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EXHAUST GAS ENERGY RECOVERY via ELECTRIC TURBOCOMPounding

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ABSTRACT

This paper presents the development of a high performance Low Pressure Turbine for turbocompounding applications in downsized gasoline engines. The LPT was designed to fill the existing technology gap where no commercially available turbines can operate effectively at low pressure ratios (1.05 - 1.3), in order to drive a small electric generator with continuous power output of 1.0 kW. The newly designed LPT was tested in a gas test stand and its impact on Brake Specific Fuel Consumption was assessed with engine testing carried out on a 1.0L EcoBoost gasoline engine.

1 INTRODUCTION

Transport sector accounts for more than 25% of the energy related CO₂ emissions worldwide. Taylor et al. [1] proposed four strategies that can be adopted in decarbonizing internal combustion engines (ICE). The strategies include: (i) enforcing strict emissions legislation and control, (ii) using sustainable fuels, (iii) reducing fuel consumption and (iv) using enhanced energy saving concepts. Currently, many legislators have started to implement stringent emission regulations by introducing vehicle taxation schemes and green zone areas in order to control the carbon emission levels in urban areas. Despite providing an immediate benefit in terms of air quality, such restrictive solutions need to be supported with a long-term plan to improve powertrain systems and therefore reduce carbon emissions. Hybrid and full electric vehicles represent a viable solution in the transportation sector; however a full switch-over from ICEs will take time. Thus, investment into exhaust energy recovery could be a sensible short to medium term solution.

Current techniques to recover exhaust gas energy in the automotive sector can be divided into, Organic Rankine Cycle [2-3], thermoelectric generation [4-5] and turbocompounding [6-7]. This paper presents the development of a novel Low Pressure Turbine (LPT) for engine exhaust energy recovery via electric turbocompounding.

2 Energy Recovery for Highly Downsized Boosted Engine

The energy in the exhaust after being expanded in the turbocharger can be further recovered by adding a downstream power turbine connected to an electric generator (electric turbocompounding). However, the presence of an additional turbine in the engine exhaust, acts as a restrictor which imposes additional back-pressure1. Higher exhaust back-pressure corresponds to higher fuel consumption for an engine delivering the same brake power. Hence

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1 Engine exhaust back-pressure is defined as the exhaust gas pressure that is produced by the engine to overcome the hydraulic resistance of the exhaust system in order to discharge the gases into the atmosphere.
the challenge in the development of turbocompounding solutions is that of minimizing the impact of back-pressure, and thus improving Brake Specific Fuel Consumption (BSFC)\(^2\).

The study and development of an electric turbocompounding was carried out by using a Ford 1.0L EcoBoost gasoline engine as a reference platform [8]. As part of the HyBoost project\(^1\), a low pressure turbine (part of an electric turbocompounding) was designed and tested on an engine. The design requirements for the low pressure turbine were those of delivering continuous power output of 1.0 kW at constant rotational speed of 50000 rpm. This is particularly challenging since the available exhaust gas pressure ratio after the main turbocharger is quite low (PR ≈ 1.05 - 1.3) thus forcing the LPT to operate at very low pressure ratios. Based on 1-D engine simulation analysis, the design pressure ratio was finally set at 1.1 (PR ≈ 1.1), with a target efficiency greater than 70%.

3 Low Pressure Turbine design

A prototype for the LPT was designed and tested at the Imperial College London cold-flow test facility. The turbine wheel was made of Aluminium Al-6082 with 1.6μm surface finish whereas the turbine volute was made of polycarbonate material. The performance of the LPT was tested for a set of five different constant speed lines spanning from 80% to 120% of the design speed. The outcomes of the experimental results are reported in Figs. 1 (a) and (b). From Fig. 1(a) it can be seen that the optimum operating conditions for the LPT occur in a much lower pressure ratio, compared to a conventional turbine. For a pressure ratio of PR ≈ 1.11, the LPT turbine efficiency is \(\eta_t\) of 75.8%. Contrarily, conventional power turbines would be operating at less than 40% efficiency.

