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# Superior application solutions and key technical points for ship shaft generator system

System Integration & Hybridization


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## ABSTRACT

A shaft generator system has become one of the conventional solutions for greener ship designs due to its excellent performance of energy saving and emission reduction. Currently two types of shaft generator solutions are dominant in engineering applications: permanent magnet and brushed electric excitation. The permanent magnet solution has the problem that the risk of failure is difficult to control, and the brushed electro-excitation solution has the problem that the brushes and slip rings are easy to be damaged, which increases the maintenance cost of the system. Therefore, it is worthwhile to discuss whether there are more appropriate solutions for shaft generator applications.

First of all, by analyzing the development path of the shaft generator system, the key technical points, advantages and disadvantages of different shaft generator solutions are studied; and then by combining the engineering application cases, the performance and energy efficiency indexes of the shaft generator system are quantitatively analyzed. Thus, the ideal application state of the shaft generator system and its design requirements can be summarized, and the direction of shaft generator system technology development and its new combination with other energy-saving and emission-reducing methods can be proposed.

# 1 INTRODUCTION

The International Maritime Organization (IMO) has put forward a series of regulations to reduce greenhouse gas emissions from ships, requiring them to transform into green and low-carbon ships, and ship energy efficiency has become an important assessment index [1]. In order to cope with the increasingly stringent policy requirements, new energy-saving and emission reduction technologies are emerging [2], among which the low-speed shaft-holding generator system (abbr. as SG system) has been widely attracting the attention of shipowners for its advantages of good economy, saving engine room space and improving energy efficiency [3], [4]. Shaft generator systems are usually mounted directly on the ship's main propulsion shaft system, so that the redundant power of the main engine can be utilized to provide power to the ship [5]. The installation of the shaft generator system can save the use of auxiliary diesel generator sets and enable the main engine to run at a more economical speed, thus reducing fuel consumption [2], [6] and improving the energy efficiency of the ship. As the application of shaft generator system becomes more and more widespread, there is an urgent need to study on the effect of shaft generator system on the ship system.

# 2 EFFECT OF SG SYSTEM ON THE SHIP MAIN ENGINE

Mounting the low-speed shaft-holding generator system will affect the characteristics of the ship's main engine, so it is necessary to match and adjust the operating conditions of the main engine in combination with the SG system to meet the comprehensive optimization of the ship's navigational characteristics, such as speed, economy, emissions, and so on.

## 2.1 Ship Machine-propeller Matching Design with SG System

The purpose of ship engine-propeller matching design with the SG system is to define system specifications taking into account the main engine, loads and propeller in conjunction with the shipowner's needs for speed, economy, emissions and maneuverability.

Marine diesel engines are usually limited in terms of maximum power, minimum power, maximum speed and minimum speed in order to work economically, stably and reliably with long service life when doing engine-propeller matching. As shown in Figure 1, the maximum power allowed for a diesel engine at various speeds is limited by the overload speed characteristic (curve 4), the full load speed characteristic (curve 2), and other limiting characteristics (curves 1 and 3, e.g., torque, exhaust temperature, etc.) under different conditions. In order to avoid insufficient combustion of the diesel engine, the lowest load speed characteristic line is curve 7. In order to prevent the diesel engine from exceeding the range of speed under various loads, causing excessive reciprocating inertia force and centrifugal force which affects the safety and and economy, the curve 5 restricts the limiting value of each speed in stable operation. And the curve 6 restricts the limiting value of each speed under overload. If the diesel engine runs at too small speed, the speed of the oil pump plunger will drop, and the injection pressure will drop, resulting in poor fuel atomization and incomplete combustion. Especially when the marine main engine works according to the propulsion characteristics (curve 11), the load is also rapidly reduced at low speeds, which is prone to the phenomenon of unstable speeds. Therefore, a minimum stabilizing speed (curve 8) and a minimum running speed (curve 9) are specified.

It can be seen that a recommended operating range of the diesel engine will be formed when machine-propeller matching. And usually, according to the main engine propulsion characteristic curve (curve 11), there will be a large power margin left in the speed range below the maximum speed running point. This surplus power can be well utilized by the shaft generator system to improve the combustion efficiency of the diesel engine and enhance its utilization.

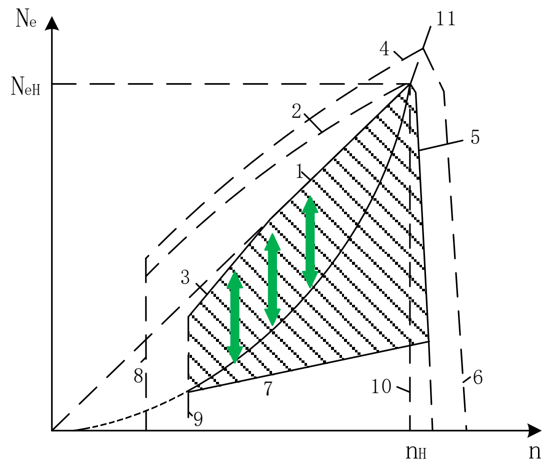



Figure 1. Permissible operating range of marine diesel engine

## 2.2 Main Engine and SG System Matching Analysis

When the main propulsion diesel engine is matched with the SG system, the most important factor to consider and analyze is the power matching between the main propulsion diesel engine and the SG system. It is analyzed from the following two working conditions [7]:

1 Ship maneuvering conditions

When a ship enters or leaves a port, berths or sails away from a dock, the main propulsion diesel engine is most of the time in the operating state of maneuvering navigation, in which the ship's drag characteristics remain unchanged but the rotational speed is constantly changing. Theoretically analyzing, under this operating condition, there is no need to change the fuel supply to the main propulsion diesel engine, but only need to increase the power of the SG system, so as to reduce the rotational speed of the propeller. Typically, the SG system matched to the main propulsion diesel engine is required to deliver full power at 70% to 100% of the main engine's rated speed, and the SG system should deliver 50% of its equipment's rated power at the lower limit speed of the main propulsion diesel engine.

