

A Stability Enhancement Method for Centrifugal Compressors using Active Control Casing Treatment System

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Abstract. The centrifugal compressors are widely used in many fields. When the centrifugal compressors operate at the edge of the surge line, the compressor will be unstable. In addition, if the centrifugal compressor runs at this situation long time, the damage will be occurred on compressor. There are some kinds of method to improve and enlarge the range of the centrifugal compressors, such as inlet guide vane, and casing treatment. For casing treatment method, some structures have been researched, such as holed recirculation, basic slot casing treatment and groove casing treatment. All these researches are the passive methods. This paper present a new stability enhancement method based Active Control Casing Treatment (ACCT). All parts of this new method are introduced in detail. The control strategy of the system is mentioned in the paper. As a research sample, a centrifugal compressor having this system is researched using CFD method. The study focuses on the effect of the active control system on the impeller flow. The vortex in impeller is changed by the active control system. And this leads to the suppression of the extension of vortex blockage in impeller and to contribute to the enhancement of the compressor operating range.

1. INTRODUCTION

The centrifugal compressors are widely used in many fields. The centrifugal compressors have a very important character, which is that there is a stable working condition range. When the centrifugal compressor operates at/pass the edge of the surge line, the compressor will be unstable. Hence, in the industry systems, there is the anti-surge control system to make the compressors working at the stable condition.

There are some kinds of method to improve and enlarge the stable range of the centrifugal compressors, such as inlet guide vane [1-3] and casing treatment [4-8]. For casing treatment method, some researches have been done, such as holed recirculation, basic slot casing treatment and groove casing treatment. All these researches are the passive methods.

This paper present a new stability enhancement method based Active Control Casing Treatment (ACCT). All parts of this system and the control method are introduced in detail in this paper.

As a research sample, a centrifugal compressor having this system is researched using CFD method. The study focuses on the effect of the active control system on the impeller flow. The vortex in impeller is changed by the active control system, which leads to the suppression of the extension of



vortex blockage in impeller. Hence, the stability of compressor enhanced and the operating range enlarged.

2. STABILITY ENHANCEMENT METHODS FOR COMPRESSORS

Surge suppression of centrifugal compressor is very useful for centrifugal compressor when it is operating at the small mass flow rate. The main mechanism of surge suppression is to maintain the steady flow in impeller. The main flow separation in compressor is avoided using these surge suppression methods.

There are many kinds of methods, which can enhance the stability of the centrifugal compressor. The details of these methods are presented as follows.

2.1. Inlet guide vane (IGV)

The inlet guide vanes can significantly extend the stable operating range of centrifugal compressors. The inlet guide vanes can be turned to induce a controlled prewhirl in the front of the compressor impeller. This method is widely used to regulate the pressure ratio and the mass flow rate at constant rotational speed centrifugal compressors in industry system.

Wallace studied the theory and experiment of IGV at 1975[10]. The experimental results indicated that the stable operation could be extended to low mass flow rates by positive prewhirl using IGV. Figure 1 shows the Geometry of IGV and the performance of compressor at different setting angles.

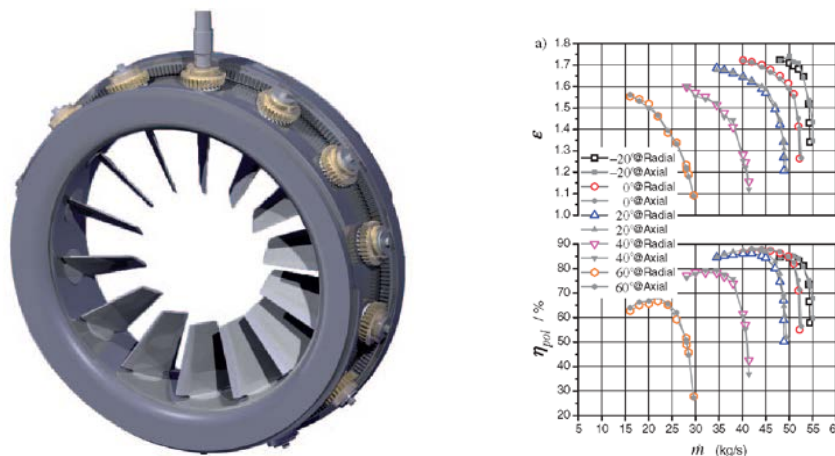


Figure 1. Geometry of IGV and compressor performance [9]

