脱炭素に
技術と叡智
IHI

On Advanced Turbocharger Technology and Development

FILSINGER Dietmar : Ph.D., Technical Supervisor, IHI Charging Systems International GmbH
IOSIFIDIS Georgios : Manager, Prototyping & Validation Department,
IHI Charging Systems International GmbH
DURBIANO Loic : Manager, Development & Application Department,
IHI Charging Systems International GmbH
KIRSCHNER Christian : Supervisor D&C Engineering, IHI Charging Systems International GmbH
EHRHARD Jan : Ph.D., Head of Engineering, Chief Technology Officer, General Manager,
IHI Charging Systems International GmbH

Recent political announcements, especially in the European Union, imply that passenger car propulsion technology based on Internal Combustion Engines (ICE) is outdated and will not be further developed. Nevertheless, next to battery electric propulsion turbocharging and turbocharged ICE are seen as a technology path that can and will support transformation into a society that does not depend on fossil fuels. Related expertise and development capabilities will contribute to further enhancing propulsion systems with highly efficient turbochargers (TCs) that combine lifetime durability with best quality, but also best cost. The paper at hand provides an overview of advanced TC technologies and their specifics serving modern propulsion systems. It showcases development expertise that is relevant for many carbon-free technology areas.

1. Introduction — society context and industry transformation

Propulsion of passenger car vehicles is currently an area of exhaustive, but to a certain degree dogmatic discussions. For example, some countries plan to ban Internal Combustion Engines (ICEs) for private passenger car use. Such decisions are driven by assessment of local tail-pipe emissions and are neglecting life-cycle emissions. Assessments of life-cycle emissions are mandatory for a fair and open technology evaluation with the paramount goal to reduce CO_2 emissions. Life-cycle assessments take into consideration vehicle production and well-to-tank emissions caused by fuel production. Limited tank-to-wheel assessments — the EU legislation is one example — create a strong bias in favor of Battery Electric Vehicles (BEVs) despite the fact that in certain regions the CO_2 emissions per kWh of the utilized energy mix for electric power generation are exceeding emissions of most advanced ICEs.

Avoiding local emissions is certainly of utmost importance for large mega-cities with the highest population densities to allow pleasant and healthy life. There is also no doubt that propulsion efficiency of BEVs is advantageous since e-drives have the lowest losses. On the other hand, losses from fast battery charging and operation under cold climate do have negative effects on the energy utilization of e-drives but are often neglected in dogmatic discussions. The use of CO_2 neutral synthetic e-fuels in ICEs is not allowed under “tail-pipe legislation,” which limits technology openness. BEVs show obvious benefits for limited range and suburban mobility in districts with a high population density and therefore pollution caused by humans. For other regions turbocharged e-fueled ICE in hybrid systems offer a valid technology option. Moreover, turbocharging technology is still one important enabler to realize efficient commercial ICE applications that require high pay load, short down time and long range. Utilization of H_2 or e-fuels from green electricity will allow ICEs to have very favorable life-cycle emissions(1). Such propulsion systems will have their share in the market.

Energy transport and storage to equalize the spatial and temporal imbalance between energy consumption and energy production will help to diminish the current commercial disadvantage of synthetic fuels. Another dogmatic debate is in progress here. This discussion partly neglects that highly industrialized countries will need to import (green) energy through suitable energy carriers, such as e-fuels, H_2 or ammonia. Selecting the best locations for electricity generation via photovoltaic and/or wind power will enable higher energy harvesting by up to a factor of three compared to less favorable regions, e.g., northern Europe. Much less installed power is required, and synthetic fuel cost will be accordingly attractive(2)–(4).

For these reasons turbocharging and turbocharged ICEs are seen as one technology path that can and will support transformation into a sustainable society that does not depend on fossil fuels. Employing various technology options next to simple electrification adapted to local needs and given boundary conditions will help to accelerate societal transformation.

Outstanding turbocharger (TC) expertise and development capabilities will contribute to further enhancing propulsion systems that offer not only excellent efficiency and lifetime durability with the best quality, but also the best cost. The paper at hand gives insight into development and analysis methods and related capabilities facilitating optimal adjustment of advanced TC technology to requirements of modern propulsion systems. A general description of TC modeling is followed by propulsion system analysis. Numerical methods are described while showcasing selected technology options.

2. Computer Aided Engineering (CAE)

State-of-the-art development and research are strongly based on virtual three-dimensional (3D) computer aided design (CAD) and numerical simulation methods. Product requirement analysis based on intended applications results in needed product functions and properties. Accordingly, new products are detailed in CAD of multi component assemblies, sub-systems and systems. These data allow to prepare numerical models or sub-models in different level of detail and for different purposes to assess in an initial virtual verification loop the function, performance and durability without the need to manufacture a prototype. Costs are evaluated after assigning appropriate materials, based on expected operating conditions and evaluating different manufacturing methods with their specific accuracy based on functional requirements.

Requirement analysis of TCs needs system investigations on an engine level. In contrast to later product design, such investigations do not need to consider actual 3D geometries but can be performed assuming only one-dimensional (1D) behavior. Only this simplification allows investigation on such complex multi component systems. The modeling effort as well as the cost for calculations, namely CPUh, is significantly reduced and enables multi parameter studies, virtual Design of Experiment (DoE), and optimizations with sufficient accuracy.

