Development of Large Marine Hybrid Turbocharger for Generating Electric Power with Exhaust Gas from the Main Engine

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When a generator is connected directly to the rotor shaft of a marine hybrid turbocharger, in addition to the conventional turbocharging functionality, electrical power is provided for shipboard consumption. The generator is driven by part of the shaft power of the turbocharger, which is impelled by exhaust gas from the diesel engine, and thus an energy-saving effect is anticipated. For this reason, a compact, high-output, high-efficiency generator is required, capable of operating at high speed. In this research, the MET83MAG hybrid turbocharger was developed for large marine propulsion engines, in cooperation with NYK Line (Japan) Ltd., Universal Shipbuilding Corp., and Hitachi Zosen Corp.

1. Introduction

Generally, exhaust gas from the main diesel engine is directed entirely to the turbocharger turbine. The induced force drives a compressor in a configuration in which air for combustion is compressed and supplied to the engine by the turbocharger. Accordingly, the efficiency of the turbocharger is measured by the ratio of the adiabatic heat drop of the turbine to the adiabatic compressive work of the compressor. Due to the increased efficiency of marine diesel engine turbochargers in recent years, sufficient air can be supplied to the engine even when a portion of the exhaust gas is diverted from the engine for purposes such as electrical power generation. Waste heat recovery systems have been developed for practical application, in which about 10% of the exhaust gas is used to drive a power turbine connected to a generator.

Hybrid turbochargers utilize a portion of the rotational output of the turbocharger turbine (derived from exhaust gas energy) to drive a generator, thus providing a type of waste heat recovery system. Mitsui Engineering & Shipbuilding Co., Ltd. developed an electrical power recovery system in 2009, in which a generator is directly connected to a large marine turbocharger. The generator in this system has an output of 1,300 kW and is installed on the outside of the air intake silencer. Since diodes are employed for rectification, the generator cannot be used as a motor[1].

In the case of the marine hybrid turbocharger developed by Mitsubishi Heavy Industries, Ltd. (MHI), the generator is integrated within the turbocharger main unit. Hence the space required is essentially the same as for a conventional turbocharger, and no major modifications are required on the engine side. Also, since active rectification is employed, the generator can be used as a motor. The challenges that had to be overcome in achieving this included a reduction in the size of the generator and a structural design allowing the generator to be housed within the turbocharger unit.

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2. Hybrid Turbocharger Overview

2.1 Main specifications

Table 1 lists the main specifications of the MET83MAG hybrid turbocharger compared to those of the MET83MA conventional model. Wherever possible, the components are the same as those of the conventional MET83MA, with modifications on the compressor side that enable the generator to be housed within the silencer. The resulting hybrid version is 313 mm longer and 4,600 kg heavier than the MET83MA. At a speed of approximately 9,000 rpm, the maximum design output is 754 kW for a permanent magnet-type synchronous generator rotating at the same speed as the turbocharger.

Table 1 Main specifications of the MET83MAG hybrid turbocharger

Type			MET83MAG	MET83MA
Total length		(mm)	4,013 (exc. Connection box)	3,700
Total width		(mm)	2,250	2,250
Total height		(mm)	1,188	1,188
Total weight		(kg)	15,700	11,100
Maximum allowable speed		(rpm)	11,300	11,300
Maximum allowable gas temp.		(°C)	580	580
Generator	Generator type		Permanent magnet-type 3-phase synchronous	
Generator	Number of poles		4	
Generator	Maximum output	(kWmi)	754	
Generator	Bearings		Externally forced lubrication sleeve bearings	
Generator	Cooling		Freshwater, air	

2.2 Turbocharger structure

Figure 1 shows a cross-sectional diagram of the hybrid turbocharger. The generator is positioned within the turbocharger silencer, but since the silencer itself lacks sufficient rigidity to support the generator, a two-part (upper and lower) cast steel shell is attached to the compressor scroll to compensate for this. Consequently, the compressor scroll was also redesigned to provide greater rigidity. During assembly, the lower half-shell is first attached to the turbocharger, and the generator is then put in place and connected to the turbocharger rotor shaft and coupling. The lower half-shell also serves as an oil pan to collect lubricating oil discharged from the generator. The air intake silencer is mounted on the outside of the shell, with air passing over the outside of the shell to enter the compressor. **Figure 2** shows the generator installed in the lower half-shell. The generator rotor and turbocharger rotor are connected by means of a flexible coupling.

