Utilization of Turbocharger Speed Data to Increase Engine Power and Improve Air Path Control Strategy and Diagnostics

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Abstract

Turbocharging is significantly changing design and control strategies for Diesel and gasoline engines. This paper will review new advances in the turbocharger speed measurement. Until recently, the highly accurate and fast turbocharger speed data, based on the physical speed sensor signal, has been mainly used to safely decrease conservative safety margins for turbocharger speed and surge limits. In addition to significantly increasing power and low end torque, new generation sensor technology is providing new opportunities to utilize turbocharger speed data. New, state-of-the-art active eddy current based speed sensor technologies, including a configurable high temperature Application Specific Integrated Circuit (ASIC), and the extremely fast delivery of accurate turbocharger speed data, will not only benefit engine and turbocharger performance but also improve control, allow for advanced diagnostics and enable the possibility to virtualize other powertrain sensors (e.g. mass air flow and exhaust gas temperature sensors). The resulting optimized engine efficiency will equate with lower emissions, fuel savings and increased reliability.

1. Introduction

The invention of the turbocharger, a forced induction boosting device driven by engine exhaust gas, is over a hundred years old (1). Over the last 10 years the turbocharger has become a key enabler for the downsizing of engines and exhaust gas emissions, while maintaining the performance of a larger naturally-aspirated engine (2). In addition to providing advanced performance benefits, turbocharging helps to increase fuel efficiency by up to 40% in Diesel engines and up to 20% in gasoline engines, whilst also decreasing exhaust gas emission levels, thereby addressing key macro-economic and environmental issues (3).

In a turbocharged Diesel engine a shorter ignition delay period is obtained, due to higher air density and higher temperatures at the end of the compression stroke. As a result of a shorter ignition delay period, the fraction of fuel burned during the premixed combustion phase is decreased thereby resulting in lower Nitrogen Oxide (NOx) and hydrocarbon emissions. A high excess of air also results in lower soot particle emissions (19). With turbocharging, the injection timing can be retarded to further lower NOx emissions without compromising fuel efficiency and power.

Strict emission regulations and the development of the Variable Geometry Turbocharger (VGT) led to the adoption of the turbocharger speed signal measurement in the truck industry 15 years ago. This signal provides important data to the Engine Control Unit (ECU), both in terms of the number of rotations of the turbocharger and in terms of usefulness for controlling overspeed, traditionally via a reactive correction loop based on look-up table estimation. It has also supported Original Equipment Manufacturers (OEM) in meeting global emission regulations through better turbocharger control and achieving a higher power-to-weight ratio gain for the powertrain. VGT technology was primarily developed to improve low speed torque and transient response, but it also provides emission reduction under low load operating regimes as well a better optimization of air flow over the whole engine operating range.

The number of engine airflow path sensors within a single vehicle is rapidly increasing, and commonly ranges from pressure and temperature sensors to turbocharger speed sensors, position sensors and flow rate sensors. There is also a current trend to adopt 'virtual' sensors based on numerical models, rather than physical sensors. The aim being to reduce overall vehicle costs, while maintaining or increasing reliability and functionality. Which sensors are virtualized and which remain physical will often be a question of cost, performance and redundancy of information.

This paper will review and summarize over twenty versatile, new and unique opportunities for benefitting from turbocharger speed data for a broad range of automotive and commercial / industrial transportation applications including passenger cars, trucks, off-highway and motorsport vehicles. It will also highlight a control strategy overview, based on the comparison of various means to measure turbocharger speed.

2. The Automotive Turbocharging Market

During the next five years, over 200 million vehicles will be equipped with a turbocharged engine. The global market in terms of value for on-highway applications is estimated at USD 13.6 Billion in 2015 and is expected to show double-digit compound annual growth, reaching USD 22.1 Billion by 2020, the growth being largely driven by North America and China (4).

As stricter emission standards are being enforced worldwide, and fuel prices are aligning with global prices, many OEMs are focusing on the local production of turbocharged vehicles for China and other Asian markets such as India. By 2020, over 40% of all vehicles on sale in China and India will be turbocharged in order to improve power rating, emissions and fuel economy. This fast rate of adoption is mainly driven by the growth in boosting of gasoline vehicles (4). Given the increasing need to deliver both drive-ability and compliance to regulatory standards, the application of the turbocharger speed signal will provide a wide range of benefits and opportunities for automotive manufacturers.

3. The Turbocharger Compressor Map

Each turbocharger configuration has a maximum rated rotational speed provided by the turbocharger manufacturer. Transient driving conditions or certain ambient conditions may lead the turbocharger to overspeed. This is particularly the case if safety margins are insufficient. Overspeeding the turbocharger can quickly cause damage to the assembly and lead to catastrophic failure. Examples of dangerous operating conditions for a turbocharger are:

- High altitude operation
- High dynamic / transient operation
- Engine brake (turbocharger-assisted) operation

The setting of large double-digit safety margins in the ECU, while being a widely adopted and accepted approach, leads to turbocharger performance loss. The result is that the majority of engine control units do not utilize the full potential of the turbocharger as safety margins of 10% up to 20% are kept. These large safety margins can be overcome through accurate real time measurement of turbocharger speed or precise estimation thereof.

Turbocharger performance is governed by the compressor map (Figure 1) provided by the turbocharger manufacturer and it forms the basis for the turbocharger speed calculation. The map displays constant speed and efficiency as a function of compressor pressure ratio and compressor mass flow rate. Both values, the pressure before and after the compressor and the mass flow rate, are typically available in terms of direct measurements. Combining the information of mass flow and pressure ratio, the ECU can derive the approximate speed of the compressor wheel through interpolation. However, several variables may affect the accuracy of this derivation, these are:

1. Inaccuracy of input sensors (pressure and mass air flow)
2. Degradation of input sensors over life time
3. Delay of input sensor data
4. Part-to-part variation
5. Lab-based mapping
6. Altitude compensation
7. Interpolation by the ECU

Points 3 and 4 are a result of conflict between ideal condition mapping and the real world situation. For example, the inlet and outlet geometry of a compressor or turbine, have a significant impact on its efficiency. Another example is the linear constant gas flow approach on a gas stand compared to the dynamic pulsations from an engine exhaust. Therefore, per engine application, there are slight uncertainties in the exact speed reading. This in combination with unknown altitude conditions, input sensor inaccuracies and model inaccuracies, requires the setting of conservative safety margins (of double digit figures) with the corresponding loss in turbo and engine performance.