Additionally, due to the complexity of the sea going state during maneuvering conditions, the use of the SG system under maneuvering conditions is not recommended to ensure the safety of the ship's navigation, although the SG system shows improvement.

2 Ship at constant speed condition

When the ship is sailing at a constant speed, the speed of the main propulsion diesel engine will not change if the ship's drag characteristics remain unchanged. When the ship's drag characteristics change, the engine speed will change accordingly.

If the main engine is mounted with a SG system, the propeller speed will be reduced, and the corresponding main engine power will be reduced. At this time, the main engine not only needs to provide propulsive power to the propeller to maintain the speed, but also needs to provide the power required by the SG system, then the operating power of the main propulsion diesel engine should be increased, and this is the principle of the matching design which is usually carried out for newly-built ships. Another scenario is to reduce the propeller speed, i.e., to operate at reduced power from the existing base, creating redundant power to provide for the power required by the SG system and this scenario usually applies to the matching design for retrofitting ships.

### 2.3 SG System Power Selection Case

Mounting a low-speed shaft-holding generator system mainly affects the selection of the Service Maximum Continuous Rating Point (SMCR) of the ship's main engine and the light pitch margin of the propeller.

For the retrofit ship, the matching design of SG system is more representative because the main engine type parameters and propeller are solidified. For the rebuilt ship, the matching process of ship-engine-propeller with low-speed shaft-holding generator system is as follows: firstly, confirm the limit of the main engine's external characteristic and the corrected propeller power curve after sailing test, and then confirm the main engine surplus power and speed range from the differential value between the two. Additionally, according to the communication with the main engine factory, the SG system is usually not used below 50% of the rated speed, because the load rate of the main engine is low in this working condition, and the auxiliary blower is not powerful enough after stacking the SG system. If running for a long time under this condition, it will easily induce an increase in the carbon deposit of the main engine and shorten the maintenance cycle. After confirming the permitted speed range of the main engine, the final range of using the SG system is checked according to the power load calculation report and the ship's power station load during the voyage, taking into account a certain safety coefficient.

Figure 2 shows the speed power curve of a 180,000 DWT bulk carrier after retrofitting a low-speed shaft-holding generator system. Analyzing the external characteristic curve of the main engine and the propeller design curve of this ship, it can be seen that the corresponding rotational speed of the main engine SMCR is 91 r/min. Under the common sailing conditions of this ship, the running speed range of the main engine is 60-75 r/min, and the daily load of the sailing process is about 700 kW. Considering the load ratio of the SG system and the power margin of the main engine, the low-speed shaft-holding generator system of 1,100 kW is selected initially. Then, according to the external characteristics of the engine and the design characteristics of the propeller, the power curve of the SG system in the power-take-out mode (PTO) is plotted, and after comprehensively analyzing the output power in the PTO mode and the permitted operating boundary of the engine, the operating speed range of 58 r/min to 91 r/min is selected as the permitted operating speed range of the SG system, and the output power of the SG system is 1,100 kW at this time. Take this as a reference for the next step of program design and calibration revision.

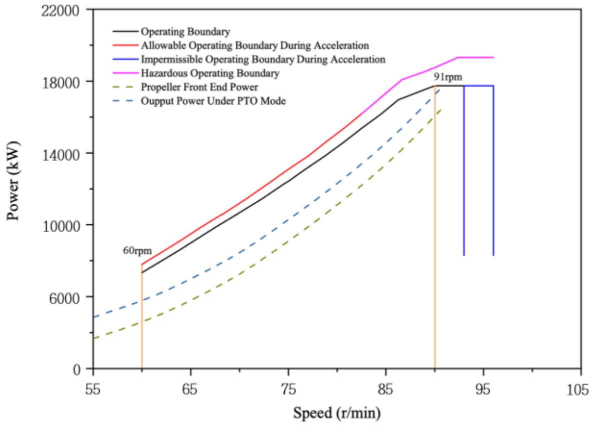



Figure 2. Main engine speed power curve

### 2.4 Summary

Analyzing from the original principle of ship machine-propeller matching, it can be seen that adding the SG system is able to improve the utilization rate of the remaining power of the diesel engine on the original basis.

At present, in order to meet the requirements of EEXI, the existing ships will also adopt measures such as reducing the speed operation, increasing the sail rotor, bubble drag reduction, etc., all of which release the usable power of the diesel engine to a certain extent, and SG system can be cooperated with them in order to realize a better utilization of the usable power, and further enhance the energy-saving effect.

## 3 EFFECT OF SG SYSTEM ON THE SHIP SHAFT SYSTEM

The SG mounted on the ship's shaft system has a certain impact on the shaft system alignment and torsional vibration, so verifying whether the impact on the ship's shaft system after mounting the SG is within a reasonable range is an important part of the design work. The 180,000 DWT bulk carrier is taken as the research object, and a simplified model is established to carry out the calculation of shaft system alignment and torsional vibration analysis.

