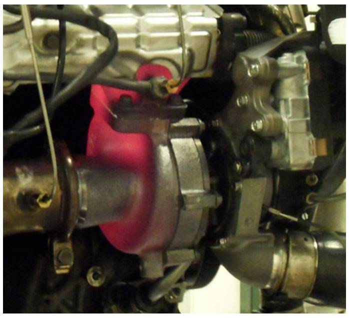
# A Variable Geometry (VG) Turbocharger for Passenger Cars to Meet European Union Emission Regulations



YASUAKI JINNAI*1 HIROYUKI ARIMIZU*2
NAOTO TASHIRO*2 MASAKI TOJO*2
TAKAO YOKOYAMA*3 NORIYUKI HAYASHI*4

*Once simply used to increase engine output, turbochargers are now used to produce high-performance vehicles with improved fuel economy and a smaller engine size. This development has allowed European car manufacturers to expand their small diesel engine applications into the mid-sized range, providing a turbo-diesel engine system with high torque at the low end, and high responsiveness under load conditions. The variable geometry (VG) turbocharger is an indispensable application that not only improves drivability and fuel consumption, but also satisfies stringent emission regulations. This report introduces the newly-developed VG turbocharger, which can be used from small to large-sized vehicles.*

## 1. Introduction

Passenger-car fuel economy has been improved in the EU, Korea and Japan in response to stringent emission regulations and the desire to reduce the environmental impact through reduced fuel consumption. Steady progress has been made in the development of Japanese hybrid and electric vehicles (EV) and the downsizing of turbocharged small gasoline engines in Europe. Similar approaches are underway in North America, China and developing countries.

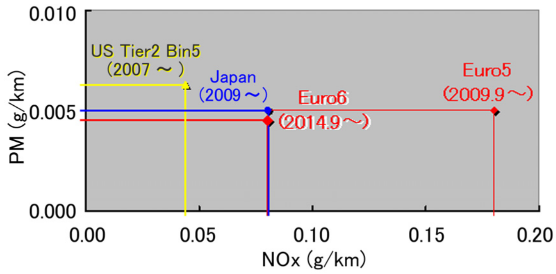
Diesel engines are more efficient than other internal combustion engines: for the same amount of work output, they use less fuel and discharge less carbon dioxide ($CO_2$). The development of the turbo-diesel engine has been advanced by European car manufacturers, and variable geometry (VG) turbochargers have been used in diesel engines for more than 10 years, mainly in the EU market.

The EU has particularly strict emission regulations for diesel engines with regard to the amount of particulate matter (PM) in the exhaust, but EU regulations are rather lax with regard to nitrogen oxide ($NO_x$) emission, compared with Japan and the United States. **Figure 1** shows the emission regulation values for passenger-car diesel engines and the test mode. The Euro 6 regulations, to be implemented in 2014, will be as rigorous as those in Japan and the U.S. The test mode used to evaluate the emission values and fuel consumption is another important consideration. Compared with Japan and the U.S, the New European Driving Cycle (NEDC) specifies higher vehicle speeds, in addition to many transient operations in the driving test mode. To cope with these conditions, a turbocharger must rapidly increase the boost pressure in the small-flow-rate zone, while maintaining good performance under large-flow-rate conditions. To minimize costs, many turbochargers used in popular 1.4 to 1.6-liter diesel engines are equipped with a simple wastegate valve system. Many engines in this class are now used in compact and mid-sized cars. For mid-sized vehicles, the VG turbocharger enables good fuel efficiency and high performance from low to high speed driving while satisfying Euro 6 emission regulations.

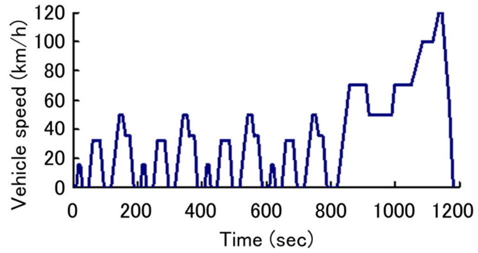
The VG turbocharger design requires precise engineering mechanisms and high-strength materials to ensure reliability. As a result, the price is relatively high compared with that of wastegate turbochargers. Although VG turbochargers are more readily found in high-grade

*1 Manager, Turbocharger Engineering Department, Turbocharger Division, General Machinery & Special Vehicles
*2 Turbocharger Engineering Department, Turbocharger Division, General Machinery & Special Vehicles
*3 Nagasaki Research & Development Center, Technology & Innovation Headquarters
*4 Research Manager, Nagasaki Research & Development Center, Technology & Innovation Headquarters

vehicles, which can absorb the cost impact, cost reduction of these systems is essential for future applications of small-displacement common-specification engines to low-price compact and mid-sized cars.




Exhaust gas regulations




NEDC (New European Driving Cycle) test pattern

| | Euro | U.S. | Japan | |
|---|---|---|---|---|
| Test mode | NEDC | LA-4 | 11 mode | 10, 15 mode |
| Condition at start | Cold | Cold&Warm | Warm | Cold |
| Average speed (km/h) | 33.6 | 31.5 | 29.1 | 22.7 |
| Mode time (sec) | 1180 | 1372 | 505 | 660 |
| Idling time ratio (%) | 23.7 | 17.8 | 31.4 | 25.5 |
| Max. speed (km/h) | 120 | 91.2 | 60 | 70 |

Note) The UN European Committee is now creating the Worldwide harmonized Light-duty Test Procedure (WLTP). March, 2012

Test mode comparison

**Figure 1 Emission regulation values for passenger-car diesel engines and the test mode**[1]

## 2. Features of the VG Turbocharger

**Figure 2** shows an external view of the VG Innovation 3.1, which has been newly developed by Mitsubishi Heavy Industries, Ltd. (MHI). By controlling the movable vane nozzles in the outer circumference of the turbine wheel, the VG turbocharger allows for optimal boost pressure control and good turbine efficiencies over a wide flow range. This not only improves the low-end torque, but also improves fuel efficiency at higher speeds. In addition, it is widely utilized for the improvement of environmental effects as it has good compatibility with emission gas recirculation (EGR) and a capability to enhance the EGR amount by controlling the vane opening.