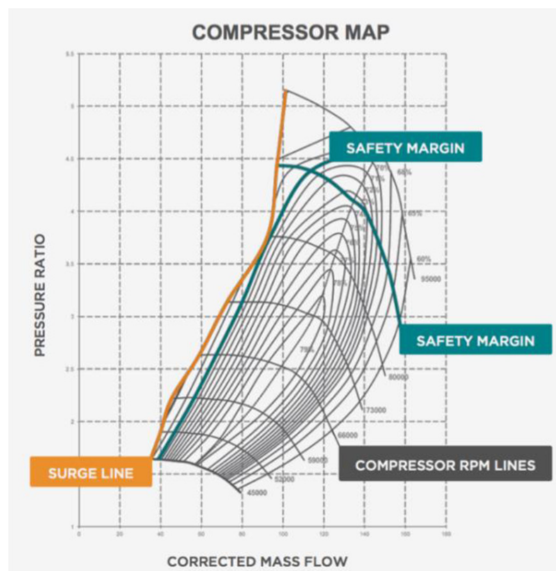

Figure 1. Compressor map

4. Turbocharger Speed Sensing Technologies

The available technologies for the measurement of the turbocharger speed are based on optical, Hall Effect, variable reluctance (VR) or eddy current (EC) principles. These technologies can be categorized into two groups: intrusive and non-intrusive. Given the harsh operating conditions of high temperatures above 160°C continuous and vibration levels of up to 50G, only some technologies are feasible for robust and low-cost, high-volume, serial-production applications.

Non-intrusive measurement technologies typically employ the use of a magnetized nut or an optical reflective surface on the compressor wheel assembly. Alternatives include vibrational analysis based on accelerometers or audio frequency analysis based on microphone inputs. The former two are more suitable for R&D laboratory applications than serial use on production vehicles, mainly because of the installation complexity and its sensing requirements. The latter two technologies are at early stages of development, and are an indirect measurement of speed and therefore more subject to disturbances and inaccuracies. Intrusive turbocharger speed measurements make use of a sensing element that is placed either in the compressor housing or the bearing housing (Figure 2).

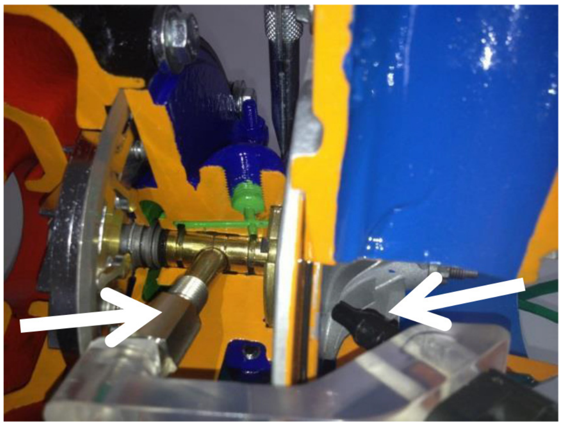

Figure 2. Cutaway turbocharger with shaft sensor (left) and blade pass sensor (right)

Whereas both principles utilize the same physical components, one distinguishes between variable reluctance and eddy current sensing depending on the properties of the target object.

Sensor mounting - through-hole or blind-hole

Concerns regarding intrusive "through-hole" turbocharger speed sensors and their potential negative impact on the air flow and compressor efficiency due to the creation of air flow disturbances have recently been raised. Results from a recent Computational Fluid Dynamics study by the authors show that the velocity fields resulting from five varying "through-hole" sensor positions in the compressor cover have little or no impact on the streamlines or velocity (Fig.3).

Therefore the effects of an intrusive turbocharger speed sensor (compared to a non-intrusive or "blind-hole" approach), may not be significantly different in terms of an impact on air flow or compressor efficiency. However a non-intrusive approach presents significant challenges for manufacturing a "blind-hole" sensor port which has a very thin, and intact, membrane of metal that separates the sensor tip from the compressor space. This presents a high risk in the manufacturing thereof and durability in application.

Variable Reluctance Principle - Shaft Rotation Detection

The detection of ferrous electromagnetic targets (i.e. the cartridge shaft of a turbocharger), uses the variable reluctance (VR) principle in which a permanent magnet inside a VR sensor creates a magnetic field which penetrates the shaft or other electromagnetic target structures. Typically a flat area milled onto the shaft creates variations in the magnetic field as the shaft rotates. These variations are transformed into a sinusoidal voltage signal by the sensor coil which is then sent to the ECU for processing and calculation of turbocharger speed. A broad range of VR sensors for heavy and light commercial vehicles has been commercially available for more than 15 years. Typical fabrications of VR sensors include either a stainless steel or an injection molded sensor head with variations in the wire harness (i.e. convolute, heat shield, clips, etc.).

Passive Eddy Current - Passing Blade Detection

For electrically conductive non-ferrous targets, (i.e. an aluminium or titanium compressor wheel), the eddy-current principle is utilized. The target induced eddy-current thus influences the magnetic field of the magnet. These effects are amplified and transformed into a digital square wave voltage signal which is sent to the ECU. Sensors based on this principle are termed Passive Eddy Current Sensors and have more recently been on the market for the last 10 years.