### 3.1.1 Calculation of Shaft System Alignment

The purpose of the shaft alignment calculation is to find a set of vertical offsets for the intermediate shaft bearings and the mainframe bearings to ensure that the loads on all bearings remain within limits. Shaft alignment is calculated for both hot and cold conditions.

### 3.1.2 Shaft Alignment Modeling

A propulsion shaft system with a SG installed generally consists of a diesel engine, intermediate shaft, intermediate bearing, low-speed shaft-holding generator, front stern bearing, after stern bearing, etc. Taking the 180,000 DWT bulk carrier as an example, its shaft system arrangement is shown in Figure 3.

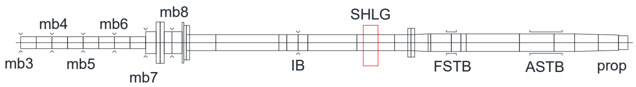



Figure 3. 180,000 DWT bulk carrier shaft system arrangement drawing with SG installed

Establish a simplified model for shaft system alignment calculation, including uniform loads, such as shaft segments, and concentrated loads, such as hubcaps, propellers, SG rotor, and diesel engine reciprocating parts, etc., and then carry out the shaft system alignment calculations.

### 3.1.3 Calculation Conditions

Calculations should take into account thermal expansion of the main engine, propeller thrust effects and bearing deflections. Cold and hot calculation conditions are shown in Table 1。

Table 1. Calculation condition

| Condition | Temp. | Propeller Immersion |
|---|---|---|
| Cold Static | 20℃ | 50%, 100% |
| Hot Static | 20℃ | 100% |
| Hot Running | 55℃ | 100% |

Basic parameters of SG are shown in Table 2.

Table 2. Shaft generator

| No. | Name | Unit | Parameters |
|---|---|---|---|
| 1 | rotor mass | kg | 8600 |
| 2 | rotor inertia | kg*m$^2$ | 2350 |

### 3.1.4 Calculation Results

**3.1.3.1 Cold Condition Offsets** Comparing the cold condition offsets of the shaft system before and after the installation of SG, the results are shown in Figure 4. In cold condition, the vertical offsets of the bearings are reduced after the shaft system was mounted with the SG, thanks to the fact that the installation of the SG added a new pivot point to the shaft system.

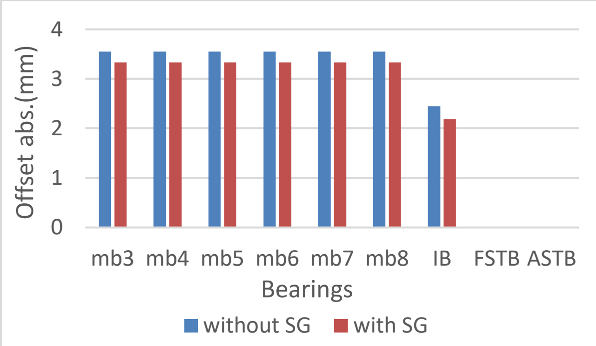



Figure 4. Comparison of offsets in cold condition

**3.1.3.2 Hot Condition Offsets** Comparing the hot condition offsets of the shaft system before and after the installation of SG, the results are shown in Figure 5. In hot condition, the vertical offsets of the bearings before and after the installation of SG is basically the same, and only the vertical offset of the intermediate shaft bearings decreases, which indicates that the SG will not adversely affect the vertical offsets of the shaft system, and will also improve the displacement offset of the intermediate bearings.

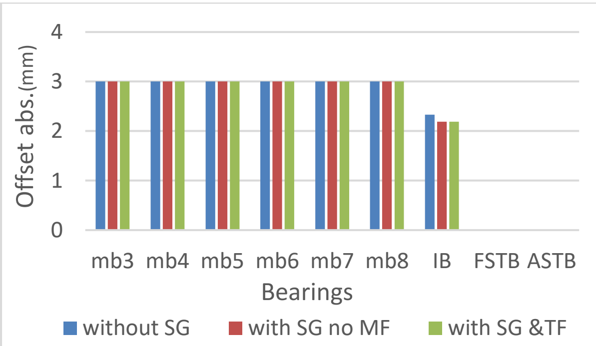



Figure 5. Comparison of offsets in hot condition

**3.1.3.3 Bearing Loads Comparison in Cold Condition** Comparing the bearing loads in cold condition before and after installing SG, the results are shown in Figure 6. In cold condition, the load on the intermediate bearing is slightly reduced with SG installed, while the load on the front stern bearing is slightly increased. It may be related to the installation position of the SG, but basically has no impact.


Figure 6. Comparison of loads in cold condition

**3.1.3.4 Bearing Loads Comparison in Hot Condition** Comparing the bearing loads in hot condition before and after installing SG, the results are shown in Figure 7. When the SG is configured on the intermediate shaft, if the magnetic force is not considered, the intermediate bearing load is obviously increased. However, the fact is that there has unbalanced magnetic force when installing SG, and the upward magnetic force makes the intermediate shaft bearing load reduced to similar with the case of no SG.

Therefore, it should be ensured that the direction of the magnetic force must be upward when installing, which is beneficial to the shaft alignment.

