Czech Technical University in Prague
Faculty of Mechanical Engineering
Department of Automobiles, Internal Combustion Engines and Railway Vehicles

A 1-D Unsteady Model of a Twin Scroll Radial Centripetal Turbine for Turbocharging Optimization

Author: Zdeněk Žák

Supervisor: prof. Ing. Jan Macek, DrSc. Supervisor specialist: doc. Ing. Oldřich Vítek, Ph.D.

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Motivation

The trends of downsizing, downspeeding and hybridization of vehicle powertrain units are obvious. The interactions between internal combustion engine and turbocharger, when the turbine operates under unsteady pulsating flow conditions, significantly influence the overall engine efficiency due to the continually increasing boost pressure level.

Standard turbocharger maps are measured on the steady flow hot gas stands with open loop. In the case of map based approach for twin scroll turbine, the special turbine map has to be measured for each particular level of impeller admission with changing pressure and blade speed ratios. It is essential to measure much more working points in comparison with the map-less approach, what is demanding and very expensive. The most frequent manner how to simulate the turbocharger turbine in engine simulation codes is to utilize the steady flow maps of corrected or reduced mass flow rate and isentropic efficiency of a turbine as a function of the pressure ratio. The quasi steady 0-D map based approach is a standard for 1-D/0-D simulation codes.

The thesis describes the methodology based on the map-less approach and the twin scroll centripetal radial turbine in detail. The classical steady flow maps of a turbine are not utilized during the entire process of the turbine model development.

Goals

The main goal of the thesis is to develop comprehensive methodology, based on the map-less approach, which enables to describe the performance of the radial centripetal turbine with twin scroll under steady and unsteady conditions by the full 1-D model.

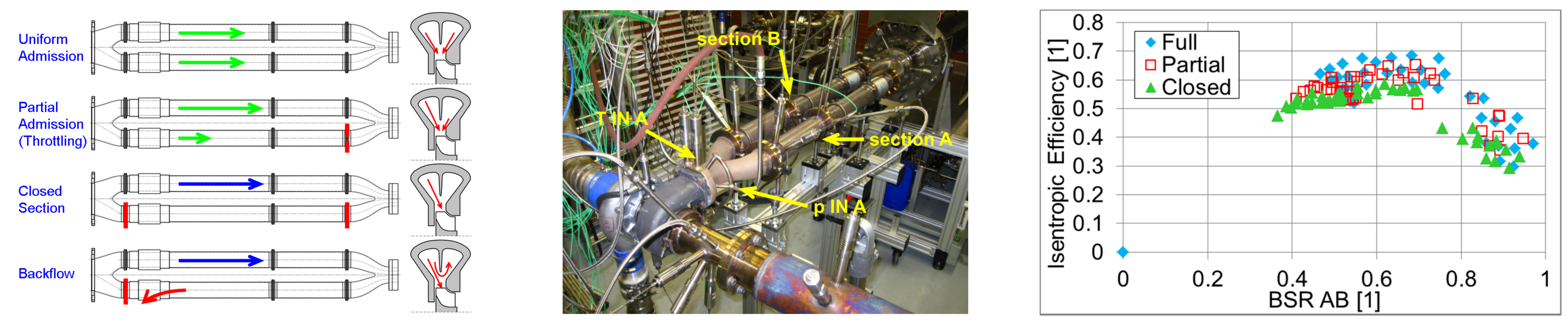
The first goal is to develop the specific turbocharger test bed, which is capable to measure the performance of the twin entry turbocharger turbine under steady flow with the different level of the impeller admission.

The second goal is to develop the modular unsteady 1-D model of a radial centripetal turbine with twin scroll in available 1-D simulation software. The model must be able to describe the phenomena inside a turbine, mixing of flows upstream of the impeller, arbitrary level of impeller admission and interactions between the reciprocating internal combustion engine and the turbocharger.