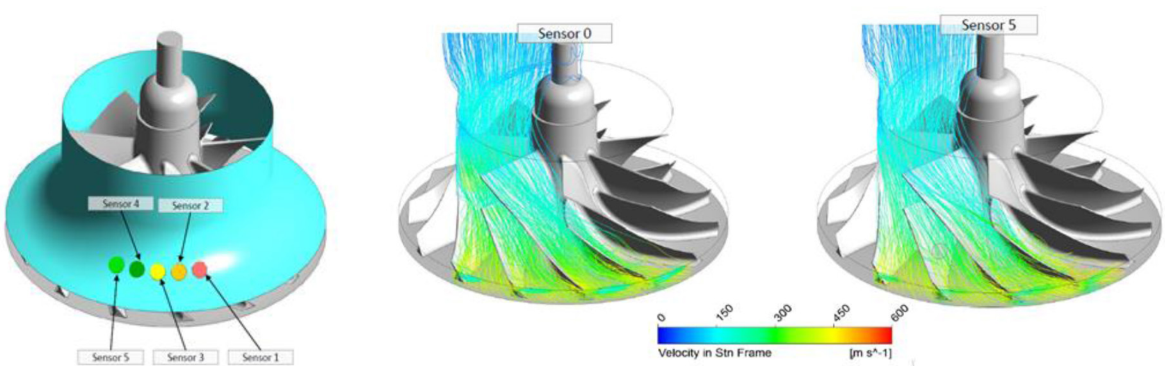

Figure 3. Velocity streamlines resulting from different "through hole" sensor positions in a compressor wheel

Active Eddy Current - Passing Blade Detection

Both VR and passive-EC sensors continue to provide functionality and reliability in a variety of automotive on- and off-road applications ranging from light and heavy commercial vehicles to passenger cars and motorsport. The next generation of compressor wheel blade counting sensors no longer makes use of a permanent magnet and changes in magnetic field, but rather relies on measuring a change in frequency of an oscillating circuit as the blades pass in front of the sensor tip. Using this approach the signal is no longer strongly dependent on target speed and target conductivity values. This new generation of sensors is termed Active Eddy Current Sensors (Figure 4 - An active eddy current turbocharger speed sensor).

Passive VR and Eddy Current (EC) sensors typically begin to detect speeds from 8’000 - 10,000 turbocharger rpms onwards, whereas an active EC sensor detects speeds from 1000 rpms onwards. Active ECs provide a wide range of practical benefits, ranging from a broader range turbocharger speed measurement, to added diagnostic capabilities on the sensor, turbocharger and engine level. The diagnostics are based on the interpretation of the turbocharger speed signal and its derivative. Active ECs may also make use of innovative coil geometries to overcome difficulties faced with passive ECs e.g. erroneous speed readings caused by blade and coil geometry dependencies.

Cost lowering technical advances

Innovative active EC speed sensor technology has enabled the production of a high temperature ASIC (operation at +200°C continuous / +220°C peak) which can be configured to specific customer needs.

The configuration model includes divider ratio, pulse width and error flagging for example for over-temperature. This unique feature, together with the integration of the ASIC into the sensor shaft, should enable a high volume mass production strategy, compared to a typical batch production approach for customized sensors, therefore making the next generation of turbocharger speed sensors a more cost-effective approach to meet the expectations of the automotive industry.

5. Virtualization of Turbocharger Speed Sensors

The basis for the virtual estimation of turbocharger speed is the relation between the TBS, the compressor mass flow and the pressure ratio. Interpolation generates maps that allow reading of the turbocharger speed n_{TC} as a function of the compressor pressure ratio π_C and the mass flow $\dot{m}_C$:

$$n_{TC} = f(\pi_C, \dot{m}_C)$$

(Eq. 1)

Recently published studies have assessed and proven the feasibility of a virtual turbocharger speed sensor to estimate turbo speed based on the compressor equation (Figure 5) and mathematical models and algorithms which utilize other physical sensor readings in the air path.

At high turbocharger speed operating conditions, the estimated accuracy of such models can reach +/- 5% (Figure 6) utilizing the following set of inputs: mass air flow, manifold pressure, intake air temperature, lambda and atmospheric pressure (5).

This physics-based, dynamic calculation model is a promising approach for safely replacing or enhancing the physical turbo speed sensor by a virtual sensor based on algorithms implemented within the ECU which only occupy a small data footprint. The virtual turbocharger speed sensor is expected to provide a cost-effective solution for estimation of turbo speeds during transient and altitude conditions, albeit with a likely trade-off on accuracy, performance and diagnostic or modelling use of speed data compared to physical sensors. This approach may be of interest for mass market, small turbocharger configurations i.e. where the cost of a physical turbospeed sensor may be considered to be excessive for the Bill of Material (BOM), and also where increased diagnostic coverage, or virtualization of other sensors (which are based on the physical measurement of turbocharger speed) is not required.