Since the heavy generator is ultimately supported by the bearing pedestal via the shell and compressor scroll, relevant stress and deformation due to heat and static load were analyzed, and the confirmation was made that this configuration would not be subject to excessive stress.

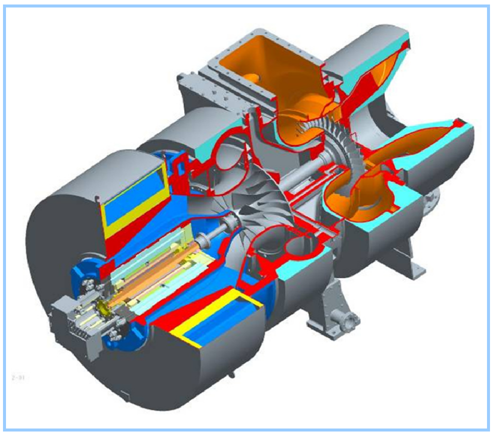

Figure 1 Cross-sectional diagram of the MET83MAG turbocharger
The generator is housed within the air intake silencer and connected to the turbocharger rotor shaft.

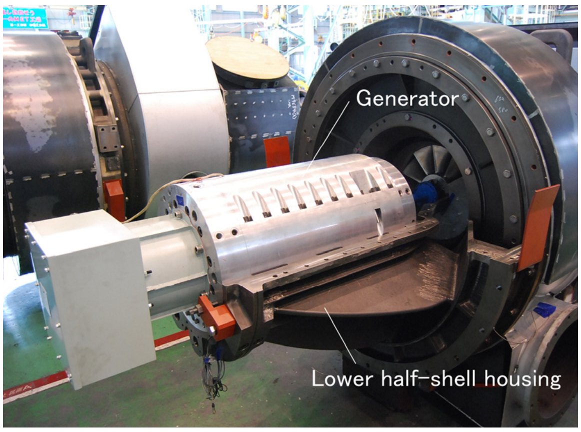

Figure 2 The generator installed in the lower half-shell housing
The generator and turbocharger are connected, with the upper half-shell still to be attached.

3. High-Speed Generator

3.1 Basic structure

The generator rotor features magnets that are fixed by adhesion in an arc encircling the periphery of the steel shaft. To prevent detachment due to centrifugal force during high-speed revolutions, the magnets are further affixed by means of carbon fiber windings, and a cooling water jacket made of aluminum surrounds the outside of these rotor windings. External cooling air is supplied to points at both ends and at the center of the windings. Since positioning along the axial direction of the rotor is determined by magnetic force, no need exists for thrust bearings inside the generator. The radial sleeve bearings are the same as those of the MET53MA model turbocharger, which is advantageous for obtaining replacement parts. Labyrinth seal fins are employed to prevent oil from leaking on the output shaft side or entering the windings, and sealing air is circulated in the gap between the fins and the shaft to prevent external oil leakage.

The bearings and the seal labyrinth are supported at both end bells, with the center housing sandwiched in between. The aluminum alloy housing is in two (upper and lower) pieces, but since the rotor slides in axially, this structure does not have to be disassembled during maintenance.

3.2 Rotor stability

The generator output shaft is mechanically connected to the turbocharger rotor shaft by means of a diaphragm-type flexible coupling. **Figure 3** shows the results of a hazardous speed analysis of the generator rotor. In the normal operating region between the primary and secondary hazardous speeds, sufficient separation was confirmed. Furthermore, an independent running test was performed on the turbocharger while the rotor shaft was connected to the generator, and mechanical behavior was observed. Generator shaft vibration was measured, and remained within 10 mm until the maximum allowable turbocharger speed was reached. Thus, the determination was made that dangerously unstable vibration does not occur.

