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Design and experiments of two-stage intercooled electrically assisted turbocharger

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ABSTRACT

The demand for continually improving the efficiency of large diesel engines requires increasing the pressure ratio and efficiency of turbochargers. One answer to these requirements is to use two-stage electrically assisted turbochargers, which will enable higher pressure ratios than before but also generate electricity in sufficient operating conditions. This study shows the design and experimental performance of the novel two-stage single-shaft electrically assisted turbocharger. It was predicted that an increase of 2.5 percentage points in overall efficiency can be achieved by using a two-stage single-shaft intercooled electrically assisted turbocharger in a 1200 kW diesel engine instead of a conventional single-stage turbocharger. It is experimentally shown that the studied turbocharger has potential for improving the engine efficiency although the performance was below the expected. Additionally, the critical points for the design improvements are assessed to guide future development work.

1. Introduction

More energy efficient and less polluting processes are required in the energy generation sector. Diesel engines are widely used in generating electricity in land, marine and transportation. Therefore, improvements in the diesel engine energy efficiency will have a direct influence on the variety of applications. The constant increase of mean effective pressure (MEP) within large two-stroke diesel engines requires higher turbocharger pressure ratios but also improved efficiency [1]. Simultaneous NO_x emission reductions are also needed to fulfill the TIER III goals [2], where the use of Miller timing offers one solution but requires higher boost pressure from the turbocharger. On the other hand, the reduction of the CO_2 emissions is of major concern in every energy generation sector. To meet these constraints, the design of future engines strives for better utilization of the engine waste heat, but also substantial improvements in the turbocharger performance are required.

Several studies have shown that marked improvements can be expected on the overall engine fuel consumption and efficiency while using a separate power cycle to recover the engine waste heat. A good approximation for the recoverable potential was given by Baldi and Gabrielii [3], who suggested that 5–15% fuel savings are realistic in the studied ship. Multiple methods for converting waste heat into electricity have been shown to have potential. Several authors have shown the Organic Rankine Cycle (ORC) to be a good alternative in converting engine waste heat into electricity [4–7]. Additionally, the potential of the Kalina cycle [7], the conventional Rankine cycle [7–9] or the combination of the conventional Rankine cycle and ORC [10] have been shown. In addition to waste heat recovery by means of Rankine cycles, the use of thermoelectric generators that are capable of converting heat directly into electricity by using the Seebeck effect have been identified as another potential technology for recovering waste heat from engines [11–13].

To increase the pressure ratio of the turbocharger, a two-stage compressor has been recommended if the pressure ratio exceeds 4.5 [1] in large marine diesel engines and approximately 3.5 in road use [14]. In currently available designs, this is done by using separate low pressure (LP) and high pressure (HP) turbochargers. Cui et al. [15] have carried out a theoretical optimization of a two-stage turbocharger for a marine diesel engine with Miller-timing for reducing NO_x emissions. They concluded that two-stage turbocharging should be applied in this type of engine, since single-stage turbocharging cannot reach the required pressure and efficiency level to avoid the power reduction of the engine caused by Miller timing. Wik et al. [16] highlight that the state-of-the-art simulation models can be used for predicting the engine performance with different types of turbocharging configurations, but experimental work has to be carried out especially when evaluating the NO_x emissions in engines adopting two-stage

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Nomenclature

b	blade height (mm)
D	diameter (mm)
Δh	enthalpy change (J/kg)
M	Mach number (–)
N	number of blades (–)
N	rotational speed (rpm, 1/s)
N_s	specific speed (–)
P	power (kW)
q_v	volume flow (m^3/s)
R	degree of reaction (–)
R^2	coefficient of determination (–)
π	pressure ratio (–)
ψ	blade loading coefficient (–)
σ	von Mises stress (MPa)

Subscripts

amb	ambient
g	gauge
h	hub
in	inlet
out	outlet
s	isentropic
t	tip
t-s	total-to-static
t-t	total-to-total
1	compressor inlet
2	compressor rotor/turbine stator outlet

