Turbocharger Joint Research Organization with Imperial College London

YASUAKI JINNAI[*1] SEIICHI IBARAKI[*2]
TORU HOSHI[*3] MOTOKI EBISU[*4]
TAKAO YOKOYAMA[*5] NOBUHITO OKA[*6]

In Europe, which is a major market for turbochargers, Imperial College London (ICL) and the Mitsubishi Heavy Industries (MHI) Group have a history of nearly 20 years of joint research, people-to-people exchanges and other activities. Amid calls for decarbonization and the electrification of passenger cars, a joint research organization (UTC: University Technical Centre) was established with ICL in 2019 to intensively carry out innovative and targeted research. In this report, we describe the results of our research with the university that contributed to the improvement of MHI turbocharger technology, the activities of the newly established organization and our involvement in the turbocharger business of Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (MHIET).

1. Introduction

The MHI Group has been mass-producing turbochargers for passenger cars since the 1970s and initially developed the technology in Japan. Since the main turbocharger market is in Europe, our turbocharger business has gradually shifted its focus to Europe, where the business has grown by developing and manufacturing turbochargers for local automobile manufacturers. We recognized the necessity of developing turbocharger technology in accordance with the requirements of the European market at an early stage and the MHI Research & Innovation Center has been conducting joint research with European universities and research institutes. Mitsubishi Turbocharger and Engine Europe B.V. (MTEE), which produces turbochargers at its European base, acquired engineering functions in the late 1990s and research and development functions for turbochargers in the 2010s.

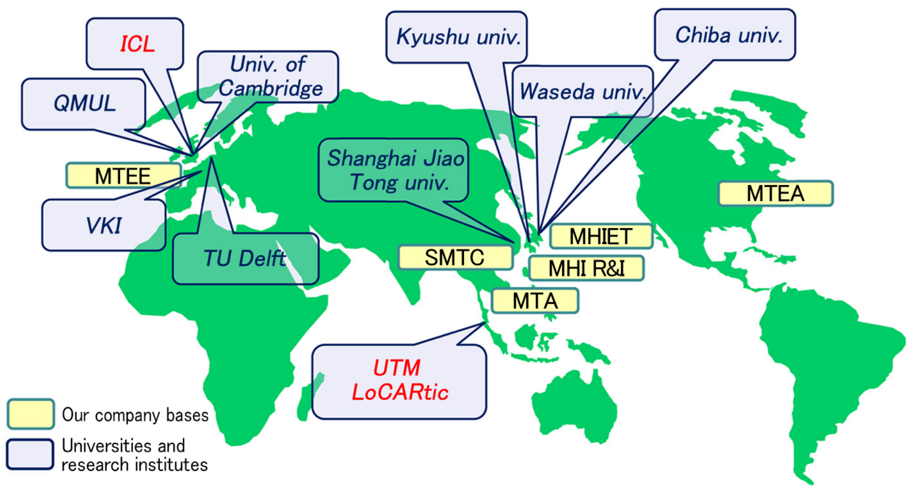
There is an ever increasing need decarbonization in countries around the world, Europe, is home to many environmentally-advanced nations and where industry-academia cooperation between automotive manufacturers and universities is active. MHIET has developed a system to disseminate Mitsubishi turbocharger technology by establishing a strong development partnership there utilizing MTEE, which has grown its engineering functions, as well as cooperative networks developed mainly by the MHI Research & Innovation Center.

2. Cooperation in Global Development of Mitsubishi Turbochargers

The MHI Group is developing turbochargers not only at the MHI Research & Innovation Center and overseas bases of the MHI Group, but also in cooperation with universities and research institutes in various regions. The development system is shown in **Figure 1**. Our bases in Europe

*1 Deputy Director, Engineering Department, Turbocharger Division, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd.
*2 General Manager, Turbomachinery Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.
*3 Turbomachinery Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.
*4 Chief Staff Manager, Engineering Department, Turbocharger Division, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd.
*5 Chief Staff Researcher, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.
*6 Engineering Department, Turbocharger Division, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd.

and China, which are major markets for turbochargers, have engineering and development functions, and also conduct exchanges with local universities and research institutes. Each base, university and institute are developing products that meet the needs of each market, while taking advantage of their characteristics and fields of expertise, aiming to improve their overall capabilities by leveraging each other. Technological innovation in turbocharging systems for passenger car powertrains requires research and development in a wide range of fields including: fluid mechanics, thermodynamics, tribology, electrical control and development needs. It becomes difficult to advance our development in the light of the speed of the market change, as such, collaboration with external research institutes is becoming increasingly important.