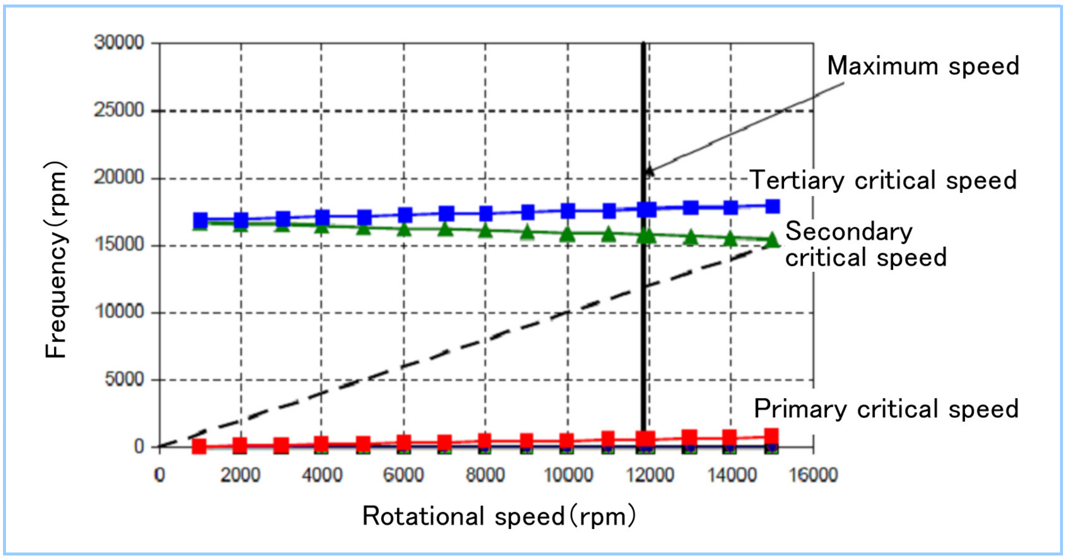

Figure 3 Critical speed analysis results for the generator rotor

3.3 Cooling of the generator

Since the speed of this generator is much higher than that of an ordinary generator, its size is relatively small compared to its output. However, cooling is an issue due to the level of heat accompanying the output. In addition, since the generator is placed inside the silencer, the external dimensions must be as small as possible. Accordingly, supply and discharge channels are provided within the generator housing for cooling water, cooling air, and lubricating oil. Since air scavenged from the engine is used for cooling air, the higher the load and the more heat generated, the greater the pressure of the cooling air will be.

Figure 4 illustrates the numerical model used for thermal analysis of the generator. Assuming an effective flow of cooling air and cooling water, a safe temperature was predicted to be maintained even during continuous operation at maximum output. Temperature sensors are embedded in the windings of the actual generator, and these are used to trigger an alarm in the event of an abnormal increase in the winding temperature.

