One Dimensional Simulation Study of Active Control Turbocharger (ACT)

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Abstract This paper presents the comparative study between Variable Geometry Turbocharger (VGT) and a new type of turbocharging technique called Active Control Turbocharger (ACT). One dimensional simulation package was used to model a 13L diesel engine, and simulation was run for both VGT and ACT operating modes. The study was carried out for the engine speed from 800RPM to 2000 RPM, and for the fuel-to-air (F/A) ratio from 0.017 to 0.057. The simulation results showed that ACT improved the performance of engine greatly at low engine speed zone, with the greatest improvement in brake power up to 50.6%. Meanwhile, the fuel efficiency was also found to reduce by maximum of 5.6 g/kW-h for ACT engine as compared to VGT engine at low engine speed zone.

Introduction

The future trends of IC engine development are universally toward down-sizing, higher power density, produce less CO_2 and consume less fuel. Among many technologies revolutionizing IC engine downsizing development, turbocharging is considered as a significant enabler to meet the ever increasing future demands [1-2]. The current state of the art in turbocharging is the Variable Geometry Turbocharger (VGT). VGT has overcome many of the conventional turbocharging problems such as turbolag and engine matching. However, VGT is controlled based on engine load and speed, which does not completely address the pulsating nature of the exhaust pulse. An advanced turbocharging technique called Active Control Turbocharger (ACT) was proposed in Imperial College London to overcome the shortcoming of the VGT. The ACT is a turbocharger system with system and method of operation, which regulates the turbine inlet area throughout each engine exhaust gas period, thereby actively adapting to the characteristics of the high frequency, highly dynamic flow. This so far untapped energy source lends itself to exploitation [3]. This paper discusses the development of the 13L turbocharged diesel engine model using one dimensional simulation package, and demonstrates the superiority of ACT over the VGT.

Turbocharged Engine Model Construction

A commercial one dimensional simulation package was chosen to perform the modelling and simulation work. A commercial 13L, inline six cylinders, 4 strokes diesel engine equipped with VGT, for which the performance maps are available, was chosen for this study. The basic engine geometrical data are depicted in Table 1.

Table 1: Engine geometrical data

Engine parameters	
Bore [mm]	125
Stroke [mm]	140
Compression Ratio	16.5:1
Valves/Cylinder	4
Speed Range [RPM]	800-2000

The engine has four valves per cylinder, two at the intake side and the other two at the exhaust side. The first three cylinders constitute a group and the last three cylinders constitute another group. In other word, there are two entries to the turbine. Meanwhile, firing order 1-5-3-6-2-4 was chosen for this study. A user defined function (UDF) was used to define the rack position in both VGT and ACT modes. For VGT operation, the turbine rack was set as constant for the given engine speed and load. ACT operation, however, the turbine rack was set to fluctuate (Eqn. 2) at each exhaust gas period. The turbine maps used in this study were tested in a cold flow rig at the Imperial College London and consist of five different rack positions, as depicted in Table 2:

Table 2: Relationship between vane angle and rack position

Vane Angle [°]	Rack Position	% Inlet Open Area
40	1.00	100
50	0.71	71
60	0.55	55
65	0.37	37
70	0.26	26

VGT Simulation and Validation

The turbine rack position was changed during different engine speed and load to make sure that engine can operate at its optimum level. The rack positions that produced maximum brake power and torque were found to increase as engine speeds and loads stepped up. This is because at higher engine speeds and loads, inlet pressure to the turbine is increased, and thus requires higher rack position in order not to block the flow of exhaust gas and creates undesirable backpressure to the engine. The simulation results were compared with engine manufacturer's data at F/A=0.057. As shown in Figure 1, the simulation results matched well with the data provided by the manufacturer for both brake power and torque at F/A=0.057.