Figure 4. An active eddy current turbocharger speed sensor

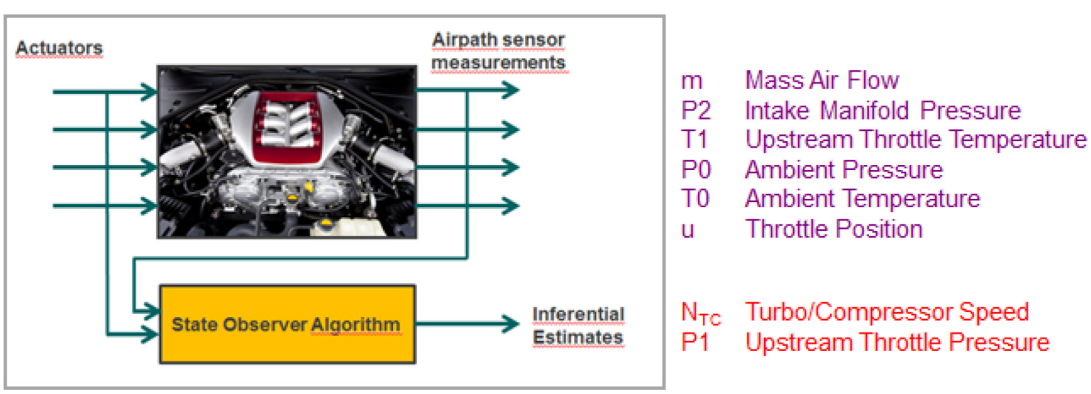

Figure 5. Airpath sensor array for virtual estimation of MAF

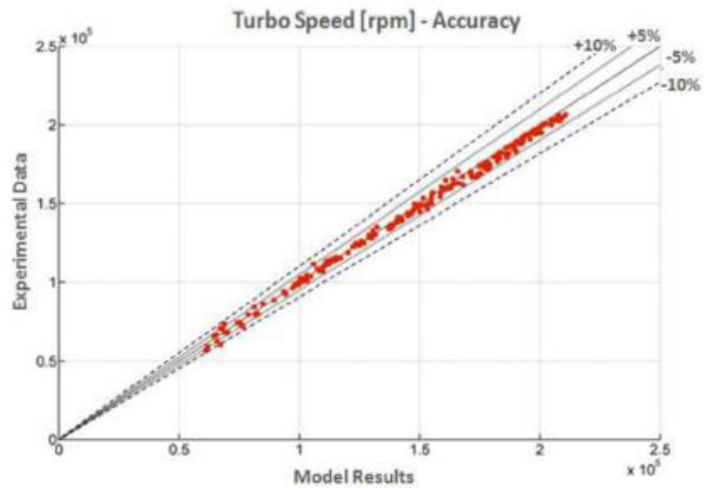

Figure 6. On engine turbospeed prediction accuracy with physics based virtualization

	LOOK UP TABLE BASED	PHYSICS BASED VIRTUAL SENSOR	VARIABLE RELUCTANCE SENSOR	PASSIVE EDDY CURRENT SENSOR	ACTIVE EDDY CURRENT SENSOR
TURBOCHARGER CONTROL					
1. Protect from catastrophic failure due overspeed	YES	YES	YES	YES	YES
2. Maximize power output by reducing safety margins		YES	YES	YES	YES
3. Maximize low end torque by reducing safety margins		YES	YES	YES	YES
4. Minimize turbo lag		YES	YES	YES	YES
5. Adapt to changing altitudes		YES	YES	YES	YES
6. Adapt to transient behaviour		YES	YES	YES	YES
7. Synchronize multii-turbo configuration			YES	YES	YES
8. Optimize transition points in multi-compressor systems			YES	YES	YES
9. Minimize harmful operation - avoid critical speed and resonance zones		YES	YES	YES	YES
MODELLED DATA					
10. Virtualize and eliminate Mass Air Flow sensor – or create reference data					YES
11. Virtualize and eliminate exhaust gas temperature sensor (T4)- or create reference data					YES
12. Calculate dynamic exhaust back pressure (P3)					YES
13. Virtualize and eliminate cam shaft index sensor					YES
DIAGNOSTICS					
14. Detect clogged air filters			YES	YES	YES
15. Data redundancy / reference data			YES	YES	YES
16. Improve compressor efficiency monitoring			YES	YES	YES
17. Improve EGR mass flow control and monitoring					YES
18. Optimize engine cold start					YES
19. Optimize engine ignition performance by injector drift compensation					YES
20. Improve air path leak detection			YES	YES	YES
21. Turbocharger condition monitoring through eigenfrequency, idle speed or decelaration analysis					YES

Figure 7. Turbo speed sensing benefits by measurement method

6. Turbocharger Speed Sensing Benefits

The proximity to the engine's cylinders implies short transit times of the gas flow. In order to optimize performance and minimize emissions, the engine control unit aims to achieve specific predetermined states in the engine's combustion chambers depending on the actual operating condition. Therefore, short response time and minimal delay of control variables in relation to the combustion processes have a positive effect on control quality. The turbine is typically located within a short distance of the cylinder outlet valves and therefore almost immediately experiences changes of the exhaust enthalpy. Such changes can be detected by the turbocharger speed sensor.

The full scope of opportunities appears when the turbocharger speed signal from an active EC is also used as an input for observer models for control logic and diagnostics (Figure 7). These models allow the calculation of state variables that can further be used as inputs for ECU functions. This concept is state-of-the-art and now applied in current engine ECUs (6). Expectations for powertrain sensors are tougher than ever before. They must be robust, accurate, fast, easy to install, non-degrading over life-time and should not require maintenance or calibration. They must provide multiple functionalities and benefits, not just one.

The application of the turbo sensor as a measured input offers additional possibilities such as the replacement of other sensors or the calculation of control and diagnostics with higher precision and reliability. Such diagnostic strategies will play an important role in strategies for the adoption of physical turbocharger speed sensors as compared to model-based virtual estimation of turbo speed, or basic look up table estimations for reactive correction of overspeed.

The following sections of this paper address a selection of the turbo speed sensing benefits in more detail.

6.1. Maximize Power and Low End Torque

A significant gain of power can be obtained through minimization of the operational safety margins of the compressor. By allowing the turbocharger to run closer to the surge line an increase in low-end torque can be obtained. By allowing the turbocharger to run closer to the maximum speed line an increase in peak power can be achieved. Having a precise knowledge of turbo speed therefore allows conservative safety margins to be reduced from double digit figures to single digits (figures in the value of around 2%).

A recent case study has shown that addition of a physical speed sensor to a turbocharger on a 2.0L Diesel engine can result in a gain of 6kW power through safe reduction of the margin to overspeed (7). It will also allow for fast adaption to changing conditions, and enhance the drivability of configurations with a "downsized" engine. In configurations of a "downsped" engine, which operates at a narrower and lower speed range, the engine relies on the turbocharger for an increased boost pressure and low end torque performance. To achieve this, the turbocharger needs to be driven close to the surge line of the compressor map. Addition of a turbospeed sensor will therefore provide added control and support running of the compressor near the surge line boundary.

Another condition in which fast, seamless adaptation of the turbocharger is required for maintenance of engine performance, is at altitude. As altitude increases, the air becomes thinner. Naturally aspirated engines lose power and performance, typically in the order of 3-4% for every 300 meters of altitude gain. At an altitude of 3'000 meters above sea level power losses of around 40% or more, can be expected.

