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An experimental investigation of the effects of cyclic transient loads on a turbocharged diesel engine

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HIGHLIGHTS

- The effects of cyclic loads on the BSFC and NOx emissions of a CI engine are investigated.
- Compared to static loads, the largest deviations are 6.7% and 9.1%, respectively.
- For the quasi-steady estimations, the largest errors are 2.9% and 4.3%, respectively.
- The effects primarily depend on the average load level.
- The quasi-steady estimations show good results except for a low load with high frequency.

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ABSTRACT

This paper presents the results of the experimental investigation on the effect of cyclic transient loads on a turbocharged diesel engine with respect to fuel efficiency and NOx emissions. The transient loads in this test program are time varying torque in the form of a sinusoidal wave with a fixed amplitude at different frequencies and different mean values. The measurements from the transient tests are compared to the cases of constant loads and to estimations provided by a quasi-steady mapping. The largest influences are found at the lowest mean load (24.6%) and the highest frequency (0.2 Hz). For fuel efficiency, the transient deviation is 6.7%, while the estimation error is −2.9%. For NOx measurement in volume fraction, they are −9.1% and 4.3%, respectively. The results also show that the magnitude of the effect grows as the mean power load decreases. Finally, a graphical method is presented to evaluate the effect of load shifting operations for a diesel engine using the steady-state fuel consumption rate curve.

1. Introduction

1.1. Background

Shipping is one of the most efficient way to convey goods or people from one place to another. While it is transporting approximately 77% of the internationally traded goods [1], the total CO_2 production from shipping accounts for only 2.6% of the total global production according to the International Maritime Organization's (IMO) study [2]. Still, the effort to mitigate its contribution to global warming has led to new mandatory measures by the IMO such as the energy efficiency design index (EEDI) and the ship energy efficiency management plan (SEEMP) [3]. However, the current measures consider only a single operating point, or are based on the steady-state efficiency of the power producers, which are predominantly turbocharged diesel engines.

When a turbocharged diesel engine is used as a single source of power or as a part of an aggregate in a small scale power plant, it is easily exposed to transient loads. For example, when an ocean-going vessel encounters waves in rough weather, the diesel engine experiences varying torque loads and shaft speed. Transient loads for a diesel engine can either be speed variations under constant torque or torque variations under a constant speed or simultaneous change of both [4]. The effect on fuel efficiency, emissions and a system response are of prime interest for researchers and developers.

1.2. Transient behavior of a turbocharged diesel engine in marine applications

The thermodynamic transient behavior of a diesel engine is caused by the following reasons: (i) air flow delay due to the

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Acronyms

BSFC	break specific fuel consumption
CNOx	NOx measurement in ppm by volume
EEDI	energy efficiency design index
ESD	energy storage device
HC	hydrocarbon
IMO	International Maritime Organization
KPI	key performance indexes
PM	particulate matter
RPM	revolutions per minute
SEEMP	ship energy efficiency management plan

turbocharger response, (ii) energy transport delay and (iii) thermal transient [5]. In addition, a system delay due to the inertia of the mechanical components should also be taken into account. Among those delays, the delay due to turbocharger response is the most important phenomena influencing the diesel engine performance in a system perspective. The delay due to a turbocharger occurs when the amount of fuel injection increases rapidly, but the increase in air flow does not follow at the same rate. This causes a rich combustion in the chamber as well as limiting the amount of fuel injection to help ensure complete combustion without a production of smoke. As a result, the output torque is delayed compared to the command from an operator or a controller. In addition, the charge in the cylinder becomes very rich, which increases the instantaneous production of NOx and particulate matter (PM). The time scale of the phenomena is in the order of seconds, which often coincides with the time scale of the external transient loads.

Understanding the processes of the diesel engines under the transient conditions and their effects is essential to assessing the plant with regard to its reliability, efficiency and relevant emission factors in the actual operational conditions. However, the performance and emission data of the diesel engines for marine applications are primarily given based on the steady-state measurements. The random nature of the environmental loads and various operation modes of ships make it difficult to define the standard cycle as in the automotive industry.