2.2. Traditional casing treatment

The casing treatment was proposed and researched in axial compressor firstly. Many research have been done based the cave/cavity on the diffuser and casing of compressor. Fisher researched a recirculation casing treatment in a turbocharger compressor [4]. It was called ported shroud housing (shown in Figure 2a). Wei Xu proposed and researched a recirculation casing treatment structure in recent years based on the research of Fisher [5]. Figure 2b shows the main structure of it.

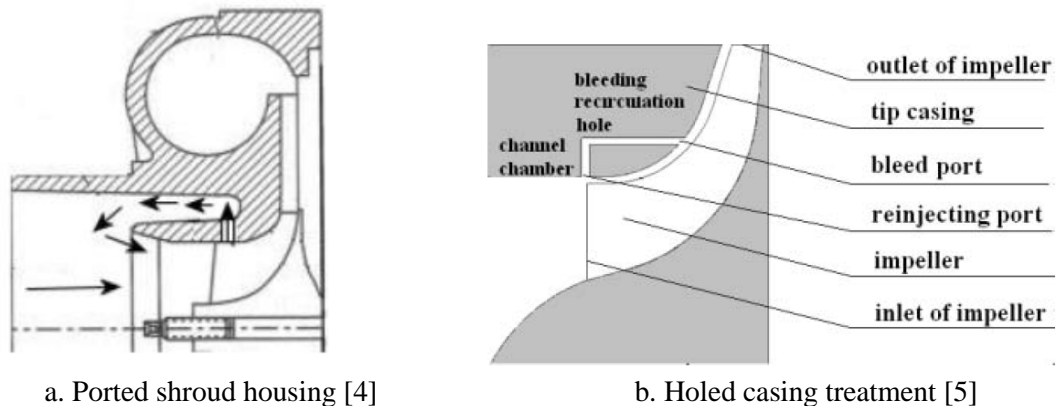


Figure 2. Structure of casing treatment.

For this traditional casing treatment, there is a flow path from the blade tip to the inlet of impeller on the shroud of compressor. When the compressor is running, some gas flows in this channel. Usually, the gas bleeds from the tip of blade and then inject into the front of impeller.

The flow resistance in the flow path can be utilized to balance the static pressure difference between the bleed port and injecting one [5]. That means the flow rate is decided by the static pressure difference of this two ports. At the low mass flow rate conditions, the static pressure near the bleed port is high enough to drive an injected flow from the bleed port to the injecting one. The flow field at the tip of impeller is disturbed by the flows. In addition, the unsteady flow in the impeller is changed by it. The steady operating range of centrifugal compressors is enlarged by this method.

2.3. New casing treatment

For the traditional casing treatment, all of them are passive methods. The casing treatment is working at all the time when the compressor is running. People cannot change the situation of casing treatment. That means when the compressors operate at the design point, the traditional casing treatment are still working. That leads to the decrease of the efficiency of compressor.

Because the static pressure difference between the two ports is small, the flow rate in this flow pass is small, which can not change the unsteady flow in the impeller when the compressor flow rate is very low.

The Active Control Casing Treatment (ACCT) is presented in this paper basing on the traditional passive casing treatment methods. Figure 3 shows the basic structure of ACCT. there are bleeding ports on the casing near the tip of blades. The injecting port is on the inlet pipe of compressor. There is the control device in the middle of the flow pass between injecting and bleeding ports. Here the control device can be control valve or small compressor.