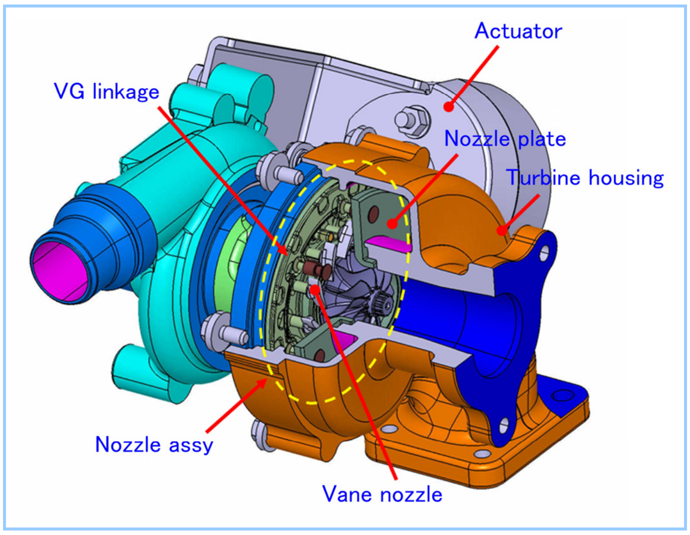



**Figure 2 External view of VG Innovation 3.1 from Mitsubishi Heavy Industries, Ltd. (MHI)**

MHI began developing the VG turbocharger in 1984 for truck applications[2], and mass production began in 1994. Utilizing this technology, the VG turbocharger for automobiles was launched in 2001. We have continuously improved the product in response to new demands and changes in the market. The most improved component is the nozzle assembly, shown in **Figure 3**.

The nozzle assembly, which operates at gas temperatures from 780°C to 850°C without lubrication, must open and close the vane nozzle without fail. Important elements in the first-generation nozzle assembly included high material strength and more reliable sliding of the VG linkage. Second-generation development was reported in the MHI Technical Review, Volume 43, No. 3 (2006).[3] In this case, Euro 4 emission regulations required wear reduction of the VG linkage, good controllability over the turbocharger's lifetime and wear-resistant cobaltic material for the production of sliding parts. From the beginning of development, computational fluid dynamics (CFD) were used to optimize the vane profile and ideal shaft pivot position to improve controllability and CFD studies also improved turbine efficiency. At that time, we made the transition from a cobaltic material to a physical vapor deposition (PVD) coating on a standard stainless-steel base to reduce costs. The third-generation nozzle assembly is the latest edition. The technical upgrades are well-balanced in VG Innovation 3.0, which began mass production in 2009. Specifically, these upgrades include better reliability of the modified-linkage structure, simplification of the scroll-shaped turbine housing to prevent cracking, and further improvement in the turbine efficiency. In VG Innovation 3.1, costs were reduced by simplifying the part supply chain and minimizing weight and size for improved packaging and mountability of the unit.