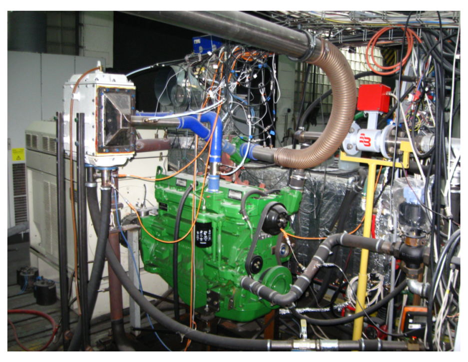
The third goal is to validate and verify the mentioned methodology by the simulation of the internal combustion engine with the unsteady 1-D model of a twin scroll turbine at steady states and transients. The simulation results have to be compared with experimental data measured on the experimental diesel engine.

Experiments

The first aim was the development of the specific turbocharger test bed, which would allow the measurement of the turbochargers equipped with a twin entry turbine. It is necessary to separate the turbine sections on the test bed and to control the flow parameters upstream of the turbine. The twin entry turbine may be measured under full admission of the impeller. It is possible to achieve arbitrary level of partial admission via throttling in sections. The extreme level of partial admission is attainable through the enclosure of a section. The map-less approach requires several levels of turbine load (BSR), pressure ratio and impeller admission. It is necessary to measure extreme cases, i.e. full admission and partial admission of an impeller when one turbine section is closed. The map-less approach needs mass flow rates in individual scroll sections and total turbine power at given turbine speed.



Scheme of the developed turbocharger test bed for twin scroll turbines; Test bed overview; Evaluated isentropic efficiency of a turbine vs. blade speed ratio - full admission of an impeller (blue); partial admission (red squares); extreme partial admission - one turbine section closed (green triangles)



Experimental internal combustion engine - six cylinder diesel

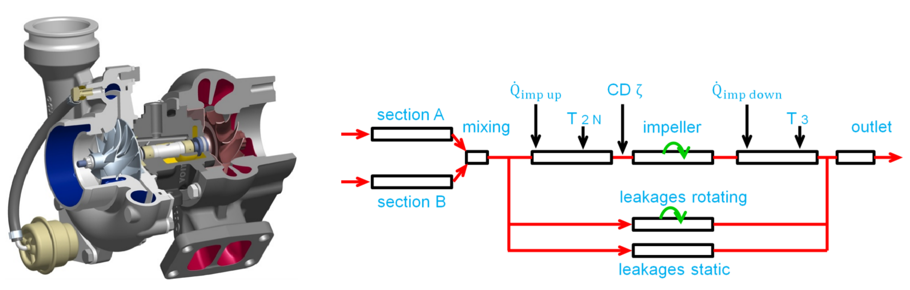
The goal of the experimental research on the turbocharged internal combustion engine was to describe the synergy between the engine and turbocharger under real conditions. Engine transients were the integral part of experimental research on the engine test bed.

The transients are generally the most demanding operating modes of the simulation models. Raw experimental data was processed for the utilization during the calibration processes of developed models in GT-SUITE. The verification of the predictive capability of the developed 1-D twin scroll radial centripetal turbine model under highly unsteady real conditions, which are typical for the turbocharged internal combustion engine, is the most important part of the thesis.