QMUL：Queen Mary Univ. of LondonQMUL
VKI：von Karman Institute for Fluid DynamicsVKI
TU Delft：TU Delft Univ. of Technology
UTM：Universiti Teknologi Malaysia
LoCARtic：Low Carbon Transport
MHIET: Mitsubishi Heavy Industries Engine & Turbocharger, Ltd.
MHI R&D: Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.
MTA: Mitsubishi Turbocharger Asia Co., Ltd.
SMTC: Shanghai MHI Turbocharger Co., Ltd.
MTEA: Mitsubishi Turbocharger and Engine America, Inc.
MTEE: Mitsubishi Turbocharger and Engine Europe B.V.

Figure 1 Global bases for Mitsubishi turbochargers and cooperation in global development with universities and research institutes

3. History of collaboration with Imperial College London and achievements to date

ICL was established in 1907 through the merger of the Royal College of Science, the Royal School of Mines and the City & Guilds College and is currently ranked among the top three universities in the EU and in the top ten universities worldwide (The Times Higher Education World University Rankings 2020). ICL is a science and engineering university which consists of engineering, medicine, science, and business faculties. In particular, social contribution through innovative research and development is being promoted, as is practical research focusing on industrial applications. Professor Ricardo Martinez-Botas of the Thermofluids Division of the Faculty of Engineering at ICL focused on the importance of unsteady performance of radial turbines used in turbochargers for the first time anywhere in the world. He proposed ideas for the effectiveness and performance enhancement of mixed flow turbines under pulsating flow by elucidating unsteady phenomena and developing a one-dimensional performance evaluation method using a test device developed by ICL that can measure performance and flow phenomena under pulsating flow as shown in **Figure 2**. In 2003, the MHI Research & Innovation Center held an exchange meeting with the professor and officially started joint research on the unsteady performance of radial turbines in 2005. Since then, joint research on performance innovation of turbocharger turbines and compressors has continued. As a representative result, in order to improve turbine efficiency under pulsation of the engine, a new turbine volute and a mixed flow turbine were developed by optimizing the rate of change of a cross sectional area in the circumferential direction and high performance was achieved in a turbine unit test and engine test(1). The technology was jointly developed as patent in 2013 and mass-produced in 2016, contributing to the reduction of CO_2 emissions from automobiles. In the case of the compressor, the test equipment shown in **Figure 3** was constructed to simulate pressure pulsation accompanying air supply to the actual engine. With the equipment, performance and surge characteristics under pulsation, which had been difficult to understand in the past, were measured and internal flow was clarified by unsteady flow analysis(2). **Figure 4** shows the pressure-flow characteristics of the compressor with and without pulsation. It was found that under pulsation, the surge flow rate decreased by about 8% from the steady flow due to the inertial effect of the flow accompanying the unsteady increase/decrease of the flow rate and surging was suppressed. This result is also being applied to the design of high efficiency compressors of mass-produced products that are actually affected by pressure pulsation. In this way, MHI group has established an effective transfer cycle in which the innovative technologies created through joint research with ICL are rapidly applied to actual products. MHI group has also realized social contributions, which is our joint mission with ICL, and also created a strong relationship of trust. In 2019, MHIET and ICL established a joint research organization (UTC) in order to further strengthen cooperation and enhance the research and development capability. **Figure 5** is a photo of officials from ICL and MHI group at the UTC founding ceremony held in Tokyo.

