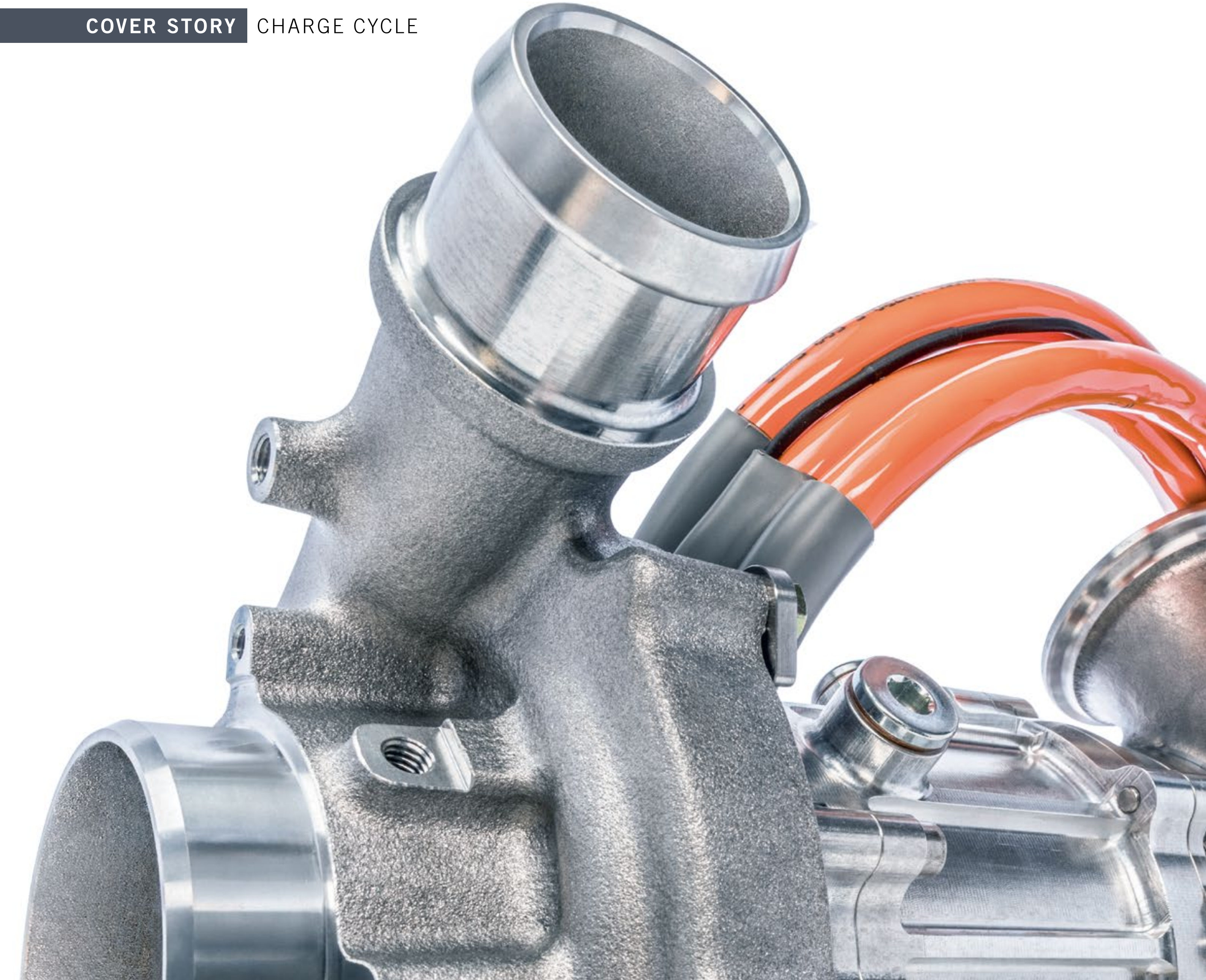

Electrically Assisted Turbocharger for the 48-V Board Net

Pankl Turbosystems and Federal-Mogul Powertrain have jointly developed an electrically assisted turbocharger (EAT) for the 48-V board net. This flexible charging system serves to meet core requirements of modern powertrain development. Simulation and rigorous testing programs have demonstrated the potential to enhance enjoyable driving characteristics while at the same time improving fuel efficiency.