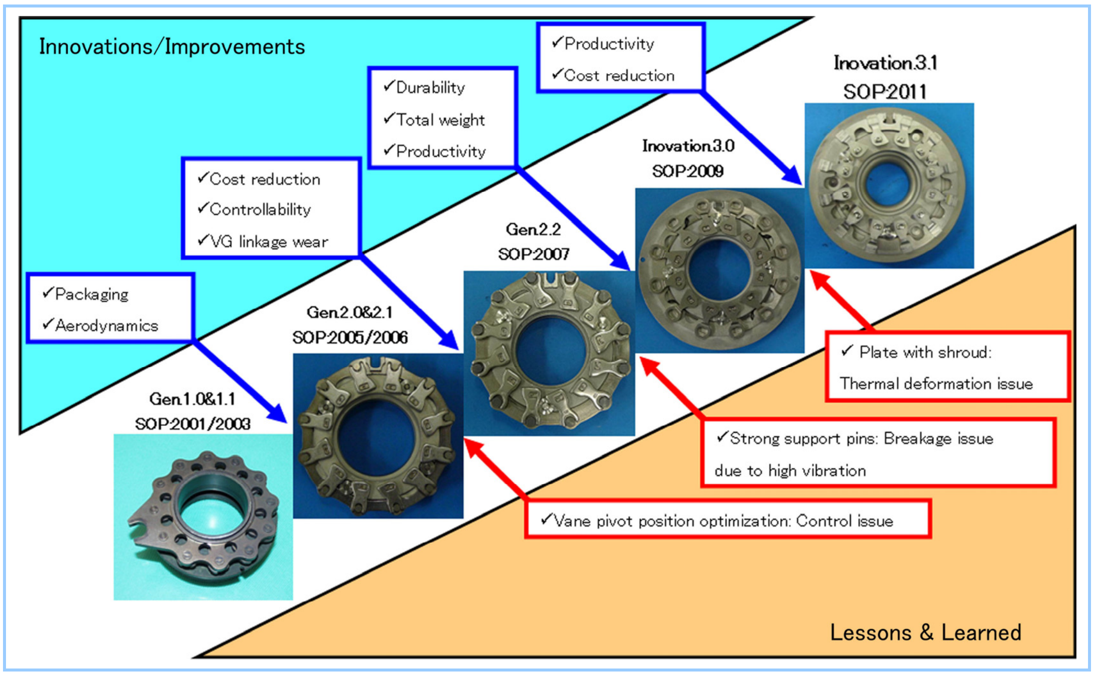



**Figure 3 Improved nozzle assembly for the automobile VG turbocharger**

## 3. Attempt for Improvement of Aerodynamic Performance and Transient Characteristics

### 3.1 Performance requirements

The NEDC test is used in the EU to assess engine performance and efficiency over a wide range of transient driving conditions (e.g., from cold starts to 120 km $h^{-1}$). $CO_2$ emissions and fuel consumption are measured over an entire cycle. Gas emissions and regulator values are checked for each possible operational condition, and the turbocharger is required to have high efficiency over the entire range of operation.

### 3.2 Turbine wheel

One important technical issue to study was improving the transient characteristics of the VG turbocharger, specifically reducing the inertia of the turbine rotor. We have successfully developed and manufactured a low-cost titanium-aluminum turbine wheel, which is applicable to a maximum diesel-engine gas temperature of 850°C. The new turbine rotor reduces inertia by 50% compared with the conventional Inconel turbine rotor. This new rotor is used in combination with VG Innovation 3.0 in mass-produced diesel engines.

Blade shape improvement of Inconel material has been also conducted. **Figure 4** presents the performance of the newly developed VG Innovation 3.1 turbine, with blade-shape improvement of the Inconel material for the TD025-VG 1.5-liter diesel engine. The inertia of the turbine rotor is a function of the fifth power of the rotor diameter. Studies have shown that reducing diameter effectively optimizes transient characteristics. We repeatedly remodeled and analyzed CFD until we produced a new turbine wheel with a small diameter of φ34 and a large capacity. The new turbine wheel covers the same range as the conventional φ37 wheel (Figure 4) and outperforms the latest φ35.5 wheel in turbine efficiency. The conventional turbine wheel design was problematic due to its turbine efficiency degradation in the small-diameter and large-capacity wheel. Now, the large capacity balances high efficiency by adjusting leading edge incidence and blade height.

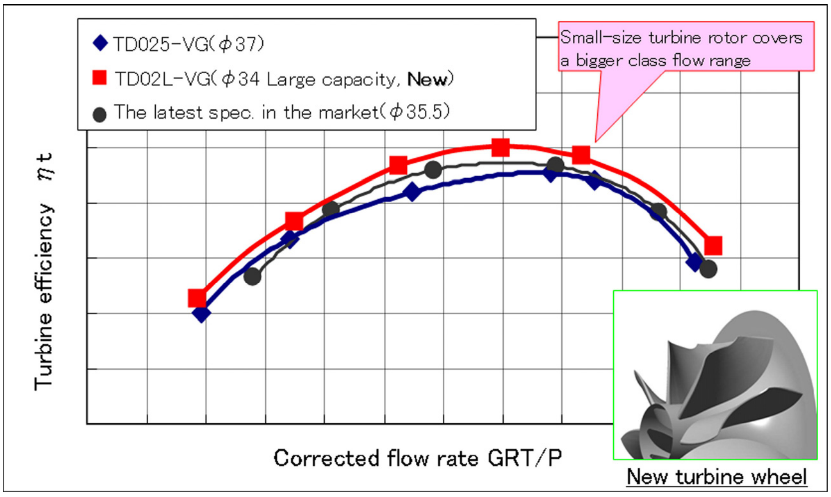



**Figure 4 Performance of the newly developed VG Innovation 3.1 turbine with blade-shape improvement**

## 3.3 Vane nozzle

In the small-flow-rate zone, where the low-end performance is determined, the nozzle is narrowed with a small vane opening and the degree of reactance is low. The degree of reactance can be simply expressed as the ratio of the turbine wheel expansion to the overall turbine expansion. In a small-flow-rate zone, low reactance refers to a high degree of expansion in the vane nozzle, and the vane shape optimization contributes to improved performance in the flow zone. We applied a curved-back vane (or 'arc vane' – see Reference 3) to the first-generation model.[4] Repeated upgrades have resulted in a rather conventional curved back vane with good controllability and high turbine efficiency. In contrast, another typical solution is the S-shape blade design. **Figure 5** shows the CFD results for the vane nozzles.