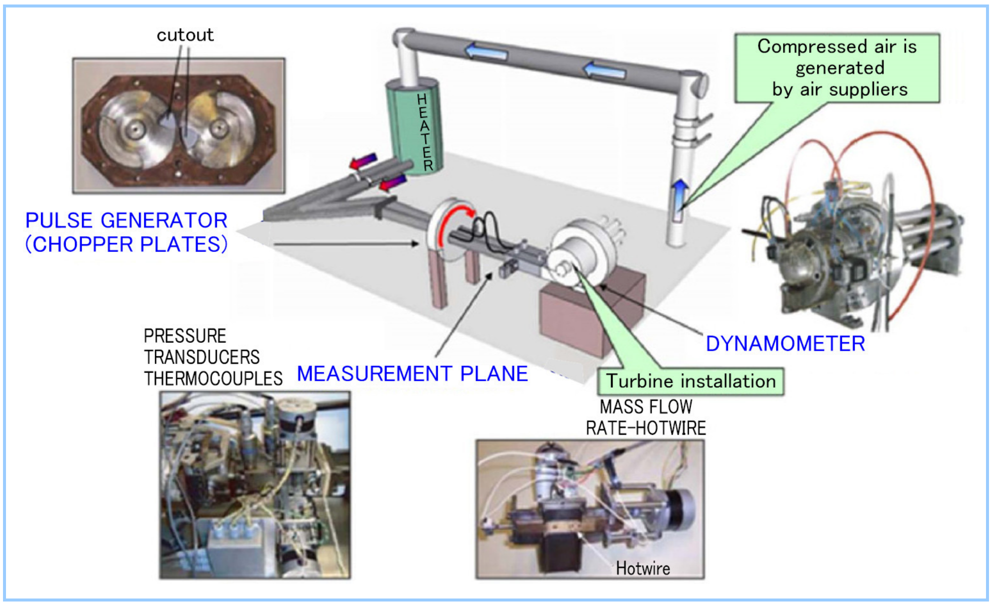


Figure 2　Turbine pulsating flow test equipment at ICL,

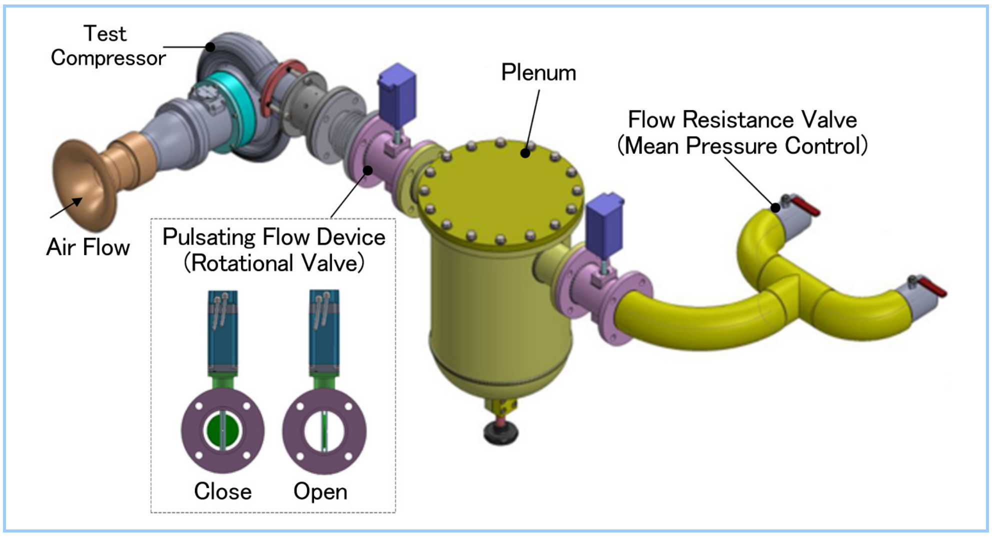


Figure 3　Compressor pulsating flow test equipment

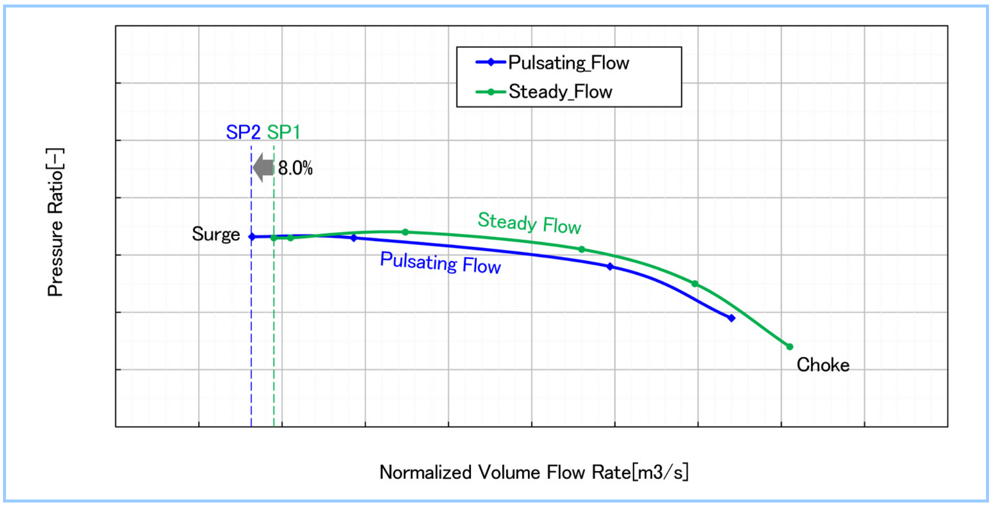


Figure 4　Relationship between presence of pressure pulsation and surge flow rate

Figure 5　UTC funding ceremony, group photo of ICL and MHI Group officials

4. Joint Research Organization and System

In addition to the MHI Research & Innovation Center, which has built a deep relationship through various joint research efforts with ICL on turbochargers for a long time, MTEE, which is a European development base and MHIET, which has a turbocharger business division, have established the MHIET-Imperial Future Boosting Innovation Centre, a joint research organization (University Technical Centre) with the university, under the leadership of the MHI Group. In collaboration with Universiti Teknologi Malaysia (UTM), ICL has also established Low Carbon Transport in Cooperation with Imperial College London (LoCARtic), a research organization which has engine test bench and the system for various verification tests, at UTM to