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ENHANCED REQUIREMENTS TO THE CHARGING SYSTEM

In recent years, charging the combustion engine – especially the combination of downsizing and downspeeding – has proved to be a valuable approach to improving fuel efficiency, reducing emissions and increasing driving performance [1]. However, if increasingly strict emissions regulations are to be met by ongoing engine development, the transient response of highly-charged engines during load steps is an obstacle which needs to be overcome via new charging system concepts. To fulfil these requirements, widespread hybridisation as the next evolutionary step of the conventional powertrain is likely to be the answer [2]. Electrification of the charging system is one of the options for addressing the challenge [3-5]. The prototypical electrically assisted turbocharger (EAT) portrayed as follows was developed to work with a 48-V board net and 2.0-l four-cylinder gasoline engine designed for a sporting mid-size vehicle. The development goal was to bring down fuel consumption while improving driving performance. This target was met by combining an EAT with a downspeeded powertrain. Another aspect that has been explored is the potential for recovering energy from the exhaust gas to increase efficiency. Drive cycle simulations and real driving situations were simulated to compare the EAT with competing solutions.

CONCEPT AND DESIGN OF THE ELECTRICALLY ASSISTED TURBOCHARGER

Based on Pankl's deep turbo know-how and leveraging Federal-Mogul Powertrain's expertise on materials, tribology and engine testing, an EAT concept was defined, which offers a high level of flexibility and customer-specific applicability plus easy assembly. In addition to its suitability for various powertrain and engine concepts, the EAT supports different levels of powertrain hybridisation and on-board infrastructures of 48 V or higher. **FIGURE 1** provides a cross section of the EAT.

The EAT mass is split roughly 50:50 between the turbocharger and the electric motor. In the longitudinal direction it only adds 90 mm to a conventional turbocharger at a stator length of 100 mm. Packaging and weight could be further optimised with increased power density of the e-machine. Compared to a dynamically adapted charging system in combination with an electrically assisted compressor (EAC), the EAT offers packaging benefits thanks to the reduced number of components.

Integrating the electric motor with its added rotor mass significantly affects system's rotordynamics, which requires the development of a custom, robust bearing system and specific balancing process. This resulted in a newly developed hybrid bearing assembly. It consists of a journal bearing (floating bushing) on the turbine side and a double-row oil-lubricated ball bearing with an optional squeeze film damper on the compressor side. Combining the stiffness of a ball bearing with the