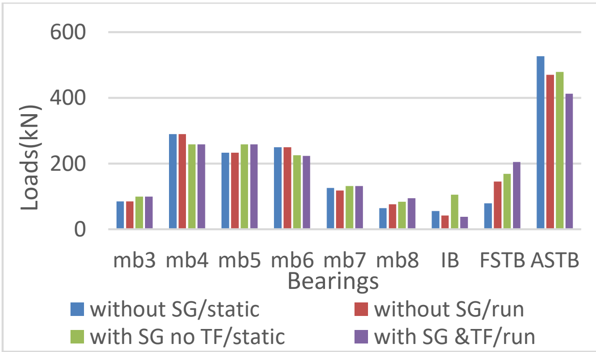



Figure 7. Comparison of loads in hot condition

**3.1.3.5 The Shear Force and Bending Moment Loads** After SG installed, in the cold static condition, the shear force and bending moment load behind the main engine flange are both within the permissible range as shown in Figure 8. The hot running state is the same as above, as shown in Figure 9.

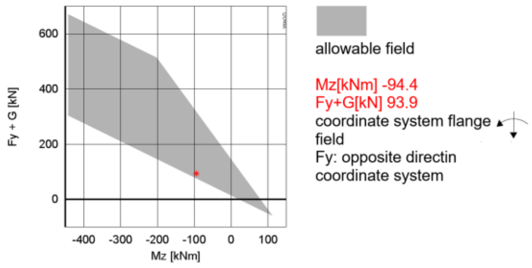



Figure 8. Cold static shear force vs. bending moment between mb8 and IB

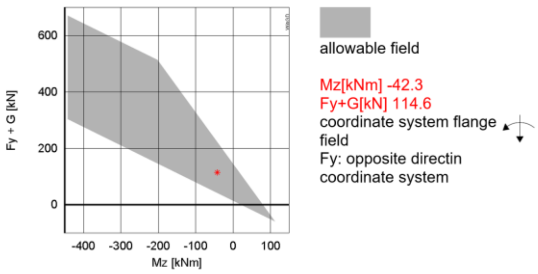



Figure 9. Hot running shear force vs. bending moment between mb8 and IB

### 3.1.5 Summary

The installation of SG optimizes the vertical offset of the shaft system bearings, but when installing the SG should ensure that the magnetic force is upward, so that the SG can also do a favor in the shaft system bearing loads. Therefore, it can be concluded from the study that a reasonable arrangement of the SG is helpful for shaft system alignment.

## 3.2 Shaft Torsional Vibration Analysis

The purpose of the torsional vibration analysis of the shaft system is to calibrate the effect of SG on the shaft system torsional characteristics, such as intrinsic frequency, torsional stress, angular acceleration and so on within a reasonable range.

### 3.2.1 Shaft Torsional Vibration Modeling

Taking 180,000 DWT bulk carrier as an example, the torsional vibration-equivalent system model of the shaft system is established as shown in Figure 10, and appropriately discrete centralized mass points are selected and labeled with mass ID from the bow to the stern.

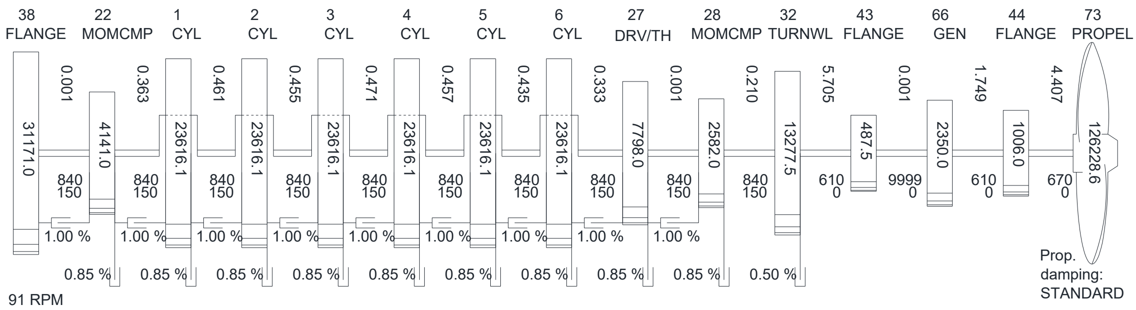



Figure 10. 180,000 DWT bulk carrier torsional vibration equivalent model

### 3.2.2 Calculation Conditions

The main engine crankshaft before mass ID 1,2,3,4,5,6,27, the intermediate shaft before mass ID 43,44, the propeller shaft before mass ID 73, and the intermediate shaft before the mass ID 66 mounted SG (noted as SG shaft) are selected to carry out the torsional characteristic calculation.

The table of shaft system equivalent parameters for installing a SG is shown in Table 3.

Table 3. Shaft system equivalent parameters

| ID no | Mass name | Inertial (kg*m²) | $D_{out}$ (mm) | $D_{in}$ (mm) |
|---|---|---|---|---|
| 38 | Flange | 31171.0 | - | - |
| 22 | Moment Comp. | 4141.0 | 840 | 150 |
| 1 | Cylinder | 23616.1 | 840 | 150 |
| 2 | Cylinder | 23616.1 | 840 | 150 |
| 3 | Cylinder | 23616.1 | 840 | 150 |
| 4 | Cylinder | 23616.1 | 840 | 150 |
| 5 | Cylinder | 23616.1 | 840 | 150 |
| 6 | Cylinder | 23616.1 | 840 | 150 |
| 27 | drive + thrust | 7798.0 | 840 | 150 |
| 28 | Moment Comp. | 2582.0 | 840 | 150 |
| 32 | Turning Wheel | 13277.5 | 840 | 150 |
| 43 | Flange | 487.5 | 610 | 0 |
| 66 | SG | 2350.0 | 9999 | 0 |
| 44 | Flange | 1006.0 | 610 | 0 |
| 73 | Main Propeller | 126228.6 | 670 | 0 |

