IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

Noise Reduction Design of the Volute for a Centrifugal Compressor

To cite this article: Zhen Song *et al* 2017 *IOP Conf. Ser.: Earth Environ. Sci.* **81** 012171

IOP Conf. Series: Earth and Environmental Science **81** (2017) 012171 doi:10.1088/1755-1315/81/1/012171

Noise Reduction Design of the Volute for a Centrifugal Compressor

Zhen Song, Huabing Wen, Liangxing Hong, Yudong Jin

Jiangsu University of Science and Technology, Zhenjiang, China

Corresponding author :Huabing Wen; E-mail: wen-huabing@163.com

Abstract. In order to effectively control the aerodynamic noise of a compressor, this paper takes into consideration a marine exhaust turbocharger compressor as a research object. According to the different design concept of volute section, tongue and exit cone, six different volute models were established. The finite volume method is used to calculate the flow field, whiles the finite element method is used for the acoustic calculation. Comparison and analysis of different structure designs from three aspects: noise level, isentropic efficiency and Static pressure recovery coefficient. The results showed that under the concept of volute section model 1 yielded the best result, under the concept of tongue analysis model 3 yielded the best result and finally under exit cone analysis model 6 yielded the best results.

1. Introduction

With the improvement of energy saving and emission reduction of internal combustion engine, the supercharging technology has been greatly developed. The turbocharger has become one of the core technologies of advanced internal combustion engine. However, as the pressure ratio continues to increase, the problem of noise begins to emerge. Aerodynamic noise is the dominant noise in a supercharger, which comprises of two basic components: Tonal noise and turbulence noise. The volute of the centrifugal compressor is an important part of the supercharger, which strongly affects the overall performance, stability, operating range and the location of the best efficiency point of the compressor[1]. The aerodynamic noise inside the volute is turbulence and vortex shedding noise.

At present, most of the research conducted on the volute is focused on the improvement of aerodynamic performance, rarely involved in the field of noise reduction. Some investigations suggested modifications to the volute cross-sectional areas in order to improve compressor pressure ratio and efficiency of the compressor. Harri Pitkanen et al[2] modified a rectangle-semicircle-shaped cross-section to fully circular cross-sectional shape and results showed to have good effect. Martin Heinrich[3] investigated the genetic optimization of the cross-sectional shape of the volute of a centrifugal compressor. Some studies suggested that modifying the volute tongue can improve the performance of the compressor. Cheng Xu[4,5] calculated the flow field of a compressor with different tongue. His results showed that the round tongue produces better performance than the sharp tongue. In addition, the exit cone could be considered as an exhaust diffuser with a highly-distorted flow, Mohammad Mojaddam[6] investigated the effects of cone angle on volute performance. In the aspect of noise control, Till Raitor[7] experiment investigated on the noise production mechanism of centrifugal compressor. Ibrahim Shahin[8] conducted an experiment using numerical study of a high-speed centrifugal compressor noise characteristics. J. Galindo[9] studied the impact of different inlet geometries on the noise emission. It is of great significance to study the noise reduction design of compressor. This paper is based on the characteristics of turbocharger noise source, research on noise reduction and design of volute on centrifugal compressor.

2. Simulation Method

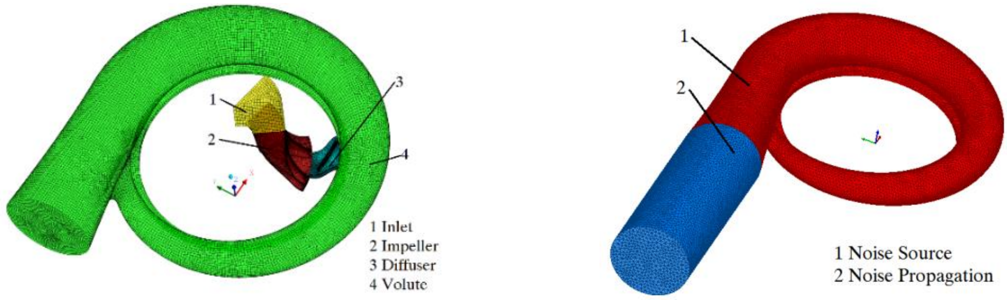
2.1. Compressor geometry
In order to design the noise reduction of the compressor volute, a centrifugal compressor is provided. The design speed is 40000r/min with a flow rate of 3~6kg/s, and a single-stage maximum pressure ratio of 5.0. There are 8 main and 8 splitter blades with vane diffuser.