Abbreviations

BMEP	brake mean effective pressure
BSFC	brake specific fuel consumption
CFD	computational fluid dynamics
HP	high pressure
LP	low pressure
MEP	mean effective pressure
ORC	organic Rankine cycle
PM	permanent magnet

turbocharging. Codan and Huber [17] have concluded that the use of two-stage turbocharging, together with extreme Miller timing represents an effective way to reach high fuel efficiency, low NO_x emissions, high operational flexibility, and high power density. Serrano et al. [18] have carried out an experimental study for a low NO_x emission two-stage turbocharged heavy-duty engine. Their results show that two-stage turbocharging can significantly improve drivability and reduce NO_x emissions especially in transient operation when compared to single-stage turbochargers. Galindo et al. [19] have studied the impact of different two-stage turbocharging architectures, especially on pumping losses in automotive engines. Their study generated equations for describing the relation between the total compression and expansion ratio of a two-stage turbocharger as a function of engine parameters. They compared the use of a single-stage and two-stage turbocharger for different pressure levels and their results showed that significant efficiency improvements can be achieved with a two-stage configuration, especially when the pressure ratio of the turbocharger is high. The two spool design, however, requires more space than a design where LP and HP compressors and turbines are on the same shaft. Space limitation is an important design constraint especially for diesel engines in marine use.

Electrically assisted turbochargers have an electric motor/generator connected to a turbocharger to assist the turbocharger or convert excess energy to usable form. The general idea is to speed up the turbocharger acceleration during startup and to produce electricity when the engine runs at higher loads. Ono et al. [20] reported successful operation of an electrically assisted large turbocharger, which was suggested to be the world's first practical application of a marine hybrid turbocharger. Terdich et al. [21] showed the applicability of electric turbocharger assist on a 200 kW diesel engine. Terdich and Martinez-Botas [22] also provided an experimental characterization of the turbine and electric motor/generator of an electrically assisted turbocharger designed to be applied to non-road medium duty diesel engines. A study by Millo et al. [23] demonstrated 1–6% reductions in fuel consumption while employing an electrically assisted turbocharger on a heavy-duty diesel engine.

From this background, it can be concluded that very little information is available in public literature about the use of electrically assisted turbochargers, and there are no reported applications where the two-stage compression would be made in a single-shaft turbocharger. There is also a clear lack of detailed design information about the complex system and discussion on the practical design constraints of the electrically assisted turbocharger. This study attempts to fill this gap of information as it presents the design and experimental performance of a novel two-stage single-shaft electrically assisted turbocharger that is designed and tested with a 1200 kW diesel engine in real operating conditions. From the turbocharger design point of view, special attention is paid to the mechanical design, which is usually the main limitation of the whole process from idea to prototype.

The preliminary design of a two-stage turbocharger is presented first to show the advantages of the current approach in comparison with the conventional single-stage turbocharger. This is followed by a section discussing the design of the turbomachinery and the electric machine. Also the mechanical design is presented in separate chapters including stress, bearing, and rotor dynamic analyses. Finally, the experimental setup and the results are presented and analyzed.

2. Preliminary simulations on two-stage turbocharger

The simulations were carried out for a 1200 kW impulse charged diesel engine with a conventional single-stage turbocharger and a two-stage intercooled electrically assisted turbocharger (more information about the diesel engine in Section 5). The schematic diagrams of the two studied cases are shown in Figs. 1 and 2. The conventional single-stage turbocharger does not contain an electric machine, and the turbine runs the compressor that is directly coupled on the same shaft. In the two-stage intercooled electrically assisted turbocharger, the turbine, the LP and HP compressor, as well as the electric machine are directly coupled on the same shaft, and the electric machine is connected to the electric network via a frequency converter. The idea is to use the electric machine as a motor to speed up the turbocharger acceleration during the diesel engine startup and as a generator to produce electricity when the diesel engine runs at higher loads.

First, the turbine as well as the LP and HP compressor stages were preliminarily designed, including the off-design calculations, to model the performance of the turbocharger. Then, simulations were conducted for comparing the performance of the diesel engine–turbocharger system when the conventional single-stage