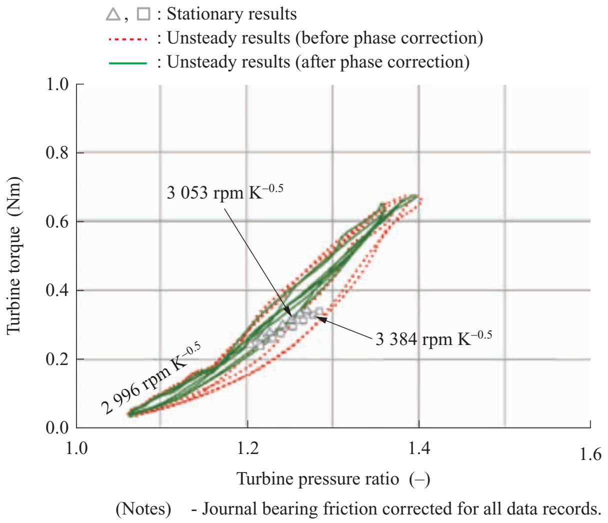
2.1 Turbocharger modeling

Reliable 1D modeling of TCs requires a predictive abstraction of the real machine behavior. This is a rather challenging task due to the small geometric size and the close vicinity, and therefore interaction of fast rotating components that either are exposed to heat or generate heat due to friction or compression. Moreover, cooling and lubrication ensure safe operation via oil and/or water, whereas the media inlet temperature is subject to change related to vehicle operating conditions. In this regard, extensive experience has been gained via numerous experimental investigations with variation of TC operating conditions, in testing boundary conditions, and variation in temperature of the supplied media. These test series were the base to establish testing procedures and boundary conditions to reach the best accuracy, repeatability and comparability of TC performance measurements. A simple temperature correction with only three parameters — one quantifying the heat flow and two representing the temperature situation at the turbine and the compressor — describes the heat flow behavior of a single TC type in an engine installation sufficiently accurately(5). It is worth mentioning that most uncertainty in thermal behavior is created due to unknown outer boundary conditions and heat transfer via (internal) contact interfaces. The inner boundary conditions and the inner heat flow of the flow channels of the TC can be accurately predicted. More complex heat flow modeling is possible, but calibration is difficult and requires detailed input from measurement, which is often not existing(6).

Novel test methods were created. A so-called semi-unsteady method that relies on the effect of significantly increased rotor inertia allows turbine map measurements on a steady state test bench but covering the wide operation range seen under pulsating flow. This is realized with transient measurements under constant inlet pressure and temperature conditions during rotor acceleration and deceleration while the shaft torque is contactless monitored via magnetostriction(7).

A scientific milestone was achieved by employing exactly this unique shaft torque sensing method during TC measurements under fired engine operation at the Technical University of Stuttgart. Quasi-steady behavior of the TC turbine under pulsating conditions — the most important pre-requisite for state-of-the-art TC turbine modeling in 1D simulations — was experimentally proven for the very first time. **Figure 1** shows exemplary measurement results. The dotted and solid curves show pressure signals versus turbine torque before and after phase correction for exemplary operation, indicated by the reduced speed value. Phase correction is necessary to account for filling-and-emptying effects of the volute volume along the length of the flow path of the turbine stator, which is often misleadingly labeled as unsteadiness. For comparison stationary results from hot gas stand testing with very similar reduced speeds are shown in grey. After phase correction the orbits of the non-stationary measurement curves collapse to form a line. The agreement with the stationary rotor torque values from the hot gas test stand regarding curve position and its slope is very good and it can be concluded that turbines under pulsating engine conditions behave quasi-steady(8).

One major loss during TC operation is bearing friction. To allow predictions and elaborate design improvements, sufficient understanding and modeling of the related



(Notes) - Journal bearing friction corrected for all data records.
- Revised from Reference (8).

Fig. 1 Turbine torque vs. turbine pressure ratio for steady and unsteady turbine inlet boundary conditions(8) phenomena is required. A transparent bearing housing and a high-speed camera allowed to measure the rotational speed Ω_{FR} of the Floating Ring (FR), which is one major parameter to validate numerical models for full floating bearing systems. Experimental data related to the rotation speed of the shaft Ω_R can be seen in **Fig. 2**. A simple numerical model allows the basic effects such as inner and outer oil-whirl, constant tone, and rotor bending to be detected. General agreement with the measurement was achieved, although the complexity of the real investigated system exceeds that of the numerical rotor-bearing-model by a multiple. For sufficient model quality the natural frequencies of the unsupported rotor and a temperature dependent oil viscosity needed to be introduced(9).

In later studies conducted with the Technical University of Darmstadt, the numerical tool was further improved to better predict oil-whirl and -whip, which are two important excitation mechanisms to be considered during the design process of full-floating journal bearings. The resultant sub-synchronous vibration can lead to noise emissions or even risks for rotor integrity. For precise prediction rotordynamic, fluid dynamic, and thermodynamic mechanisms are coupled. The resulting complex system offers challenges to be resolved with numerical methods(10).

Next to the radial bearings also the axial bearing that capture the axial force imbalance need to be treated. Experimental investigations showed that the drag torque, which is a loss, increases linearly with rotating speed for constant oil supply conditions and thrust free operation. The dependency of the friction loss on external thrust load has been determined by performing a thrust load variation at a constant rotating speed. The resulting friction increases proportionally to the square root of the applied thrust load. Therefore, the thrust load situation can be considered by simply assuming disk friction loss under no load conditions and applying the classical thrust bearing theory under load(11).

Through an ingenious combination of newly introduced experimental methods and numerical investigations, as well as the utilization of simple correction models, the behavior of TCs can be comprehensively modeled and analyzed for both steady (hot gas stand) as well as unsteady (engine) boundary conditions. A quasi-steady turbine behavior was proven. The filling and emptying of flow volumes needs to be adequately considered. With rather simple map correction methods on heat flows, the quality of stationary turbine maps — the basis for engine simulation — can be substantially increased. Friction losses from the bearings can be described.