In marine operations, the transient loads on the diesel engine often appear in a cyclic form. For example, when a ship is traveling in rough weather, waves cause a periodic change in the propeller inflow, which results in cyclic torque variations on the shaft [6]. In offshore drilling operations, the active heave compensation system on the drilling string causes periodic variations in the electrical power. Station-keeping operations in the extreme sea will cause a large degree of cyclic load fluctuations to the power plant [7]. In such operations, the average influence of such loads on fuel consumption and emissions, rather than an instantaneous value, is of interest.

The influence of a cyclic transient load can be analyzed in two ways. The first is to analyze the influence of cyclic loads compared to a constant load with the same mean value. In recent developments of hybrid technology in marine power plants [8], it is possible to use an energy storage device (ESD) such as batteries, supercapacitors and flywheels for handling the fluctuation part of the load while the main prime mover provides power at a constant level, a so-called load shifting operation. This kind of operation may be beneficial for the operational reliability, but the gain or loss in terms of fuel consumption and NOx emissions is not well identified [9]. Therefore, analyzing the influence by the experimental investigation can provide guidance for the application of this novel concept.

The other analysis attempts to verify the validity of the quasi-steady mapping method as presented in [10–13]. In this method, the specific fuel consumption and emission factors are given as a function of the shaft torque and the engine speed, which are measured from steady-state conditions. The fuel consumption and emissions are then estimated for the given set of transient engine speed and torque from measurement or simulation. However, there may be additional transient influences due to the nonlinear effects of the operating conditions. In this regard, comparing the results of the transient load tests to the estimation from the quasi-static mapping will provide an indication of such influences. If the influences are significant, a correction factor may be found to adjust the estimations.

1.3. Literature review on transient performance and emissions for diesel engines

Researchers have attempted to identify and quantify the influences by either experimental investigations or numerical simulations. In the work by Rakopoulos et al. [14], a transient diesel engine model and its simulation for the dynamic responses of the shaft speed are presented with validation by the experimental measurement. It also gives parametric studies of the main engine characteristics such as mass moment of inertia of the turbocharger, cylinder temperature wall and effectiveness of the aftercooler model. Even so, fuel consumption and emissions were out of the scope. In addition, a review by Rakopoulos and Giakoumis [4] and Chow and Wyszynski [15] provide knowledge and insight into the physical processes related to the transient performance and emissions of the turbocharged diesel engine.

Hagena et al. [16] performed an experimental investigation on the effect of the aggressiveness of acceleration in a road vehicle with a diesel engine, with a specific interest in NOx and particulate emissions. In the study, the throttle position was changed from approximately 18% to 40% in three different time periods. It has been demonstrated that there is a significant increase in the instantaneous emission levels of NOx and PM during ramp up, a maximum of 1.8 times the steady-state value of the final conditions. He also proposed a quasi-steady mapping method using steady-state engine maps without actual models or validation.

A similar research was undertaken by Nuszkowski et al. [17], but what is unique in this work is that they quantitatively compared the influence of the driving aggressiveness for five different diesel engines in a specified driving cycle (US Federal Test Procedure). The diesel engines under the test had similar power ratings, but they were built in different years from 1991 to 2004. The test showed negligible differences in the specific fuel consumption for all engines whereas a small decrease in NOx emissions and a significant increase in PM emissions were observed only for old engines. The newest engine showed negligible differences in emissions except for CO and hydrocarbon. This suggests that the influence of the transient loads is engine-specific, which may depend on the engine conditions, control strategies or specific technologies applied to the engine, such as variable geometry turbines, advanced fuel injection systems and various valve timings.

Yang et al. [18] performed an experimental investigation on the influence of load torque increase in different time periods on fuel consumption and emissions. They managed to obtain both the instantaneous and average values of break specific fuel consumption (BSFC), and compared them to cases of different time periods.