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Research on Laval Nozzle and Overall Simulation Analysis Based on High Speed Precision Air Bearing Spindle Pneumatic Turbine System

Du Xi
School of Mechatronic Engineering
Xi'an Technological University
Xi'an, China
E-mail: 493125654@qq.com

Liu Bo
School of Mechatronic Engineering
Xi'an Technological University
Xi'an, China
E-mail: 976361823@qq.com

Fang Zhou
School of Mechatronic Engineering
Xi'an Technological University
Xi'an, China
E-mail: 27381788@qq.com

Zhang Jun-an
School of Mechatronic Engineering
Xi'an Technological University
Xi'an, China
E-mail: zja128@163.com

***Abstract*—Laval nozzles for important component in high-speed precision air-floating spindle gas drive systems, to establish a cross-sectional ratio is calculated by analysis of their simplified model of the two stages. Use of computational fluid dynamics (CFD) to simulate the Structural parameters of Laval nozzle-- pneumatic turbine and analyzed the gas flow and flow rate. The simulation results show that the airflow impinges on the turbine blades and then flows out to the surroundings. The gas flow is accelerated in the Laval nozzle, reaching a maximum at the outlet, and the dynamic pressure in the Laval nozzle is high, reaching a maximum at the nozzle outlet. The simplified Laval nozzle model meets the design requirements. Then the article analyzes the problems in the model simplification and lays the foundation for the subsequent engineering experiments**

Keywords-Laval Nozzle; Cross Section Ratio; CFD

I. INTRODUCTION

The history of Laval nozzles (also known as convergent-diffusion nozzles) dates back to 1897[1]. At the time, a Swedish inventor named Gustav Laval made a metal tube that looked like an hourglass and was originally used on a steam engine[2].For more than 100 years, Laval nozzles have long ceased to be patents in the field of steam engines[3]. Laval nozzles are widely used in various supersonic aircraft propulsion systems, such as solid rocket engines and supersonic jet engines[4-6].

The airfoil spindle supported by Laval nozzle -- pneumatic turbine drive and gas bearing can greatly reduce the friction loss of the bearing and achieve a high rotational speed.It is an important development trend of the main shaft.In this study[7], high-speed precision air bearing spindle bench as the application background, to develop high-performance air bearing spindle for the purpose of the study is mainly the bench with a gas drive system[8].

Among them, the Laval nozzle is a key component of the drive system. The airflow first accelerates to the speed of sound in the subsonic section through the contraction nozzle[9], and then further accelerates to supersonic speed through the expansion nozzle[10].In this study, a supersonic nozzle that is firstly contracted and expanded, that is, a Laval nozzle, is used, and a pneumatic turbine is used to increase the rotational speed of the air-floating spindle. In the Laval nozzle modeling process, the typical working conditions are simplified[11]. The calculation method of the Laval nozzle outlet parameters when the nozzle area ratio and the inlet flow change are given in detail. and simulation of the air flow with its internal CFD[12].

II. STRUCTURE OF THE GAS DRIVE SYSTEM

Figure 1 shows the gas drive system structure includes a shell, a Laval nozzle, a turbine housing, a pneumatic turbine, and the like. Considering that the quality of parts is minimized under the premise of ensuring performance, the material is made of 2a12 aluminum alloy. The design and calculation of the pneumatic turbine and the Laval nozzle is the core of the power part, which is the basis for the design of the components and the overall structure of the air-floating spindle.

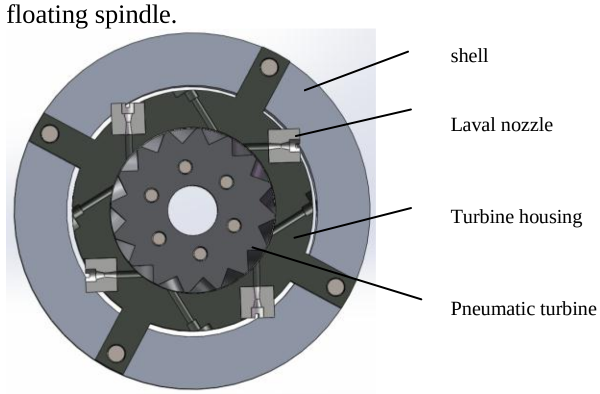

Figure 1. Structure diagram of the gas drive system

The gas is accelerated by the Laval nozzle, and the airflow is blown to the turbine blades to drive the air-floating main shaft to rotate. Considering the gas source capacity, if the flow rate is too large, the gas supply cannot be continued, but if the flow rate is too small, the speed of the air-floating spindle is not improved. Therefore, the Laval nozzle is very important for the acceleration of airflow and the control of gas flow.

III. LAVAL NOZZLE MATHEMATICAL MODEL

The Laval nozzle is divided into two parts, a contraction section and an expansion section. The airflow is first accelerated to the speed of sound in the subsonic section by the contraction nozzle, and then further accelerated to the supersonic speed by the expansion nozzle.