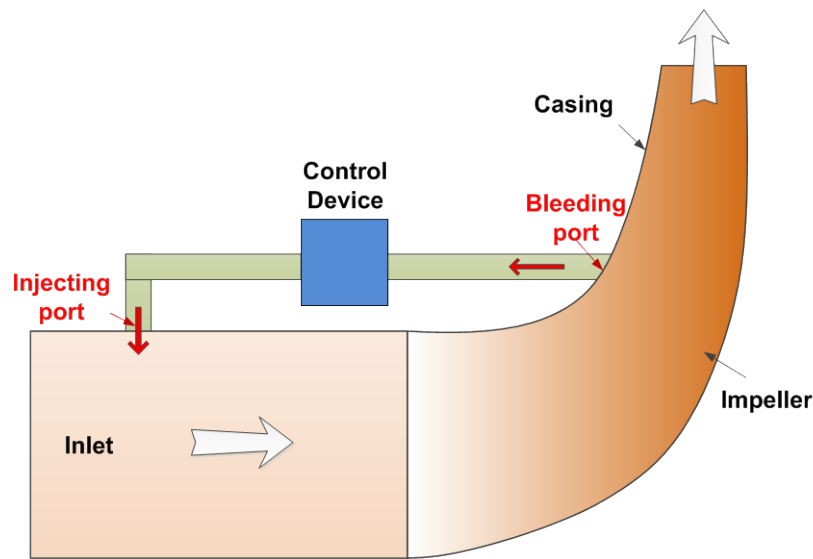


Figure 3. Schematic diagram of ACCT

Figure 4 shows the control flow chart of ACCT. The difference between ACCT and anti-surge systems also shows in Figure 4.

The yellow part in Figure 4 is the anti-surgeing system. In the anti-surgeing system, there are the pressures or other kinds of sensors, which can measure the stability of centrifugal compressors. When the compressor is on unsteady working condition, the controller of anti-surgeing system calculates the value of the control signal and put this signal to the anti-surge valve. Then some high-pressure gas flows back to the inlet of compressor through the anti-surge valve. Here the gas with the discharge pressure is put back to the inlet. The power which was used to compress this part gas is waste.

The blue part in Figure 4 shows the ACCT system. In the ACCT system, the sensors and controller are like with the anti-surgeing system. The main difference between these two systems is the state of gas that flows back to the inlet of compressor. In the ACCT system, the static pressure is just a little higher than the suction pressure of the compressor, which means that only a very small power was waste in this system.