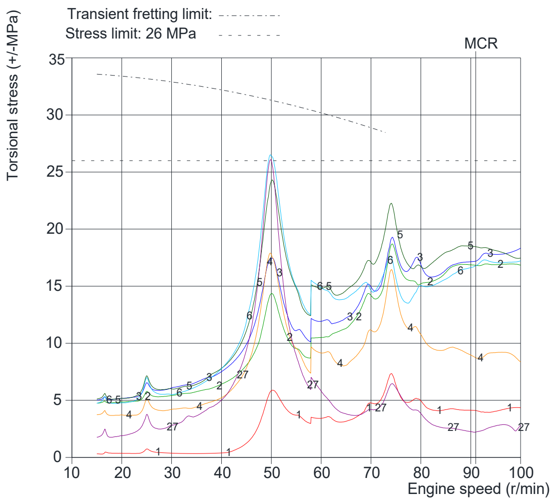
### 3.2.3 Calculation Results

**3.2.3.1 Vibration Characteristic** The natural frequencies of the shaft system before and after the addition of the SG are calculated, specifically considering the first order (no. 1), second order (no. 2) and third order (no. 3) natural frequencies, and the results are shown in Table 4. It can be found that after installing the SG, the fluctuation rate of no. 1 natural frequency is 0.5%, which is almost unchanged, and no. 2 natural frequency and no. 3 natural frequency fluctuate slightly, with the fluctuation rate of 1.9% and 1.6%, respectively, which is not much changed. This indicates that the addition of SG has basically no effect on the natural frequency of the shaft system.

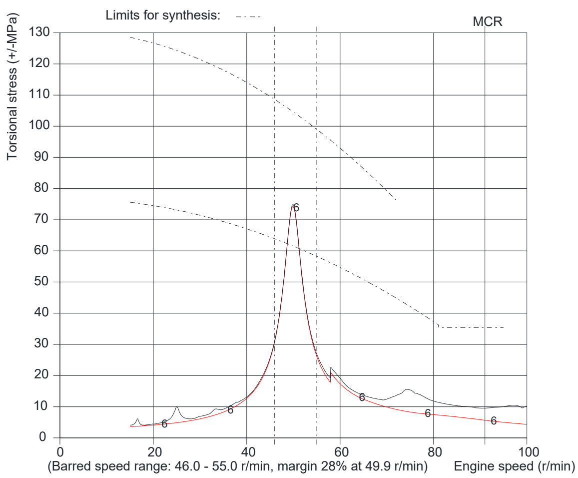
Table 4. Shaft natural frequency

| Mode no. | without SG | with SG |
|---|---|---|
| 1 | 5.018 Hz | 4.995 Hz |
| 2 | 18.887 Hz | 18.519 Hz |
| 3 | 37.190 Hz | 36.580 Hz |

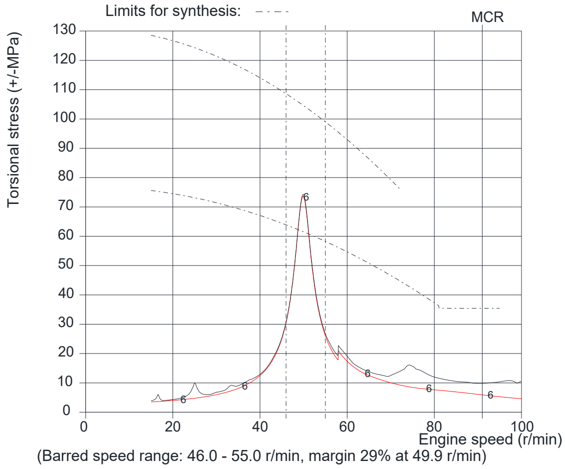
**3.2.3.2 Torsional Characteristic** Under the normal operating condition of the main engine, the steady state response of the torsional stress on the crankshaft, intermediate shaft and propeller shaft of the main engine after the installation of the SG and the angular acceleration (ang. acc.) of the SG shaft are calculated, and the results of the calculations are shown in Figure 11.



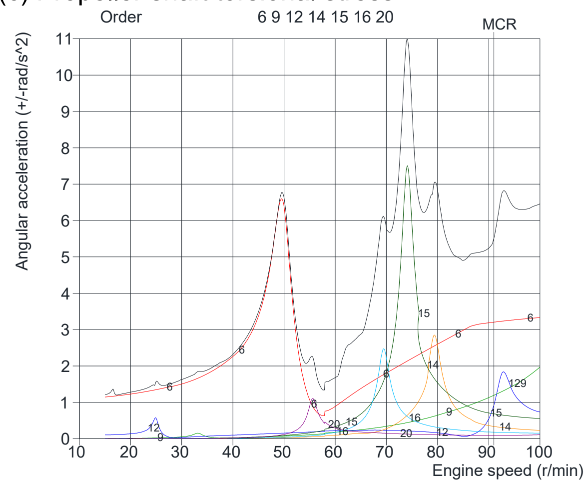

(a)M.E. crankshaft torsional stress




(b) Intermediate shaft torsional stress




(c) Propeller shaft torsional stress




(d)SG shaft angular acceleration

Figure 11. Shaft system torsional characteristics with SG installed

The analysis shows that the torsional stresses of the ship's shaft system after the installation of the SG are below the transient permissible value, and the maximum angular acceleration of the SG shaft is only 11 rad/s$^2$, which is much smaller than the dangerous angular acceleration of 50 rad/s$^2$. This indicates that the application of the SG system will not adversely affect the torsion of the ship's shaft system.