Through the use of turbocharging, the effect of altitude power loss can be fully or partly compensated, depending on turbocharger design and the required maximum altitude level. Current control strategies keep a speed margin during the operation at sea level in order to ensure operation without power reduction until a certain altitude level. Above that, the engine power is reduced depending on ambient pressure measurement in order to protect the turbocharger from overspeeding. The usage of turbocharger speed information allows more elaborated control strategies that simplify the calibration process. Safety margins can be reduced as influences from ambient temperature, turbocharger ageing or production tolerances need not to be taken into account. This leads to an improved overall performance with increased reliability.

6.2. Synchronize Multi-Stage and Bi-Turbo Configuration

Multi-stage turbochargers can be used to overcome turbocharger lag. Typical configurations include a small turbocharger for low engine speeds and a larger turbocharger to accommodate the exhaust mass flow and high speeds. As the high pressure turbocharger reaches its rated speed limit, the ECU will have to adjust the turbocharger control means (i.e. waste gate or compressor bypass) to ensure that its air flow is reduced. This transition phase can represent a discontinuous event for engine operation. However the turbocharger speed signal can be used in the implementation of sophisticated control strategies to enable smooth transition phases and utilization of the full dynamic potential of the turbocharger and maximize power output of the engine.

For bi-turbo configurations, for example on a V-engine where each turbo is responsible for one of the cylinder banks on the engine, the turbocharger speed sensor can help optimize the balance of power by synchronizing the speed of each turbocharger. This also helps to overcome production tolerances and differences between engine banks which may otherwise lead to an uneven engine performance and wear.

6.3. Minimize Harmful Operation

Each turbocharger configuration has its own resonant frequencies which are determined by the manufacturer. Such resonance modes should be avoided during operation of the turbocharger. Accurate measurement of turbocharger speed will help to avoid those zones of operation occurring at critical speed(s) which result in resonance and vibration that can be harmful to the turbocharger, thereby increasing its life and condition.

Despite long experience and highly sophisticated design and dimensioning methods, failure of a turbocharger can still occur before the expected end of its useful lifetime. Common failure mechanisms are creep (due to high operating temperatures) as well as low and high cycle fatigue. They are caused by resonance vibration and lead to fatigue fractures in the turbine blades. Fatigue is one of the dominating failure modes for turbochargers of large Diesel engines (8). Resonant vibrations are rarely detected during operation but usually lead to catastrophic failure. Their occurrence during operation is highly dependent on the specific load cycle and hence cannot be predicted. Consequently statements about a possible lifetime until failure cannot be made. Therefore, other measures to ensure the reliability have to be considered.

A promising strategy based on the avoidance of operation at known resonant frequencies has been reported (9). Practically this means that the turbocharger speed needs to be actively increased or decreased once it begins to operate at a critical speed associated with a resonant frequency. It should also be remembered that the speed of the turbocharger (and resonance) is also influenced by its own actuators (e.g. VGT, waste gate, or compressor bypass) and other control elements such as the Exhaust Gas Recirculation (EGR) valve or the intake throttle. The main prerequisite for a control strategy based on this approach is a precise knowledge of the turbocharger speed, as provided by the turbocharger speed sensor.

6.4. Idle Speed Analysis

Turbocharger idle speed analysis can form a basis for diagnostic function. The simplest analysis is that of idle speed deviation, which can provide indications of friction changes due to lubrication, bearing wear, or even air path leakage. Upon engine ignition and "spool-up" of the turbocharger after cold start, it is important that the turbocharger quickly reaches it operating temperature and speed, in order to keep exhaust emissions low and in compliance with regulations. Further diagnostics on the condition of the air filter can be performed through a relative easy comparison of the estimated pressure ratio and measured pressure ratios over the compressor.

6.5. Air Mass Flow Calculation

The Mass Air Flow (MAF) sensor commonly used in today's Diesel powertrains, plays an important role in the meeting and controlling engine performance and emission requirements. It is an essential requirement for a large number of important control functions, for example smoke limitation, EGR control or urea injection for the SCR system. Common methods for the determination of the air mass flow involve a calculation with a cylinder-filling model based on the engine speed, and the measurement of the pressure and temperature in the intake manifold.

Alternatively a direct measurement of the air mass flow is commonly performed. Two types of sensors are widely used, namely the hot-film air mass meter and the Venturi tube with differential pressure measurement. Both methods imply a certain calibration effort to adapt them to specific applications as they are sensitive to the direction of the advancing air flow. From a practical perspective this means that installing the same platform engine into different vehicles will, in most cases, require a new calibration of the mass air flow (MAF) sensor.

Several challenges exist with the use of MAF sensors and are typically related to ageing, inaccuracy, impact on design, and reduction of air flow for instance. Limits in design freedom and air flow reduction lead to performance trade-offs. Accompanied with a sense element that wears over time, and an accuracy that degrades over time, MAF sensors are facing tough scrutiny by OEMs. The hot-film air mass meter is very sensitive to particles and humidity in the intake air as these components can cause deterioration of the sensor membrane and inaccurate measurement values (10, 11). Engines with an EGR typically use both methods, the filling model and direct measurement, in order to calculate the amount of recirculated exhaust gas.

The basis for the air mass flow calculation is the compressor map which is provided by the turbocharger manufacturer. It provides constant speed and efficiency data as a function of compressor mass flow and pressure ratio. Interpolation generates maps that allow reading the mass flow $\dot{m}_C$ as a function of turbocharger speed n_{TC} and the compressor pressure ratio π_C:

$$\dot{m}_C = f\ (\pi_C\ , n_{TC}\ )$$

(Eq. 2)

Since the compressor data provided generally does not cover all operating points of the engine, extrapolation techniques need to be applied to allow a reliable determination of the air flow e.g. at low speeds or small mass flows (12). It is also essential to tune the compressor map data with real time engine measurements as shown below (Figure 8).