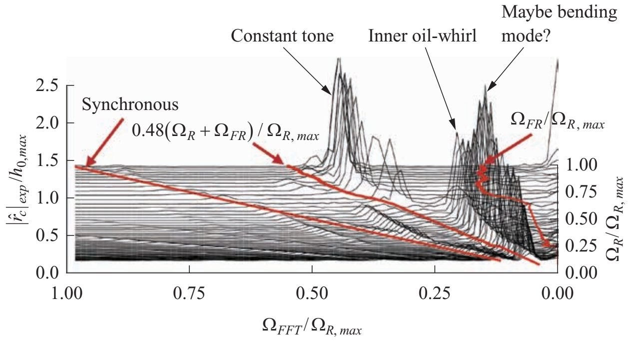
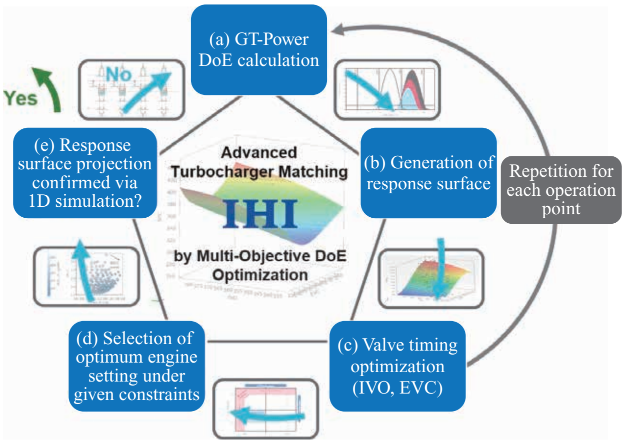


Fig. 2 Waterfall diagram from run down measurements with trans parent bearing housing
Amplitude $|\hat{r}_c|$ plotted in relation to the maximal radial clearance $h_{0,max}$ of the full floating bearing(9)

2.2 Engine modeling and turbocharger definition

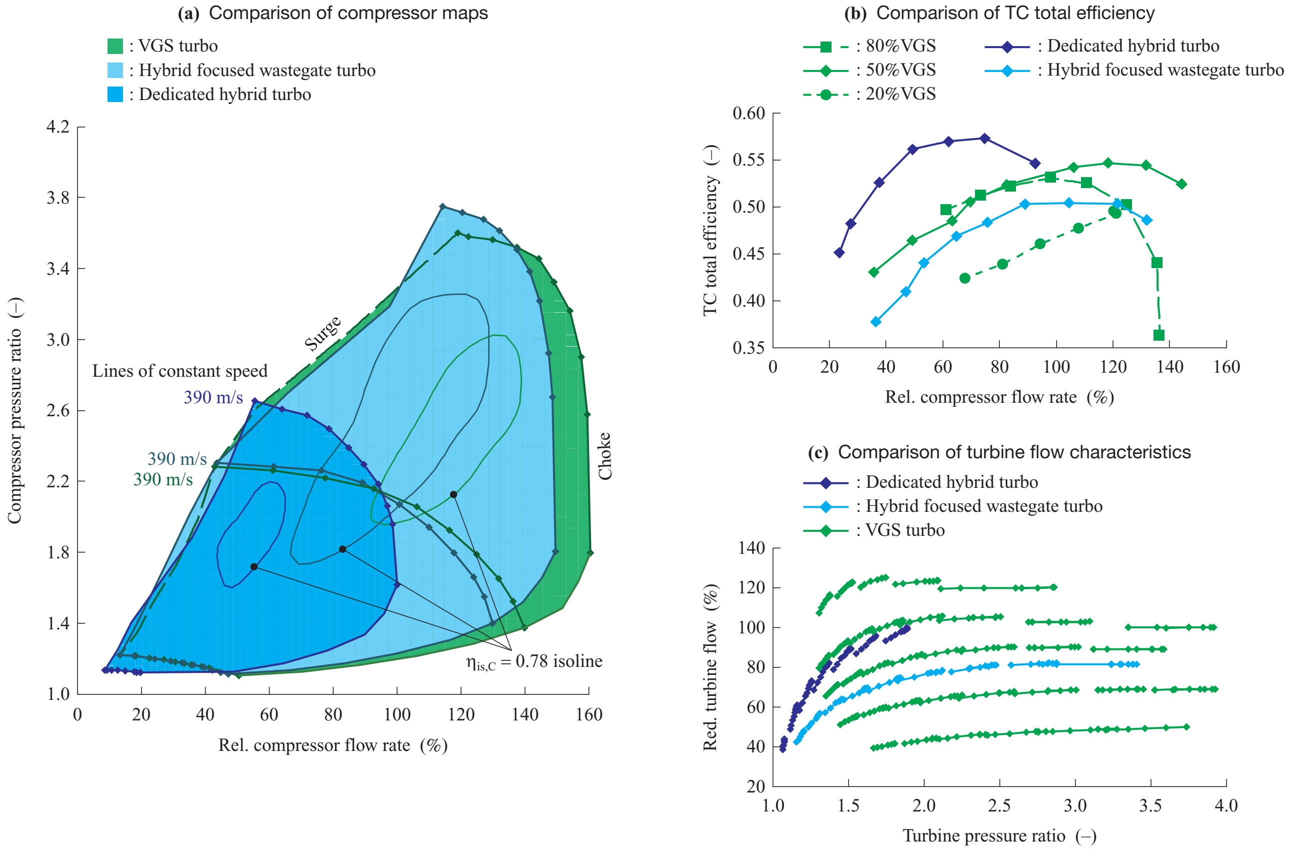
Based on this extended modeling experience, a 1D screening methodology to refine turbocharging technology for ICE in modern propulsion systems was developed. It is essential that this method is valid for stand-alone ICEs with its various applications, but can also treat hybrid architectures with different levels of electric capabilities, ranging from 48 V mild hybrid to dedicated hybrid engines(12). It is based on 1D gas exchange simulation with the ability to consider different fuel types (e.g. gasoline, diesel, e-fuels, H_2), but also includes elements to analyze cost and manufacturing. To predict best matches between the various engine and charging systems, a wide variety of engine and TC parameters need to be investigated under controlled boundary conditions and given constraints. The methodology is presented in **Fig. 3**. Multiple GT-Power 1D gas exchange DoE calculations **(a)** produce input for generating response surfaces with an external optimization tool of various engine parameters such as Compression Ratio (CR), intake and exhaust valve timing as well as TC sizing **(b)**. Based on these response surfaces, valve timing, such as for example Inlet Valve Opening (IVO) and Exhaust Valve Closing (EVC), can be optimized for specific parameter combinations **(c)**. This process is repeated for a number of relevant operating conditions — Low End Torque (LET), peak power and part load — to select the best set of variables **(d)**. In the final step the optimization needs confirmation **(e)**.