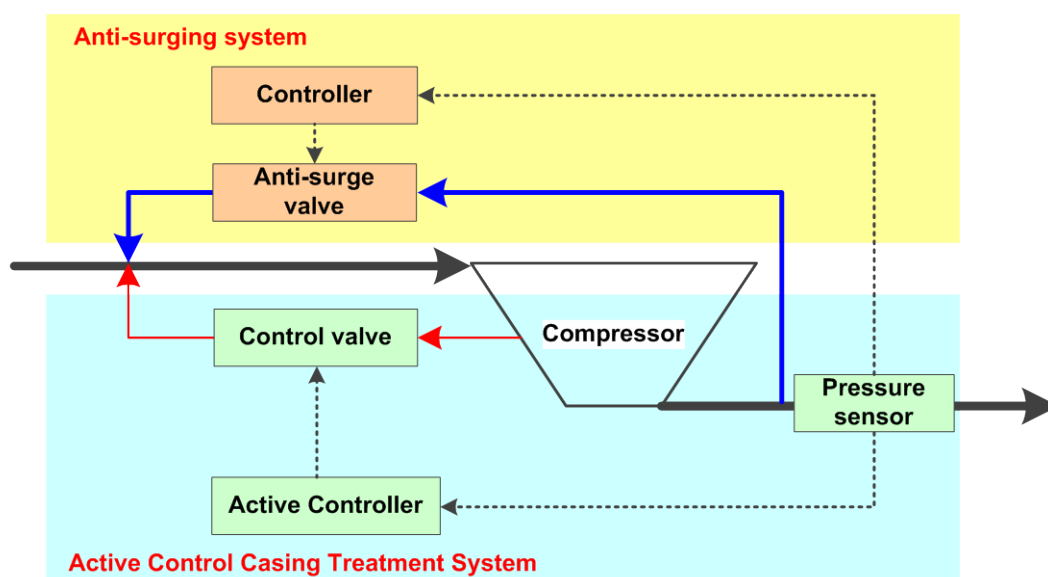


Figure 4. Schematic diagram of ACCT

The difference between ACCT and traditional casing treatment systems is the control ability of the system. In the traditional casing treatment system (Figure 2), there are always some compressed gas flowing from the impeller to the inlet of compressor, whatever the compressor is at the stability working conditions or not. That will lead to the low performance when the compressor operates at the normal working conditions (design working conditions). However, in the ACCT system, when the compressor operates on the normal working conditions, the control valve can be closed by the controller. When the compressor operates on the unstable working condition, the controller can decide the lift of control valve based on the strength of instability of compressor.

Using the above control method, the ACCT system can make the compressor maintain at the stable condition like the anti-surfing system. At the same time, the efficiency of compressor is not decreasing largely on the low mass flow rate working conditions.

3. PERFORMANCES SIMULATION

As a sample, a centrifugal compressor is simulated by CFD method to verify the reasonable of ACCT system.

3.1. CFD model

Figure 5 shows the simulation mesh using in the CFD calculation. The centrifugal compressor has a radial impeller. The number of normal blade and splitter blade is 11 respectively. The outlet diameter of impeller D is 300 mm. The cycle speed of impeller is 300 m/s.

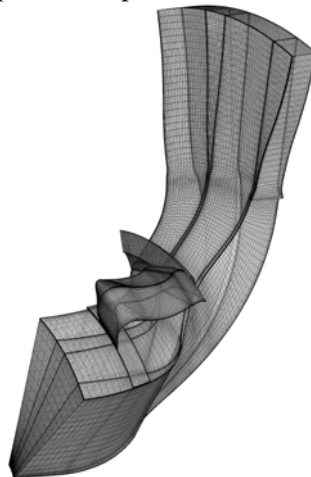


Figure 5. Simulation mesh

3.2. Define of stability

It is very important to evaluate the stability enhancement of centrifugal compressors. Here the ability of the stability enhancement of centrifugal compressors is defined as the following equation.

$$\phi = (m_{sta,ori} - m_{sta,CT}) / (m_{cho,ori} - m_{sta,ori}) \quad (1)$$

In Figure 6, the red line is the normal compressor performance curve. The pink short dash line is the extension part of performance curve when the ACCT system is used. The blue dot dash line is the boundary of unstable working conditions. The move of blue line from right to left (low mass flow rate) means the enhancement of stability of centrifugal compressor.

