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EXTENSION OF DIESEL ENGINE POWER VIA ELECTRICALLY ASSISTED TURBOCHARGER

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ABSTRACT

The power demand for unmanned ground systems (UGS) and unmanned aircraft systems (UAS) has been ever-increasing to support important military operations. Mild hybridization technologies have the potential to address the ever-increasing power demand. The objective of this study is to investigate the capability of an electrically assisted turbocharger (EAT) as one mild hybridization method. A motor-generator (M/G) was integrated to a turbocharger to generate electricity using the engine exhaust energy, or to spin the turbocharger using the energy stored in energy storage device. The EAT was implemented to a 2-liter turbocharged direct-injection diesel engine fueled with jet fuel. Then, the operation of the EAT was examined and the results were compared to the baseline. The target manifold pressure was regulated by the M/G, which applies varying amounts of positive or negative torque to increase or decrease the speed of the EAT. The energy recovered from the exhaust stream and converted to electricity by the EAT was equal to approximately 5% of the maximum rated engine power. Furthermore, the EAT was able to extend the engine power by 6% at the same equivalence ratio by providing more air to the combustion chamber and in turn more fuel.

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1. INTRODUCTION

Because of their reliability, high power density, and high fuel efficiency, many unmanned ground vehicles and unmanned aircraft systems use diesel engines [1]. The

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power demand for such engines has been ever growing to meet the increased power requirements. Forced air induction system such as turbochargers have increased engine power [2]. Furthermore, mild hybridization technologies, which provide conventional engines with partial energy recovery and increased usable power output by using electric machines, have a potential to further address the ever-increasing power demand [3].

Extensive research has been performed for mild hybridization of ground vehicles [2,4-5]. Among various electrification methods, the present study focuses on electrically assisted turbocharger (EAT) which has an integrated motor-generator (M/G) located between compressor and turbine wheels. To date, considerable research has been performed on transient response and efficiency of EATs [6,7]. For low engine loads, an EAT spins the shaft resulting in faster compressor speed and higher boost pressure with faster transient response minimizing turbo lag. At high engine loads, it slows the shaft down, generating surplus electrical energy and reducing turbine speed, which increases engine exhaust back pressure.

The present study, however, investigated a capability of EAT from a different aspect to enable additional engine power. For this aim, an EAT attached to a diesel engine was characterized first for all engine loads. Then, an engine power extension experiment was performed maintaining an equivalence ratio at the maximum rated engine power. This was achieved by increasing the EAT speed and in turn the manifold absolute pressure (MAP), and by carefully adding more fuel through a full authority digital engine controller (FADEC).

2. EXPERIMENTAL SETUP

A M/G system was integrated into the turbocharger to form an EAT. It functions as a generator to produce electrical power by recuperating waste energy and as a motor to provide on-demand boosting by controlling the rotor speed of the turbocharger spool. A schematic of the EAT system utilized in this study is presented in Fig. 1. The EAT replaced the legacy turbocharger which was attached to a 2-liter diesel engine. It was matched to the boundary conditions of the legacy turbocharger The M/G was controlled by an inverter/controller. The power stage of the inverter/controller is SiC-MOSFETs. The bus voltage of the M/G system was 400 VDC. The mechanical parts of the turbocharger such as bearings were cooled by the same oil that was supplied from and returned to the engine. The electrical parts such as the M/G and inverter/controller were cooled by water. To protect the M/G system from exceeding the speed limit, the turbocharger speed was monitored using a fiber optic coupled optical speed sensor [8].

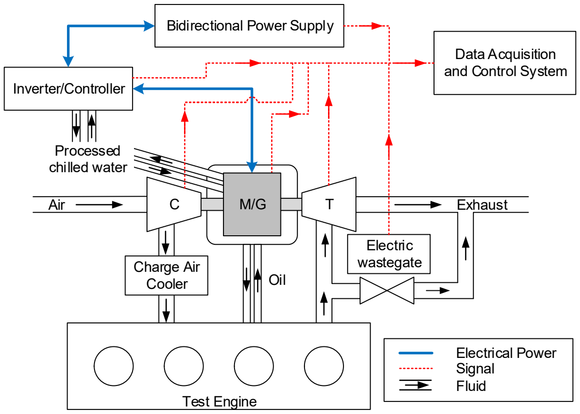

Figure 1: Schematic of EAT System.

An electric wastegate was adopted in this study, which was operated by an electric actuator. Conventional pneumatic actuators are operated by a valve spring using the intake manifold boost pressure to prevent the turbocharger and the engine from the damage associated with overspeed. However, electric actuators can be actively controlled regardless of the intake manifold pressure state and hence provide better controllability.

A bidirectional external power supply system was used to emulate the energy storage. It can transmit electrical power to and from the M/G system.

FADEC was used to control the engine. However, the FADEC was tuned for the legacy turbocharger, and not for the EAT investigated in this study. Therefore, the master data acquisition and control (DAC) system was separately set up to control the EAT. The master DAC adjusted either the spool speed or the electric wastegate position to achieve the MAP targets. The MAP targets were referred to the ones obtained from the legacy turbocharger originally attached to the engine. F-24 jet fuel was used for the engine, and the FADEC controlled fueling based on the fuel map implemented in the FADEC logic.