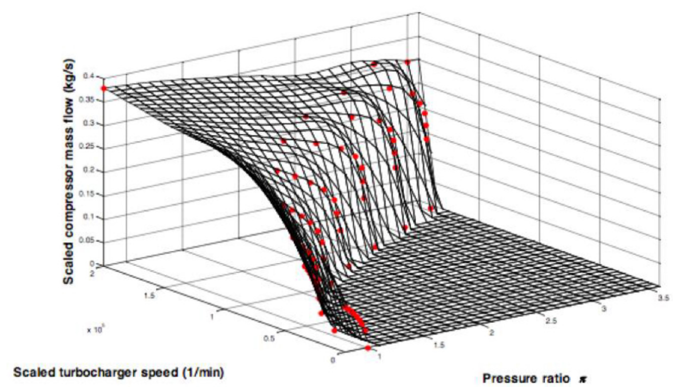

Figure 8. Extrapolated Compressor map showing small mass flow values

The map shows high gradients in the region of small mass flows which cause the calculation to be sensitive to measurement errors of the speed sensor. The precision of the mass flow value is therefore strongly dependent on the quality of the speed sensor signal and accuracy of the speed measurement. A closed loop approach based on the measured turbocharger speed has been claimed to improve the precision of the mass flow calculation (13, 14).

The mass flow equation shown above can be used to estimate the mass air flow from other sensor measurements within the engine airpath. The first required input parameter is the pressure ratio upstream and downstream of the compressor. Both these pressure values are typically readily available given the standard sensor set on a production vehicle. Addition of the real-time dynamic turbo speed signal not only provides accurate way of strengthening MAF-based engine control, but also provides an opportunity to replace the physical MAF sensor with a virtual one (Fig.9). A virtual MAF sensor approach may be more robust and reliable, being less susceptible to the dirt, particles and humidity that adversely affect physical MAF sensors.

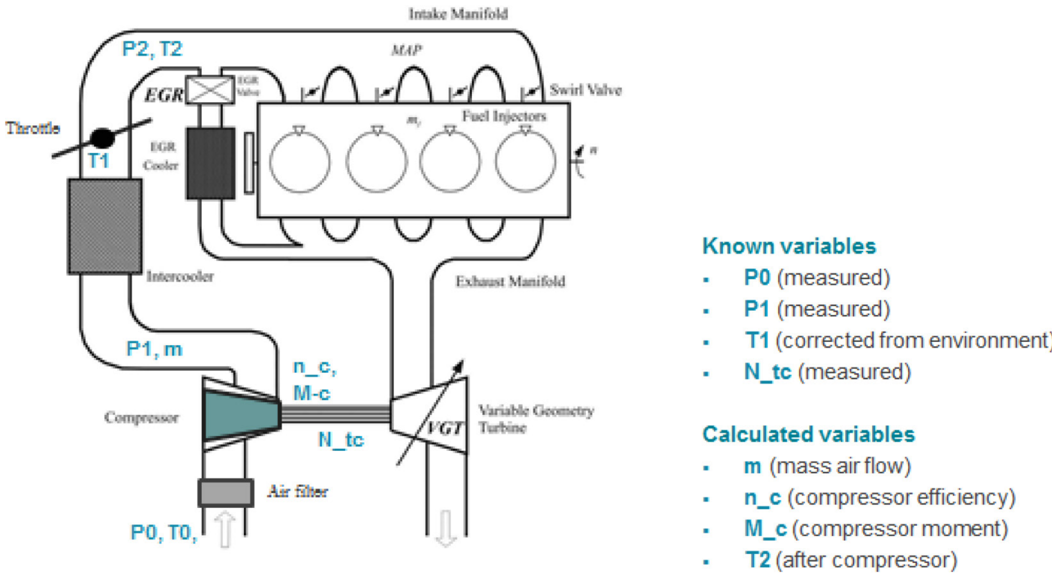

Figure 9. Airpath sensor inputs for virtual estimation of MAF

6.6. Exhaust Manifold Temperature Calculation

Exhaust temperatures are essential state variables for the exhaust after-treatment system control, as well as for EGR modelling and control, and can also be applied for component protection functions. Virtual estimation of exhaust temperatures based on algorithms fed by input from other sensors within the engine airpath (Fig. 10) can replace physical measurements or serve as redundant signals for diagnosis functions. Based on compressor angular speed ω_{TC}, efficiency η_C, mass flow $\dot{m}_C$, pressure ratio π_C and temperature T_1 as well as the specific gas characteristics upstream the compressor, the compressor torque M_C can be determined:

$$M_C = \frac{1}{\omega_{TC}} \dot{m}_C \frac{\kappa_1}{\kappa_1 - 1} R_1 T_1 \frac{1}{\eta_C} \left(\pi_C^{\frac{\kappa_1 - 1}{\kappa_1}} - 1 \right)$$

(Eq. 3)

In steady state the turbine must generate the compressor torque as well as the friction torque M_f of the turbocharger bearings. In transient state the change of angular speed $d\omega/dt$ can be calculated:

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{M_T - M_C - M_F}{\Theta_{TC}}$$

(Eq. 4)

The bearing friction torque M_{fb} can be modelled as a function of oil temperature and turbocharger speed. However it is already included in the turbine efficiency in many cases. Assuming this and with knowledge of the compressor torque, the turbocharger speed and the inertia of the rotor $\varnothing_{TC}$ the turbine torque M_T can be calculated.

The turbine efficiency η_T is a function of the running number u/c_0 (a non-dimensional parameter to characterize turbo machines), the scaled turbocharger speed $n_{TC_{scl}}$ and, if applicable, the wastegate or VGT position $DC_{VGT/WG}$:

$$\eta_T = f\left(\frac{u}{c_0}, n_{TC_{scl}}, DC_{VGT/WG}\right)$$

(Eq. 5)

The second turbine map allows the determination of the turbine pressure ratio π_T. It is a function of the turbine efficiency, the turbocharger speed and the waste gate or VGT position:

$$\pi_T = f\left(\eta_T, n_{TC_{scl}}, DC_{VGT/WG}\right)$$

(Eq. 6)

Exploiting this information the formula for the turbine torque can be rearranged to calculate the temperature in front of the turbine T_3. It can be noticed that the gas characteristics specified by the isentropic exponent κ_3 and the specific gas constant R_3 at this location are not known. In a numerical simulation these can be taken over from the previous calculation step causing only a negligible error.