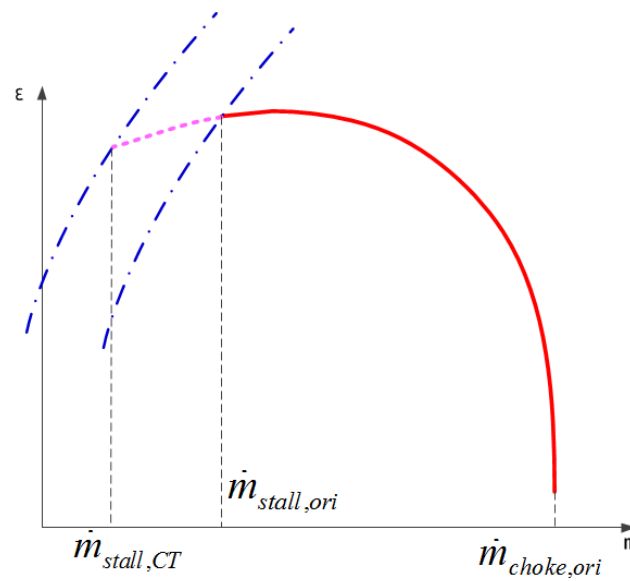
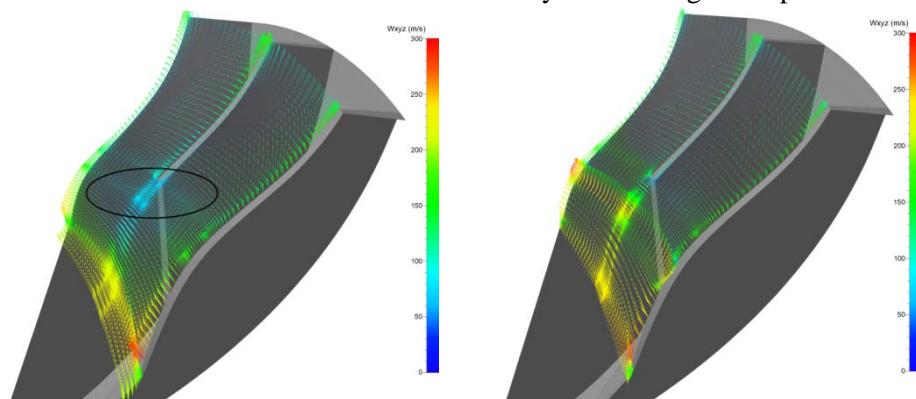


Figure 6. Define of the ability of the stability enhancement

4. RESULTS AND DISCUSSIONS

4.1. Flow analysis

Figures 7 and 8 show the details of flow in the impeller of centrifugal compressor. For the original structure compressor, the flow speed is low at the near of split blade (shown in Figure 7a). When using the ACCT structure, there is some gas bleeding at the split blade and that leads to the increase of flow speed at this area. This effect has the benefit to the stability of centrifugal compressor.