### 3.2.4 Summary

Calculation results show that after the addition of SG, the natural frequency of the shaft system is slightly reduced but the fluctuation is slight, as well as the torsional stress of each segment of the ship's shaft system is still within the permissible range. This shows that the addition of SG has almost no effect on the ship's shaft system, thanks to the split-half structure of the SG, whose modular design makes only the rotor mass and inertia attached to the shaft, which greatly reduces the impact of the shaft-holding generator on the shaft system.

# 4 EFFECT OF SG SYSTEM ON THE SHIP ENERGY EFFICIENCY

## 4.1 Definition of Energy Efficiency Indicators and Value Basis

### 4.1.1 $CO_2$ Emission Design Index Requirements for Operating Ships

As for the attaching symbol CDEx for the $CO_2$ emission design index sub-element for operating ships, the Attained EEXI and Required EEXI are defined as follows:

- Attained EEXI: refers to the actual EEXI value achieved by a single ship.
- Required EEXI: Refers to the maximum Attained EEXI value permitted for a particular ship type and size as specified in MARPOL Annex VI, Chapter 4, Regulation 25.

The Attained EEXI value for an operating ship shall be less than or equal to the Required EEXI value corresponding to that ship.

### 4.1.2 Attained EEXI Calculation Equation

According to MARPOL Annex VI/ Reg.25.1， required EEXI value can be calculated from *Eq. (1)*.

$$Attained\ EEXI\ \le Required\ EEXI = \left(1-\frac{Y}{100}\right)\% \times RLV \qquad (1)$$

In the Eq. (1): RLV- refers to Reference line value (RLV), calculated by Eq. (2):

$$RLV = a \times b^{-c} \qquad (2)$$

In the Eq. (2): When the ship type is bulk carrier, the value of each parameter is as follows:

- a=961.79
- b is the ship deadweight tonnage (DWT). b=DWT for DWT ≤ 279000, b=279000 for DWT>279000.
- c=0.477

Y- Refers to the reduction factor used to determine the Required EEXI to be met by each ship. When the type of ship is a bulk carrier, the following provisions shall be met:

- 10,000≤DWT＜20,000时，Y=0-20
- 20,000≤DWT＜200,000时，Y=20
- DWT≥200,000时，Y=15

The Energy Efficiency Index (Attained EEXI) of an existing ship after the application of the SG system shall be calculated by Eq. *(3) or (4)*:

When $0.75 \times P_{PTO} < P_{AE}$,

$$EEXI = \frac{(P_{ME}\cdot C_{FME}\cdot SFC_{ME})}{f_i\cdot f_c\cdot f_l\cdot Capacity\cdot f_w\cdot V_{ref}\cdot f_m} + \frac{(0.75\cdot P_{PTO}\cdot C_{FME}\cdot SFC_{ME})}{f_i\cdot f_c\cdot f_l\cdot Capacity\cdot f_w\cdot V_{ref}\cdot f_m} + \frac{(P_{AE}-0.75\cdot P_{PTO})\cdot C_{FAE}\cdot SFC_{AE}}{f_i\cdot f_c\cdot f_l\cdot Capacity\cdot f_w\cdot V_{ref}\cdot f_m} \qquad (3)$$

When $0.75 \times P_{PTO} = P_{AE}$,

$$EEXI = \frac{(P_{ME}\cdot C_{FME}\cdot SFC_{ME}) + (P_{AE}\cdot C_{FME}\cdot SFC_{ME})}{f_i\cdot f_c\cdot f_l\cdot Capacity\cdot f_w\cdot V_{ref}\cdot f_m} \qquad (4)$$

The definitions of the indicators in the equation and the basis for their values are as follows:

**Main engine power ($P_{ME}$)**

For ships with a transgressible power limiting /power reduction modification, the $P_{ME}$ for each main engine is 83% of the limiting power ($MCR_{MElim}$) or 75% of the original engine power ($MCR_{ME}$), whichever is lower.

For ships with both power limiting/power reduction modifications and the SG system, the $P_{ME}$ is calculated according to *Eq. (5):*

$$P_{ME} = 0.75 \times (MCR_{MElim} - P_{PTO}),\ and\ 0.75 \times P_{PTO} < P_{AE} \qquad (5)$$

**Carbon conversion factor ($C_F$)**

$C_F$ is a dimensionless factor that converts fuel consumption to $CO_2$ emissions based on its carbon content, expressed as t-$CO_2$/t-Fuel. $C_F$ is the carbon conversion factor for the fuel at the time of the SFC in the applicable test report included in the technical dossier determining the definition of the $NO_x$ Technical Rule. The values of $C_F$ are shown in the Table 5:

Table 5. $C_F$ value

| Fuel type | Reference level | Low calorific value (kJ/kg) | carbon equivalent | $C_F$ |
|---|---|---|---|---|
| Diesel/Gasoline | ISO 8217 DMX- level DMC | 42,700 | 0.8744 | 3.206 |
| Light fuel oil | ISO 8217 DMX- level DMC | 41,200 | 0.8594 | 3.151 |
| Heavy fuel oil | ISO 8217 DMX- level DMC | 40,200 | 0.8493 | 3.114 |
| Liquefied petroleum gas | Propane | 46,300 | 0.8182 | 3.000 |
| | Butane | 45,700 | 0.8264 | 3.030 |
| Liquefied Natural Gas | | 48,000 | 0.7500 | 2.750 |
| Methanol | | 19,900 | 0.3750 | 1.375 |
| Ethanol | | 26,800 | 0.5217 | 1.913 |

**Auxiliary power ($P_{AE}$)**

$P_{AE}$ means the power of auxiliary machinery required to provide the normal maximum sea load of the ship when sailing at $V_{ref}$ speed in assumed windless and wave-free conditions, including the power required for propulsion machinery/systems and for life on board (e.g. main engine pumps, navigational systems and equipment, and living accommodation on board) but excluding the power that is not used for propulsion machinery/systems (e.g. side thrusters, cargo pumps, cargo lifting equipment, ballast pumps, refrigeration equipment for cargo maintenance, and cargo hold fans, etc.).