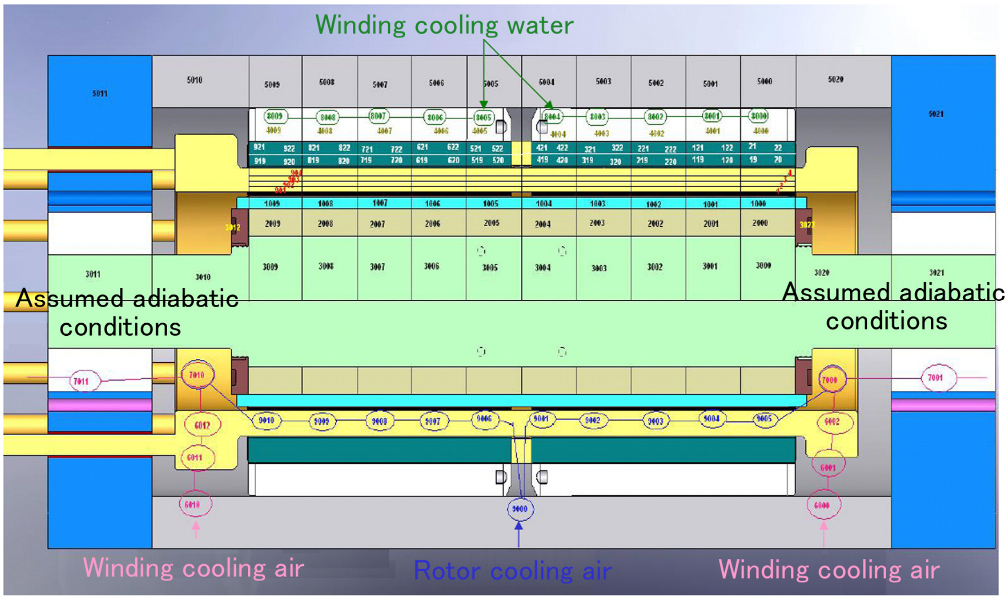

Figure 4 Model used to analyze the internal temperature distribution of the generator

4. Advantages of the Hybrid Turbocharger

As with conventional exhaust gas turbines, the MHI hybrid turbocharger with integrated generator produces electrical power from exhaust gas energy at the turbocharger inlet, but also offers several distinct advantages:

(1) With only slight increases in the outer dimensions of the turbocharger, and no need for piping or valve control, little modification of the main engine is required, and retrofitting is relatively simple.

(2) No piping loss occurs, and efficiency is high due to heat recovery by the turbocharger turbine.

(3) The generator functions as a motor to assist the turbocharger when power is provided.

Since the voltage and frequency of the three-phase AC power from the generator are dependent upon the speed of the turbocharger, the output power cannot be applied directly to meet shipboard needs. Consequently, after initial DC rectification, the output power is converted to the appropriate voltage and frequency for shipboard consumption. To accomplish this, the system utilizes an IGBT for active rectification, as well as an inverter. Since these two elements also function in reverse, power from the ship can be supplied to the generator, so that it acts as a motor to accelerate the turbocharger rotor. In the case of a two-cycle, low-speed diesel engine, sufficient air for combustion cannot be supplied by the turbocharger alone during low-load operation, and hence an auxiliary electrical blower is provided. With the hybrid turbocharger considered here, the motor function substitutes for this auxiliary blower. In addition, since air is efficiently compressed by the turbocharger compressor, the power required is less than what would be consumed by a blower. **Figure 5** shows the external appearance of the active rectification panel and the inverter panel. The DC power from the active rectifier is fed to the inverter panel, and the re-converted AC power is employed to provide shipboard power.

Figure 5 External view of frequency conversion equipment

5. Turbocharger Independent Running Test Results

In the independent running test of the turbocharger, compressed air from the turbocharger compressor is supplied to a combustor, and combustion gas is formed that is used to drive the turbocharger turbine. The efficiency of the turbocharger is expressed as the product of the compressor efficiency and the turbine efficiency (including mechanical efficiency). However, since the compressor driving force and the turbine output are the same, the turbocharger efficiency can be written as

$$\text{Turbocharger efficiency} = \frac{\text{Compressor adiabatic head}}{\text{Turbine adiabatic head}}$$

On the other hand, for a hybrid turbocharger, the efficiency will be underestimated by the above formula, since the turbine output is used to drive both the compressor and the generator. For the sake of distinction, the efficiency of a hybrid turbocharger or exhaust gas bypass is referred to as turbocharging efficiency.

Figure 6 shows the turbocharging efficiency during the independent running test of the hybrid turbocharger. With no load on the generator, turbocharger efficiency was reduced by approximately 0.5%. This was caused by bearing loss in the generator, windage loss, and electromagnetic loss.