Exemplary results of adapted TC properties considering different degree of hybridization are exhibited in **Fig. 4**. Striking is the very different compressor map width that is selected based on the ICE's desired operating range. Compromising ICE range for dedicated hybrid systems via phlegmatization and load point shift allows the highest TC



(Note) Revised from Reference (12).

Fig. 3 The IHI multi-objective optimization methodology procedure(12)



(Note) Revised from Reference (12).

Fig. 4 Performance maps of TCs adapted for ICEs with different degrees of hybridization(12)

efficiency despite the small component size. With a compressor diameter in the 40 mm range, the latest TCs reach an efficiency exceeding 55%. Through proper hybridization, driving performance does not need to be compromised. Striking is also the turbine performance of the Variable Geometry System (VGS). Variability allows the best TC efficiency over a wide range. This is an enabler for realizing innovative ICE architectures with advanced exhaust gas after treatment.

Still wastegate (WG) TCs, especially with Mixed Flow Turbine (MFT) technology, are a valid option offering wide range operation and beneficial response that is decisive for the best fuel consumption and lowest emissions in highly transient driving cycles(13).

Powertrain electrification carries further potential for mitigating the conflict between transient, low-end steady state and rated power requirements of the engine and allows the introduction of the so-called e-xR concept(14). This compact electric TC concept for highly efficient, low emission Miller gasoline ICEs utilizing Low Pressure Exhaust Gas Recirculation (LPEGR) employs MFT without control elements and achieves extraordinarily high charging efficiencies. Turbine sizing can be decoupled from the response behavior due to the integrated e-motor. The realized e-xR TC is shown in **Fig. 5**. The concept is challenging in terms of component sizing, electric system demands and aggressive Miller parameters, as well as dynamic LPEGR load control. Strong benefits in terms of Specific Fuel Consumption (SFC) in the 80 kW/*l* market segment were shown. The concept is also suitable for higher power density engines > 150 kW/*l*.

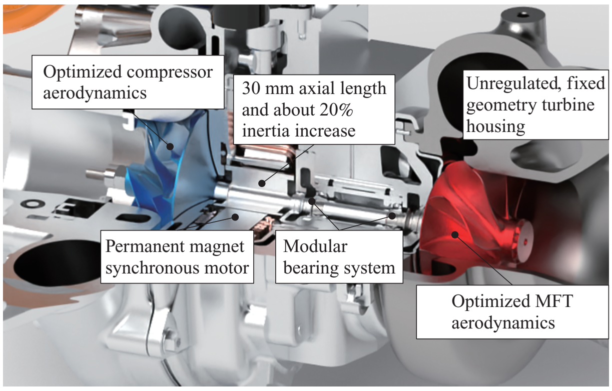


Fig. 5 3D section view of electric assisted turbocharger in the e-xR concept version

In a further study on how to realize stoichiometric combustion and avoid enrichment for the complete engine range while respecting the temperature limits of the exhaust after treatment system, the Miller principle was again rated as very beneficial. The TC and the turbine behavior are decisive since providing sufficient air for the engine is challenging. The turbine outlet temperature prescribes the catalyst inlet temperature. However, as expected, the turbine size and especially the turbine efficiency have no influence on the outlet temperature as soon as constant compression power and, therefore, turbine output is requested from the ICE. An electrified TC makes it possible to achieve stoichiometric operation while respecting turbine outlet temperature limits(15). **Figure 6** summarizes the results of this specific study. Desired is less or no enrichment which is correlated with the change of temperature difference across the turbine. The study limits the outlet turbine temperature to a fixed allowable value. The Miller cycle offers the best potential and energy recuperation is a valid option.

Based on requirements from propulsion systems and related ICE optimization — examples were shown in the chapter above — the TC needs to offer specific tailored product properties. To realize these, design and analysis methods are explained in the following sections. For reasons of brevity selected examples are presented.

2.3 3D Computational Fluid Dynamics (CFD) on compressors and turbines

CFD is an appropriate tool for defining and verifying TC design improvements. Map width and efficiency are the most important compressor characteristics. One possibility to achieve improvements for operation with low flow offers a reduction of the inlet flow area. Results from investigations on this phenomenon are depicted in **Fig. 7**. It shows the axial flow velocity contours from CFD for inflow without **Fig. 7-(a)** and with flow area reduction to 60% **-(b)**. The blue color indicates negative flow direction. In **Fig. 7-(b)** the recirculation bubble is confined to the compressor wheel. Therefore, much less fluid is reworked. Moreover, the smaller recirculation bubble lessens the mixing losses. Both effects increase the efficiency by up to 7% points, which was proven experimentally. Interestingly the incidence at the wheel inlet for no flow restriction in **Fig. 7-(a)** is better since the blockage is higher and therefore, the axial velocity near the hub is higher. Incidence improvement is therefore not the reason for the better efficiency of compressors with a restricted inflow area. It is important to understand such phenomenon in detail to be able to introduce related product features reliably and cost effectively into the TC design. Later progress in this regard is documented in Reference (16).