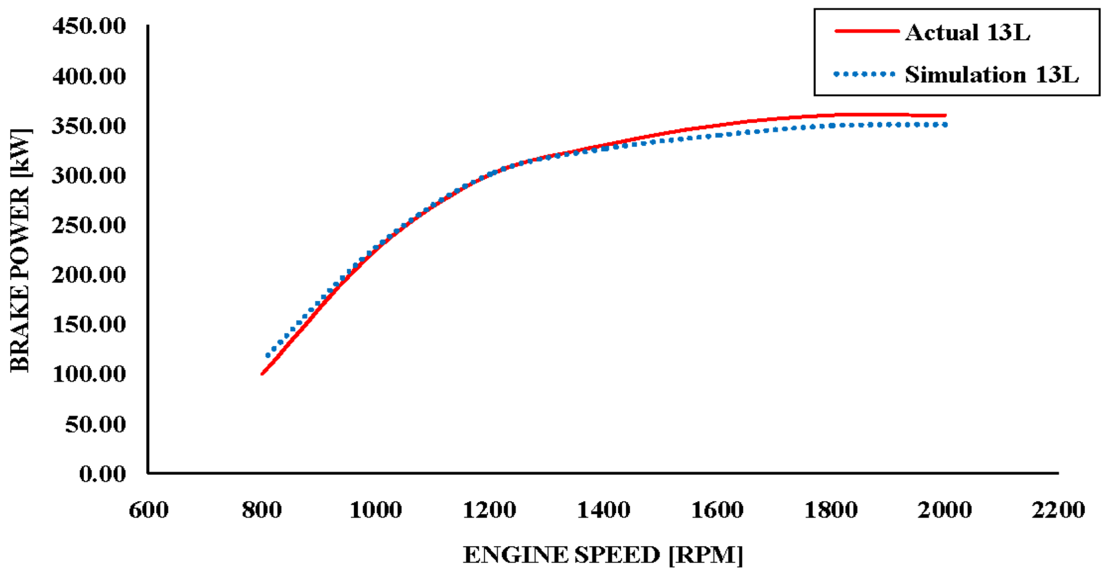

Figure 1: Brake power comparison between actual and simulated VGT engine

ACT Simulation

The important parameters in ACT operation are: (1) Waveform, (2) Frequency, (3) Amplitude, (4) Null Point, and (5) Phase, as given in Eqn. 1. Just before the ACT can be implemented, optimum inlet area under VGT operation has to be determined first. Once the optimum inlet area has been found, other ACT parameters have to be optimized in order to improve the ACT equipped engine. The instantaneous position of the turbine rack is depicted as following:

$$\theta_{ACT} = \theta_{ACT,min} + a\left[1 - \left(\frac{\sin(\omega t)}{\sin(\omega t)_{\min}}\right)\right] \tag{1}$$

Where, $$a = \theta_{ACT,max} - \theta_{ACT,min} = \theta_{VGT} - \theta_{ACT,min} \tag{2}$$

On the other hand, the frequency of the exhaust pulse emitted into turbine is given as:

$$f = NGC/30n \tag{3}$$

Where, f and ω are exhaust frequency, N is engine speed, G is number of Group connected to turbine, G is number of cylinder per group, C is number of cylinders per group, n is number of stroke, θ is the rack position, and t is time.

ACT-VGT Comparison

The performance of the IC engine is dependent to the amount of fuel available for the combustion [4]. In software environment, one possible way of simulating the variation in engine load is by changing the F/A ratio. For a diesel engine, the F/A ratios typically lie between 0.014 and 0.056. Based on this, five different ratio values between 0.017 and 0.057 were chosen to simulate a possible range of engine loads change [3]. Figure 2 depicts the brake power comparison between ACT engine and VGT engine. Brake power for ACT engine was found significantly greater than VGT engine for 1200RPM and below, regardless of the loads. Maximum increment in brake power in this region was found up to 50.6%. However, the performance of ACT engine declined as the engine speed stepped up. ACT improvement was only significant up to 1200 RPM, for the higher engine speed, ACT was essentially identical with VGT.

