20th International Conference
ENGINEERING MECHANICS 2014
Svratka, Czech Republic, 12 – 15 May 2014

SIMULATION AND IMPLEMENTATION OF TURBOCHARGING A 600CC ENGINE FOR FORMULA SAE

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Abstract: *The aim of this work was to analyze turbocharging for a Kawasaki 600cc motorcycle engine using Ricardo WAVE® and the implementation of the turbocharger based on the findings of the engine simulations. The simulations showed that for the purposes of a FSAE® car, the Kawasaki 600cc engine should be equipped with the Pulse System Turbocharging (PST) rather than Constant Pressure Turbocharging (CPT). The turbocharger simulated and used was a Honeywell GT15V variable geometry unit. The optimum compression ratio found for the PST setup was 7. Implementation on the Kawasaki engine was done by placing a decompression plate between the cylinder block and crankcase. Experiments were also conducted on alternative cylinder head gasket designs. The engine was tested on a waterbrake dynamometer and using a programmable ECU. The turbocharger vane mechanism showed to highly effect the engine response and turbocharger spool up time. A cam sensor was integrated into the engine to run the electronic engine control in fully sequential mode. A charge air cooler was implemented to provide consistent air temperature even in the boosted operation during dynamometer testing.*

Keywords: Engine-downsizing, Turbocharging, FSAE., Pulse system turbocharging.

1. Introduction

Engine downsizing assisted by turbocharging has become an important aspect in engine technology. Engines not originally turbocharged must be modified before implementing a turbocharged setup. One such modification is the reduction of the compression ratio. The lowering of compression ratio for the engine leads to changes in the gasketing setup. Attard (2007) at the University of Melbourne preferred to go to a gasket-less setup providing the benefits of reduced crevice volumes and reusability without need for replacement gasket. However the gasket-less design did result in teething problems. At the University of Malta the used Kawaski 600cc Ninja engine provides a split at the engine block to crank case and therefore a decompression plate was placed there with the benefit of still using OEM head gasket. A PST setup was preferred versus CPT to utilize the kinetic energy in the exhaust pulses, reduce exhaust manifold weight, and require compact runners which allow a low centre of gravity installation of the relatively heavy turbocharger. The ignition timing, valve timing and other parameters are not the same for CPT and PST. Attard describes how when the turbocharging setup was changed from CPT to PST, engine torque reduced by as much as 20% with severe knock problems at previously determined Minimum spark timing for Best Torque (MBT). Boost levels had also to be reduced on the fixed geometry GT12 turbocharger used by Attard. A GT15V variable geometry turbocharged was chosen to be used at the University of Malta. A simulation study using Ricardo Wave® was conducted by Grech (2007) who determined that PST was the preferable setup for the GT15V on the Kawasaki 600cc engine.

2. Constant Pressure Versus Pulse System Turbochraging

The two turbocharging methodolgies sited by Watson and Janota are the Constant Pressure Turbocharging CPT and the Pulse System Turbocharging PST.

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In CPT, the exhaust ports from all cylinders are connected to a single exhaust manifold whose volume is large enough to dampen down the unsteady flow. As Watson and Janota (1984) describe, when the exhaust valve opens, the gas expands down to the constant pressure in the manifold without doing useful work. However the only energy lost is that due to heat transfer.

PST uses narrow pipes between the exhaust valves and the turbocharger's turbine. In this case a pressure build-up will occur during the exhaust blow-down period since flow of gases entering the manifold through the valve exceeds that of gases escaping through the turbine. Similar to CPT, just as the valve opens the pressure difference across the exhaust valve is above critical and hence flow through the valve will be sonic. Stagnation enthalpy remains constant and hence the flow from the valve is accompanied by an entropy increase. The gas then expands through the turbine to atmospheric pressure doing useful work. With pulse operation, a much larger portion of the exhaust energy can be made available to the turbine by considerably reducing throttling losses across the exhaust valve. It also causes a rapid fall in manifold pressure towards the end of the exhaust process improving scavenging and reducing piston pump work.

CPT causes steady flow to reach the turbine, losses from unsteady flow in the turbine are absent and this setup was preferred by Attard (2007) for use on his Wattard engine developed at Melbourne University.. However since it takes time for the pressure to rise in the large exhaust volume, the turbocharger response to an increase in throttle is slow *i.e.* it is not ideal for rapid changes.

3. Turbocharging Simulation in WAVE®

WAVE uses compressor and turbine components to model turbochargers. Each component is represented by a performance map produced by the TCMAP pre- and post-processor. Turbocharger models may be linked with engine models to fully simulate turbocharged engines. The turbine and compressor may also be operated in isolation as part of a simple system, *e.g.*, ambient-duct-compressor-duct-ambient. This is done to test the component alone.

The simulation relies on the data contained in steady-state maps typically obtained on a steady-state flow rig by the turbocharger manufacturer (it is of course a fact that the flow through a turbine and possibly the compressor is usually non-steady). Thus results from a PST simulation may have some level of inaccuracy.