$$T_3 = \omega_{TC} \frac{1}{M_T \dot{m}_T R_3 \eta_T} \frac{\kappa_3 - 1}{\kappa_3} \left(1 - \pi_T^{-\frac{\kappa_3 - 1}{\kappa_3}} \right)^{-1}$$

(Eq. 7)

With knowledge of the turbine inlet temperature and the turbine efficiency, the turbine outlet temperature T_4 can also be calculated:

$$T_4 = T_3 \left(1 - \eta_{tot,T} \left(1 - \pi_T^{-\frac{\kappa_3 - 1}{\kappa_3}} \right) \right)$$

(Eq. 8)

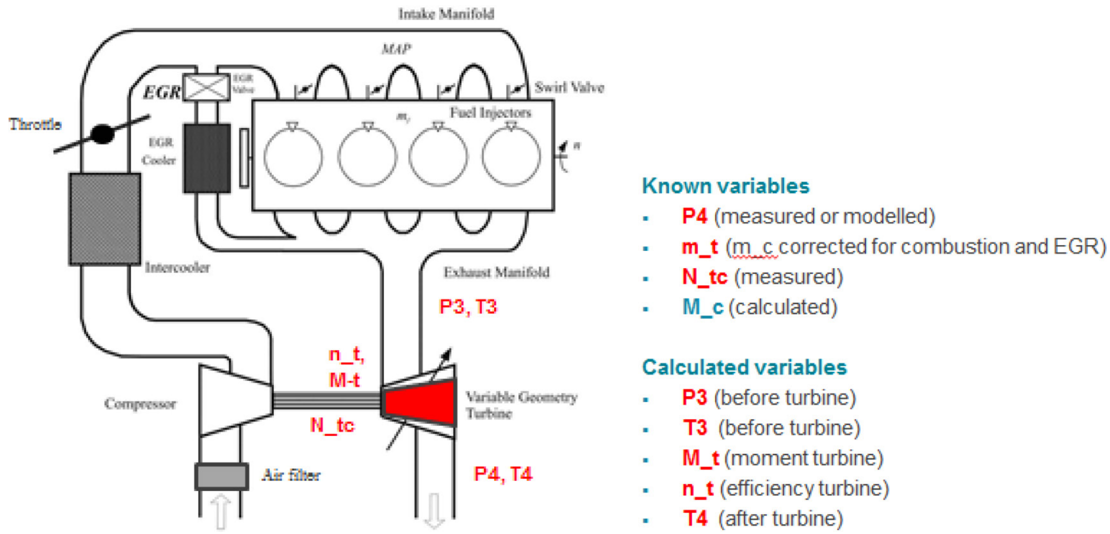

Figure 10. Airpath sensor inputs for virtual estimation of T_3 and T_4

The advantage of this virtual approach is that it provides a way of strengthening the T_4 approach (15). Virtualization of T_4 will provide real time information of exhaust temperature, thereby enabling a faster closed loop control on the combustion process.

6.7. High Pressure EGR Mass Flow

Exhaust Gas Recirculation (EGR) is one of the NOx emissions reduction technique used in gasoline and Diesel engines. The EGR system recirculates a portion of an engine's exhaust gas back to the engine cylinders. This dilutes the oxygen in the incoming air stream and provides gases inert to combustion to act as absorbents of combustion heat to reduce peak in-cylinder temperatures. In a gasoline engine, this inert exhaust displaces the amount of combustible matter in the cylinder and inhibit knock (16). In a Diesel engine, the exhaust gas replaces some of the excess oxygen in the pre-combustion mixture. Because NOx forms primarily when a mixture of nitrogen and oxygen is subjected to high temperature, the lower combustion chamber temperatures caused by EGR reduces the amount of NOx the combustion generates. Most modern engines now require EGR to meet emissions standards.

Precise measurement and control of the EGR mass flow is essential in order to achieve the required balance between noxious and soot emission and low fuel consumption levels. Several strategies have been developed for this purpose including the direct measurement of the mass flow with a hot film probe or a Venturi type sensor, or the comparison of the measured fresh air mass flow with cylinder mass flow calculated with a filling model. These methods are costly or large inaccurate due to imprecise and slow sensor signals.

Petrovic (17), has proposed a method for the measurement and control of EGR mass flow based on turbocharger speed measurement. The method is based on the fact that the enthalpy of the turbine decreases with increasing EGR mass flow. Given this relationship, the change in turbocharger speed can be used for the estimation of the mass flow rate in accordance with a turbocharger speed set point map. The difference between the actual measured speed and the value read from the map corresponding to the EGR mass flow can then be used as a control input.

6.8. Exhaust Gas Pressure Calculation

Turbocharger speed varies as a function of engine speed, with regular pulsations in the turbospeed signal and exhaust pressure being evident between two ignition strokes (Figure 11). A weaker exhaust pulse, which may for example be resulting from an improper combustion event, would therefore be reflected in an irregular turbo speed signal. This provides the basis of a diagnostic or prognostic approach for condition monitoring of the engine.

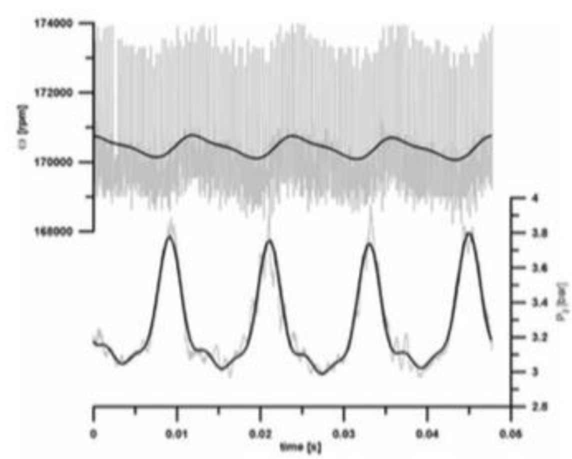

Figure 11. Exemplary turbo speed (top) and exhaust pressure (bottom) (18)

Knowing the temperature and mass flow conditions in the exhaust manifold allows for the calculation of the absolute mean exhaust back pressure P3 using the thermal state equation for ideal gases. However, the turbocharger is working constantly under changing conditions due to the cyclic operating principle of the combustion engine. This means that it is exposed due to strong variations in temperature and mass flow, and consequently back pressure.