2.2. Numerical Model
Acoustic calculation using acoustic analogy method, which divides sound field calculation area into sound source area and sound propagation area. The sound source area is the area where the noise is generated. The propagation area is the area where the sound waves propagate outward, and no noise is generated. As shown in equation (1), the left side represents the acoustic propagation under non-uniform flow, and the right side corresponds to the aerodynamic sound source of the wave propagation, which can be calculated using the CFD result. The flow field is calculated by the Smagorinsky turbulence model for unsteady incompressible calculations. The total pressure inlet and static pressure outlet are set. The unsteady time step is 5×10^{-5}s and the total time is 0.16s. The velocity and density variables of the fluid are calculated at the sound source. The turbulence noise of volute is considered in the sound field calculation.

$$\begin{aligned}
&\frac{\partial}{\partial t}\left(\frac{\tilde{\rho}}{\rho_T^2 c^2}\frac{D\tilde{b}}{Dt}\right)+\nabla\cdot\left(\frac{\tilde{\rho}\tilde{\mathbf{v}}}{\rho_T^2 c^2}\frac{D\tilde{b}}{Dt}-\frac{\tilde{\rho}}{\rho_T^2}\nabla\tilde{b}\right)\\
&=-\nabla\cdot\left(\frac{1}{\rho_T}(\tilde{\rho}\tilde{v}\times(\nabla\times\tilde{\mathbf{v}})-\nabla\tilde{\tau})\right)\\
&+\nabla\cdot\left(\frac{1}{\rho_T}\left(\frac{\partial\tilde{\rho}}{\partial\tilde{s}}\tilde{\mathbf{v}}\frac{\partial\tilde{s}}{\partial\tilde{t}}-\tilde{\rho}\tilde{T}\nabla\tilde{s}\right)\right)\\
&+\frac{\partial}{\partial t}\left(\frac{1}{\rho_T}\frac{\partial\tilde{\rho}}{\partial\tilde{s}}\frac{\partial\tilde{s}}{\partial\tilde{t}}+\tilde{\rho}\tilde{v}\cdot\nabla\frac{1}{\rho_T}\right)
\end{aligned}\tag{1}$$

Where $\tilde{\rho}$ and $\mathbf{v}$ is the density and velocity of flow, $\tilde{b}$ is scaled enthalpy, ρ_T is total density and c is sound speed.

2.3. Meshing
The computational grid consists of two categories: a fluid and an acoustic. The impeller, diffuser and the volute are used in the fluid calculation. As shown in the Fig.1(a), the grid adopts the structured hexahedron and the boundary layer of the flow surface. As shown in the Fig.1(b), the acoustic grid includes two parts a sound source area and a sound propagation area. The sound source area is the volute part, whiles the acoustic propagation area is the protracted section of the volute, the outlet is set to the duct mode, simulating the free and non-reflective propagation of the sound. At the same time, set a measuring point in the sound propagation area to measure the exit noise spetrum.



(a) (b)

Figure.1 CFD and CAA computation mesh

3. Design proposal

The design of six volute models was carried out from three aspects: Circumferential area, volute tongue and Exit cone. Tab.1 shows six different volute models and specific design methods, respectively, named Case1 to Case 6.