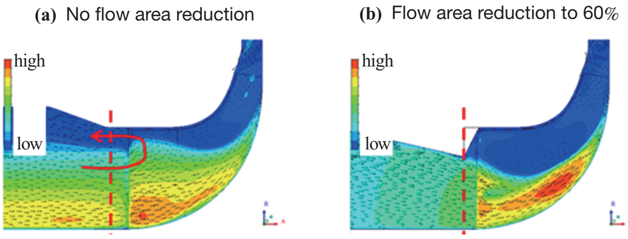
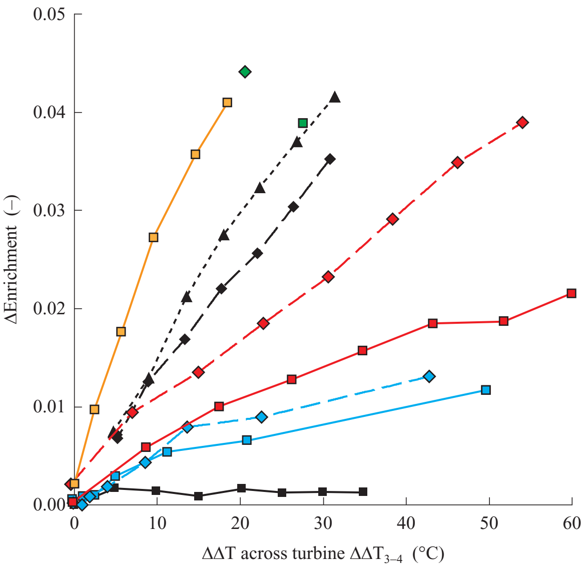


Fig. 7 Axial velocity contours from CFD

Variable turbine systems offer superior efficiency over a wide operating range since the flow area can be adapted to the available amount of exhaust gas from the ICE. Just as described above, only this allows to realize certain engine systems that require high turbine power under low flow conditions. Flow path optimization requires understanding the sources of losses and leakage. The smaller the geometric size of the TC, the more important it is to minimize parasitic losses. Variable nozzle vanes need to have Nozzle Side Clearances (NSC) to avoid sticking under (transient) temperature loads. In the area of the NSC the flow will not have the desired direction, which leads to efficiency loss. This can be significant since under closed nozzle conditions, up to 10% of the flow is leaking through this gap.

It has been experimentally established at Queens University Belfast that a 4.5% increase in efficiency is found by operating with hub side NSC at low mass flow operation. With CFD analysis of the system it was shown that two tip

(a) Change of enrichment



(b) Overview of measures

Concept	Measure		Comment
Throttling before engine intake	—■—	Closed throttle	
	–◆–	Turbogenerator after CAC	
	- -▲- -	Turbogenerator after CAC	Energy fed back to crankshaft
Recirculation of compressed air	—□—	From after compressor	
	–◇–	From after CAC	
Electrically assisted turbocharger	—■—	Exhaust energy recovery	
	–◆–	Exhaust energy recovery	Energy fed back to crankshaft
Turbogenerator parallel to TC	■	Exhaust energy recovery	
	◆	Exhaust energy recovery	Energy fed back to crankshaft
Miller timing	—□—	Advance IVO	

(Notes) CAC : Charge Air Cooler
Revised from Reference (15).

Fig. 6 Comparison of measures to reduce enrichment related to the change of temperature difference across the turbine $\Delta\Delta T_{3-4}$(15)

leakage vortices formed: one at the leading edge and one after the spindle in the clearance gap of the stator vanes. This was confirmed with flow visualization on the test rig as can be seen in **Fig. 8**. Two stator vane tip leakage vortices cause the incidence angle of the flow in the region of their formation to be shifted in the negative direction. The use of the hub side NSC showed improved efficiency compared to operating with the shroud side NSC, which caused additional tip leakage in the rotor domain(17).

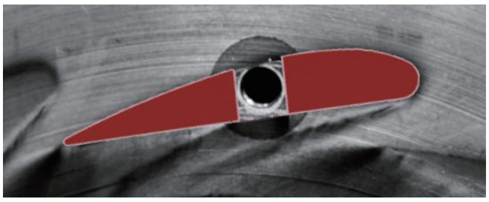
Based on this fundamental understanding of the flow field, major design improvement could be introduced into the variable turbine system. This can reliably serve diesel and gasoline engine concepts with best efficiency over a wide range and allow turbine inlet temperatures that several years ago were not seen as possible(18).

Revealing these complex 3D flow structures also shows that 1D component modeling will have its limits, especially for passenger car TCs, with its small size. Highly efficient component design requires advanced numerical 3D methods with detailed temporal and spatial resolution.

2.4 Fluid Structure Interaction

Interdisciplinary development is essential if aerodynamics are to have a direct influence on structural behavior. Heat transfer from the fluid into walls is a standard task that needs to be mastered to reliably design housings for durable operation under a transient and steady state high temperature load. Component loading by thermal stresses needs to be limited by balancing thermal expansion via local adaptation of stiffness and compliance while accounting for the specific material properties.

(a) Test rig



(b) CFD

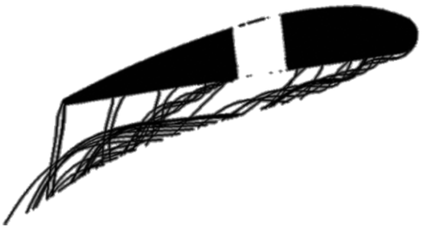


Fig. 8 Tip leakage vortices found in stator domain(17)

Another challenging example is turbine blade vibrations induced by pressure fluctuation. In VGS turbines one source of excitation is the upstream nozzle vanes. If the excitation frequency and wheel eigenfrequency match, resonance conditions are given. Under these conditions the blade vibration amplitudes causing dynamic stresses in the wheel need to be limited to values that are safe for long term operation. The amplitudes in question depend on the strength of the excitation and the damping, which are accumulated from aerodynamic (damping) forces on the blades and energy dissipation in the structure. Massive influence on blade vibration amplitudes is from spatial interaction of the eigenform with the dynamic pressure fluctuation for the resonance frequency. If locations of the structure with high displacement are subject to high pressure fluctuations the response of the structure will be stronger compared to a situation when high local pressure fluctuations do coincide with regions of the structure with low displacements. This allows to develop design guidelines but requires reliable prediction methods for structural vibration behavior and aerodynamic excitation as well as detailed understanding of the damping behavior. Intensive experimental and numerical investigations and research allowed to establish a forced response calculation process(19) that is illustrated in **Fig. 9**.