develop turbocharger technology and other low-carbon technologies for transportation equipment. As shown in **Figure 6**, a virtual organization was established to bind these elements. Dr Maria Esperanza Barrera-Medrano (ICL) is the manager of the centre and leading the organization. In this organization, research is conducted on multiple themes at the same time and regular steering meetings are held to confirm the progress of research and review the development strategy.

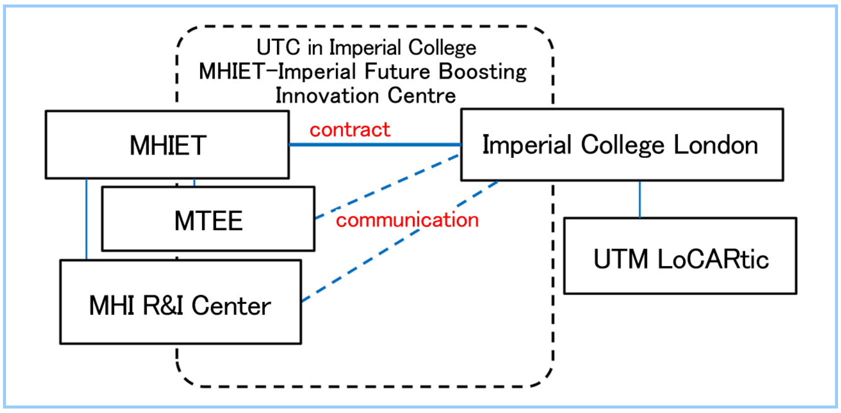


Figure 6 Joint Research Organization and System

5. Contents of Activities

In the joint research with ICL, the flow phenomenon was clarified by unsteady performance measurement under exhaust pulsation and large-scale flow analysis as described above and this led to the development of new high-performance turbines and compressors. At present, in order to respond to the diversification of technical requirements, the scope of the joint research has been expanded from performance enhancement of turbines and compressors to supercharging systems, engine systems and vehicle systems. Examples of research and development at UTC are introduced below.