The WAVE knock model is based on Douaud and Eyzat's induction correlation and is applicable to both the WAVE and IRIS cylinders. The Knock Model is applicable only to SI engines with two-zone combustion. The induction time (ignition delay) in seconds is calculated at every time step. In general, this induction time continually decreases as combustion progresses and the unburned zone temperature rises. The end-gas auto-ignites (knocks) if the induction time is less than the flame arrival time. When knock occurs, a spontaneous mass burning rate due to knock is determined and fed back to the cylinder, leading to rapid rise in cylinder pressure and temperature.

Turbocharging simulation was a development from the simulation study of a naturally aspirated restricted Kawasaki 600cc by Cauchi (2006). For each step the simulation took about 25 hours to complete. Such long computational times were required since WAVE was simulating the turbocharger and occurrence of knock, apart from the engine itself. Also, 220 simulation cycles were necessary for the simulation results to converge. Normal simulation of naturally aspirated engine would usually require 50 cycles.

3.1. Results for the Constant Pressure Turbocharging

Simulations of the CPT system showed that a boost of 1.7 bar was not achievable. On the other hand, instability was also noticeable at a boost pressure of 1.2 bar and below, especially at high engine speeds at which point the exhaust pressure was probably too high and the VGT stator vanes could not open enough to maintain a low boost. Hence the range of boost that was investigated was set from 1.2 to 1.5 bar. The model was then run at a boost pressure of 1.3 bar for different heat transfer coefficients (k) of the intercooling stage. The reduction in temperature affects the magnitude of the knock event. However the results showed that the intercooling stage did not effectively reduce knock levels, but slightly shifts the curve to lower engine speeds. The torque on the intercooled engine was higher as a result of the charge being denser. The intercooling stage was shown to be advantageous since for the same level of knock, the torque and b.h.p. were increased. The final set of simulations was to find the compression ratio that eliminated knock. The compression ratio was varied from 11 to 8 and the resulting engine performance is shown in Fig. 1.

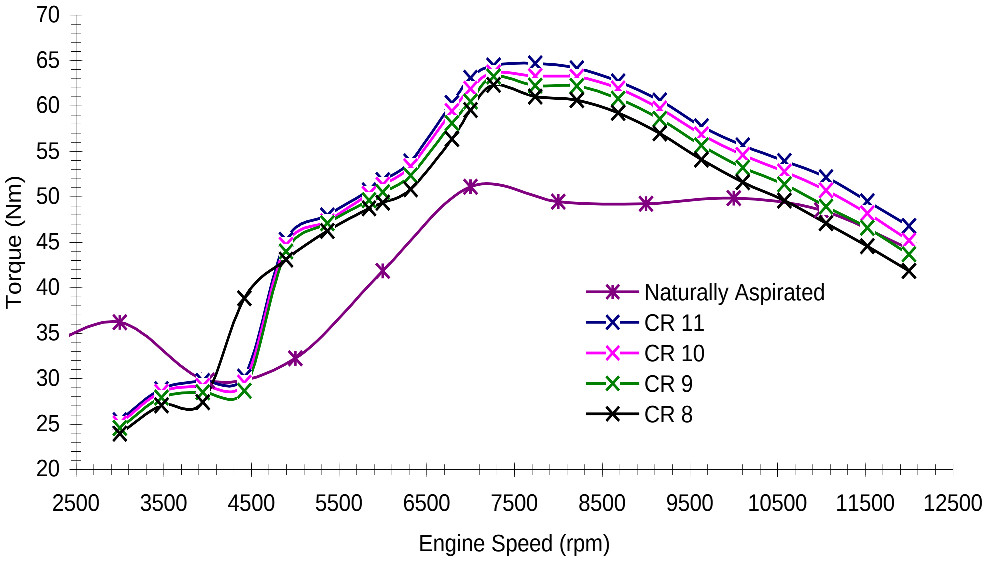

Fig. 1: CPT Torque curves for various compression ratios simulated.

3.2. Results for Pulse System Turbocharging

As in the CPT simulation, the PST setup was run under different boost pressures to check the range of boost achievable. The simulations showed that in a PST type setup, the boost pressures achieved are higher than for CPT confirming the statement by Attard (2007) that converting from CPT to PST caused problems in the engine including increased knock and worst torque characteristics. The simulations showed that stable boost pressures from 1.5 bar to 1.9 bar are possible. A boost of 1.4 bar could not be maintained throughout the entire engine speed while a pressure of 2 bar was very unstable. High boost pressures gave high peak power but over a narrow engine speed range apart from inducing high levels of knock. It was therefore determined that high boost pressures in this case provided no particular advantage and that low boost pressures will induce less knock, improve torque and power over a wider speed range while peak power is not much lower than for high levels of boost. With this reasoning, a boost pressure of 1.5 bar was selected for the PST setup. The last stage was that of determining the compression ratio to eliminate knock. Reducing the compression ratio obviously lowered the engine’s performance but still give more power than the naturally aspirated version as shown in Fig. 2. A compression ratio of 7 was enough to totally eliminate knock throughout the entire engine speed range.