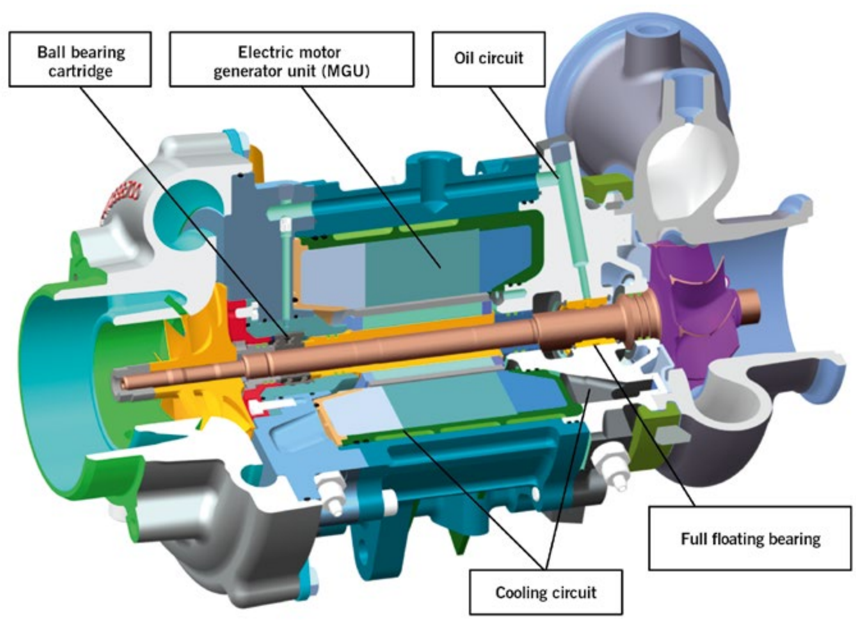

FIGURE 1 Cutaway view of the electrically assisted turbocharger (EAT) (© Pankl Turbosystems | Federal-Mogul LLC)

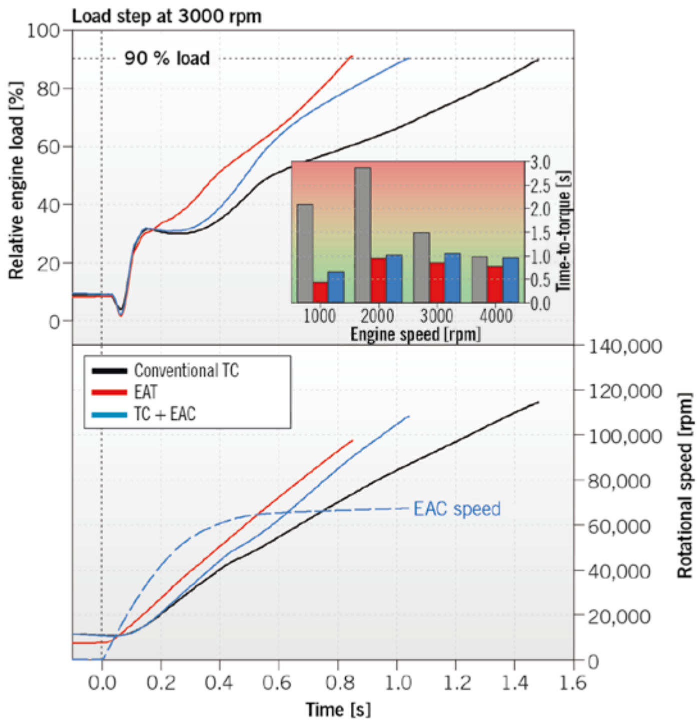

FIGURE 2 Transient load step response of the three charging systems under review (© Pankl Turbosystems | Federal-Mogul LLC)

damping properties of a bearing bushing made it possible to design a durable bearing system suitable for the high rotational speed of a conventional turbocharger.

The EAT's cooling circuit was scaled to allow the combustion engine to run at up to 1050 °C exhaust gas temperature and to run the electric motor permanently at full load at the same time. The cooling system's performance was validated by computational fluid dynamics (CFD) simulation and during hot gas stand testing.

The electric motor was tuned to meet the static and dynamic specification requirements at an optimal power-to-weight ratio. A key element of this was the use of a specific stator design with layered high-frequency sheet, a high copper filling factor and a permanently excited synchronous motor with a low number of pole pairs. Materials and technologies were chosen with industrialisation in mind. Considering the underlying 48-V electrical system, the power was limited to 20 kW albeit ensuring that the maximum continuous torque remains available up to maximum motor speed.

The aerodynamic components were optimised according to the requirements of the EAT system. The compressor stage was given an increased efficiency level and an improved stability near the surge line. The turbine stage inertia was designed using traditional turbocharger principles: using a relatively small turbine wheel together with a closed wastegate at the engine LET point. Further effort went into optimising the turbine with a view to harvest exhaust gas energy to increase the drivetrain efficiency.

