



Research  
Report

## Development of Wide Flow Range Compressor with Variable Inlet Guide Vane

Hiroshi Uchida, Akinobu Kashimoto, Yuji Iwakiri

---

### Abstract

To improve low-end torque and the transient response of a turbocharged engine, there is a need to develop a wide flow range compressor for use in turbochargers. Especially, we must improve the surge limit of the compressor because this restricts the boost pressure rise at low engine speeds.

We studied the surge characteristics of a turbocharger compressor by experiment. Firstly, we developed a casing treatment that featured a curved wall cavity. We then went on to investigate the effects of the dimensions of the casing treatment on the surge limit. As a result, we found that both the surge limit and the compressor efficiency were improved by use of the casing treatment. The installation of the casing treatment reduced the surge flow rate by 30 % relative to a conventional compressor at a

pressure ratio of 2.5. Secondly, we investigated the synergy effects of the Variable Inlet Guide Vane (VIGV) with the casing treatment. The surge flow rate was found to have been reduced significantly compared with their being used separately, due to the synergy effect. Also, the surge flow rate was reduced by 59 % relative to a conventional compressor at a pressure ratio of 2.5, again due to the synergy effect. Furthermore, the surge limit with a VIGV setting angle of 80 degrees was not changed by reducing the backward angle of the impeller relative to the radial direction, despite an increase in the choke flow rate. As a result, we were able to develop a compressor with a significantly wide flow range and an impeller with a low level of centrifugal stress.

Keywords

Turbocharger, Centrifugal compressor, Aerodynamics, Surge, Variable inlet guide vane, Turbocharged engine, Casing treatment

## 1. Introduction

Recently, the development of a wide flow range compressor has been recognized as being important for the turbochargers used in automobiles. A turbocharged engine with a high boost pressure across the entire operating region offers advantages both in terms of fuel consumption and emissions due to its realizing the ability to enable lean-boost and downsizing. To increase the boost pressure at low engine speeds, however, the surge limit of the turbocharger compressor has to be improved. The flow becomes unstable and a periodic pressure fluctuation that is characterized by a loud noise occurs at flow rates below the surge limit. So, many studies of centrifugal compressors have been undertaken in an attempt to improve the surge limit.<sup>1-4)</sup>

In this study, the surge characteristics of a turbocharger compressor were investigated and means of improving the surge limit were developed experimentally. A numerical flow analysis revealed the vortex caused by the reverse flow through the tip clearance with the shroud of the impeller at flow rates near the surge limit. It is thought that the size and strength of the vortex strongly influences the surge limit. Therefore, methods of controlling the vortex were researched in order to improve the surge limit. Firstly, we developed a casing treatment consisting of a curved wall cavity. The surge limit and the compressor efficiency were both improved through the use of this casing treatment. Secondly, the synergy effects of combining the Variable Inlet Guide Vane (VIGV) with the casing treatment were investigated. It was found that the surge flow rate was reduced significantly relative to when they are used separately, thanks to the synergy effect. The surge flow rate was found to be 40 % less than that with the casing treatment alone at a pressure ratio of 2.5, and 55 % less than that for the conventional compressor.

## 2. Design of a wide flow range compressor

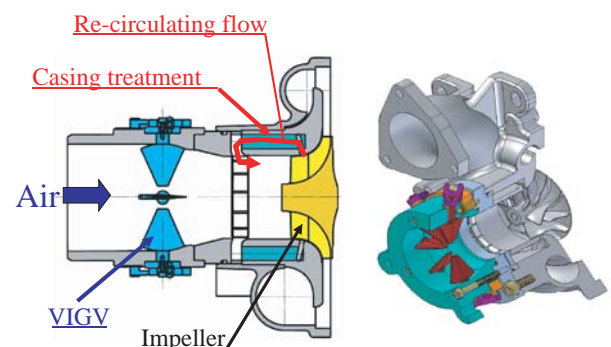
With the goal of improving the surge limits, we designed a turbocharger compressor with the VIGV and casing treatment. **Figure 1** shows the structure of the compressor. The VIGV is located upstream of

the casing treatment and is able to control the pre-whirl of the impeller inlet flow. The VIGV has seven vanes, the angles of which, relative to the flow direction, can be changed by an electrical actuator and a link mechanism. The casing treatment features both a cavity incorporated into the shroud of the compressor housing and two slits. One of the slits is located in the shroud wall between the leading edge of the impeller and that of the splitter blade. The other is located in the shroud wall downstream of the VIGV. Therefore, the air can be re-circulated from the impeller to a point downstream of the VIGV.