4. Experimental Setup

4.1. Decompression plate manufacture

The calculation of the required decompression plate thickness resulted in a value of 3.22 mm thicker than the stock gasket. The stock compression ratio was 11.8 while the target was 7. The OEM gasket found between the cylinder block and the crankshaft/transmission assembly had a thickness of 0.3 mm which implied that the total new thickness required was 3.52 mm. However, due to lack of availability from local suppliers and in order to facilitate machining, it was decided to machine the decompression plate from a 3mm thick aluminum sheet. This brought the compression ratio up to around 7.5, which was still within the knock prevention limits as determined by Grech (2007).

Due to excessive oil leaks from the compressor to the intake, a mechanical seal was integrated into the compressor side. For this reason a purposely designed compressor plate was manufactured to accept an off-the-shelf mechanical seal. This worked excellently and boost levels were still reached as before. A charge air cooler was also implemented to stabilize air temperatures downstream of the compressor. This is in contrast to Attard where he states that intercooling was found not to be necessary. Sequential operation of the engine electronic control was achieved by implementing a cam sensor onto one of the camshafts.

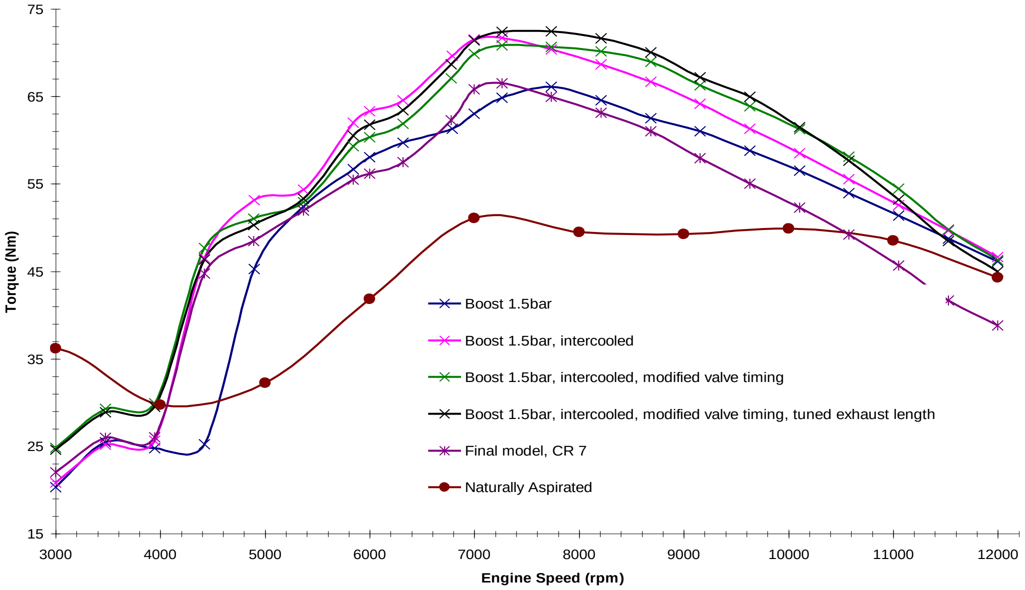

Fig. 2: Comparison of torque curves from various PST turbocharging stages.

4.2. Engine testing

The engine was started first using TPS as the load parameter and later changed to MAP. This was carried out since the TPS based map of the naturally aspirated engine was still valid for engine starting conditions and pre-boost operation

To safeguard the engine and reduce testing time, only sweep tests were carried out. The main aim of these tests was to indicate that the turbocharger actually produced boost and that the opening and closing of the vane system worked and produced a difference in turbocharger response time.

After proper engine warm up, the throttle was opened gradually and the variation in engine speed, MAP, air to fuel ratio and inlet air temperature were measured by a data acquisition system for both the closed vanes and open vanes situation. A maximum MAP value of around 170 kPa was obtained at 7200 rpm, while a rapid increase in MAP value above 5000 rpm occurred. The high boost pressures reached led to the decision to implement a external wastegate on the test stand so that boost levels other than the maximum can be stabilized in order to be able to experimentally determined proper fuel quantity and MBT timing. The testing of the external wastegate system together with the control system is currently being tested. Knock monitoring will be a next major goal in this development work. Changing of valve timing by design and production of our own camshafts is also another milestone to look forward to.

5. Conclusions

This study showed that a PST setup is more favourable for a Formula SAE vehicle. The one dimensional engine simulation software was used to find an optimal compression ratio, exhaust runner length and valve timing. The valve timing was not eventually modified but the compression ratio and exhaust runner lengths were implemented on the turbocharged engine. Experimental sweep tests on an engine dynamometer showed that the boost pressure reached 170 kPa with turbine vanes closed without any engine knock.

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