Macián et al., (18) have presented a method to model the exhaust back pressure as a function of the turbocharger speed. They suggest a discrete-time moving average model where the output value is composed of the basis of a weighted sum of previous measurements of the input signal.

6.9. Turbocharger Condition Monitoring

It is also possible to determine the condition of the turbocharger bearings and lubrication in a transient turbocharger state. At any one moment, given that there is no compressor torque and no turbine torque as, i.e. the engine of the vehicle is switched off, the only remaining moment present, is the moment of friction. Therefore monitoring the deceleration rate of the turbocharger over time, can provide an indication of the moment of friction changes over time, Hence, using this approach an analysis of the condition and wear of the turbocharger cartridge can be made.

Alternative methods that allow an indication of turbocharger wear are idle speed analysis. A deviation to the turbocharger idle speed can be due to cold start cycles, air leakage and/or lubrication issues. Especially a cold start analysis can be of use in ensuring lower emissions and meeting regulations.

6.10. Injector Drift Compensation

Single injection events require precise dosing of very small amounts in order to achieve the noise and emission targets. The precision of an injection event is characterized by the production tolerances, ageing and fouling effects (also referred to as injector drift) of the individual injectors. Whereas the total injection quantity of a working cycle can be controlled and adjusted with a lambda-sensor, this is not feasible for a single injection event. Only a cylinder pressure signal could allow tracing back to single injection events and provide information about their individual characteristics. However, due to cost, cylinder pressure sensors have not been widely established in mass applications. The inability to resolve single injections implies the risk that injection events do not take place as it was determined during calibration but lead to significantly higher or lower injection amount. The result can be an increase in combustion noise which is noticeable by the driver or higher pollutant emissions which need to be compensated by the exhaust after-treatment system including all negative consequences.

Several methods have been developed to compensate injector drift (19). They include the usage of the crank signal, a cylinder pressure signal or the rail pressure signal. They all have disadvantages that are inherent to the concept such as limitation to certain operating conditions, large minimum detectable error or the requirement for additional sensors.

The turbocharger speed sensor can offer a beneficial option to detect and compensate injector drift effects. Due to the low inertia of the turbocharger rotor single cylinder discharge events can be seen in the turbocharger speed signal and can be related to a specific cylinder. This observation may be used as a practical basis for systematically tuning the injection amount of a single injector during engine idle (i.e. decrease the injection amount). In practice the operating point 'engine idle' is particularly appropriate because as shown by Macián (18):

- The expected total injection amount is known from the engine friction condition
- Longer periods of steady state operation are occurring e.g. at traffic lights
- Small injection amounts allow mistuning of single injection events without large influence on the engine behavior

The minimum duration required for injection of a fuel quantity which leads to combustion also gives information about the rate of wear. Based on this knowledge the decision can be taken if the injector will further be used with specific adaptions to the control signal or if the driver will need to bring the vehicle to a garage for servicing.

6.11. Combinations of Turbo Speed Measurement Benefits per Targeted Performance

The goals of advancing powertrain performance varies per OEM and model. While lowering emissions is one of the key goals of automotive industry, turbo speed data can in addition be focused on other performance related goals. Examples:

Improved Performance with minimizing safety margins

- Engine power
- Multi-compressor system control
- Low end torque

Strengthen Reliability with diagnostic features

- Turbo overspeed protection
- Airpath monitoring and diagnostics
- Avoid critical speed operation
- Turbocharger condition monitoring
- Data redundancy and reference data by modelling sensors

Lower Emissions with accurate and real-time data

- EGR mass flow control / monitoring
- Fuel injector drift detection and compensation
- Exhaust gas temperature determination
- Exhaust gas pressure determination

Increase Efficiency with accurate and real-time data

- Air mass flow determination
- Compressor efficiency monitoring

Lower Cost by modelling of sensors and increased power

- Elimination of sensors due to sensor modelling opportunities
- Increased performance with smaller engine / turbo platforms

7. Summary & Conclusions

The fast transient behavior of an automotive turbocharger has necessitated the setting of conservative safety margins for turbocharger maximum rated speed and surge limits. Installation of a physical speed sensor now helps to maximize turbocharger performance by allowing for a safe reduction of the overspeed margin on the compressor map. Most importantly, engine power and performance will benefit due to improved control and diagnostics over the air flow, which can now be regulated faster and more accurately, allowing optimal performance during changes in driving conditions and at high altitude. Increased engine efficiency will also equate with fuel savings and reduced emissions.

The turbocharger speed signal contains valuable information that can be utilized for monitoring turbocharger performance and also for diagnosis of problems within the air path. Active eddy current based physical sensors allows for sensor self-diagnosis, as well as diagnosis of turbocharger and engine diagnosis. Virtual turbocharger speed sensors, which are based on physics-based models, provide a constant estimation of speed data from algorithms in the ECU which receive sensor inputs for compressor mass flow and pressure (ratio). Different turbocharger speed measurement and estimation principles each have their own pros and cons and will each most likely serve different markets and applications.

The turbocharger speed signal can also be used for the virtual estimation of other key air path parameters, thereby strengthening their information based control algorithms and offers an interesting business case for the adoption of physical turbocharger speed sensors. More concretely, the MAF determination through the turbocharger speed sensor signal, means that one can overcome challenges faced through accuracy degradation of emission critical sensors such as MAF.

Through the implementation of smart control strategies and new approaches to air flow and emissions control, the turbocharger speed sensor can be the basis for realizing a broad range of benefits and opportunities in coming years. With an increasing number of OEMs adopting the use of a turbocharger speed sensor, and with the turbocharger manufacturers offering the installation of such a sensor in their product portfolio, it is likely that ECU manufacturers will soon follow with new control algorithms that can utilise the full potential of such a sensor.8.

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