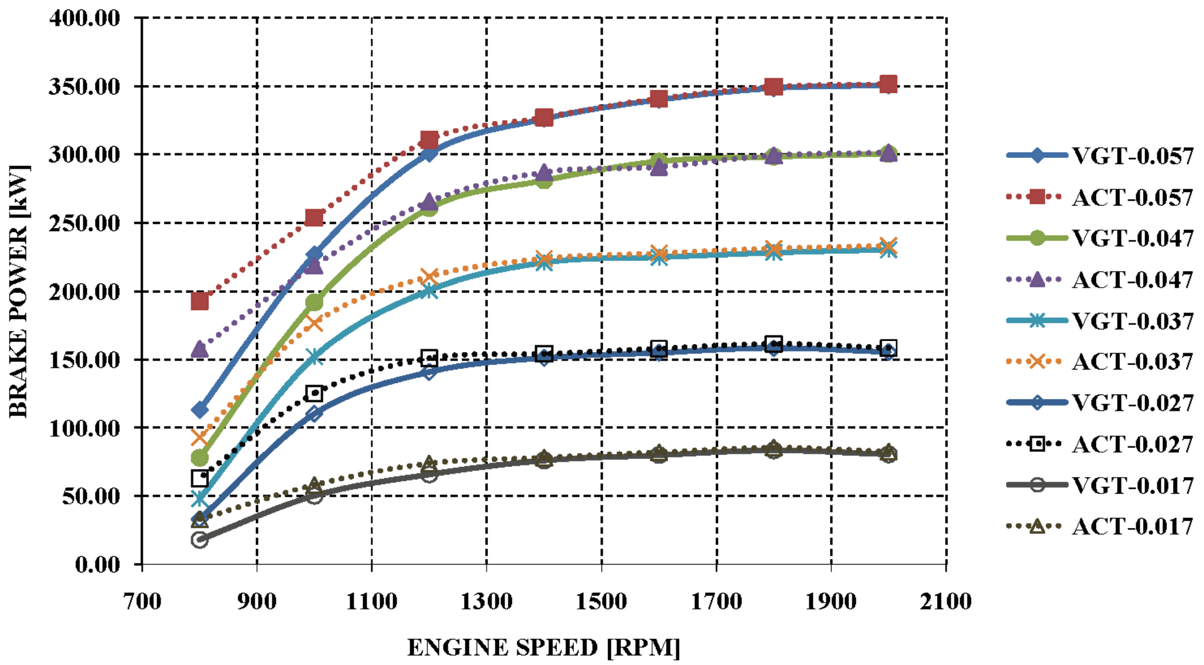

Figure 2: Comparison of brake power between ACT and VGT

The same trend applies for the brake torque, as brake torque was obtained by dividing the brake power with the respective engine speed. Figure 3 depicts that ACT does not perform at higher engine speed zone due to the increase of exhaust flow frequency. This is because increasing the exhaust flow frequency would shift the peak pressure away and thus reduces the energy levels available for the ACT system to harvest, regardless of the ACT phasing [5].