Fast fourier transformation of pressure from unsteady CFD allows calculation of forced response amplitudes. The statistical behavior of the real structure is dominated by mistuning, which is variation of vibration behavior from geometric deviation(20). Mistuning can be determined by blade frequency measurements of multiple turbine wheels. The related numerical modeling by a variation of E-modulus and/or local geometry allows Monte-Carlo simulations to determine the behavior of a fleet of wheels, which is mandatory to create safe designs(21). This evaluation of

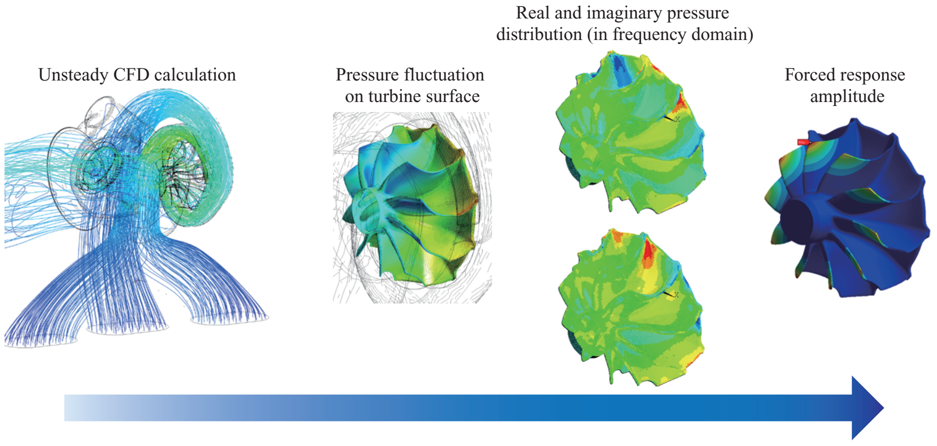


Fig. 9 Forced response calculation method(19)

maximum blade amplitude allows the selection of worst-case wheels for final experimental validation. Mandatory input is next to the material properties reasonable damping values, which are influenced by the wheel mode shape, namely the blade interphase angle, but also operating conditions. Aerodynamic damping dominates, but the structure also contributes(22). Aerodynamic mistuning through production tolerances has a rather small effect on the actual excitation(23). Based on this deep fundamental understanding, elaborated together with the Karlsruhe Institute of Technology, reliable VGS turbine designs were generated and validated and are introduced to various engine applications(18).

The described method to evaluate blade vibrations serves also for the development of Double Scroll (DS) turbines. DS technology offers beneficial low-end performance since with closed scroll connection valve the effective flow area of the turbine can be small to generate higher inlet pressures and therefore high turbine power for low exhaust gas mass flow. Under high load conditions the scroll connection valve is open, and the effective flow area can be adjusted to values of highly efficient mono scroll housings. Maximum back pressure limits of the ICE can therefore be kept. Thus, this technology offers certain turbine variability but also pulse separation for low load conditions with its positive effects for the combustion behavior(24), (25). Due to the partial admission of the housing and therefore, pressure differences, blade excitation is higher compared to excitation in mono scroll housings. This is illustrated in **Fig. 10** and needs specific attention in the early design phase to avoid experimental development loops(19). The available forced response calculation method allows this. Adaptation of hot gas test benches enable the related experimental validation of performance and durability(26), (27).

By electric actuating, the scroll connection valve combines the function of wastegating and variable turbine admission. It is exposed to high temperature pulsating flow, and under valve closed conditions leakage needs to be minimized for best low-end performance. Reliability is of the utmost importance and therefore, FEV Europe GmbH, the RWTH Aachen University and IHI conducted dedicated multi-step research and method development work that focused on improved simulation and testing of DS systems. The measurement results were used to calibrate an elastic Multi Body Simulation (MBS) model and revealed the dominant parameters of this highly non-linear system. Good agreement between measurement and simulation was achieved. This work represents a consequent step towards frontloaded analysis for shortest development times of new TCs(28). Respectively, the DS turbine is introduced into IHI's product portfolio(29).

2.5 Automized Optimization

Advanced numerical simulation allows automized optimization. Various methods and optimization algorithms are readily available and can be applied. Most of the effort is usually on automizing the calculation process to enable wide parameter variation without manual interaction. Educated engineering input is required in terms of identifying relevant parameters and their range of variation as well as suitable target definition. Many publications imply the employment of Artificial Intelligence (AI), whereas in most cases data science and in some cases machine learning via, for example, neural networks is applied. The necessary intelligence to select boundary conditions and decide on compromises between competing requirements is still from human engineers.

The herewith presented example on optimization is related to the development of TC thrust bearings. This component needs to compensate the steady and unsteady axial forces between compressor and turbine(30). The pad geometry on the circular disc is defined in a way to generate a stable oil film between the rotating and the stationary parts. The best compromise between simplicity of the layout, generated loss and offered thrust capacity is essential. **Figure 11** shows the local pressure distribution with four pads after optimization. The parameters, such as pad diameter and pad depth to name two only, were defined to assemble a Metamodel of Optimal Prognosis. Optimization was performed using a standard

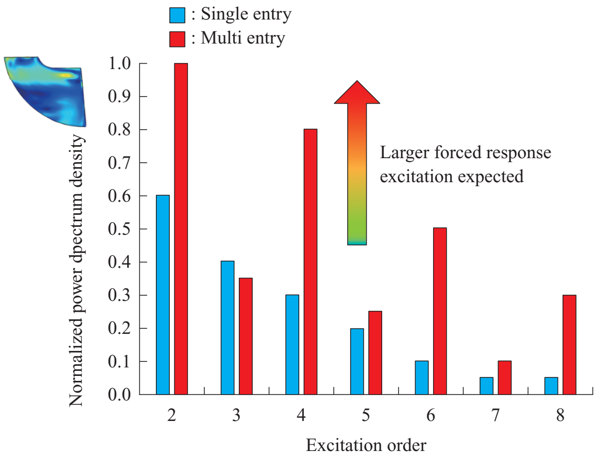


Fig. 10 Calculated blade vibration excitation for different excitation orders for single and multi-entry (double scroll) turbine(19)