Since a turbocharger drives a compressor by turning a turbine using the exhaust energy of an engine, air cannot be instantaneously supplied to the intake side and turbo lag occurs. To suppress this, it is effective to improve the transient response performance of the turbocharger and it is particularly important to improve the low flow rate performance of the compressor. To solve this problem, a new compressor cover has been developed by making the cross section distribution of the scroll in the circumferential direction nonlinear. As shown in **Figure 7**, the pressure ratio in the low flow rate region has been improved compared with that of the conventional compressor cover. In order to evaluate this effect on the engine, the ECU (Engine Control Unit) setting including the ignition timing was optimized using the engine verification test facility at LoCARtic shown in **Figure 8**, and the engine response was evaluated. As a result, as shown in **Figure 9**, the new compressor improved the transient response performance by 20% to 60% in all region. This was thought to be caused by an increase in the air density required when the throttle opening was large and the operating point of the compressor shifted to the high pressure ratio side, that is, to the low flow rate side. It was confirmed that the efficiency improvement effect of the new compressor contributed to the improvement of the engine response[3].

In engines for automobiles, performance enhancement in starting and transition is important to improve the environmental performance of the product. For example, in the case of a turbocharger, the thermal management technology downstream of the turbine contributes to the purification of exhaust gas from the engine, from the perspective of shortening the catalyst activation time when the engine is cold-started[4]. As shown in **Figure 10**, there are multiple heat sources inside the turbocharger, such as turbines, compressors, bearings, lubricating oil and cooling water. Therefore, it is necessary to estimate the transient heat transfer state of each part and evaluate the effect on performance by considering the system as a whole. For this, we are developing a transient performance simulation method considering heat transfer and pulsation with ICL.