Simulation

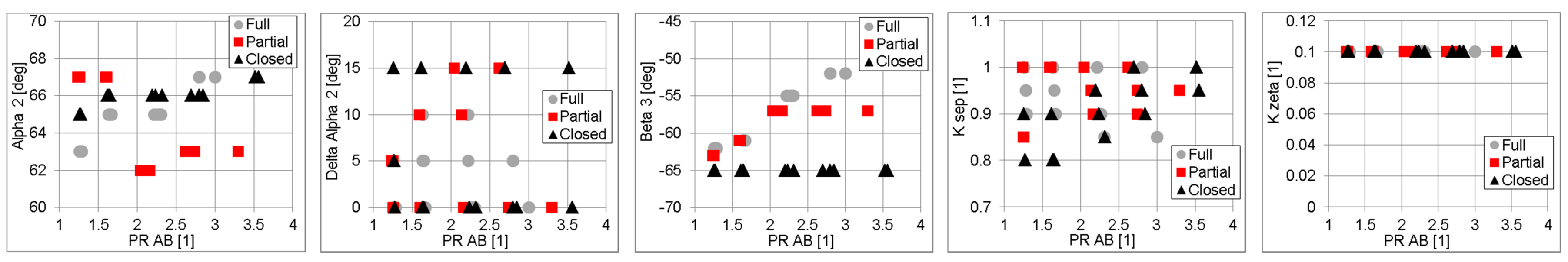
The radial turbine presented in the thesis is equipped with a parallel symmetrical twin scroll and vaneless nozzle ring. The current model is adiabatic but ready for purposes of non-adiabatic conditions. The 1-D model is fully unsteady, so it enables to describe fast changing values inside the whole turbine. The turbine basic geometry (scrolls, impeller, turbine outlet etc.) is required for the 1-D model.

Parallel sections A and B are connected in the zone of flow mixing. The diameters of inlet and outlet ports are controlled via actual dimension of vaneless nozzle ring in accordance of calibrated values. The portion of overall mass flow rate is separated in the zone of nozzle ring and flows through the parallel circuit of leakages. After the flow left the nozzle ring, the total state transformation from static coordinates to rotating coordinate system between the nozzle and rotating channel takes place. The impeller is simulated by two pipes. The first one, in radial direction, is the rotating channel exposed to acceleration. The second is the outlet part of the impeller in axial direction. The transformation from rotating coordinate system to static coordinates of stator begins at impeller outlet. After the finalization of second transformation, the mass flow rate from the parallel circuit of leakages joins the main turbine mass flow rate. The model is terminated by the outlet pipe.

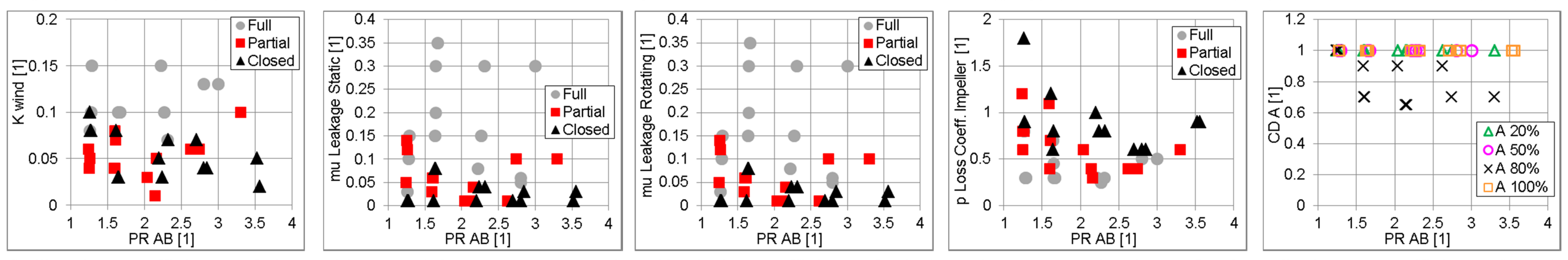


Turbocharger with twin scroll radial centripetal turbine;
Simplified scheme of a 1-D radial centripetal turbine with twin scroll

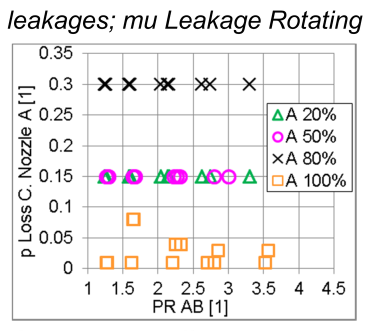
The basic torque is calculated using the Euler turbine theorem. The physical robustness of the Euler turbine theorem consists in the dependence of torque on the tangential components of absolute velocities at the impeller inlet and outlet and appropriate mass flow rates. The relevant turbine power results from the basic power, based on the Euler theorem, reduced by windage losses.