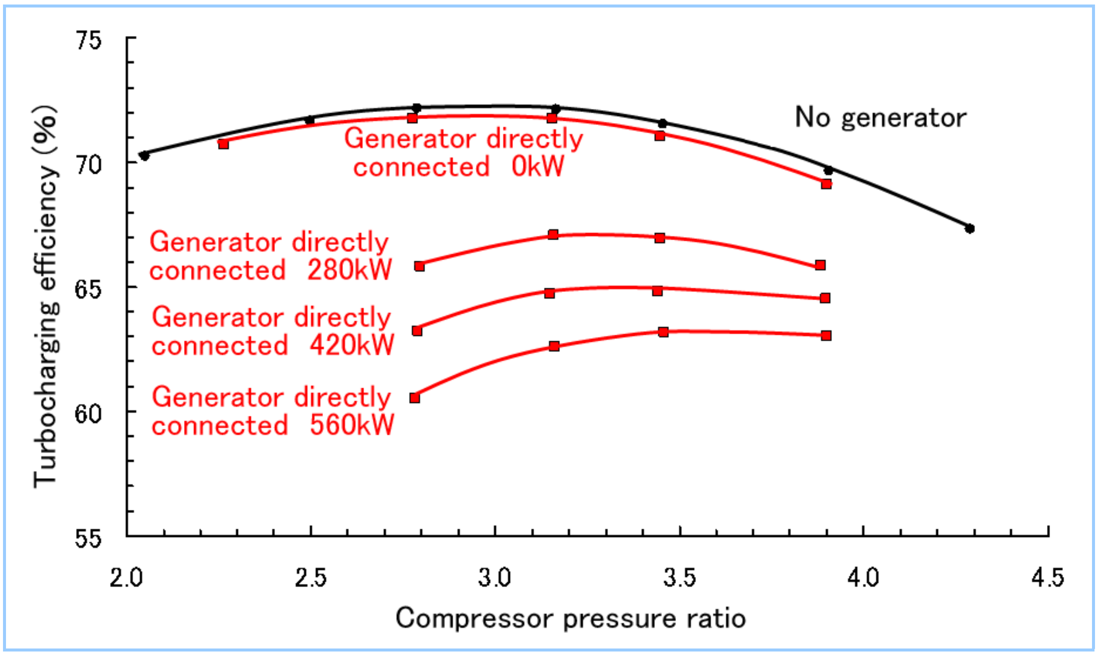

Figure 6 Turbocharging efficiency of the hybrid turbocharger during the independent running test

As noted above, the apparent turbocharging efficiency decreases with increased electrical power output. Also, in the region of low compressor pressure ratio, the same power output results in reduced turbocharging efficiency (the lower the engine load, the lower the turbine work). On the other hand, since a minimum turbocharging efficiency must be achieved to secure proper engine performance and reliability, one must reduce the generator output under low load.

6. Conclusion

MHI began development work on the MET83MAG hybrid turbocharger at the start of FY2008, and as of May 2010, assembly has been completed and independent output testing has been initiated. Turbocharger independent running tests have served to confirm the effects of the generator on turbocharger performance, the efficiency of the generator and power electronics, the quality of the generated electrical power, and transition characteristics. The new hybrid turbocharger system will be installed on a large marine two-cycle diesel engine for the first time ever in October 2010, to be followed by engine and turbocharger matching operations and power generation tests.

This hybrid turbocharger not only recovers electrical power from waste energy contained in engine exhaust gas, but (unlike conventional turbochargers that operate subordinately in response to engine output) is also capable of controlling the amount of generated power to control the turbocharger speed (i.e., the amount of combustion air supplied to the engine). This functionality should provide an applicable response to a wide range of energy conservation requirements and environmental regulations, and confirmation of actual operating conditions aboard the first vessel so equipped will be highly useful in developing turbochargers of other sizes.

In closing, we would like to express our sincere appreciation for valuable observations and technical guidance received from NYK Line (Japan) Ltd., Universal Shipbuilding Corp., Hitachi Zosen Corp., Taiyo Electric Co., Ltd., and Calnetix Inc.

Reference

1. Morio, K. et al., Development of Large-Scale Turbocharger Generator Unit, Mitsui Zosen Giho No.199 (2010-2)