The performance of the compressor was measured by using turbocharger performance test equipment at a turbine inlet temperature of 873 K. The surge limits were detected by sensing the frequent pressure oscillations at the compressor exit.

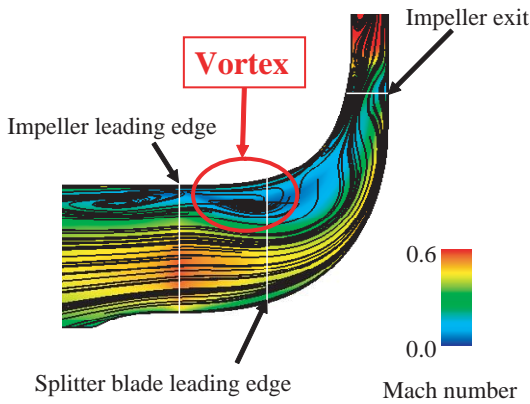
## 3. Development of the casing treatment

The streamlines in the impeller flow path at the surge flow rate, as shown in **Fig. 2**, were obtained by a numerical flow analysis for a conventional compressor. The large vortexes appear in the shroud side of the flow path at the surge limit. So, it is important to control the vortexes in order to improve both the surge limit and the efficiency of the compressor. **Figure 3** shows the shape of the spoon-type casing treatment. The casing treatment consists of six cavities enclosed by a spoon-like curved wall, and two slits located in the shroud of the compressor housing. The shape of the cavities was designed so as to smoothly change the velocity of the re-circulating flow from the circumferential to the axial

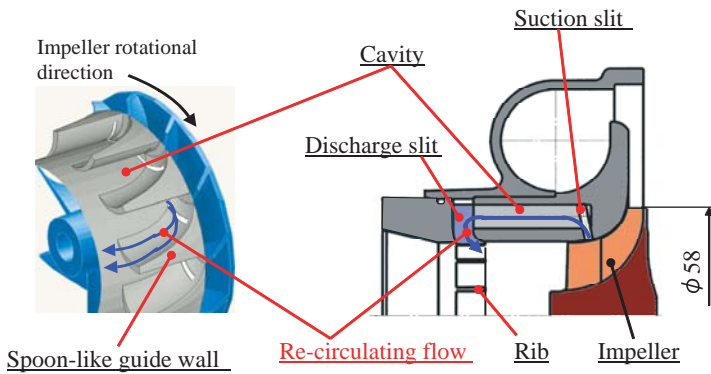


**Fig. 1** The structure of the compressor with VIGV and the casing treatment.

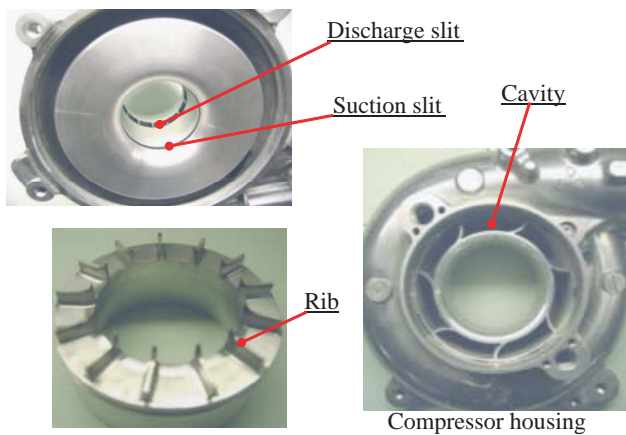
direction. The location and the width of the two slits in the casing treatment were investigated experimentally so as to improve the surge limit. The



**Fig. 2** The streamline in the impeller flow path at the surge flow rate. (Conventional compressor)



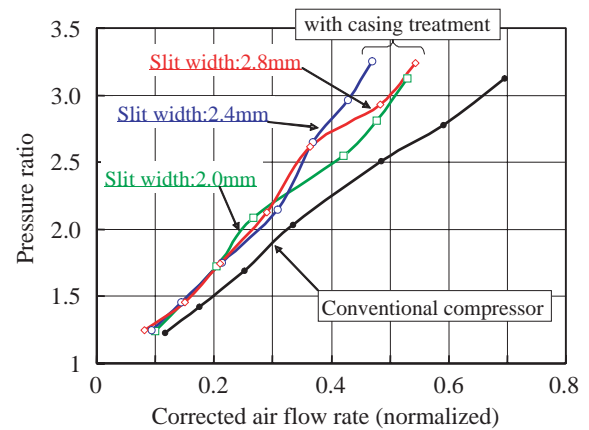
**Fig. 3** The structure of the casing treatment.