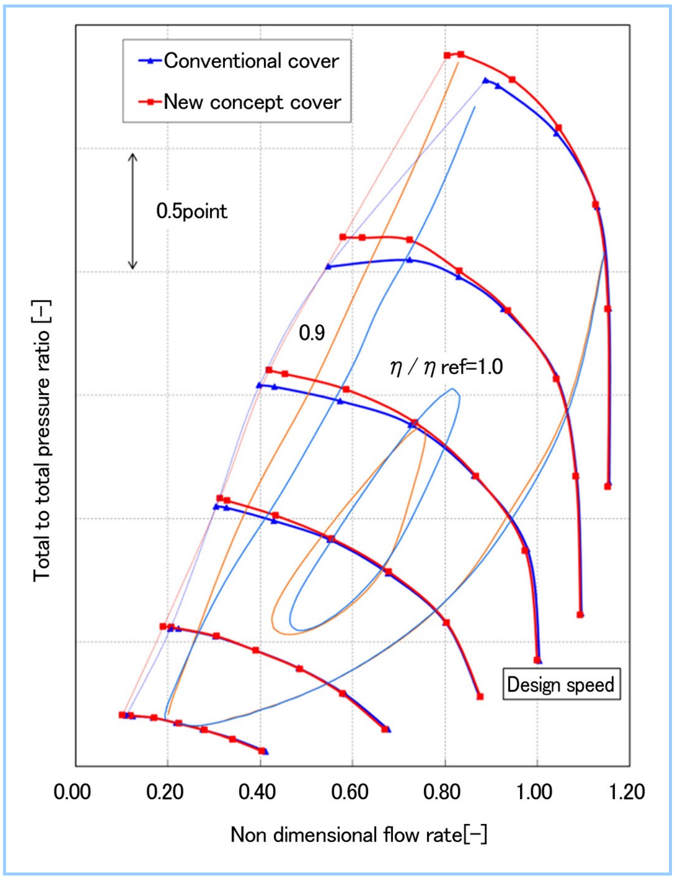


Figure 7　Compressor performance test result

Figure 8　Engine test facility at LoCARtic

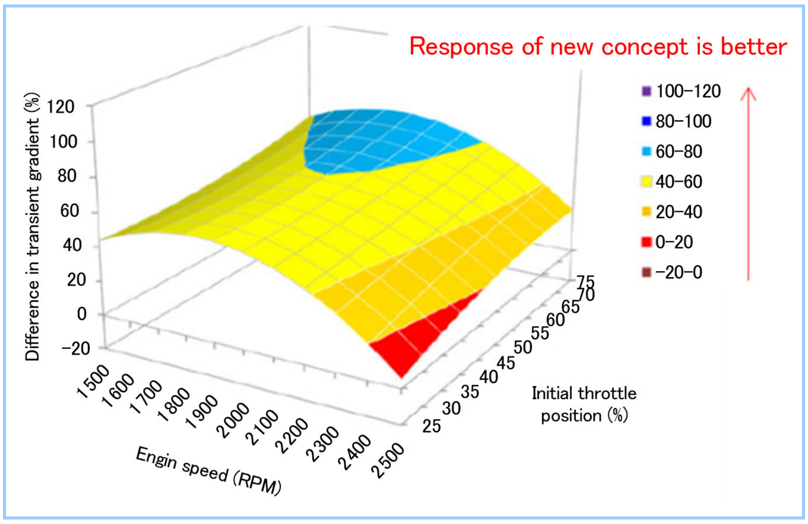


Figure 9　Comparison of engine response between conventional compressor and new concept compressor

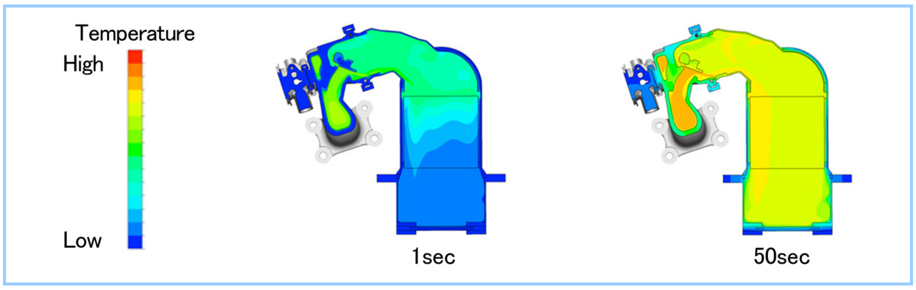


Figure 10 Unsteady turbine CHT (Conjugate Heat Transfer) analysis result at cold start

The realization of the optimum matching of the engine and turbocharger in the development stage of the engine is important for achieving good transient performance and low fuel consumption, which leads to the shortening of the development period. In general, the engine model is treated as quasi-steady instead of considering the transient behavior of the turbocharger. Although this conventional approach can adequately predict steady-state engine performance, there are challenges in accurately predicting transient engine performance. Regarding unsteady low-dimensional models for evaluating the transient behavior of turbochargers, several research efforts have been conducted in the past(5)(6). However, there are still few examples in which these models have been integrated into a one-dimensional engine model for detailed analysis and sufficient knowledge has not been obtained. In order to solve this issue, we are working on the development of a one-dimensional engine simulation method, by which engine performance under exhaust pulsation can be instantaneously predicted and the optimum turbocharger will be proposed according to the customer's engine, as shown in **Figure 11**.