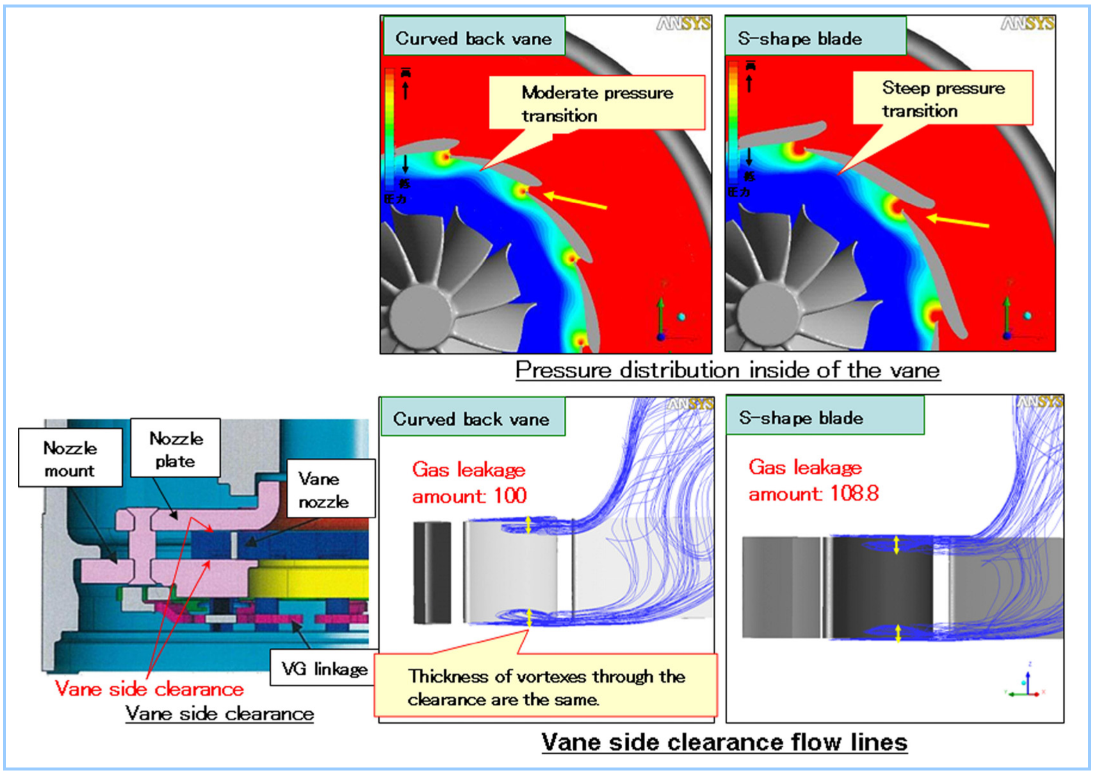



**Figure 5 CFD results for the vane nozzles**

For our curved-back vane design, the pressure distribution inside the vane indicates a moderate pressure distribution at the periphery of the turbine wheel and a smooth flow into the turbine wheel. Gas leakage at the vane side clearance, one of the factors limiting turbine efficiency, is 8.8% greater for the S-shape blade compared with that of the curved-back vane. For large-flow rate zone, the turbine wheel characteristics contribute more to performance than the vane nozzle. CFD analysis did not reveal any advantages with the S-shape blade under various conditions. Currently, VG Innovation 3.1 uses the curved-back vane design. Investigations continue on the vane inlet (leading edge) shape and vane number utilizing our accumulated data and analysis technology, and the results will soon be applied to VG Innovation 3.1.

## 3.4 Compressor

Range-widening of the compressor is critically important to ensure advantageous VG turbocharger performance. Compressors must create a high boost pressure in the small-flow-rate zone to secure a greater surging margin close to the peak torque point of the engine. MHI has worked on this issue by using CFD analysis to investigate the internal flow from the compressor inlet to the compressor wheel and diffuser. We have successfully met the required performance using our new compressor, which improves the range by 12–14% compared with the current compressors used to meet Euro 5 regulations (including those made by other manufacturers).

Surging characteristics are affected by the air-supply piping shape of the engine and its volume. **Figure 6** shows the compressor performance difference with and without engine piping, revealing a 30% wider surging margin at the maximum piping difference for the same compressor. This phenomenon depends on the compatibility between the engine piping layout and the compressor characteristics. From the early stages of performance calibration decisions, in accordance with each project schedule, MHI has developed turbochargers in collaboration with engine manufacturers. The development includes such processes as an analytical model CFD with engine-piping and performance measurement capabilities.

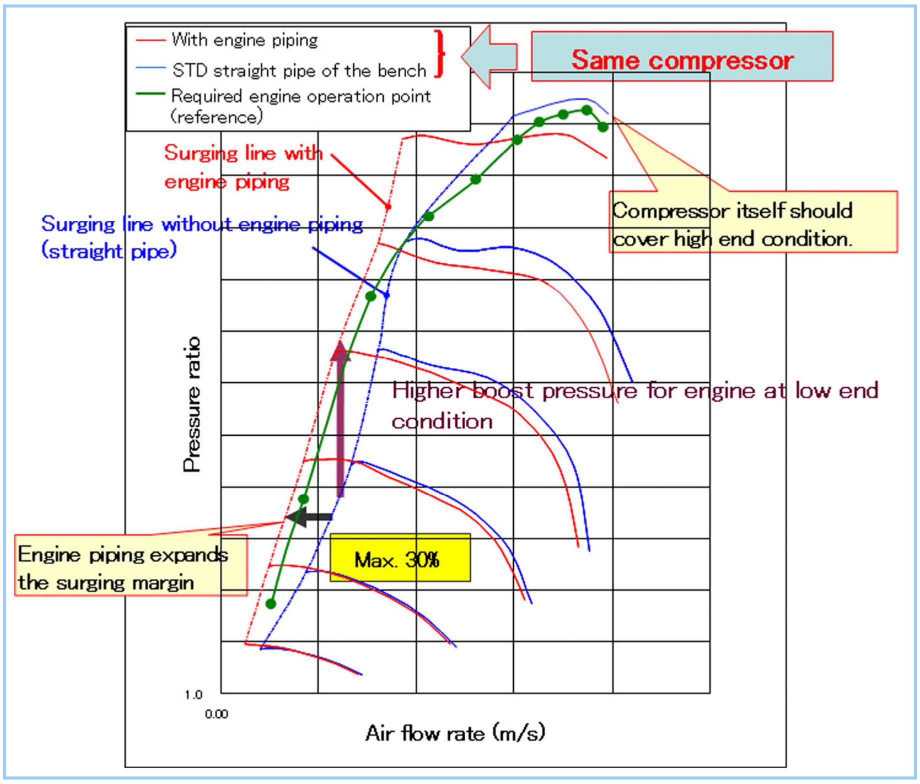



**Figure 6 Compressor performance difference with and without engine piping**

# 4. Reliability

## 4.1 Reliability verification process of VG turbocharger

For the VG turbocharger to be marketed and ensure optimal customer satisfaction, we needed to investigate and validate many technical requirements, as well as simplify complicated technical details. The technical requirements of VG turbochargers include not only the aerodynamics described above, but also the secured vane open/close operation at high temperatures (without lubrication), the reduced wear of VG linkage, being free from deformation and cracking, having stable clamping and sealing and provisions for resonance control. These requirements must be met while maintaining high productivity and low cost.