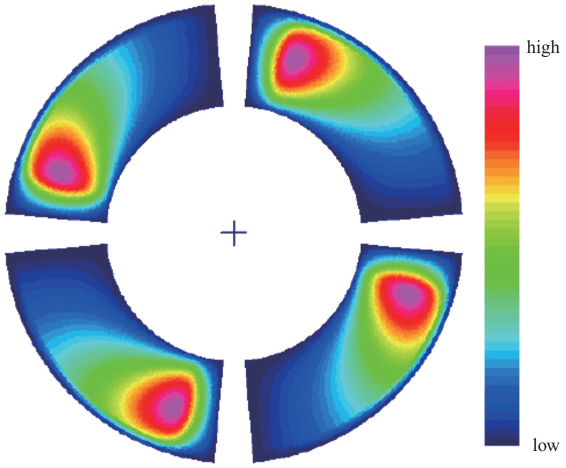


Fig. 11 Local pressure distribution on a thrust bearing with four pads after optimization(31)

evolutionary algorithm. More than 10 000 different designs were calculated, considering always two selected operating conditions. The results show a more homogeneous pressure distribution on the thrust bearing. Under the same conditions the oil film thickness is increased by 35% while the frictional loss is reduced by 15%. The experimental validation was successful and confirmed the prediction.

Additionally, numerical parameter variation allows the judgment of the design robustness considering tolerances from manufacturing. This permits cost optimization since tolerances can be increased in a way that robust function is not compromised(31).

In daily engineering work parameterized CFD models help to minimize losses in TC housings and flow channels including ducts to the neighboring engine components in the given design space. Flow uniformity downstream of the turbine is an explicit optimization target for optimal catalyzer function. Stress optimization is also routine work. Parametric models for Finite Element Analysis (FEA) helped to increase compressor tip speed over the years without any compromise on proven stress limits.

The presented methods are not restricted to serve ICE development but can be applied to various carbon free technologies with their need for pressurized gases, loss minimization and general optimization as well as complex multi objective system optimization.

3. Turbocharger technology for a carbon free society

This large field cannot be treated comprehensively in this paper but is limited to very few examples from hydrogen Fuel Cell (FC) technology.

Pressurizing Proton Exchange Membrane (PEM) FCs reveal better power density and efficiency with a sweet spot in the range of about 2.5 bar operating pressure. Depending on the pressure loss of the stack a turbine can recover more than 30% of the compression power(3). Accordingly, centrifugal turbomachinery is most suitable(32). For turbine operation with wet air, experience from investigations on compressors with LPEGR can be utilized(33). High-temperature PEM FCs operated at about 200°C have even better recuperation potential and are less challenging in terms of water management. Waste heat recovery can be employed by using a bottoming cycle with compression and recuperation(34).

The high temperature (800 to 900°C) and pressure operation of molten carbonate FC and solid oxide FC make them even more suitable for energy recovery via turbomachinery. For the challenges from high temperature operation, experience from ICE TCs up to 1 050°C can be utilized.

4. Summary

The paper at hand gives insight into advanced TC development. It describes methods and efforts taken to analyze, understand and model TC behavior under engine operation. This understanding is fundamental for sophisticated requirement analysis employing engine system simulation. Based on this, TC product properties are tailored to achieve the best propulsion system performance and efficiency as well as the lowest emissions considering modern electrified powertrains. Related development methods are briefly explained, and exemplary results are described. Interplay of simulation and experimental work and collaboration with universities and research institutes enabled composing a set of tools for predictive, front-loaded, and therefore efficient development. Based on the existing technology portfolio the methods will serve for future improvements and adaptations of TC technology for low emission and low fuel — as well as e-fuel — consumption engines. It will support transformation into a society that does not depend on fossil fuels.

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REFERENCES

(1) J. Short and D. Crownover : Understanding the CO_2 Impacts of Zero-Emission Trucks – A Comparative Life-Cycle Analysis of Battery Electric, Hydrogen Fuel Cell and Traditional Diesel Trucks, American Transportation Research Institute, 2022

(2) IEA : The Future of Hydrogen, Seizing Today's Opportunities, Technology Report, 2019, < https://www.iea.org/reports/the-future-of-hydrogen >

(3) D. Filsinger, G. Kuwata and N. Ikeya : Tailored Centrifugal Turbomachinery for Electric Fuel Cell Turbocharger, International Journal of Rotating Machinery, 2021, < https://doi.org/10.1155/2021/3972387 >

(4) D. Filsinger, J. Ehrhard, G. Kuwata and N. Ikeya : Electric turbocharger for fuel cells – IHI's contribution to sustainable mobility, FC^3 Fuel Cell Conference Chemnitz, 2021, < https://d-nb.info/1258950987/34 >

(5) B. Lüddecke, D. Filsinger and M. Bargende : On Wide Mapping of a Mixed Flow Turbine with Regard to Compressor Heat Flows During Turbocharger Testing, 10th International Conference on Turbochargers and Turbocharging, IMechE, 2012

(6) Y. Watanabe, N. Ikeya, D. Filsinger and S. Okamoto : Heat Transfer Modelling in Vehicular Turbochargers for Engine Simulation, 14th International Conference on Turbochargers and Turbocharging, IMechE, London, 2020

(7) B. Lüddecke, D. Filsinger, J. Ehrhard and M. Bargende : Heat transfer correction and torque measurement for wide range performance measurement of exhaust gas turbocharger turbines, Turbocharger Conference, Dresden, 2012

(8) B. Lüddecke, D. Filsinger and M. Bargende : Engine crank angle resolved turbocharger turbine performance measurements by contactless shaft torque detection, 11th International Conference on Turbochargers and Turbocharging, IMechE, 2014

(9) W. Köhl, M. Kreschel and D. Filsinger : Experimental and numerical investigations on an automotive

turbocharger with a transparent bearing section, 11th International Conference on Turbochargers and Turbocharging, IMechE, 2014

(10) S. Leichtfuss M. Kreschel, L. Durbiano, T. Dielenschneider, R. Nordmann, H. Atzrodt, R. Pilotto and H.-P. Schiffer : Advanced measurements and model update of an automotive turbocharger with full-floating journal bearings, The 13th International Conference on Dynamics of Rotating Machinery, Copenhagen, 2019