Table.1 Design scheme of volute

	Case1	Case2	Case3	Case4	Case5	Case6
Model						
cross-sectional	Stepanoff	Pfleiderer	Stepanoff	Stepanoff	Stepanoff	Stepanoff
Tongue	Sharp	Sharp	Round (6mm)	Round (8mm)	Round (10mm)	Sharp
Exit cone	Tangential	Tangential	Tangential	Tangential	Tangential	Radial

Stepanoff and Pfleiderer are two design models of the volute circumferential area. The Stepanoff model is:

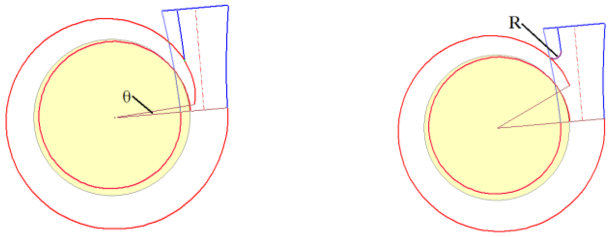
$$C_{\theta c,2\pi} = K_s \sqrt{2gH} \qquad (2)$$

K_s is an experimental constant and H is the pump head. Pfleiderer model is:

$$r_c^m C_{\theta c} = r_3^m C_{\theta 3} \qquad (3)$$

where m=1 use for compressor volute design, and case1 uses the Stepanoff model, case 2 uses the Pfleiderer model.

At present, there is little theoretical guidance on the design of the volute tongue, the literature 4 and 5 have taken into consideration the round and sharp tongue design. As shown in Fig.2, the connection of the exit cone to the volute is changed from sharp to a round design as the angle θ increases. The radius of the round tongue is R. Case2 selected sharp tongue, case3, case4 and case5 use round tongue design, the radius R were 6mm, 8mm and 10 mm.



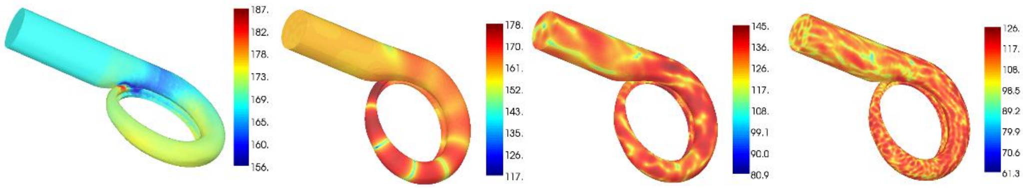
(a) (b)

Figure.2 Sharp and round tongue of volute

The exit cone could be considered as an exhaust diffuser with the highly-distorted flow[10], according to the different exit direction, it can be divided into radial and tangential one. Case1 is Tangential exit cone and case6 is radial one.

4. Results and discussion

Fig3(a), (b), (c), (d) represents case1 at 100Hz, 1000Hz, 5000Hz, 10000Hz sound pressure level. With an increase in frequency, sound pressure decreases. At the exit of the mode duct, leading to the sound source area, the noise is greater than the noise at the propagation area at low frequency and the sound pressure distribution characteristic of the volute become obvious. At high frequencies, the distribution of the sound pressure level in source region is similar to that in acoustic propagation. Therefore, in the next analysis mentioned in the sound field cloud map, 100Hz frequency is used.



(a) (b) (c) (d)

Figure.3 Sound pressure level distribution of volute at different frequencies

The calculation results are analyzed from three aspects: Aerodynamic noise of volute(Lp), entropy efficiency of compressor(η_s), and static pressure recovery coefficient of volute(C_p).

$$L_p = 20Lg\frac{P}{P_0} \tag{4}$$

P is the sound pressure, the reference pressure P_0 is $2 \times 10^{-5}Pa$.

$$\eta_s = \frac{T_{in}\pi^{\frac{k-1}{k}} - T_{in}}{T_{out} - T_{in}} \tag{5}$$

Where T_{in} is the temperature at the inlet of the compressor and T_{out} is the temperature at the outlet.

$$C_p = \frac{P_4 - P_3}{P_{03} - P_3} \tag{6}$$

Where P_4 is the static pressure at the exit of the volute, P_3 is the static pressure at the inlet of the volute, P_{03} is the stagnation pressure at the inlet of the volute.

4.1. Cross-sectional areas

As shown in Table 2, compressor volute with the Stepanoff model is better than Pfleiderer in all aspects. Compared with the Stepanoff volute, Sound pressure level of Pfleiderer spiral case increased by 14.39dB, whiles the efficiency decreased by 3.3%, static pressure recovery coefficient of a larger negative.