In calculating the EEXI of a ship, the $P_{AE}$ does not use the actual auxiliary power of the ship, but empirical *Eq.s (6) or (7)* to calculate.

For ships with total propulsion power greater than or equal to 10,000 kW:

$$P_{AE} = \left(0.025 \times MCR_{ME} + \frac{PTI}{0.75}\right) + 250 \tag{6}$$

For ships with a total propulsion power of less than 10,000 kW:

$$P_{AE} = \left(0.05 \times MCR_{ME} + \frac{PTI}{0.75}\right) \tag{7}$$

**Speed ($V_{ref}$)**

If a speed-power curve is not available, or if no EEDI or design draft is included in the sea trial report, the speed $V_{ref}$ may also be taken as the value of $V_{ref,app}$, calculated in accordance with *Eq. (8)*:

$$V_{ref,app} = (V_{ref,avg} - m_v) \times (\frac{P_{ME}}{0.75 \times MCR_{avg}})^{\frac{1}{3}} \tag{8}$$

In *Eq. (8)*: The statistical mean value of the speed distribution $V_{ref,avg}$ for a given ship type and size is calculated according to *Eq. (9)*, where the values of A, B and C are given in Table 6:

$$V_{ref,avg} = A \times B^C \tag{9}$$

Table 6. Parameters value

| Ship type | A | B | C |
|---|---|---|---|
| Bulk Carrier | 10.6585 | Ship DWT | 0.02706 |

Ship's performance redundancy ($m_V$), which is 5% of $V_{ref,avg}$ or 1 kn, whichever is lower.

The statistical mean of the distribution of the ship's main engine power ($MCR_{avg}$) is calculated according to *Eq. (10)*, where the values of D, E and F are shown in Table 7:

$$MCR_{avg} = D \times E^F \tag{10}$$

Table 7. Parameters value

| Ship type | D | E | F |
|---|---|---|---|
| Bulk Carrier | 23.7510 | Ship DWT | 0.54087 |

### 4.2 Analysis of the Effect by Retrofitting SG System on 180,000 DWT Bulk Carrier

We retrofitted a 180,000 DWT bulk carrier with a SG system, the original ship data of which is shown in Table 8:

Table 8. Original ship data

| Parameters | Value |
|---|---|
| Deadweight at Summer Load Line Draught | 179582.46 t |
| Main engine type | STX-6S70MC-C7 (Tier II) 18660 kW |
| Main engine power limit | 12000 kW |
| $SFC_{ME}$ at 83% of $MCR_{ME,lim}$ | 183.50 g/kWh |
| Maximum Continuous Rating ($MCR_{AE}$) | 960 kW |
| SFC at 50% $MCR_{AE}$ | 210.8 g/kWh |
| Required EEXI | 2.398 g-$CO_2$/ton.mile |

The Required EEXI to be achieved by the target ship is calculated according to *Eq. (1)* as specified in the ship's baseline value (RLV) algorithm in MARPOL Annex VI/ Reg. 24.3:

$$Required\ EEXI = 80\% \times 961.79 \times 179582.46^{-0.477} = 2.398(g - CO_2/ton \cdot mile)$$

Before retrofitting the target vessel with the SG system, a main engine power limit was made to meet the EEXI requirement, and the EPL was limited to 52% of the original ship's main engine power, and the EEXI was *2.396* $g - CO_2/ton \cdot mile$ after the main engine power limit.

Now the SG is added to the target ship and the main engine power limit is increased to 64% of the original ship's main engine power. According to the *Guide for Calculating and Verifying the Energy Efficiency Design Index (EEDI) for Seagoing Vessels for International Navigation*, the maximum SG power that can be discounted for each vessel (denoted as $P_{SG}$) is $P_{AE}$/0.75/0.75, and based on the data of the target ship, the $P_{AE}$ is calculated by substituting into *Eq. (6)* as:

$$P_{AE} = (0.025 \times 18660 + 0) + 250 = 716.5(kW)$$

$$P_{SG} \leq \frac{P_{AE}}{0.75 * 0.75} = 1274(kW)$$

Therefore, the maximum discountable shaft generating power of the target ship is 1274 kW. Combined with the results of the machine-propeller matching design, it is finally decided to add a 1100 kW SG system for the target ship, and $P_{PTO}$ is calculated according to *Eq. (11)* as follows:

$$P_{PTO} = 0.75 \times P_{SG} = 825(kW) \quad (11)$$

$$0.75 \times P_{PTO} = 618.75kW < P_{AE} = 716.5kW$$

So $P_{ME}$ is calculated according to *Eq. (5)* as:

$$P_{ME} = 0.75 \times (MCR_{MElim} - P_{PTO}) = 0.75 \times (12000 - 825) = 8381.25(kW)$$

Substituting into the *Eq. (8)* calculation can be obtained:

$$V_{ref,app} = (1 - 5\%) \times (10.6585 \times 179582.46^{0.02706}) \times \left(\frac{8381.25}{0.75 \times 23.7510 \times 179582.46^{0.54087}}\right)^{\frac{1}{3}} = 12.34knot$$

### 4.2.1 Improvement of Energy Efficiency Index and Performance of the Ship by SG System

Before retrofitting the SG system, the target ship has done the main engine power limitation (EPL) to meet the EEXI requirements, the original EPL limit is 52% of the original main engine power, and after the main engine power limitation, the EEXI is $2.396g - CO_2/ton \cdot mile$.