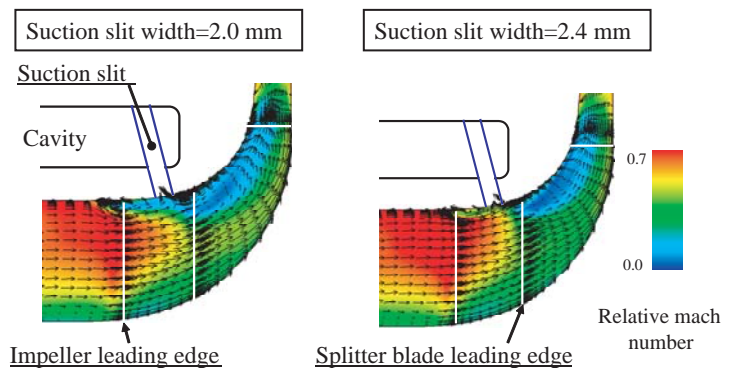
**Fig. 4** The picture of the casing treatment installed in the compressor housing.

casing treatment is illustrated in **Fig. 4**.

**Figure 5** shows the effect of the width of the suction slit on the surge limit. Relative to a conventional compressor, installing the casing treatment improved the surge limit of the flow rate significantly over the entire range of pressure ratios. Also, at high pressure ratios, the surge limit is closely related to the width of the suction slit. The surge flow rate at a pressure ratio of 2 increases as the slit width increases. On the other hand, the surge flow rate at a pressure ratio of 3 falls as the slit width increases. It is thought that the factor affecting the surge limit near a pressure ratio of 2 is different from that near a pressure ratio of 3. **Figure 6** shows the results of the numerical flow analysis for compressors with the casing treatment.



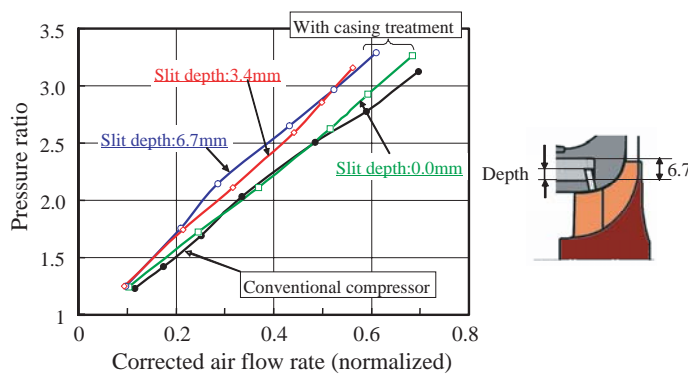
**Fig. 5** The effect of the width of suction slit on the surge limit.



**Fig. 6** The effect of the suction slit width on the flow in impeller at surge flow rate. (Normalized rotational speed = 0.88, Normalized flow rate = 0.3)

The vortex that occurs upstream of the suction slit disappears when the slit width is changed from 2 mm to 2.4 mm. This will improve the surge limit. The large vortex that occurs downstream of the suction slit, however, can not be controlled with the casing treatment. **Figure 7** shows the effect of the depth of the suction slit on the surge limit. The slit width was maintained at 2 mm. The surge limit could be improved by increasing the depth of the suction slit. It is thought that the recirculating flow rate through the casing treatment increases as both the depth and the width of the suction slit increase. On the other hand, the influence of the width of the discharge slit on the surge limit was relatively small. **Figure 8** shows how the rib installed in the discharge slit affects the surge limit. Installing the rib improves the surge limit only at high pressure ratios. As mentioned above, the influence of the dimensions of the casing treatment on the surge limit is complicated. Furthermore, it is thought that the correlation between the dimensions of the casing treatment and the impeller blade shape also affects the surge limit. These complicated phenomena will have to be investigated and it will also be necessary to devise a method for designing a compressor with the casing treatment.