Calibration coefficients of the turbine model vs. pressure ratio - Alpha 2 - nozzle exit angle; Delta Alpha 2 - deviation of nozzle exit angle; Beta 3 - impeller exit angle; K sep - flow separation coefficient; K zeta - correction of impeller incidence loss; full admission (gray), partial admission (red), one section closed (black)



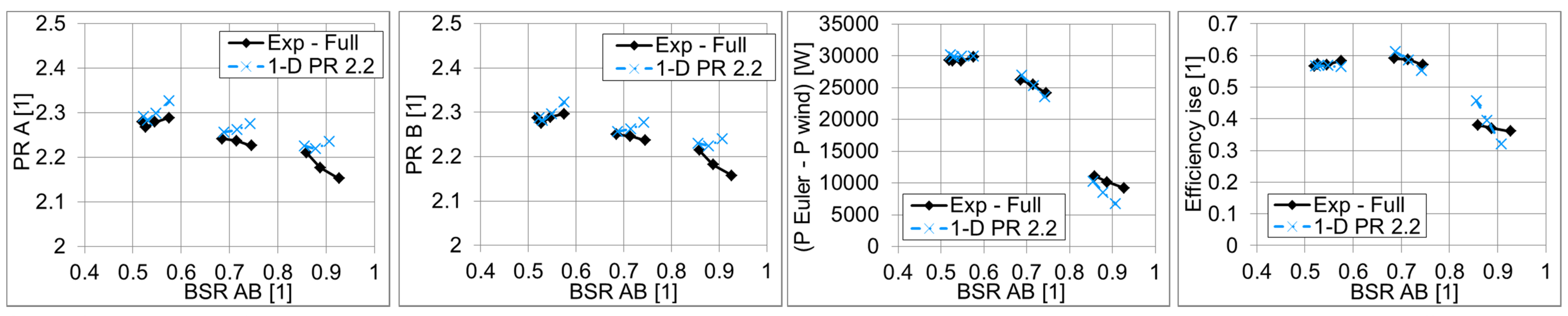
Calibration coefficients of the turbine model vs. pressure ratio - K wind - coefficient of windage losses; mu Leakage Static - discharge coefficient of static leakages; mu Leakage Rotating - discharge coefficient of rotating leakages; pressure loss coefficient in impeller pipe; discharge coefficient at section A outlet



Calibration coefficient - pressure loss coefficient in section A (analogical for section B)

The aim of steady flow calibration was to find the proper combination of all calibration coefficients with lowest overall error between simulation results and experiments. Pressure ratio of section A, pressure ratio of section B and turbine power under steady flow were taken into account.

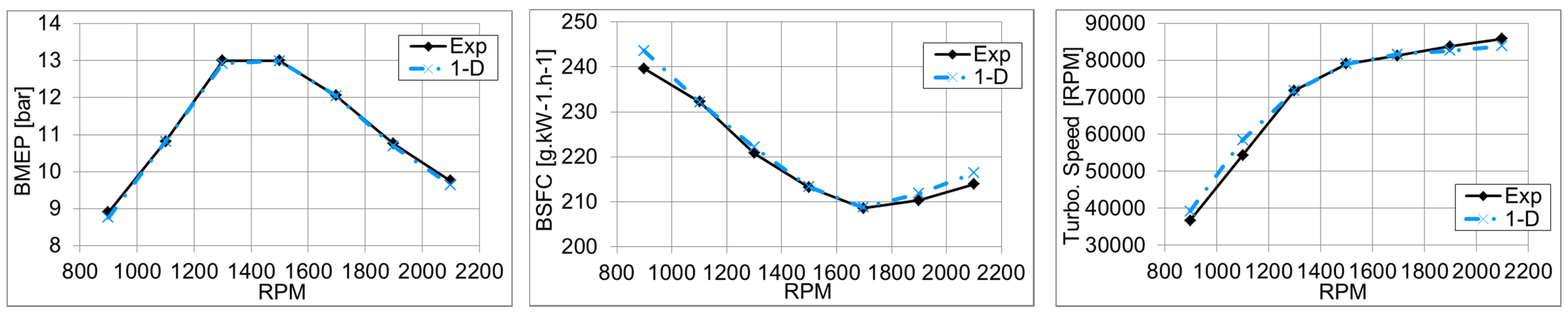
The 1-D turbine model was calibrated via coefficients: nozzle exit angle, deviation of nozzle exit angle, impeller exit angle, flow separation coefficient, correction of impeller incidence loss, coefficient of windage losses, discharge coefficient of static leakages, discharge coefficient of rotating leakages, pressure loss coefficient in impeller pipe, discharge coefficient at section A outlet (upstream of flow mixing), discharge coefficient at section B outlet (upstream of flow mixing), pressure loss coefficient in section A and pressure loss coefficient in section B.