**Figure 7** shows the flow process of simulation and durability evaluation during VG turbocharger development. MHI has created a database that spans the development and results from the VG turbocharger for trucks, first produced in 1994, to the current products for passenger cars. This database can be used for total simulation of VG turbochargers. The validity of the simulation results was verified using component tests, including a heat cycle test for the turbocharger gas stand, an acceleration test for the shaker and a durability test for the engine bench. Simplified independent tests of the requirements have minimized the need for development reworks, as well as development and production costs, and have contributed to the overall simplification of engine development for the manufacturer.

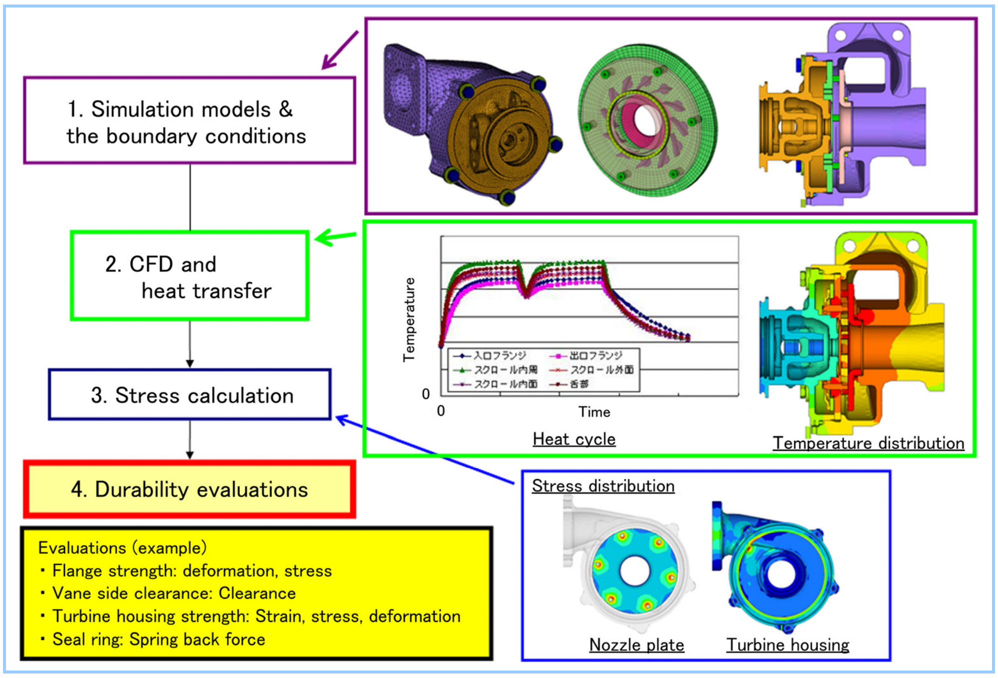



**Figure 7 Simulation and durability evaluation in VG turbocharger development**

## 4.2 Functionality

### 4.2.1 VG Linkage structure

The unique sticking phenomenon in the VG turbocharger is a concern for nozzle assembly operation at high gas temperatures (on the order of 850°C maximum without lubrication). In this case, ‘sticking’ refers to the abnormal contact pressure that arises in the sliding parts of the nozzle assembly by the dynamic movement of the vane opening and closing. The higher contact pressure is immediately transmitted to the other sliding parts, ultimately locking up the entire VG linkage. The initial sticking occurs mainly in the VG linkage or vane, and a construction having a resistance to the contact pressure increase in those components is important to avoid sticking.

In VG Innovation 3.1, the VG linkage has been significantly improved. **Figure 8** provides a graphical explanation. Ideally the VG linkage should have a structure by placing the shafts and levers on both sides of a vane, and the actuator force is applied from both sides. This improves the force transfer efficiency when the vane is opened or closed by the actuator force. However, in the case of the VG turbocharger, a large scroll is positioned on the opposite side of the VG linkage where the gas flows, leaving the single side drive with a single side lever. To solve this issue, we invented a small overhang structure in the VG linkage to improve the force transfer. We verified good functionality by comparing the driving force (Figure 8) and testing high-temperature operation on the turbocharger gas stand. Thus, the small overhang structure, a proprietary technology of MHI, reduces the contact pressure on the sliding parts in the linkage and vane and contributes significantly to the improved functionality of the VG Innovation 3.1 turbocharger.

Currently, a competitor's VG turbocharger uses a double-shaft structure (shafts on both sides), with the lever remaining on one side of the drive. However, this structure creates an additional gap at the vane side clearance and reduces turbine efficiency due to gas leakage. Performance tests confirmed that the ‘double-shaft’ structure is approximately 3% worse than the ‘single-shaft’ used in the new MHI turbocharger. The single-shaft design in the MHI VG turbocharger, developed for use in passenger cars, also offers an advantage in terms of aerodynamics.