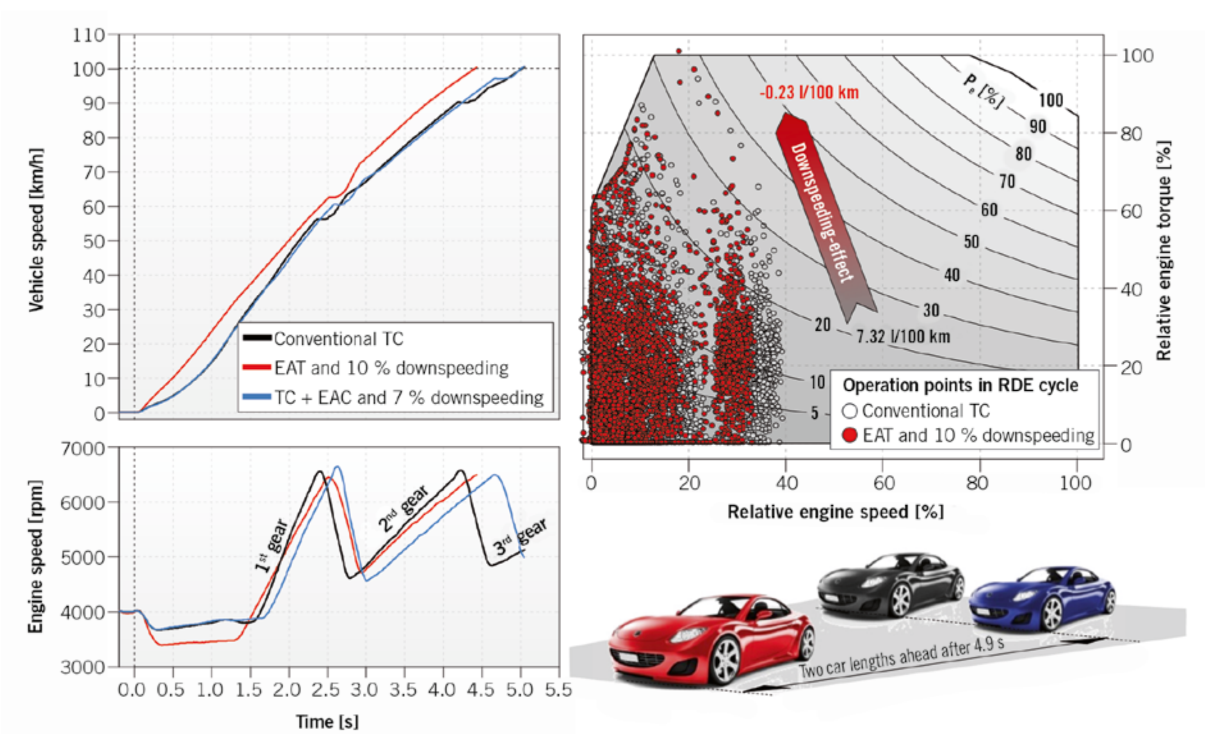

FIGURE 3 EAT and downspeeding enable improved acceleration and better fuel efficiency (© Pankl Turbosystems | Federal-Mogul LLC; cars: Rawpixel.com | Shutterstock.com)

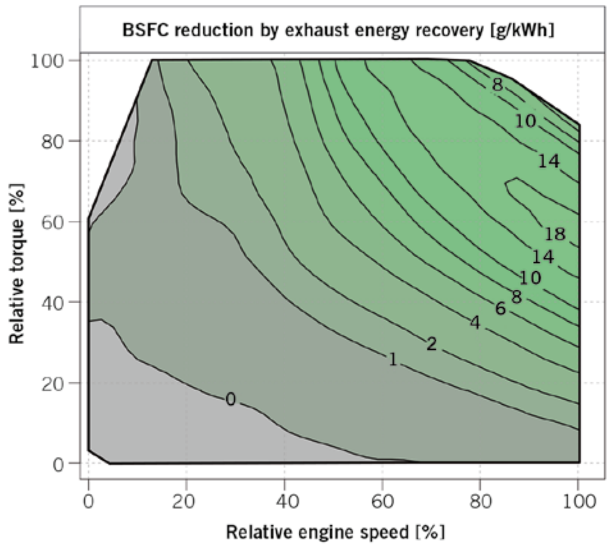

FIGURE 4 Lower brake specific fuel consumption (BSFC) via exhaust gas energy recovery (© Pankl Turbosystems | Federal-Mogul LLC)