3. RESULTS AND DISCUSSION

3.1. EAT Characterization

The baseline performance of the EAT was characterized first. During this experiment, the M/G system of the EAT was deactivated, and only the wastegate was used to control the MAP. The power lever angle (PLA) ranged from 0% to 100% to cover from the idle condition to the maximum rated engine power.

During the EAT operation, the M/G was activated and used to control the EAT speed to achieve the MAP targets. The speed of the EAT was controlled by the M/G to create the target MAP for each engine condition. However, the wastegate was fully closed during this experiment, excluding any effects of the wastegate. In the same way as the baseline case, the PLA ranged from 0% to 100%. Figure 2 shows the normalized engine power with the PLA. The two results show almost identical results.

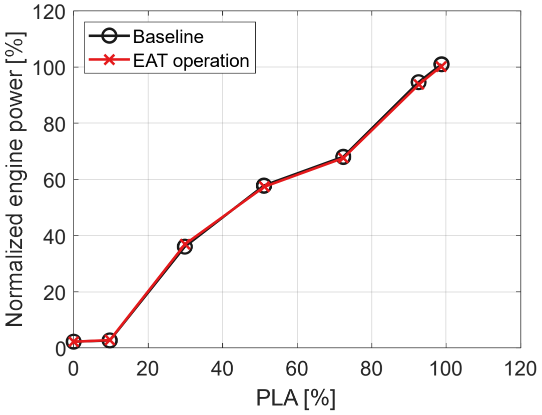

Figure 2: Normalized engine power vs. PLA.

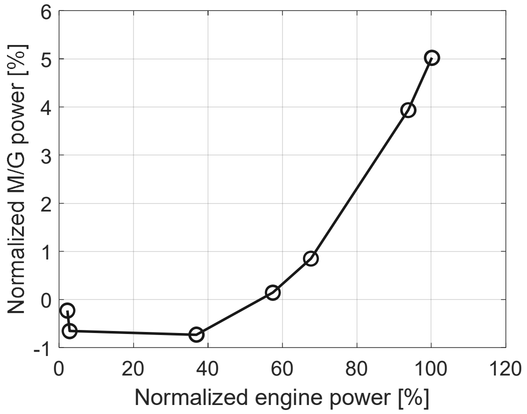

Figure 3: Normalized M/G power with normalized engine power.

The normalized M/G power with the normalized engine power is presented in Fig. 3. The M/G power and engine power was normalized by the maximum rated engine power. For low engine loads (less than 50% PLA), the M/G spun the turbocharger to meet the MAP targets (negative sign, motoring regime). For high loads, the M/G generated electrical power using some exhaust waste energy (positive sign, generating regime). It is noteworthy that this surplus energy was directed to ambient for the baseline through wastegate actuation. The EAT generated surplus electrical energy approximately 5% at the maximum rated engine power.

Figure 4 shows the normalized brake specific fuel consumption (BSFC) with the normalized engine power. BSFC is a measure of fuel efficiency. It is ratio of the fuel consumption rate ($\dot{m}_f$) to the engine crankshaft power (P_c) as presented in Eq. (1). BSFC was normalized by the value at the maximum rated engine power from the baseline.

$$BSFC = \frac{\dot{m}_f}{P_c} \qquad (1)$$

While the M/G was in a motoring regime, the BSFC decreased, which means the fuel efficiency improved. However, the BSFC increased during electrical power generation. The BSFC is the least at cruise conditions.

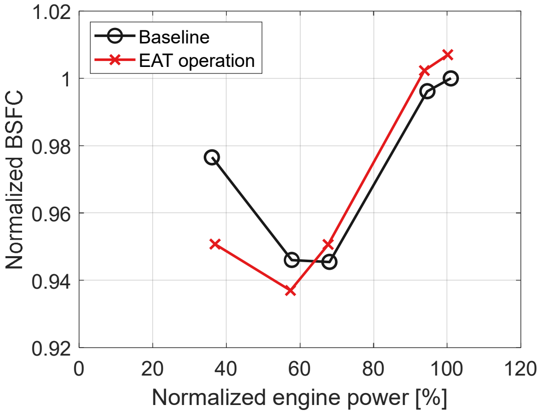

Figure 4: Normalized BSFC with normalized engine power.

The system efficiency (η) for the EAT can be calculated using the following equations. It should be noted that the system efficiency depends on the EAT operating regime.

$$\text{EAT motoring regime, } \eta = \frac{P_C}{\dot{m}_f \cdot LHV - P_{M/G}} \qquad (2)$$

$$\text{EAT generating regime, } \eta = \frac{P_C + P_{M/G}}{\dot{m}_f \cdot LHV} \qquad (3)$$

where $P_{M/G}$ and LHV represent the M/G power and the lower heating value of fuel. As mentioned, $P_{M/G}$ is negative in a motoring regime and positive in a generating regime. Figure 5 shows the system efficiency, which increased for all engine loads by virtue of the EAT recovering otherwise lost energy from the exhaust.