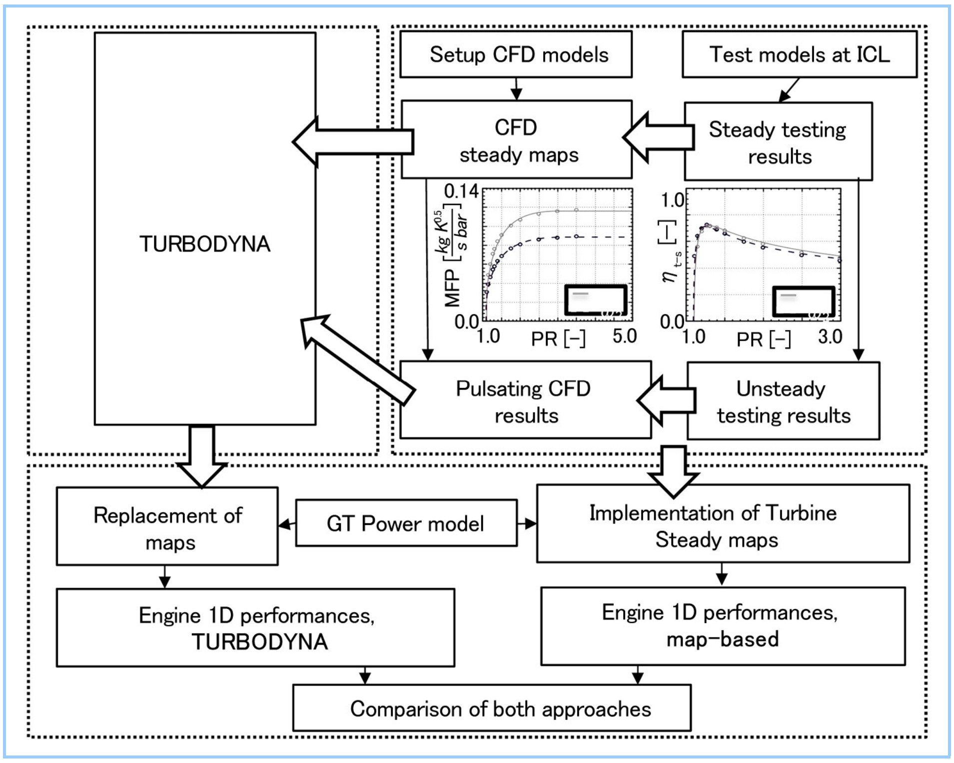


Figure 11 Development flow of engine performance evaluation method considering turbine unsteady performance

In recent years, there has been a high need for the adoption of a double entry turbine for direct injection supercharged engines. In particular, there is an advantage in that the pulsation energy generated from the engine exhaust gas is used for a four-cylinder engine or a six-cylinder engine to reduce the exhaust interference between cylinders in the exhaust stroke and to reduce pump loss.

As shown in **Figure 12**, there are two types of double entry turbines, a twin scroll turbine in which the scroll is arranged in the axial direction and a double scroll turbine in which the scroll is arranged in the circumferential direction. Until recently, the comparison of performance characteristics of these two types of turbines has been widely discussed. The scroll connection valve (SCV) shown in **Figure 13** is used as a flow rate control mechanism of the double scroll turbine and performance characteristics similar to a single scroll can be obtained by opening the valve in a high speed region while realizing the performance characteristics of a divided flow path in the low speed region of an engine. Thus, the matching of the engine and the turbocharger can be improved by making the performance at a small flow rate compatible without sacrificing the engine performance at a large flow rate. However, because it is used in a high-temperature exhaust gas pulsation environment, it is difficult to achieve both performance and reliability and development is being conducted to solve this issue.