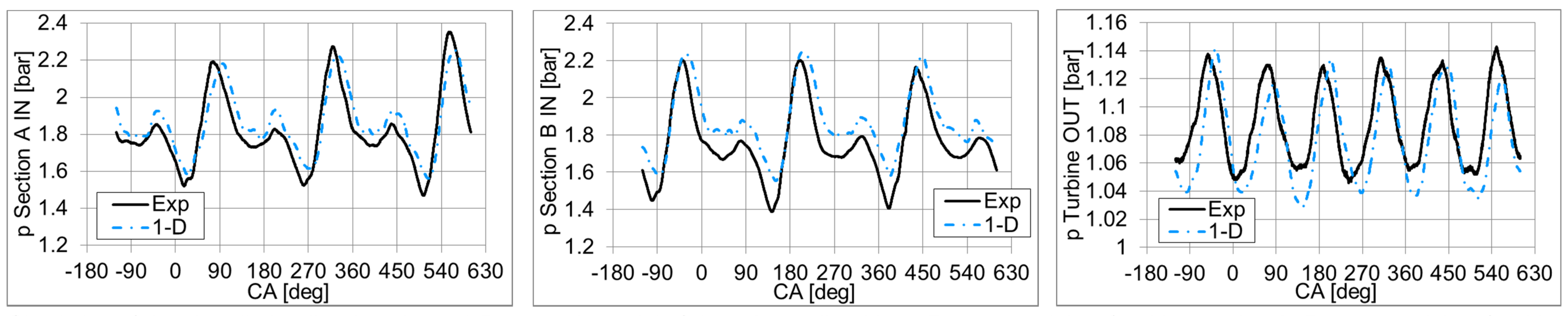
Steady flow calibration of the 1-D turbine model - Pressure ratio in turbine section A; Pressure ratio in turbine section B; Turbine power; Isentropic efficiency vs. blade speed ratio (approximate pressure ratio level PR AB = 2.2), full admission of an impeller; experiment (black); simulation 1-D turbine (blue crosses)

The goal of the on-engine simulations was the verification of the turbine model behaviour under real conditions of the highly pulsating flow. The model of the experimental internal combustion engine was properly calibrated using the available data (geometry, material properties, moments of inertia etc.) and measured physical quantities and connected with the unsteady full 1-D model of the twin entry radial centripetal turbine.