ANALYTICAL ASSESSMENT OF THE 48-V EAT SYSTEM

Development and analytical assessment of the EAT was conducted in three steps, which enabled a detailed evaluation of the system's potential. In addition to analysing various operating strategies, a comparison of several charging concepts was carried out. These included not only the conventional turbocharger (TC) and the EAT, but also a TC with an additional electrically assisted compressor (EAC). Downspeeding was considered as the primary strategy to increase fuel efficiency. Electrical charging assistance is utilised to enable downspeeding without negatively impacting driving characteristics. It is important to note that the added mass of the electric motor does increase the system's inertia, an effect which needs to be over-compensated by the electric motor. The potential for exhaust gas energy recovery was also assessed.

The starting point was TC matching based upon engine parameters and measured or CFD-calculated turbine and compressor maps, which allowed initial predictions about the charging system's stationary behaviour. The aerodynamic components are defined during this stage, taking into consideration the electric motor's boundary conditions referring to the rotor speed strength. A comprehensive evaluation of the EAT potential was done via 1-D engine process simulation, that served to assess the interaction between charging system and the engine.

In addition to analysing stationary full-load curves and engine maps, the systems' load-step response was evaluated at constant engine speed. **FIGURE 2** depicts the transient load response of the three charging systems under review at 3000 rpm plus the time required until 90 % of the maximum steady state torque is achieved. Owed to the electric motor's high torque, the EAT offers a qualitative and quantitative benefit over the conventional TC and the TC with EAC. The load response is faster and nearly constant across all engine speeds, which translates into considerably improved dynamics and driveability.

The complete powertrain was modelled and real drive cycles such as the NEDC, WLTP, and RDE applied. To assess the dynamic performance of the complete powertrain, the vehicle acceleration characteristics were simulated. In addition to in-gear acceleration (80 to 120 km/h), the acceleration from halt to 100 km/h was also calculated. The baseline was provided by the conventional TC without downspeeding.

Owed to their dynamic load response the electrified charging systems permitted 7 % downspeeding in the case of the TC with EAC, and 10 % downspeeding in the case of the EAT – without any negative impact on in-gear acceleration. Under real driving conditions, the EAT reached a fuel efficiency benefit of 0.23 l/100 km in comparison to the conventional TC. This equals a reduction of CO_2 emission by 5.3 g/km. At the same time the 0 to 100 km/h acceleration time was reduced by 0.5 s. The results are shown in **FIGURE 3**.

The potential for recovering exhaust gas energy was assessed by measuring the brake-specific fuel consumption (BSFC). The amount of harvested energy was factored in as part of the system performance following the logic that recuperation adds to the fuel efficiency. In the fired engine and under real driving conditions only a very limited potential for exhaust gas energy recovery was observed, with little leverage for an efficiency increase. However, when the engine is running at high load considerable benefits for the system-specific fuel consumption can be observed. To limit any negative influence on the engine's charge exchange, the cylinder back pressure p3 was limited to 2.5 bar via a wastegate control. By further optimising the aerodynamic components towards exhaust gas energy recovery the potential for energy harvesting can be further expanded. The research results are shown in **FIGURE 4**.

