-by-step design;
- The self-developed propeller and engine selecting system is efficient. The more instances the databases have, the more comprehensive the selection pool would be;
- Efficiency and matching margin are two most important factors in the matching design, which are often not likely to be maximized at the same time.

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