The EPL limit was increased to 64% of the original main engine power after the installation of the SG system. The EEXI data of the 180,000 DWT bulk carrier is summarized in Table 9.

Table 9. 180,000 bulk carrier data related to EEXI calculation

| Parameters | Value | Unit |
|---|---|---|
| $P_{ME}$ | 8381.25 | kW |
| $SFC_{ME}$ | 183.50 | g/kWh |
| $C_{FME}$ | 3.206 | t- $CO_2$/t Fuel |
| $P_{AE}$ | 716.5 | kW |
| $SFC_{AE}$ | 210.8 | g/kWh |
| $C_{FAE}$ | 3.206 | t- $CO_2$/t Fuel |
| $P_{PTO}$ | 825 | kW |
| $V_{ref}$ | 12.34 | knots |
| Capacity | 179582.46 | tonnes |
| Correction factor | | |
| $f_l$ | 1.000 | - |
| $f_m$ | 1.000 | - |
| $f_i$ | 1.000 | - |
| $f_j$ | 1.000 | - |
| $f_c$ | 1.000 | - |
| $f_w$ | 1.000 | - |
| $f_{iCSR}$ | 1.012 | - |
| **Attained EEXI** | **2.119** | **gr $CO_2$/ tonne nautical mile** |

Attained EEXI was calculated by *Eq. (3):*

$$Attained\ EEXI = \frac{(8381.25 \times 3.206 \times 183.50)}{179582.46 \times 12.34 \times 1.012} + \frac{(0.75 \times 825 \times 3.206 \times 183.50)}{179582.46 \times 12.34 \times 1.012} + \frac{\left((716.5 - 0.75 \times 825) \times 3.206 \times 210.8\right)}{179582.46 \times 12.34 \times 1.012} = 2.390(g - CO_2/ton \cdot mile)$$

Calculation shows that the EEXI index after installing the SG system is further reduced to $2.390g - CO_2/ ton \cdot mile$, which is smaller than the Required EEXI of $2.398g - CO_2/ ton \cdot mile$ . Compared with the original EPL scheme, the installation of the SG system can raise the upper EPL limit of the main engine while ensuring a lower EEXI, which indicates that the installation of the SG can enable the target ship to have more power reserves and have the ability to better cope with a variety of different sailing conditions.

#### 4.2.2 Enhancement of Fuel Saving Effectiveness of Ships by SG System

During the daily voyage, the SG system can utilize the surplus power of the main engine to replace the other generator unit to supply power to the whole ship, and the fuel consumption difference between the main engine and the unit can realize the effect of fuel saving.

According to the calculation of real ship data, the total load of 180,000 DWT bulk carrier is about 8,000 kW, and the fuel consumption rate of the main engine is about 175-180 g/kWh.

Assuming that the load of the main engine during sailing is about 8,000 kW, the fuel consumption rate of the main engine is about 175 g/kWh, and the load of the crew is 750 kW, the fuel consumption rate of the crew is about 240 g/kWh, then the fuel consumption of the whole ship in 24 hours is about:

$$Fuel\ consumption\ for\ the\ whole\ ship\ for\ 24\ hours$$

$$= \frac{P_{ME} \times SFC_{ME} \times 24 + P_{AE} \times SFC_{AE} \times 24}{1000 \times 10000}$$

$$= \frac{8000 \times 175 \times 24 + 750 \times 240 \times 24}{1000 \times 1000} = 37.92(t)$$

After installing 1,100 kW SG, the power generation efficiency of the SG system is calculated at 90%, and the load of the main engine during sailing is about 8,833 kW, and the fuel consumption of the main engine will be reduced to 173.5 g/kWh, and the fuel consumption of the whole ship in 24 hours at this time is about:

$$Fuel\ consumption\ for\ the\ whole\ ship\ for\ 24\ hours$$

$$= \frac{P_{ME} \times SFC_{ME} \times 24}{1000 \times 10000}$$

$$= \frac{8833 \times 173.5 \times 24}{1000 \times 1000} = 36.78(t)$$

Calculation shows that the target ship can save about 1.14 tons of fuel oil per day after the installation of the SG system, and according to the calculation of 250 days of operation per year, it can save about 285 tons of fuel oil per year. The installation of SG system makes the target ship have higher navigation economy.

## 5 CONCLUSION

This article focuses on the technical route of low-speed shaft-holding generator system, and researches the impact of its installation on the main engine, the impact on the ship's shaft system, and the impact on the ship's energy efficiency improvement. Taking the application of 180,000 DWT bulk carrier as an example, the calculation and analysis on the machine-propeller matching design, the shaft system alignment and torsional vibration, and the energy efficiency index of the ship are carried out. The results show that the application of the SG system is conducive to improving the operating characteristics of the main engine, optimizing the shaft alignment and not adversely affecting the torsional vibration of the shaft system. In addition, it can also reduce the ship energy efficiency index EEXI, save fuel consumption, and bring obvious economic benefits for the ship. The above research provides useful support for the application of low-speed shaft development system on ships.

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