The contraction section： when $0 \le Ma < 1$, Ma is the Mach number. To increase the speed of the airflow, the nozzle section must be contracted; to reduce the speed, the nozzle section must be expanded. Since the isentropic flow has no pressure loss, the total pressure and total temperature of each section of the nozzle are the same.

According to the energy equation, the continuous equation and the thermodynamic formula, the critical pressure ratio corresponding to the sound velocity of the throat is obtained as follows:

$$\beta_{cr} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{1}$$

The expansion section： when $Ma > 1$, to increase the velocity of the gas stream, the nozzle section must be expanded; to reduce the velocity of the gas stream, the nozzle section must be shrunk. According to the expansion stage, the mass flow rate remains $\dot{m}$ is unchanged, and the position of any section can be obtained:

$$\dot{m} = \sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \cdot \frac{p^*}{\sqrt{T^*}} \cdot Ma\left[\frac{2}{k+1}\left(1+\frac{k-1}{2}Ma^2\right)\right]^{-\frac{k+1}{2(k-1)}} \cdot A_e \tag{2}$$

In the middle P^*, T^*, A_e express pressure, temperature, and cross-sectional area at any position. This formula is true for any section, so the throat is used as a reference. The ratio of the cross-sectional area at any position to the throat area A_{cr} is obtained：

$$\frac{A_e}{A_{cr}} = \frac{1}{Ma_e}\left[\left(1+\frac{k-1}{2}Ma_e^{\,2}\right)\left(\frac{2}{k+1}\right)\right]^{\frac{k+1}{2(k-1)}} \tag{3}$$

Where Ma_e is the Mach number at any cross-section position，therefore, the configuration of the nozzle can be determined simply by requesting the Mach number of the outlet. According to the isentropic flow, you can pass the formula:

$$\frac{p_2}{p_{cr}} = \left(1+\frac{k-1}{2}Ma_2^{\,2}\right)^{-\frac{k}{k-1}} \tag{4}$$

Get the exit Mach number Ma_2, further, the ratio of the outlet section to the throat area, the throat section parameter, and the outlet section parameter can be obtained.

Calculate the critical section parameters of the throat：

$$\nu_{cr} = \frac{1}{\rho_{cr}} = \frac{RT_1}{P_1} \times \left(\frac{P_1}{P_{cr}}\right)^{\frac{1}{K}} \tag{5}$$

ρ_{cr}, P_{cr} is the critical surface gas density and pressure of the throat, P_1 is the Supply pressure, T_1 is the compression temperature,

$$T_{cr} = \frac{P_{cr} \times \nu_{cr}}{R} \tag{6}$$

We can calculate the critical section temperature T_{cr}.

$$C_{cr} = \sqrt{2(h_1 - h_{cr})} = \sqrt{2C_p(T_1 - T_{cr})} \tag{7}$$

h_1, h_2 is the value of the inlet and the critical surface, C_p is the air specific heat capacity, we can calculate the critical section speed C_{cr}.

$$A_{\min} = \frac{\dot{m}\nu_{cr}}{C_{cr}} \tag{8}$$

Throat cross-sectional area A_{min} can be calculated by substituting data.

Calculate the exit section parameters：

$$\nu_2 = \frac{1}{\rho_2} = \frac{RT_1}{P_1} \times \left(\frac{P_1}{P_2}\right)^{\frac{1}{K}} \tag{9}$$

Calculated at the exit section v_2 .

$$T_2 = \frac{P_2 \times \nu_2}{R} \tag{10}$$

Calculated outlet section temperature T_2.

$$C_2 = \sqrt{2(h_1 - h_2)} = \sqrt{2C_p(T_1 - T_2)} \tag{11}$$

In the formula, h_2 is the exit value, and the outlet section speed C_2 is calculated.

$$A_2 = \frac{\dot{m} v_2}{C_2} \tag{12}$$

Substituting data, calculating the throat cross-sectional area A_2.

The extended part length calculation formula is；

$$l = \frac{d_2 - d_{\min}}{2\tan\phi} \tag{13}$$

Where d_2 is the outlet cross-sectional diameter and d_{min} is the throat cross-sectional diameter, $\varphi$is the tip cone angle. Usually take the top cone angle around 10 ° , If the expansion part is selected too short, the airflow expands too fast, which may cause disturbance and increase internal friction loss; if the extension part is selected too long, the friction loss between the airflow and the pipe wall increases, which is also disadvantageous.

Through calculation, the simplified model data of the Laval nozzle can be obtained, which is convenient for the simulation analysis.

IV. OVERALL SIMULATION ANALYSIS

This section uses the commercial CFD software fluent to simulate the flow of gas inside the Laval nozzle-pneumatic turbine and analyze its aerodynamic performance. The solid model is directly established in the fluent general pre-processing software ICEM. It uses a tetrahedral mesh Tet/Hybrid, the type is Tgrid, and the grid unit side length is 0.1mm. The solid model is meshed, as shown in figure 2 and figure3. The total number of divided grids is approximately 3340000.

