CFD Analysis of a Radial Turbine during Load Step Operation of an Automotive Turbocharger

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Long Abstract

Introduction

The unsteady operation of radial turbines for automotive turbochargers under pulsating inflow conditions has been in the focus of research for many years. In [1] a good summary of experimental and numerical work is presented. In case of numerical investigations, usually a single engine operating point is analyzed. The change in turbine speed due to the pulsations is usually neglected, because the change is very small.
Another important unsteady operation of radial turbines are the so called load step tests which are used by the car manufacturers to evaluate the ability of the turbocharger to provide boost pressure as fast as possible. In these tests, the engine speed is kept constant. The test starts at steady state conditions at a defined engine torque, e.g. 20% of the maximum torque. Then the load is increased until 90% of the maximum toque is reached. The time from 20% to 90% torque is measured and used to judge the transient performance of the turbocharger and engine. The load step tests are usually run at engine test stands. So, the availability of engine and turbocharger hardware is already required.
A way of predicting the transient performance of the engine earlier in the development process is the application of 1D engine simulation software. However in this case a good model of the turbine map is necessary. Usually the turbine maps cannot be measured completely on a gas stand due to the limited operating range of the compressor which is used as brake for the turbine. Therefore the measured maps have to be extrapolated, providing possibly an additional source for errors. Also, the emptying and filling behavior of the turbine volute is not considered in the 1D simulation of a load step.
All these approaches have in common that no detailed analysis of the flow inside of the turbine is available, so that no detailed information about why a certain turbine performs better than another during a load step is available.
In the development of turbomachinery, the application of Computational Fluid Dynamics (CFD) is the state of the art for many years to investigate the flow inside of the machines. But so far, the investigation of a radial turbine during a load step including pulsating inflow conditions by means of CFD was not presented in the literature. In contrast to the unsteady operation at pulsating inflow conditions, the change in turbine speed cannot be neglected in the load step case. In this paper a method for simulating a load step and taking into account the change in turbine speed by means of CFD is presented.

1. Methods

For the CFD analysis, a model of the complete turbine including volute, wheel and wheel cavities was created (Figure 1, right).
In order to include the change in speed in the CFD simulation, the power balance between turbine and compressor has to be solved. So, an additional model of the compressor is necessary.

Also, the behavior of the engine during the load step has to be described, since the change in turbine mass flow, turbine inlet temperature and exhaust gas pulsation have to be used as boundary conditions for the CFD model. Engine and compressor are included in the CFD analysis with a User-Fortran model (Figure 1) which has been used in a similar form already in [2].

In the User-Fortran model, the compressor map is used for calculating the operating point of the compressor as the intersection of compressor speed line and engine characteristic. The load step is initiated by simulating the opening of the throttle. When the throttle opens, the swallowing capacity of the engine is increased. The intersection of compressor speed line and engine characteristic changes and the compressor is able to deliver more air to the engine. With an engine model, the conditions of the exhaust gas at the turbine inlet are calculated according to the engine inlet conditions provided by the compressor. The exhaust gas mass flow is a function of the air to fuel ratio and the compressor mass flow. For calculating the exhaust gas temperature, a thermodynamic cycle calculation for spark-ignition engines is performed. Additionally, the exhaust gas mass flow is not only increasing with load step time, but also modeled as pulsating flow as in real gasoline engines. The characteristic of a 4-cylinder engine has been chosen for the test case described in this paper.

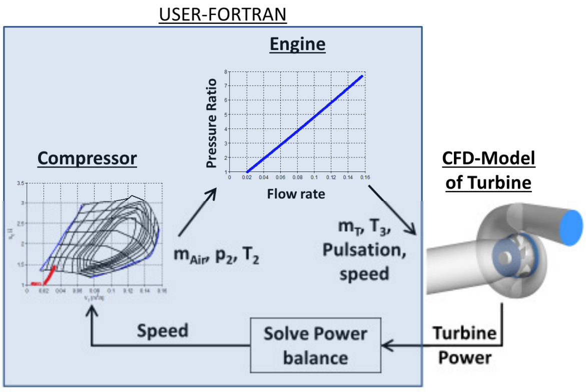

Figure 1: Schematic of Load Step Simulation

So far these calculations are performed by the User-Fortran model. From there, the turbine mass flow, turbine inlet temperature and actual speed are passed as boundary conditions to the CFD model of the turbine. After each time step, the turbine power is evaluated and passed back to the User-Fortran model. The mechanical efficiency is determined using a friction loss model. Then the power balance of compressor and turbine is solved. If the turbine power exceeds the compressor power, the turbocharger speed is increased. With the new speed and the characteristic of the engine swallowing capacity, the new operating point of the compressor can be calculated and the loop through engine model and CFD analysis starts again until a certain boost pressure is reached. At that time the load step is finished.

In the final paper, the User-Fortran model and the coupling to the CFD analysis will be described in detail. Also, the analysis of turbine performance and the flow in the turbine during the load step operation will be discussed.

References

[1] Baines, N.C., "Turbocharger Turbine Pulse Flow Performance and Modelling 25 years on", 9th Int. Conf. on Turbochargers and Turbocharging, IMechE, 2010

[2] Roclawski, H., Gugau, M., Langecker, F., Böhle, M., "Influence of Degree of Reaction on Turbine Performance For Pulsating Flow Conditions", Proceedings of the ASME Turbo Expo 2014, Düsseldorf, Germany.