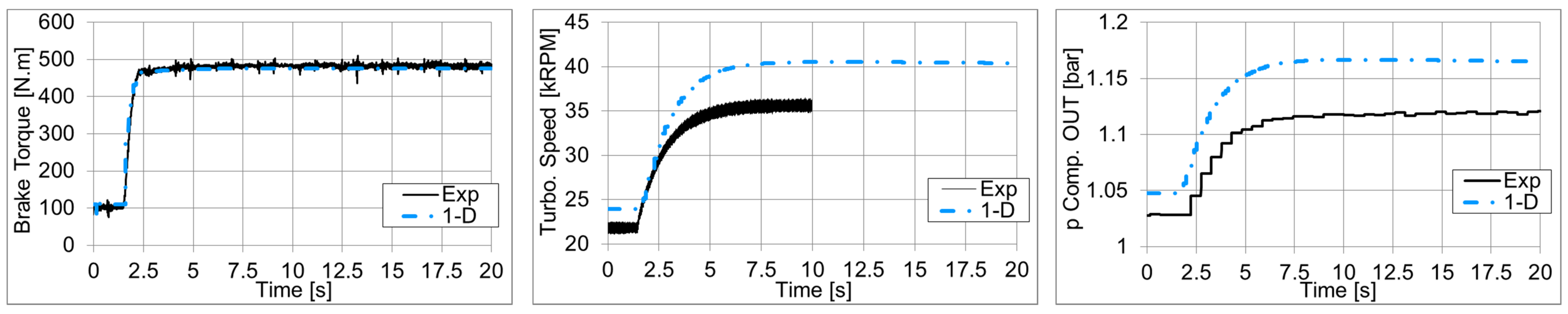
The unsteady 1-D model of the twin entry turbine was fully calibrated under steady flow conditions and utilized for the engine simulation without any modification or recalibration. For the internal combustion engine valuation as a whole machine, the important parameters are the brake mean effective pressure and brake specific fuel consumption. The goal of the transient simulation was to verify the stability, robustness and predictive capability of the full 1-D turbine model with the twin scroll. Rapidly changing conditions upstream of a turbine are the most demanding conditions for the developed turbine model.



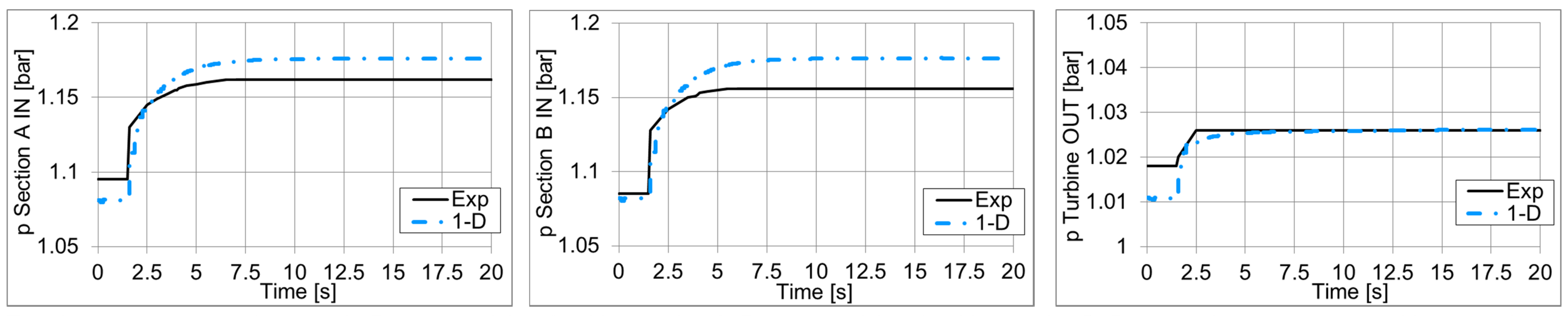
Simulation of the six cylinder diesel engine + 1-D unsteady model of the twin scroll turbine - Brake mean effective pressure; Brake specific fuel consumption; Turbocharger speed; experiment (black solid line); simulation with full 1-D unsteady turbine (blue dashed and dotted line)



Simulation of the six cylinder diesel engine + 1-D unsteady model of the twin scroll turbine - Pressure at inlet of turbine section A; Pressure at inlet of turbine section B; Pressure downstream of a turbine; experiment (black solid line); simulation (blue dashed and dotted line); 2100 RPM, BMEP = 9.8 bar



Transient at constant engine speed - Brake torque; Turbocharger speed; Pressure downstream of a compressor; experiment (black solid line); simulation with full 1-D unsteady turbine (blue dashed and dotted line); 900 RPM