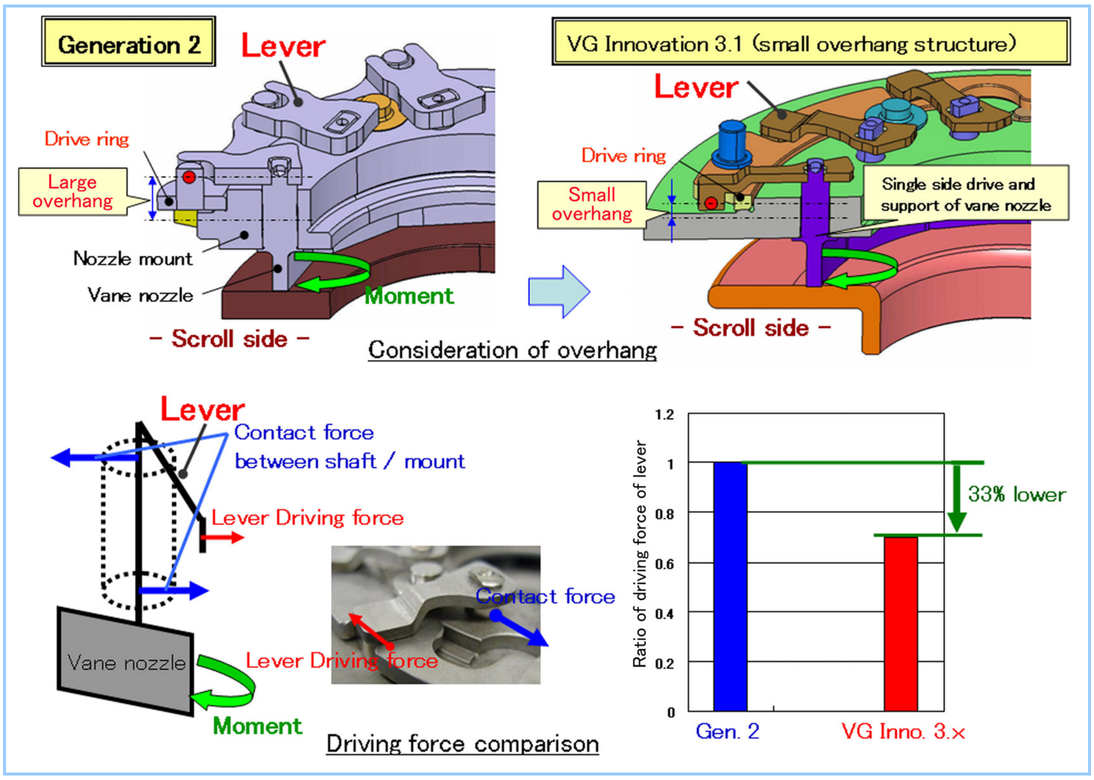



**Figure 8 Driving force comparison and overhang structure in the VG Innovation 3.1 turbocharger**

4.2.2 Surface treatment

In the present design, a surface treatment has been implemented to minimize sticking of the vane sliding surfaces in MHI VG turbocharger. The vanes in the nozzle mount and plate are exposed to pulsating high-temperature exhaust gas without lubrication. Scratches and soot accumulation on the sliding faces are inevitable over the lifetime of the engine; scratches, in particular, tend to cause vane sticking from sliding metal-to-metal contact. A ceramic chrome-carbide layer reduces adhesive wear and improves the robustness against vane sticking. From the beginning, MHI has used a diffusion-coating surface treatment to increase the surface hardness to Hv 1000 or more, resulting in a structure that suppresses scratches on the sliding face and prevents vane sticking. However, this specialized treatment, and the necessity to cast stainless steel with high carbon content, limits productivity. MHI has developed a promising new stainless steel surface treatment to solve the sticking problem. This approach appears to yield results similar to those with the specialized treatment and the special steel. **Figure 9** shows the results from an endurance test following a carburizing series of surface treatments. Corrosion by the sensitization of stainless steel was a concern. Due to the exhaust gas environment and carbon deposition on exposed surfaces, the rust-proofing of the original stainless steel material was continuously verified over the course of engine bench tests. This ensured that good functionality was maintained without significant degradation, such as corrosion or reduced hardness. As a result, a nozzle assembly that satisfies the productivity and operability requirements has been developed.