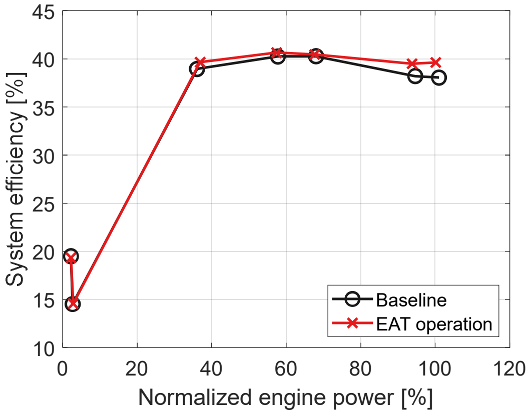

Figure 5: System efficiency with normalized engine power.

3.2. Engine Power Extension

An engine power extension experiment was performed to investigate the capability of the EAT to enable additional engine power. Keeping the engine operating condition at 100% PLA, additional fuel was carefully added through fine adjustment of the FADEC commanded value. The MAP was manually augmented by increasing the EAT speed to maintain an equivalence ratio at 100% PLA using the original FADEC fuel map. The electric wastegate was fully closed during this experiment. All the operating limits were carefully monitored to avoid potential damage to the engine.

From this experiment, it was found that the maximum extended engine power was approximately 106% of the maximum rated engine power. The scope of the experiment was limited by the maximum acceptable cylinder peak pressure.

Figure 6 shows the electrical power generated by the EAT. Although the EAT was required to operate at a higher speed to provide the required MAP, the EAT still generated electrical power. The maximum M/G power (5.6% of the rated engine output power) was obtained at 104.7% of the maximum rated engine power.

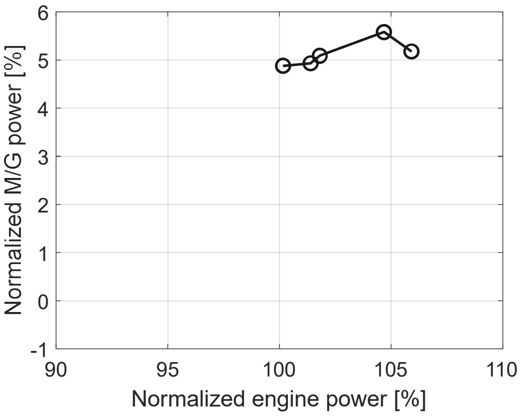

Figure 6: Normalized M/G power during power extension

Fig. 7 and 8 show the normalized BSFC and system efficiency, respectively. Both results remained almost constant during the engine power extension experiment. This shows that the power extension via EAT does not negate the efficiency.

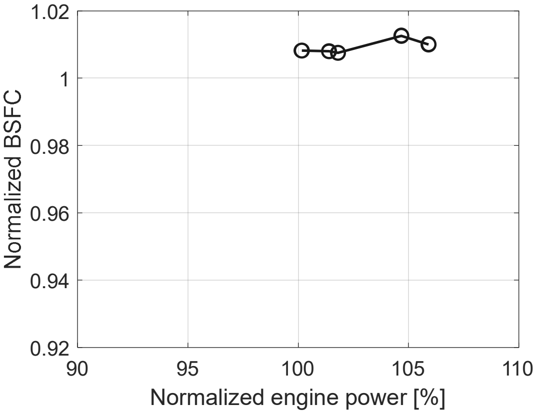

Figure 7: Normalized BSFC during power extension

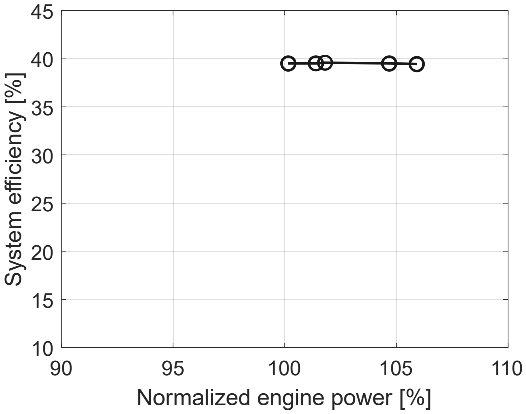

Figure 8: System efficiency during power extension

4. CONCLUSIONS

The objective of this study is to investigate the capability of an EAT implemented to a 2-liter diesel engine as a mild hybridization technology to address the ever-increasing power demand.

From EAT operation experiment, where EAT is used to actively regulate the MAP target for each condition, it was shown that the EAT generated surplus electrical energy approximately 5% at the maximum rated engine power and improved the system efficiency for all engine loads.

From power extension experiment, the EAT was able to extend the engine power by 6% of the maximum rated engine power. The M/G still generated surplus electrical power with the maximum of 5.6%. The BSFC and system efficiency remained constant during this experiment.

5. REFERENCES

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