**Figure 9** compares the performance of the compressor with the optimized casing treatment with that of a conventional compressor. Installing the casing treatment reduced the surge flow rate by 30 % relative to a conventional compressor at a pressure ratio of 2.5. Furthermore, the compressor efficiency

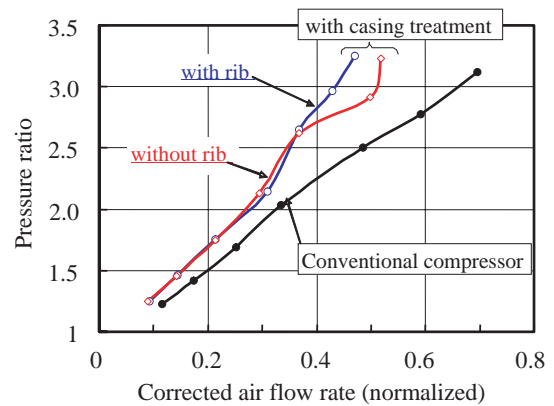


**Fig. 7** The effect of the depth of suction slit on the surge limit. (Suction slit width = 2.0 mm)

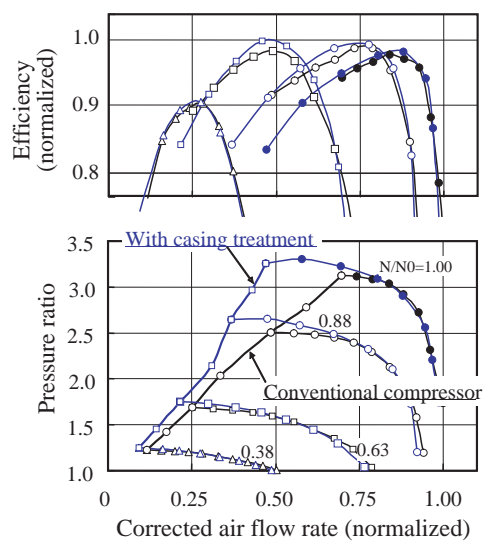
was also improved by the casing treatment.

#### 4. Synergy effect of the VIGV and the casing treatment

We evaluated the effects of each of the casing treatment, the vane setting angle of the VIGV, and the impeller backward angle on the compressor performance. The vane setting angle of the VIGV was changed from zero to 80 degrees relative to the from the axial direction. **Figure 10** shows the results of the compressor performance tests for an impeller backward angle of 35 degrees. The figure



**Fig. 8** The effect of the rib installed in the discharge slit on the surge limit. (Suction slit width = 2.4 mm, suction slit depth = 6.7 mm)



**Fig. 9** The effect of the casing treatment on the compressor performance. (Suction slit width = 2.4 mm, suction slit depth = 6.7 mm, with Rib)

shows the total for the static performances and the relative efficiencies based on the casing treatment. The effect of the VIGV setting angle on the surge limits of the compressor with the casing treatment is also indicated in Fig. 10. The surge flow rate falls as the VIGV setting angle increases. So, the surge flow rate can be reduced by 59 % relative to a conventional compressor at a pressure ratio in excess of 2.5 by changing the VIGV setting angle from 0 to 80 degrees. On the other hand, the individual effect of the VIGV on the surge limits was investigated experimentally and the results indicate a reduction in the surge flow rate of less than 15 %. Therefore, it is thought that the drastic improvement in the surge limits is caused by the synergy effect of the VIGV and the casing treatment. Additionally, we investigated the influence of the impeller backward angle on the surge limits by using a compressor with the VIGV and the casing treatment. **Figure 11** shows the performance of the compressor with an impeller backward angle of 20 degrees. The figure shows that the surge limit with a VIGV setting angle of 80 degrees is not changed by reducing the backward angle relative to the radial direction. On the other hand, both the choke flow rate and the pressure ratio at the same rotational speed with a VIGV setting angle of 0 degrees increased when the backward angle was reduced. As a result, we were

able to develop a significantly wide flow range compressor with a low level of centrifugal stress. We expect that the developed compressor will improve both the low-end torque and the transient response of turbocharged engines.

The efficiency of a compressor with the casing treatment is a little bit better than that of a conventional compressor at low flow rates. It is thought that the improvement in the velocity distribution of the impeller as caused by the casing treatment raises the compressor efficiency despite incrementing the re-circulating flow rate. The pressure loss through the VIGV increases as the vane angle increases at high flow rates. So, the compressor peak efficiency falls as the VIGV setting angle increases. But, the efficiency at low flow rates region does not fall, as shown in Fig. 10.