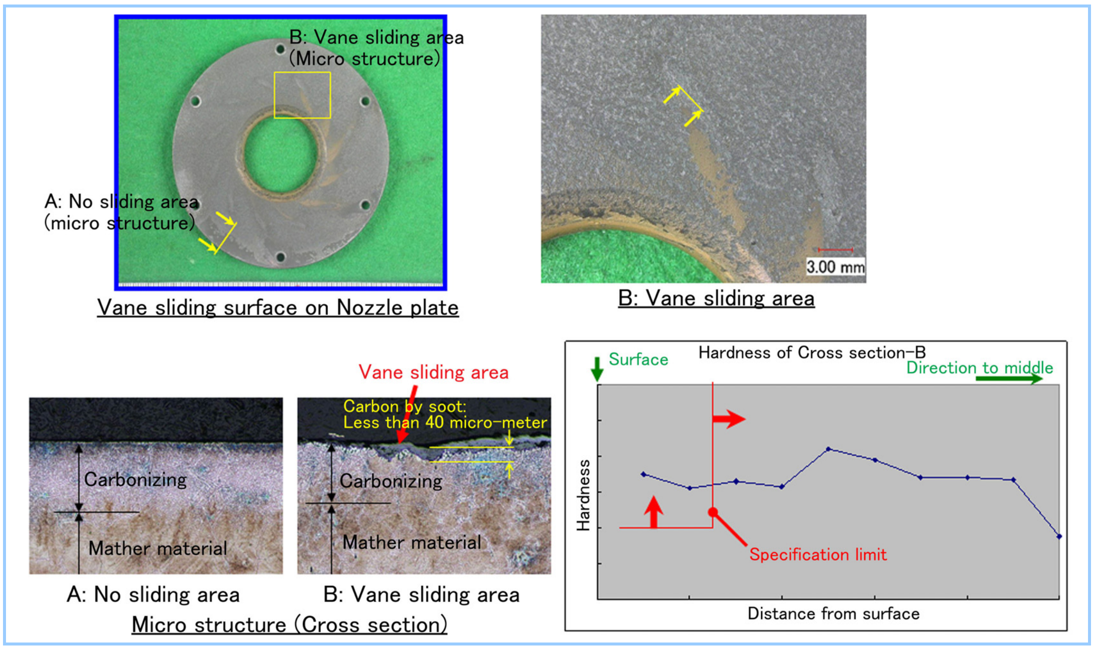



**Figure 9 Results from an endurance test following a carburizing series of surface treatments**

## 4.3 Nozzle assembly clamping structure

One important element of VG Innovation 3.1 is the clamping structure of the nozzle assembly. **Figure 10** shows the details of the clamping structure. Engine vibration significantly influences the VG linkage, which undergoes significant wear if the nozzle assembly clamping is substandard. To prevent VG linkage sticking, the nozzle assembly must have a structure that allows thermal expansion around the vane sliding area. In the past (second-generation development and earlier), MHI VG turbochargers had nozzle assembly clamping structures with a relatively small inner diameter and an outer diameter that was close to the vane and VG linkage sliding parts. Some of the latest models in today's market use a similar structure to clamp the small diameter nozzle, allowing the inner diameter assembly to be gently supported by a conical disc spring. Loose clamping is needed in this case to avoid sticking, at high temperatures or under transient conditions. In other words, tighter clamping is difficult and involves the risk of increasing the vibration of the nozzle assembly itself.

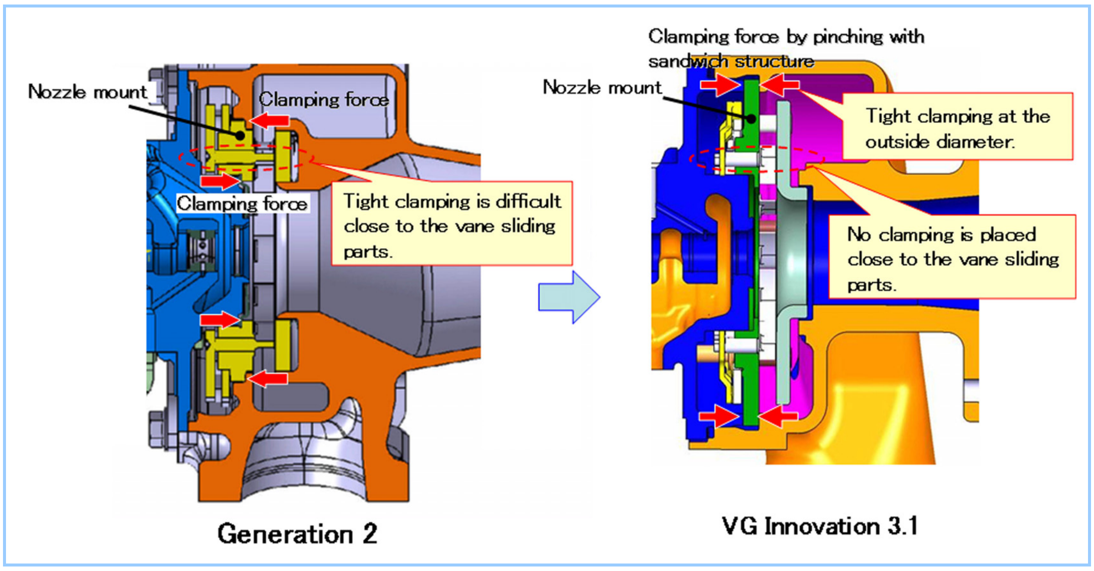



**Figure 10 Details of the nozzle assembly clamping structure**

In VG Innovation 3.1, clamping is performed at the outer diameter of the nozzle mount by pinching it using a sandwiched structure. The outer diameter can be clamped tightly because it is not in close proximity to the temperature-sensitive VG linkage system. This reduces wear on the VG linkage by minimizing nozzle assembly vibration, even when the vibration level is high. We verified the reduction in the vibration level by directly measuring the VG linkage of the turbocharger using a shaker test (**Figure 11**). The engine bench test also revealed low linkage wear as a result of the improvement to satisfy the engine manufactures' requirement.