IOP Conf. Series: Earth and Environmental Science **81** (2017) 012171 doi:10.1088/1755-1315/81/1/012171

Table.2 Comparison of noise and performance of different designs

Scheme	*Lp*(dB)	η_s(%)	C_p
Case1	190.32	80.0	0.46
Case2	204.71	76.7	-4.40

4.2. Tongue

In terms of aerodynamic noise, performance of case3 is better than others. Compared with the design of sharp tongue, the total sound pressure level of case1 decreased by 4.53dB. From the efficiency and static pressure recovery coefficient point of view, the tongue design of these two aspects of the performance is relatively small.

Table.3 Comparison of noise and performance of different designs

Scheme	*Lp*（dB）	η_s(%)	C_p
Case1	190.32	80.0	0.46
Case3	185.79	80.0	0.46
Case4	190.91	79.8	0.46
Case5	191.15	79.6	0.49

Fig.4 is the four volute design of the sound pressure level cloud. The cloud is drawn on the lateral plane (plane1) and the longitudinal plane of the tongue. (a), (b), (c), (d), respectively represents case1, case3, case4, and case5. As can be seen from the figure, the maximum sound pressure level is located at the volute tongue, and a large sound pressure level gradient appears. In contrast, the sound pressure level distribution at case 3 is relatively uniform and the sound pressure level at the same plane is relatively small.

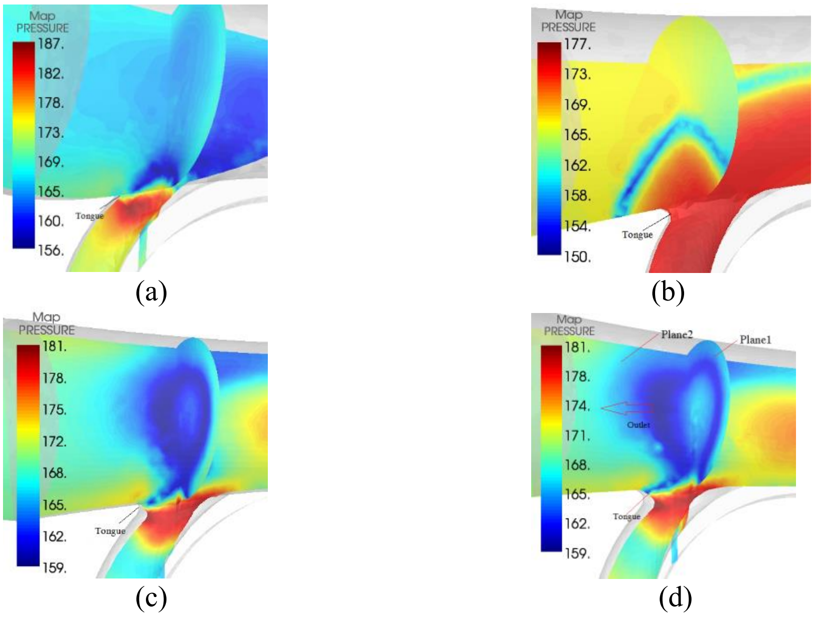


Figure.4 Sound pressure level distribution of volute tongue with different volute

4.3. Exit cone

In the aerodynamic noise, the radial cone design can play a role in noise control, reduce the volute noise up to 1.24dB. At the same time, reduce the efficiency and static pressure recovery coefficient with varying degrees

Table.4 Comparison of performance of different designs

Scheme	*Lp*（dB）	η_s(%)	C_p
Case1	190.32	80.0	0.46
Case6	188.08	79.6	0.44

Sound pressure spectra measured at the design point in the outlet duct are plotted in Fig.5. Turbulent noise in volute decreases as the frequency increases. The radial cone reaches the maximum 152dB at 225Hz, 9dB higher than the tangential one, while the other frequencies are less than the tangential setting.