TESTING ON THE HOT GAS TEST STAND

The EAT was tested on hot gas test stands. During this examination the compressor map and expanded turbine map measurement (in the closed loop mode) were complemented by endurance testing to verify the mechanical and electrical performance. The system was continuously run under thermodynamic and electric full-load conditions at up to 1050 °C. A battery simulator and a 48-V high-frequency inverter were used to drive the electric motor. In this process the system dynamics and the potential

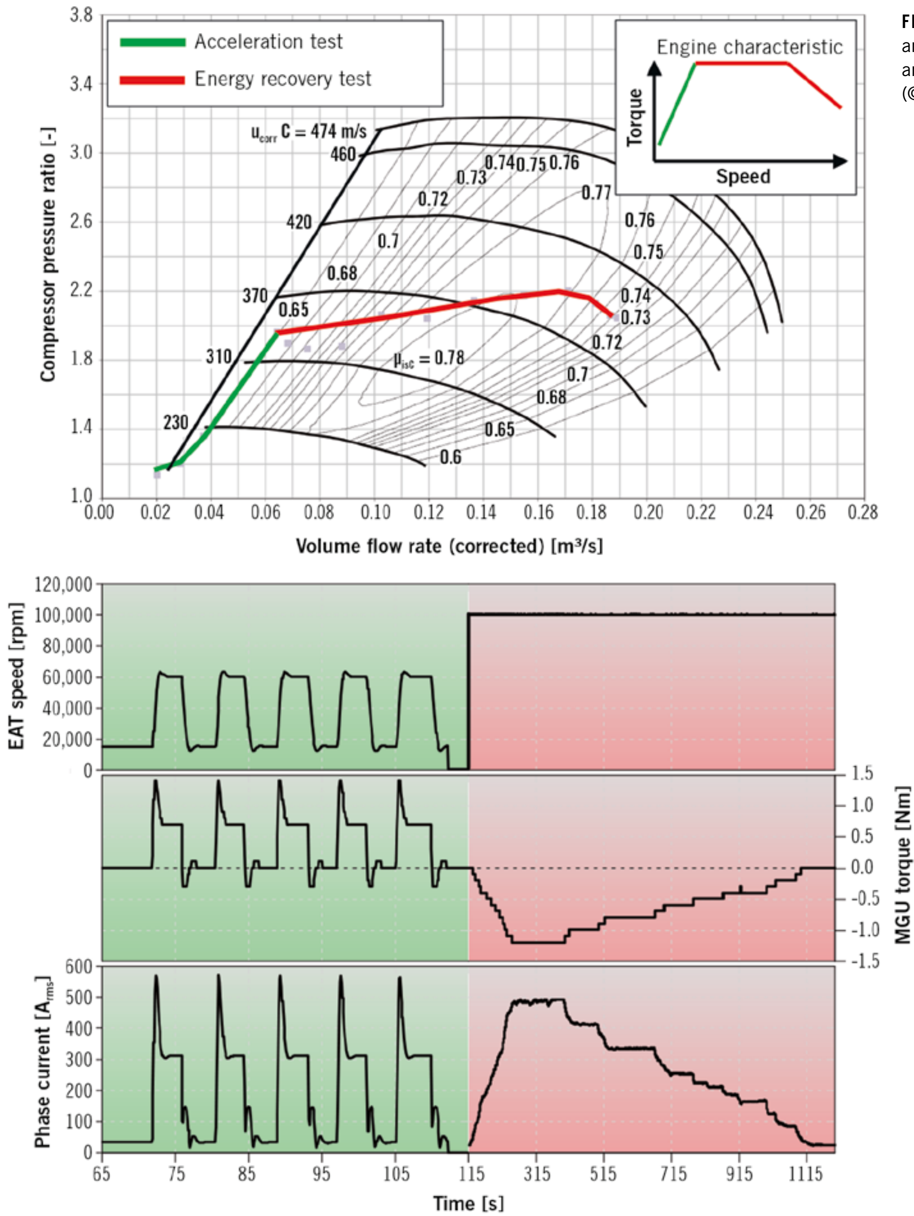

FIGURE 5 Use areas for electric assistance and respective results from acceleration and energy harvesting (hot gas test stand) (© Pankl Turbosystems | Federal-Mogul LLC)

for exhaust gas energy recovery were experimentally determined. All temperature limits relevant to the system operation could be met under full-load conditions. There was no thermal overload of either the bearing components or the electric motor. **FIGURE 5** depicts the results.