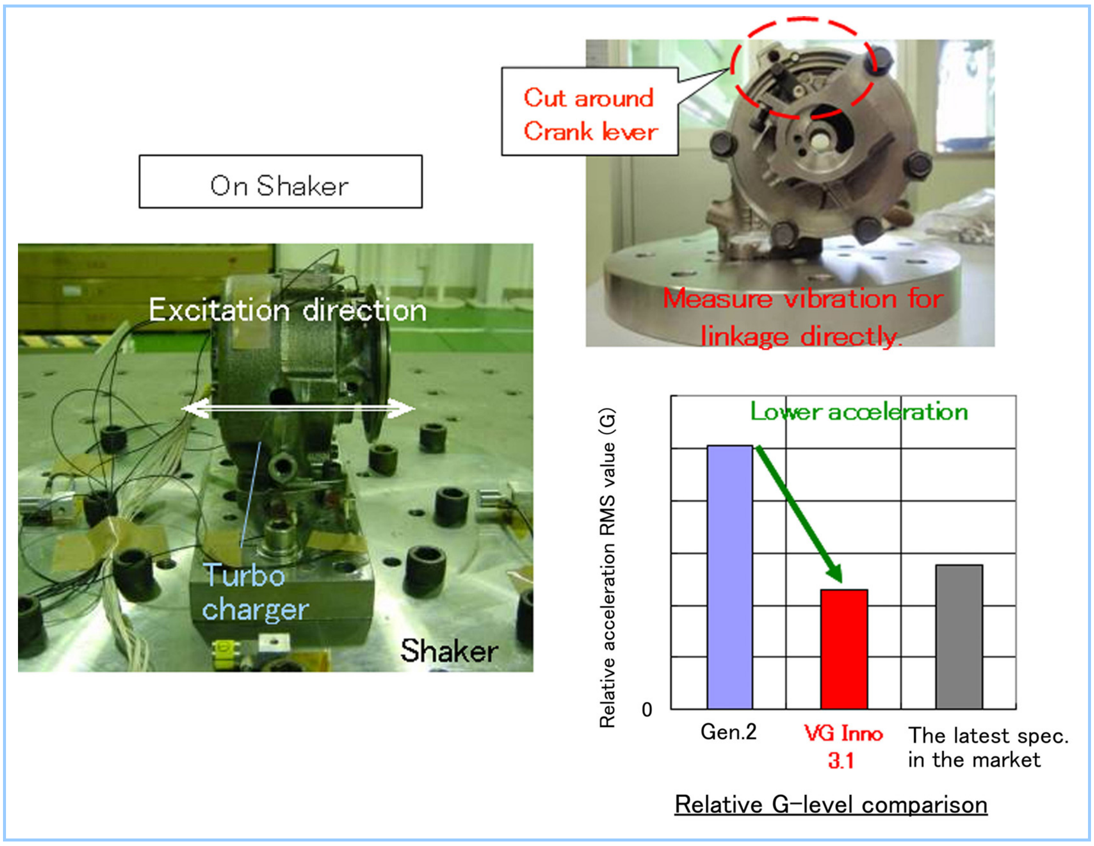



**Figure 11 Shaker test on the VG linkage of the VG Innovation 3.1 turbocharger**

### 4.4 Failure rate in series production

VG Innovation 3.0, which was mass-produced beginning in 2009, proved to be a high-quality design; the production line and field claim rate from customers and engine manufacturers was very low. VG Innovation 3.1 has adopted the improvements described above.

## 5. Weight Reduction and Expansion of Standard Material Application

In the second-generation VG linkage and earlier systems that were developed, MHI VG turbochargers required wear-resistant special materials and surface treatment, and this had a significant impact on the overall cost of the VG turbocharger. In the case of VG Innovation 3.1, a low-wear level of VG linkage can be attained even with standard materials. By reducing stress on the sliding parts through the development of the nozzle assembly clamping structure, as well as reducing the weight of linkage parts, low wear can be attained at minimal cost. In addition, standard materials that can be applied to forging are used in the production of the nozzle plate and nozzle mount, thereby reducing the machining time. The implementation of a general carburizing series for surface treatment makes it easier to procure parts for the nozzle assembly and shortens the supply chain. The results not only meet JIS standard specifications, but European standards as well. VG Innovation 3.1 is 7.3% lighter than the second-generation model, and the smaller diameter and lighter weight of the turbine and bearing housings mean that costs for parts are reduced in proportion to the weight reduction. Thus, VG Innovation 3.1 meets the required cost level for popularized small diesel engines.

MHI is currently developing a sheet-metal turbine housing to enable further cost reduction. We expect that this design will be lighter and that its heat capacity will be reduced. Several engine manufacturers are already testing this new design and the preliminary results are very promising.

## 6. Conclusions

VG Innovation 3.1 began mass production in the TD03L-VG (turbine diameter φ40) in October, 2011 (**Figure 12**). The development of the TD025L-VG (φ34 and 37) is already complete for the 1.5-liter diesel engine, used in Euro 6 and Euro 7 in the EU market. This design and its further development will be applicable to the 2- and 3-liter models (φ43 and 47). At this time, many patents are pending regarding the development of this technology. The technologies presented are also applicable to industrial-use diesel engines, and sales to these engine manufacturers will be considered following verification of the ability to meet the strict emission regulations. VG Innovation 3.1 is a well-balanced product enabling improved aerodynamics and reliability, low cost, productivity efficiency, minimization of the supply chain and regulation compliance. We will promptly proceed with the improvements in engine performance required by our customers, while ensuring that we continue to meet environmental standards and emission regulations.

**Figure 12 VG Innovation3.1 (mass produced TD03L-VG)**

## References

1. Commission Directive 2010/26/EU of 31 March 2010
2. Okazaki, Y. et al., Development of Variable Geometry Turbocharger, Mitsubishi Juko Giho Vol. 22 No. 2 (1985-3) pp. 91-97
3. Osako, K. et al., Development of the High-Performance and High-Reliability VG Turbocharger for Automotive Applications, Mitsubishi Heavy Industries Technical Review Vol. 43 No. 3 (2006) pp. 31-32
4. Matsumoto, K., Jinnai, Y. et al., Development of Variable Geometry Turbocharger for Diesel Passenger Car, C554/005/98 IMechE (1998.11) pp. 329-346