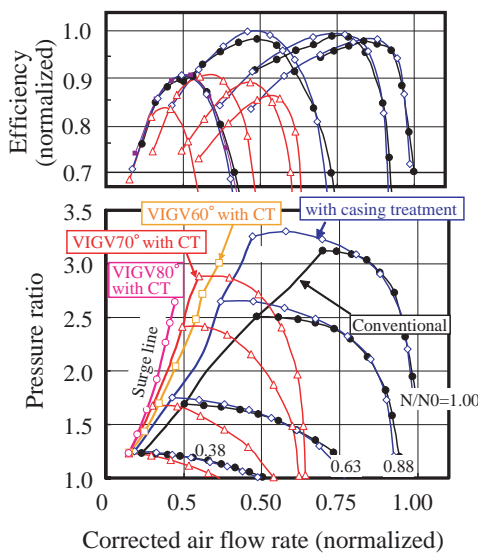
### 5. Conclusion

A wide flow range compressor with a VIGV and a casing treatment was developed for use in a turbocharger.

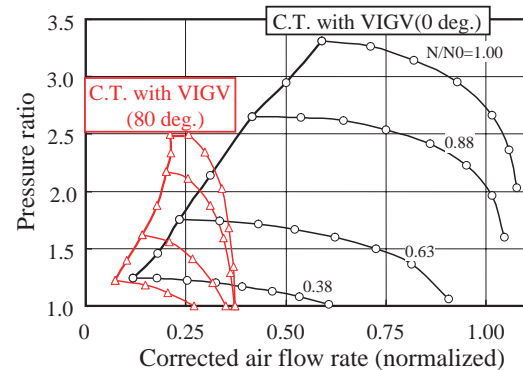
(1) A casing treatment having a spoon-type guide wall was developed for the turbocharger compressor in order to improve the surge limit.

The effects of the dimensions of the casing treatment on the compressor performance were investigated. The results indicate that the dimensions of the suction slit have a great effect on the surge limit.

(2) The installation of the casing treatment reduced the surge flow rate by 30 % relative to a conventional compressor at a pressure ratio of 2.5.



**Fig. 10** The effect of the VIGV setting angle on the compressor performance. (Impeller backward angle = 35 deg.)



**Fig. 11** The effect of the VIGV setting angle on the compressor performance. (Impeller backward angle = 20 deg.)

Furthermore, the compressor efficiency was also improved as a result of installing the casing treatment.

(3) The synergy effect of the VIGV and the casing treatment on the compressor surge limit was found. The surge flow rate was reduced by 59 % relative to a conventional compressor at a pressure ratio of 2.5.

(4) The surge limit for a VIGV setting angle of 80 degrees was not changed as a result of reducing the backward angle of the impeller relative to the radial direction, even though the choke flow rate increases. As a result, we were able to develop compressor having a significantly wide flow range with an impeller having a low centrifugal stress.

### References

- 1) McKee, R. J. and Deffenbaugh, D. M. : "Factors That Affect Surge Precursors in Centrifugal Compressors", GMRC Gas Machinery Conf., Salt Lake City, UT., (2003)
- 2) Yamaguchi, S., et al. : "The Development of Casing Treatment for Turbocharger Compressor", 7th Int. Conf. on Turbochargers and Turbocharging, Proc. of IMechE C602/016/2002, (2002)
- 3) Tange, H., Ikeya, N. and Takanashi, M. : "Variable Geometry of Turbocharger Compressor for Passenger Vehicles", SAE Tech. Pap. Ser., No.2003-01-005 (2003)
- 4) Whitfield, A. and Abdullah, A. H. : "The Performance of a Centrifugal Compressor with High Inlet Prewhirl", ASME Pap., No.97-GT-182 (1997)  
(Report received on Jun. 26, 2006)



#### Hiroshi Uchida

Research fields : Turbomachine,  
Aerodynamics

Academic society : Gas Turbine Soc. Jpn.

Awards : The Outstanding Technical  
Paper Award of Gas Turbine Soc.  
Jpn., 2002



#### Akinobu Kashimoto

Research fields : Turbomachine,  
Aerodynamics

Academic society : Gas Turbine Soc. Jpn.



#### Yuji Iwakiri

Research fields : Turbomachine,  
Aerodynamics

Academic society : Jpn. Soc. Mech. Eng.