![Fig. 1. Comparison of (a) total-to-static efficiency, \(\eta_{ts}\) and (b) Mass Flow Parameter, MFP between LPT and Conventional Turbine](image)

4 ON ENGINE TESTING

4.1 Engine Test Facility and Data Acquisition System

The LPT was installed on a Ford 1.0L EcoBoost gasoline engine and tested at Ricardo plc, Shoreham Technical Centre. The engine test facility is equipped with an eddy current dynamometer type Dynas. Steady state engine test was carried out with and without the turbocompounding unit.

\(^2\) BSFC = rate of fuel consumption (\(=\) FFR) divided by the power produce.

\(^1\) HyBoost project: refer to the Acknowledgements section
4.2 Results and Discussion

The 1.0L EcoBoost gasoline engine was tested at steady-state operation for engine speeds going from 1000 rpm to 4000 rpm at full load and part load conditions. The power generated by the LPT is proportional to the exhaust gas flow rate. The impact of the LPT installation on the engine is analysed by comparing the amount of recovered energy by the LPT to the baseline engine brake power. By definition, the engine brake power, $W_{br}$, given in Equation (1), is the product of the brake torque, $\tau$ and engine speed, $n$.

$$W_{br} = 2\pi n \times \tau$$ (1)

In order to assess the impact of the LPT, the engine total brake power, $W_{br,T,LPT}$ was calculated as the sum of the engine brake power, $W_{br,LPT}$ and the LPT power, $W_{LPT}$ (thus assuming that 100% of the LPT recovered energy was returned into the engine):

$$W_{br,T,LPT} = W_{br,LPT} + W_{LPT}$$ (2)

This was compared with the engine baseline brake power ($W_{br, baseline}$) by means of the BSFC. Two values for the BSFC were therefore calculated for the two configurations:
\[ BSFC_{T, LPT} = \frac{FFR}{W_{br,LPT}} \]  
(3)

\[ BSFC_{baseline} = \frac{FFR}{W_{br,baseline}} \]  
(4)

In order to better assess the LPT turbine power output with respect to its impact on engine operating conditions, a parameter called Load Ratio, \( LR \) is introduced. This is given in Equation (5) and it is defined as the ratio between the brake torque at part load, \( \tau_{PL} \) and the brake torque at Full Load, \( \tau_{FL} \).

\[ LR = \frac{\tau_{PL}}{\tau_{FL}} \]  
(5)

Figures 2 (a) to (d) show the effect of the LPT on the engine BSFC. The figures compare the performance of the two engine configurations (with and without LPT) at full load and part load conditions. As a general trend, it can be seen that the BSFC decreases as the engine load ratio increases. BSFC then reaches a minimum value and then increases at higher engine load ratio. It can be noticed that at lower engine load, where the amount of the exhaust gases is low, a smaller amount of energy is recovered, thus the low \( \Delta\%\)BSFC. However, as soon as the engine load increases, the reduction in the BSFC is more apparent. The maximum reduction in BSFC of 2.6 % was found at full load engine speed for 2500 rpm. At higher load ratios, although exhaust gases are at higher pressure and temperature, the LPT Wastegate is more open in order to counteract the increase in the back-pressure and therefore the reduction in BSFC is less significant.

5 ACKNOWLEDGMENTS

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6 CONCLUSION

The paper describes the design, development and on engine testing of a Low Pressure Turbine (LPT) for turbocompounding applications. The LPT was designed for a very low pressure ratio region in order to reduce the impact of back-pressure on engine performance. The LPT steady state turbine testing was conducted at the Imperial College test facility. The testing was conducted at five different speeds (80% to 120% of the design speed). Test results showed that a maximum total-to-static efficiency, \( \eta_{t} \), of 75.8% at Pressure Ratio, PR \( \approx 1.11 \) could be achieved.

Engine testing with the LPT were carried out on a Ford 1.0L EcoBoost gasoline engine. The engine was tested for a range of speeds spanning from 1000 rpm to 4000 rpm. Test results showed that a maximum BSFC reduction of 2.6 % could be achieved at an engine speed of 2500 rpm.

REFERENCES