In addition to the performance testing, numerous tests were carried out to validate the mechanical functioning of the rotor dynamics and the bearings. The correct functioning of the bearing system was evaluated and demonstrated via shaft motion and acceleration measurement, which confirmed that the system is also stable at the resonance frequency, **FIGURE 6**.

SUMMARY AND OUTLOOK

This brief review of the electrically assisted turbocharger's (EAT) development process provides an overview of the system concept and design. It also gives insight into the analytical evaluation of its contribution to fuel efficiency, and its concurrent dynamic performance advantage when measured against competing systems. The newly developed bearing solution facilitates a flexible adaptation of the concept to varying applications.

Besides the standard application of the compressor and turbine stage, an application of the electric motor to hybrid concepts and on-board systems with voltages ranging from 48 to 800 V is also possible with comparable system dimensions. The greatest system benefit lies in its flexibility, which is owed to the integration of the electric motor. Because of this, a single system configuration can serve to support many combustion engine operating strategies by optimally controlling energy flow.

The concept examined above was assessed via simulation based on a sporty mid-range application. The EAT functionality was confirmed on the hot gas test stand under full-load conditions and within transient load build up testing. As a result, the system's performance in terms of thermodynamics, mechanical and electric functionality

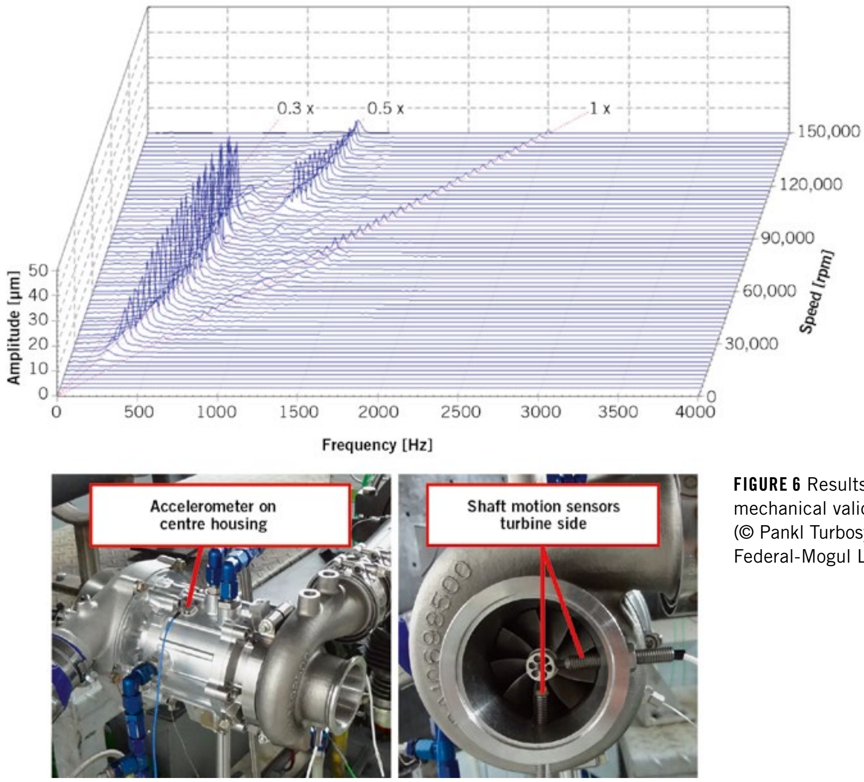

FIGURE 6 Results of mechanical validation (© Pankl Turbosystems | Federal-Mogul LLC)

was demonstrated. Simulation results and measurements showed good correlation across all areas of interest. Combining the EAT with downspeeding of the powertrain resulted in greatly improved driving performance and reduced fuel efficiency.

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