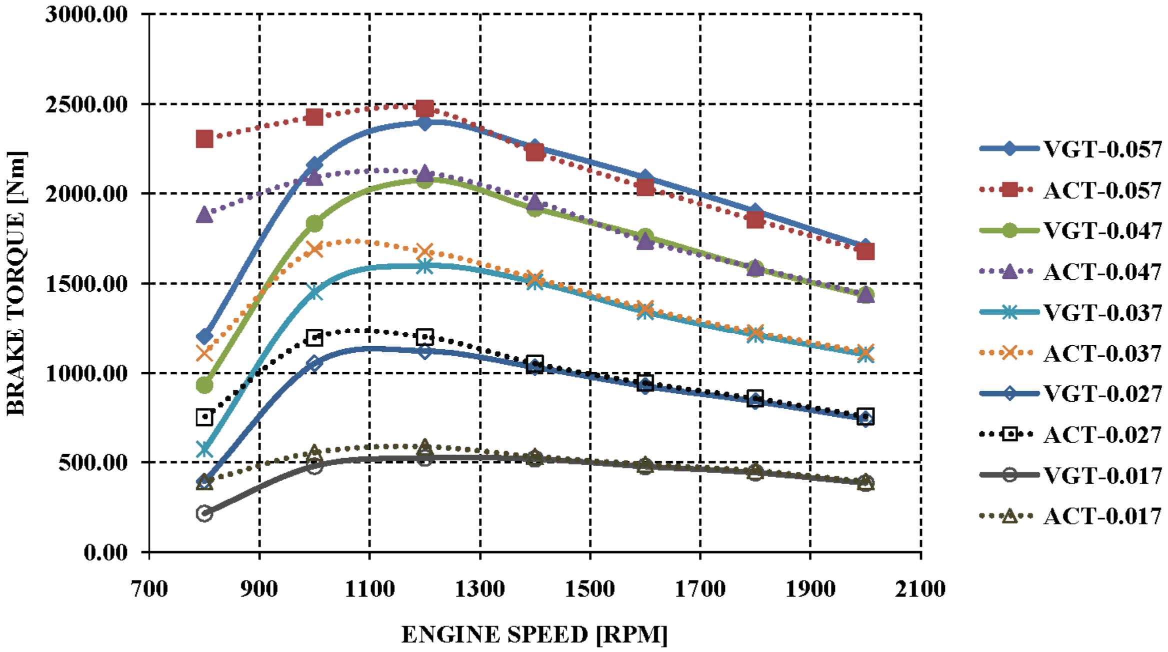

Figure 3: Comparison of brake torque between ACT and VGT

Brake Specific Fuel Consumption (BSFC) is the measure of fuel efficiency of the engine. By observing Figure 4, the BSFC for VGT and ACT are very close to each other at all speed range. BSFC, on the other hand, is defined as the ratio of fuel flow rate to the brake power of the engine.

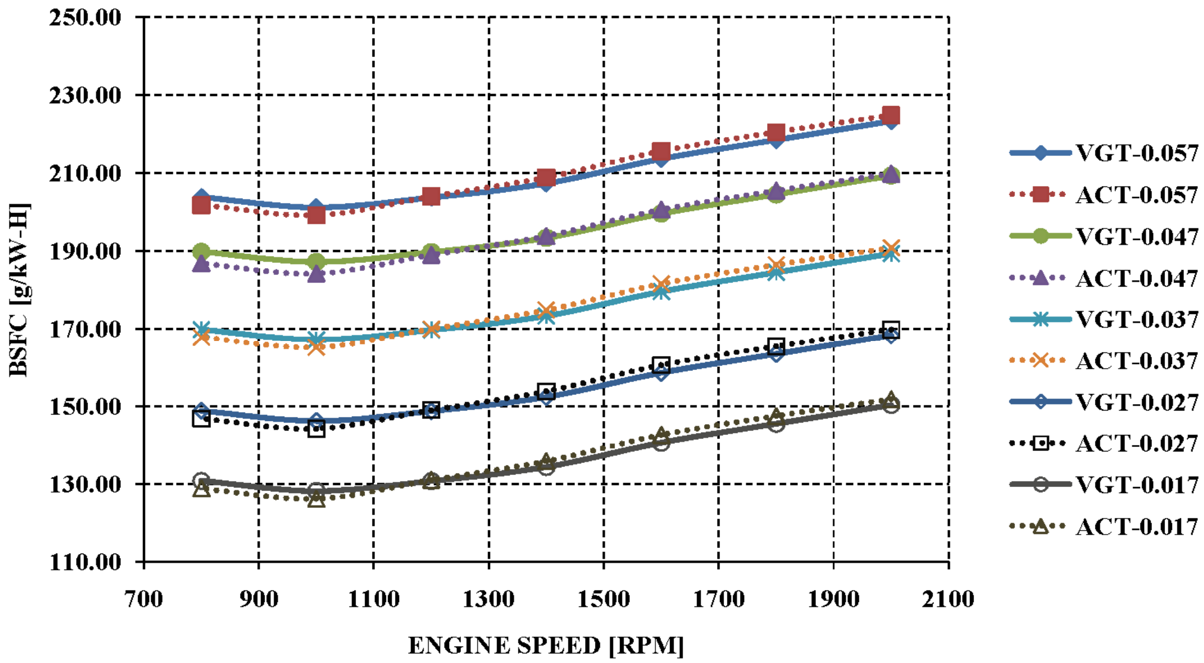

Figure 4: Comparison of BSFC between ACT and VGT

At low engine speed, say 1200RPM and below, ACT boosted up the compressor to pump more air into the combustion chamber, thus equivalent amount of fuel was injected to maintain the F/A ratio as constant. This causes the fuel consumption to be slightly higher in ACT operation than VGT operation, but at the same time engine delivers more power also, thus results in lower BSFC. At engine speed 1400RPM and above, due to the decline in ACT engine performance, thus results in slightly higher BSFC than VGT.

Conclusion

ACT was found capable of boosting the engine performance at 1200RPM and below for a 13L engine. At higher engine speed, due to the increase in flow frequency and inlet pressure waveform, currently used ACT strategy may need to be revised, and the other ACT actuating strategy may have to be proposed to enable the ACT to operate at full engine operating range.

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