a. Original structure

b. ACCT structure

Figure 7. Velocity profile of compressor near the blade tip

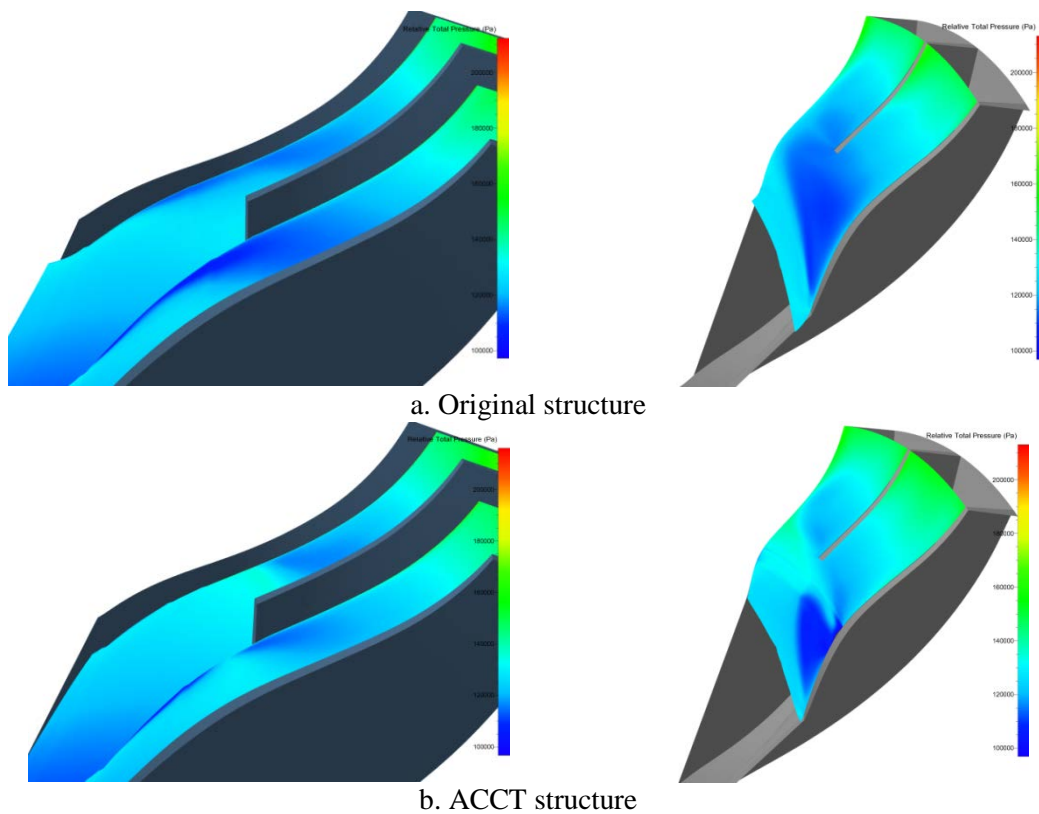


Figure 8. Total pressure of impeller

Figure 8 shows the pressure distribution of impeller. Figure 8a shows the pressure of gas in impeller at two different directions when the original structure is used. Figure 8b shows the pressure when the ACCT structure is used. The difference of these two structures can be gotten from the CFD simulation results. The area of low total pressure near the beginning end of split blade is decrease when using ACCT structure. The vortex in impeller is changed by the ACCT system. That means the flow loss is increasing and the flow is improved.

4.2. Ability of Stability Enhancement

The performance and efficiency of compressor under different ACCT parameters is simulated using the CFD methods.

Figure 9 shows the efficiency of compressor when the bleeding mass flow rate is changed (0, 0.2, 0.4, and 0.64 kg/s). From the curves of Figure 9 it can be seen that the efficiency of compressor decreases as the bleeding flow rate increases when the compressor operate at the low mass flow rate working conditions. It should be mentioned that the compressor is already at the instable working condition for original design when the mass flow rate is less than 2.95 kg/s.

Figure 10 shows the relationship between pressure ratio and mass flow rate of centrifugal compressor. From the results it can be seen that the pressure ratio increases as the increase of bleeding mass flow rate when the compressor operate at low mass flow rate condition. The ability of stability enhancement is increasing when the bleeding mass flow rate is increasing. When the bleeding mass flow rate is 0.64 kg/s, the ability of stability enhancement is 35%.

Because the focus of this paper is the stability of centrifugal compressor at the small flow rate, the performance of compressor at higher mass flow rate is not simulated.