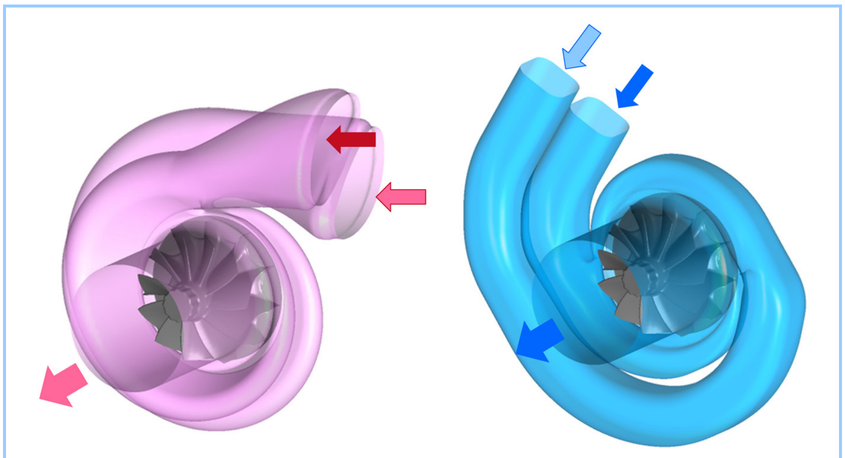


Figure 12 Comparison of double entry turbines structures

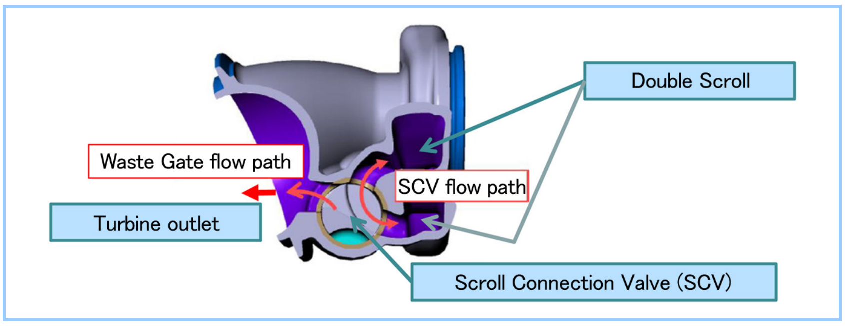


Figure 13 Cross-Sectional view of double scroll turbine SCV and functional description

The MHI Group has been developing electric compressors to improve the fuel efficiency of vehicles through high supercharging pressure and high responsiveness. We have also developed an electric supercharging system in which a turbocharger on the high or low pressure side is replaced with an electric compressor for a normal two-stage turbocharger(7). In the electric supercharging system, energy management of the engine and the battery is important. Therefore, in view of the development trend of the powertrains of passenger cars and the electrification of vehicles such as hybrid systems, we are working on the development of a modeling method of the whole vehicle system in consideration of in-vehicle power supply performance, higher voltage and energy regeneration efficiency. **Figure 14** shows an analysis and control model of the entire hybrid vehicle. In the future, we would like to propose the optimum energy management of the vehicle system by combining it with the fuel efficiency improvement technique of the engine such as the mirror cycle and lean combustion, which are actively being developed.

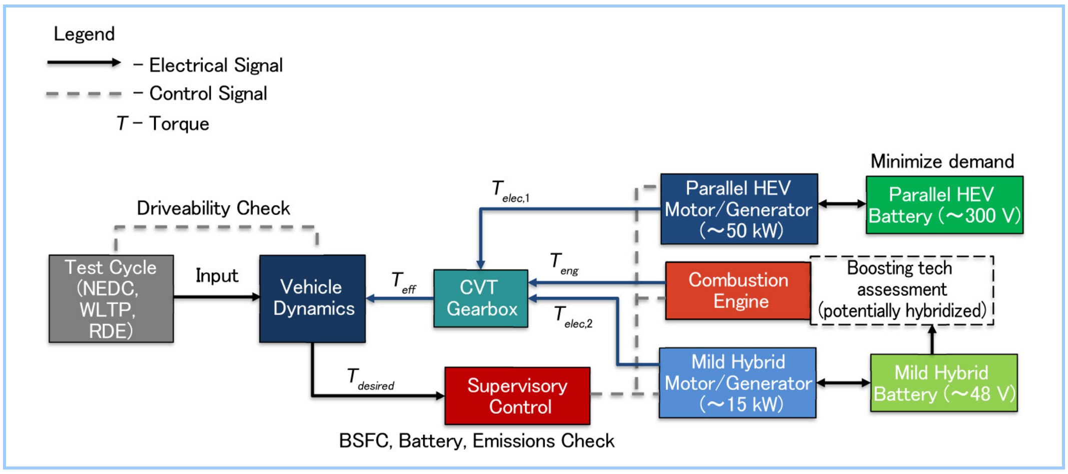


Figure 14 Structure of vehicle system model for hybrid vehicle

6. Conclusion

In the past, MHI and ICL started out with a single joint research project and by increasing the number of research themes and achieving results, the foundation for a partnership with the MHI Group was created. The partnership was not limited to research and development, but also developed into people-to-people exchanges by sending young engineers from MTEE to ICL where they obtained doctoral degrees in turbocharger research. As mentioned above, the research and development of UTC, which was launched this time, covers component technologies and overall turbocharger technology and the range is even expanding to powertrains and the whole vehicle system with an eye to the rapidly-changing development trend of powertrains of passenger cars and the electrification of vehicles. By having this organization, development with a sense of unity among each base was made possible and outcomes from this cooperation are being delivered. Mitsubishi Turbocharger technology from Europe will be introduced to the world by utilizing this UTC.

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