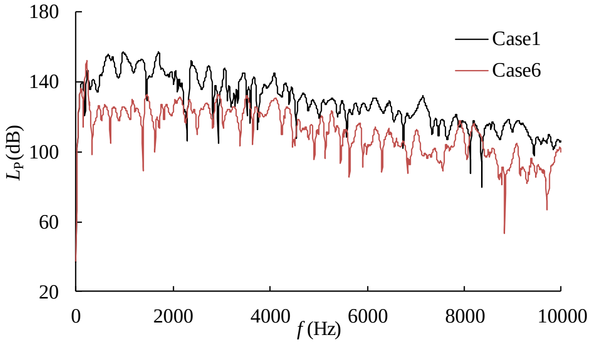


Figure.5 Sound pressure spectra in the outlet duct

5. Conclusions

In this paper, six volute simulation models were established by using different spiral sections, volute tongue and exit cone design. The flow and sound field results of each volute model were calculated. Compressor aerodynamic noise control was evaluated from noise performance, thermal performance, and aerodynamic performance, the following three conclusions were obtained:

(1) Firstly in the case of all parameters remaining same, Stepanoff volute play a better aerodynamic noise control effect than Pfleiderer volute, sound pressure level decreased by 14.39dB. At the same time, Pfleiderer volute under the machine efficiency and volute static recovery coefficient were significantly decreased, indicating that Pfleiderer volute is not suitable for use in high pressure ratio of centrifugal compressor.

(2) Secondly in the case of all parameters remaining same, 6mm radius of the round tongue design can play a better noise control effect, compared with the sharp volute tongue design, the total sound pressure level decreased by 4.53dB. On the whole, the sharp tongue and the different radius of the round tongue design have a smaller impact on the efficiency and static pressure recovery coefficient.

(3) Thirdly in the case of all parameters remaining same, radial cone design can play a better aerodynamic noise control effect. Compared with the tangential cone design, the sound pressure level of radial design decreased by 1.24dB. But the whole machine efficiency and static pressure recovery coefficient have different degrees of attenuation.

References

[1] Chehhat Abdelmadjid, Si-Ameur Mohamed, Boumeddane Boussad 2013 CFD analysis of the volute geometry effect on the turbulent air flow through the turbocharger compressor *Energy Procedia.* **36** 746-755

[2] Harri Pitkanen, Hannu Esa, Arttu Reunanen 2000 Computational and experimental study of an industrial centrifugal compressor volute *J. of Thermal Science*. **9**(1)77-83

[3] Martin Heinrich, Rüdiger Schwarze 2016 Genetic algorithm optimization of the volute shape of a centrifugal compressor *I J, of Rotating Machinery*. **2016** 1-13

[4] Cheng Xu, Michael Muller 2005 Development and design of a centrifugal compressor volute *I J. Rotating Machinery.* **3** 190–196

[5] C. Xu, R. S. Amano 2006 Eliminating static pressure distortion by a large cut back tongue volute *Proc.*, *GT2006 ASME Turbo Expo: Power for Land, Sea and Air* (Barcelona, Spain)

[6] Mohammad Mojaddam, Ali Hajilouy Benisi, Mohammad Reza Movahhedy 2015 Optimal design of the volute for a turbocharger radial flow compressor *J. Aerospace Engineering* **229(6)** 993-1002

[7] Till Raitor, Wolfgang Neise 2008 Sound generation in centrifugal compressors *J.Sound and Vibration*, **314**:738–756
[8] Ibrahim Shahin, Mohamed Alqaradawi, Mohamed Gadala 2017 On the aero acoustic and internal flows structure in a centrifugal ompressor with hub side cavity operating at off design condition *Aerospace Science and Technology*. **60** 68–83
[9] J. Galindo, A. Tiseira, R. Navarro 2017 Effect of the inlet geometry on performance, surge margin and noise emission of an automotive turbocharger compressor *Applied Thermal Engineering*. **110** 875–882
[10] Aungier RH 2000 Centrifugal compressors: a strategy for aerodynamic design and analysis *Mechanical Engineering*. **122**(9) 105