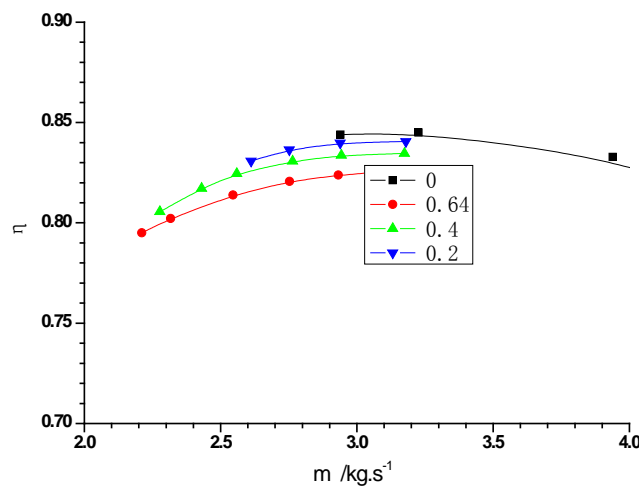


Figure 9. Efficiency of compressor

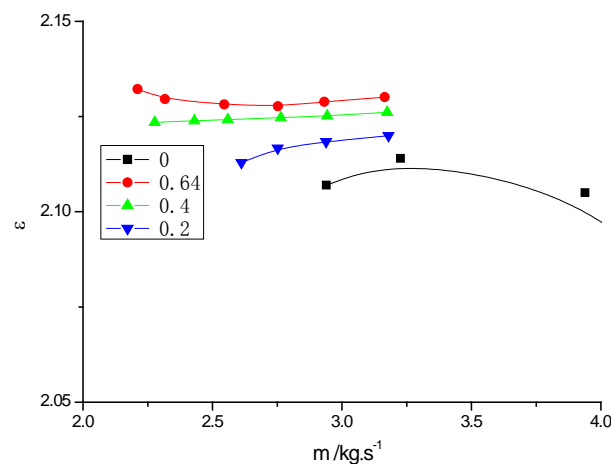


Figure 10. Performance of compressor

The test system of ACCT is building in the research lab. The test results will be gotten during the following period.

5. CONCLUSION

The main stable enhancement methods for centrifugal compressor are introduced in this paper. A new stable enhancement method based Active Control Casing Treatment is proposed in this paper. A centrifugal compressor having this system is researched using CFD method. The study focuses on the effect of the active control system on the impeller flow. The vortex in impeller is changed by ACCT system. And this leads to the suppression of the extension of vortex blockage in impeller and to contribute to the enhancement of the compressor operating range.

The pressure ratio increases with the increase of the bleeding flow rate. The compressor efficiency decreases with the increase of bleeding flow rate. The ability of stable enhancement increases when the bleeding flow rate is increasing. In addition, it is 35% when the bleeding flow rate is 0.64 kg/s.

Using ACCT system, the moment and the ability of stable enhancement can be gotten by the controller. That lead to the compressor can operate at the high efficiency and stability when the mass flow rate is low.

ACKNOWLEDGEMENTS

The work was supported by the National Key Basic Research Program of China (2012CB026000) and by the Science and Technological Fund of Anhui Province for Outstanding Youth (1508085J05).

References

- [1] Y Zhang, D Qi, and Y Mao. Experimental investigation and improvement of the inlet guide vane with plate vane in a centrifugal fan. *J. Power and Energy*, 2009(223): 401-413.
- [2] M Coppinger, E Swain. Performance prediction of an industrial centrifugal compressor inlet guide vane system. *Journal of Power and Energy*, 2000:153-164.
- [3] M M Cui. Unsteady flow around suction elbow and inlet guide vanes in a centrifugal compressor. *J. Aerospace Engineering*, 2006:11-28
- [4] Fisher, F. B. Application of Map Width Enhancement Devices to Turbocharger Compressor Stages. 1988, SAE paper No. 880794.
- [5] Wei Xu, Tong Wang, Chuangang Gu, et al. A study on the influence of hole's diameter with holed casing treatment. *Proceedings of ASME Turbo Expo 2011*. GT2011-46167.
- [6] Hideaki Tamaki. Effect of recirculation device on performance of high pressure ratio centrifugal compressor. *Proceedings of ASME Turbo Expo 2010: Power for Land, Sea and Air*. GT2010-22570.
- [7] Liang Ding, Tong Wang, Bo Yang, et al. Experimental investigation of the casing treatment effects on steady and transient characteristics in an industrial centrifugal compressor. *Experimental Thermal and Fluid Science*, 2013(45): 136-145.
- [8] Xinqian Zheng, Chuanjie Lan. Improvement in the performance of a high-pressure-ratio turbocharger centrifugal compressor by blade bowing and self-recirculation casing Treatment. *J Automobile Engineering*, 2014(228): 73–84.
- [9] J Tan, X Wang, D Qi, and R Wang. The effects of radial inlet with splitters on the performance of variable inlet guide vanes in a centrifugal compressor stage. *J. Mechanical Engineering Science*. 2011(225):2089-2105
- [10] Wallace, F. J., Whitfield, A., and Atkey, R. C. Experimental and theoretical performance of a radial flow turbocharger compressor with inlet prewhirl. *Proceedings of the Institution of Mechanical Engineers*. 1975(189): 177–186.