(11) B. Hoepke, T. Uhlmann, S. Pischinger, B. Lueddecke and D. Filsinger : Analysis of Thrust Bearing Impact on Friction Losses in Automotive Turbochargers. Journal of Engineering for Gas Turbines and Power, Vol. 137, 2015

(12) M. Rode, D. Filsinger, G. Iosifidis and L. Durbiano : Turbocharging for Combustion Engines in Hybrid Propulsion Systems, MTZ worldwide, 2021

(13) B. Lüddecke, D. Filsinger and J. Ehrhard : On Mixed Flow Turbines for Automotive TC Applications. International Journal of Rotating Machinery, 2012, < https://doi.org/10.1155/2012/589720 >

(14) M. Rode, T. Suzuki, G. Iosifidis and T. Scheuermann : Electric Turbocharger Concept for Highly Efficient Internal Combustion Engines, MTZ worldwide, 2019

(15) M. Rode, D. Filsinger, G. Iosifidis and T. Suzuki : Influencing the Turbine Outlet Temperature in Stoichiometric Gasoline Engines, MTZ worldwide, 2021

(16) T. Fujiwara, T. Bamba, R. Numakura, Y. Sasaki and Y. Yokoyama : Variable geometry compressor development to improve operating range and efficiency for automotive turbocharger, 13th International Conference on Turbochargers and Turbocharging, IMechE, 2018

(17) J. Walkingshaw, S. Spence, J. Ehrhard and X. Thornhill : An Experimental Assessment of the Effects of Stator Vane Tip Clearance Location and Back Swept Blading on an Automotive Variable Geometry Turbocharger, GT2012-69776, Proceeding of ASME Turbo Expo, 2012

(18) T. Leonard, M. Model, A. Starke, M. Kiessling and T. Asakawa : IHI Variable Geometry System Turbocharger for Gasoline Application – Performance, Durability, Industrialization, Turbocharger Conference, Dresden, 2022

(19) D. Hemberger, R. DeSantis and D. Filsinger : Double Scroll Turbine for Automotive Applications: Engine Operating Point versus Dynamic Blade Stress from Forced Response Vibration. GT2018-76590, Proceeding of ASME Turbo Expo, 2018

(20) D. Hemberger, D. Filsinger and H.-J. Bauer : Identification of Mistuning for Casted Turbine Wheels of Small Size, GT2014-25099, Proceeding of ASME Turbo Expo, 2014

(21) D. Hemberger, D. Filsinger and H.-J. Bauer : Mistuning Modeling and its Validation for Small Turbine Wheels, GT2013-94019, Proceeding of ASME Turbo Expo, 2013

(22) D. Hemberger, D. Filsinger and H.-J. Bauer : Damping Behavior of Blades from Small Radial Turbines, GT2015-42634, Proceeding of ASME Turbo Expo, 2015

(23) D. Hemberger, D. Filsinger and H.-J. Bauer : Influence of Aerodynamic Mistuning and Aerodynamic Coupling on Vibration Behavior of Mistuned Small Radial Turbine Wheels, GT2017- 63069, Proceeding of ASME Turbo Expo, 2017

(24) J. Walkingshaw, G. Iosifidis, T. Scheuermann, D. Filsinger and N. Ikeya : A Comparison of a Mono, Twin and Double Scroll Turbine for Automotive Applications, GT2015-43240, Proceeding of ASME Turbo Expo, 2015

(25) T. Suzuki, G. Iosifidis, J. Starzmann, W. Sato, D. Filsinger and T. Bamba : 1D gas exchange modelling of double scroll turbines: Experimental validation and improved modelling, 14th International Conference on Turbochargers and Turbocharging, IMechE, 2020

(26) B. Lüddecke, H. Mai, A. Spietzack, et al. : Hot Gas Test Stand Technology in the Context of Multi-Scroll TC Turbine Development, Turbocharger Conference, Dresden, 2016

(27) T. Otobe, A. Iwakami and D. Filsinger : Blade vibration visualization of dual volute turbine with vaned nozzle by using high speed Digital Image Correlation, accepted for publication 15th International Conference on Turbochargers and Turbocharging, IMechE, 2022

(28) M. Stadermann, F. Falke, J. Perge, D. Lückmann, J. Starzmann, R. De Santis, D. Hemberger, J. Huh and T. Bamba : Advanced Simulation and Testing Methods to Understand and Predict Wastegate Dynamics of a Double Scroll Turbine, Turbocharger Conference, Dresden, 2020

(29) M. Rode, T. Suzuki, G. Iosifidis, L. Durbiano, D. Filsinger, A. Starke, J Starzmann, N. Kasprzyk and T. Bamba : Boosting the Future with IHI: a comparative evaluation of state-of-the-art TGDI turbo concepts, Turbocharger Conference, Dresden, 2019

(30) B. Lüddecke, P. Nietsche, M. Dietrich, D. Filsinger and M. Bargende : Unsteady Thrust Force Loading of a Turbocharger Rotor During Engine Operation, Journal of Engineering for Gas Turbines and Power, Vol. 138, 2016

(31) L. Jaennike et al : Optimization of a Thrust Bearing for Turbocharger, Optislang Conference, 2019

(32) A. Kerviel, A. Pesyridis and D. Chalet : Boosting System Options for High Efficiency FC Electric Vehicles, 4th Biennal International Conference on Powertrain Modelling and Control Testing, Mapping and Calibration, UK, 2018

(33) D. Talmon-Gros, B. Huurdeman, B. Lüddecke and D. Filsinger : Analysis of Components for Low-Pressure Exhaust Gas Recirculation, MTZ worldwide, 2014

(34) H. Xing, C. Stuart, S. Spence and H. Chen : Fuel Cell Power Systems for Maritime Applications: Progress and Perspectives, 13, 1213, 2021, < https://doi.org/10.3390/su13031213 >

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Inquiries:
Editorial office of IHI ENGINEERING REVIEW
ihi-ty9776@ihi-g.com