Transient at constant engine speed - Pressure at inlet of turbine section A; Pressure at inlet of turbine section B; Pressure downstream of a turbine; experiment (black solid line); simulation with full 1-D unsteady turbine (blue dashed and dotted line); 900 RPM

Generalization of Results and Discussion

The map-less approach described in the thesis as a comprehensive methodology enables to create the physical based model of any turbocharger turbine. Neither the classical steady flow maps nor regressions are employed during the entire process for the appropriate turbine 1-D model development. The developed unsteady 1-D model of a radial centripetal turbine with the twin scroll is modular. It is possible to adapt current version to specific design and dimensions of the required turbine and recalibrate the new model under steady flow conditions in compliance with experiments. The number of required measurements is relatively low, compared to classical map based approach, by virtue of the physical background of the model.

The specific turbocharger open-loop test bed for a twin scroll turbine is completely prepared and verified. The methodology of the measured steady flow data evaluation, including specific regression formulas for the compressor and turbine, and their utilization in the calibration process of the 1-D turbine model is also verified and ready to use for any turbocharger.

The procedure of measurement on the steady flow turbocharger test bed should be improved in the future step by step. The sophisticated model of specific bearings would improve the prediction of losses. The calibration procedure of the 1-D turbine model might be simpler and partially automatic in relation to independent optimization tool with sophisticated algorithms. Testing of new components such as waste gate (WG), exhaust gas recirculation valves (EGR) or turbine outlet diffuser should be performed in the future research. The longtime goal is the extensive library of turbocharger models, as a part of appropriate knowledge database, based on the map-less approach, which can be also utilized for purposes of virtual prototypes.

Conclusions

The main goal of the thesis was to develop, validate and verify the comprehensive methodology, which utilizes the map-less approach for radial centripetal turbines equipped with the twin scroll. The map-less approach does not utilize the classical steady flow maps of a turbine during entire process of the full 1-D turbine model development.

The specific steady flow turbocharger test bed with separated turbine sections for measurement of the twin entry turbines was developed. The open loop hot gas stand is suitable for achievement of the arbitrary level of turbine impeller admission. The selected turbine with the twin scroll was properly tested under different level of impeller admission and load. All experimental data, measured on the steady flow turbocharger test bed, were evaluated by the in-house software developed for the purpose. The software includes the evaluation of the compressor power under adiabatic conditions, power losses in bearings and all relevant physical quantities, which describe the twin scroll turbine behaviour under steady flow conditions.

The same type of the turbocharger was measured under real conditions in conjunction with a diesel engine. The experimental internal combustion engine with six cylinder in-line design is ideal for the twin entry turbine. The important pressures at the engine and upstream/downstream of the turbine were indicated. The steady states and also transients at constant engine speeds were measured. For the verification of the full 1-D twin scroll turbine model performance in engine simulation, a detailed model of the experimental internal combustion engine was created in GT-SUITE.

The developed modular unsteady full 1-D model of a radial centripetal turbine with twin scroll is a suitable tool for the description of the interactions between the internal combustion engine and a turbocharger. The model, developed in GT-SUITE, also describes the phenomena inside a turbine. The physical approach respects conditions for mixing of flows inside the scroll, asymmetry of flow admission, turbine scroll design, dimensions of the impeller and interactions among the parts inside a radial turbine. The turbine model was properly calibrated at steady flow conditions using the experimental data measured on the turbocharger test bed. The best accordance of simulation and experimental results was achieved by proper combination of calibration coefficients. The 1-D model of a twin scroll turbine, after steady flow calibration process, is ready for highly unsteady simulation under pulsating flow conditions on the engine.

The developed, validated and verified comprehensive methodology with the map-less approach is fully prepared for the employment in practice. The simulation support of experiments, higher simulation and design, based on the full 1-D turbine models, may contribute to the acceleration of turbocharger and internal combustion engine development process. The preliminary turbocharger design, i.e. main dimensions of the divided symmetrical or asymmetrical scroll, turbine impeller and outlet may be optimized using the developed unsteady 1-D model.

Author's Publications Related to the Thesis

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