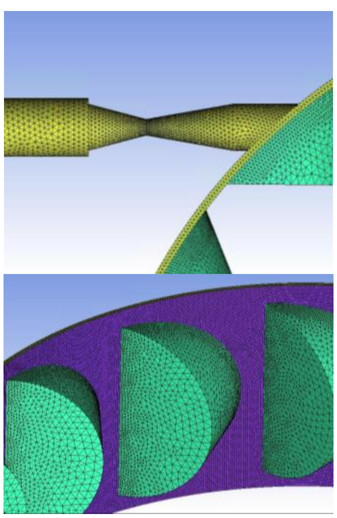

Figure 2. Local grid diagram of the runner region of the Laval nozzle and the pneumatic turbine

Figure 3. Laval nozzle - pneumatic turbine runner area grid diagram

The inlet faces of the four Laval nozzles are set as pressure inlet boundaries, the four exhaust passage exit faces are set as pressure outlet boundaries, the outer wall faces are fixed, and the inner wall faces are pneumatic turbine rotating wall faces, given the rotational speed of the pneumatic turbine. The calculation uses a three-dimensional single-precision pressure solver, and the whole flow is regarded as a three-dimensional stable flow, ideal air as a working medium, and dynamic viscosity is 1.85×10^{-5} $\mathrm{Pa \cdot s}$. Assuming that the blade is adiabatic and has no slip wall area, the gas flow is adiabatic. The $k\text{-}\omega$ model is an empirical model based on the turbulent energy equation and the diffusion rate equation. It can be used for wall-bound flow and free-shear flow, so it is calculated using a $k\text{-}\omega$ two-equation turbulence model.

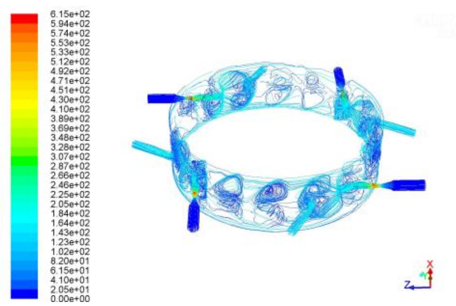

Figure 4. Laval nozzle - pneumatic turbine speed streamline diagram

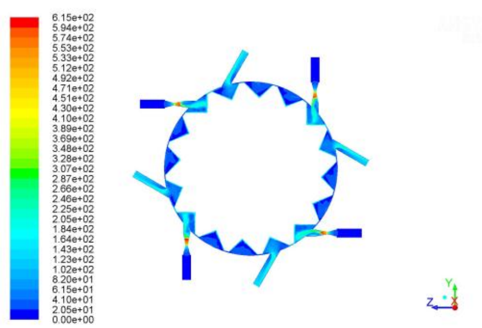

Figure 5. Laval nozzle - pneumatic turbine speed cloud

Figure 4 is a streamline diagram of the airflow drawn from the inlet, figure 5 is its speed cloud. It can be seen from the figure that the airflow impinges on the turbine blades and then flows out to the surroundings, a part of which flows forward around the turbine and flows out from the nearest exhaust port, and this part of the airflow has less influence on the turbine speed; There is also a portion of the gas flow that flows in the opposite direction, which merges with the incoming flow from the last nozzle and flows out of its reverse most recent discharge port. This portion of the reverse flow is bound to reduce the turbine's speed or torque. As can be seen from the figure, the airflow reaches the maximum at the exit of the Laval nozzle.

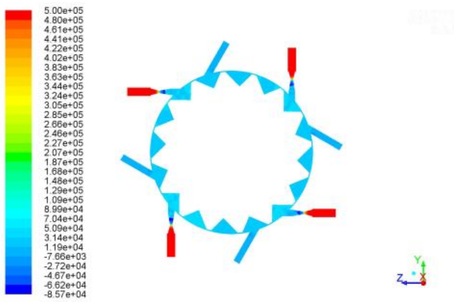

Figure 6. Laval nozzle - aerodynamic vortex pressure distribution map

Figure 6 is a pressure profile of the radial cross section of the turbine. It can be seen from the figure that the pressure in the nozzle is high, reaching the highest at the nozzle outlet, but falling sharply into the turbine chamber due to the high back pressure in the turbine chamber and the back flow of the airflow impinging on the turbine blades. This means that the exhaust port should be properly arranged to discharge the airflow in time to reduce the influence of back pressure. It can be seen that the design of the exhaust port has a great influence on the rotational speed or torque of the turbine.

V. PARTS PROCESSING

Based on the key design parameters provided by the design study in the previous section, this section has detailed design of the components and overall structure of the gas-driven part of the air-floating spindle.

Figure 7. Laval nozzle processing physical map

Figure 7 is a physical diagram of Laval nozzle processing. Based on the design calculation of the Laval nozzle, the structure is small and the internal surface precision is high. It is difficult to integrate the whole process. Therefore, the Laval nozzle will be used. It is designed and machined separately from the turbine housing and assembled by means of a threaded connection. The inlet portion of the Laval nozzle is designed with the nozzle installed, and a slot is designed at the top to facilitate installation on the turbine housing.

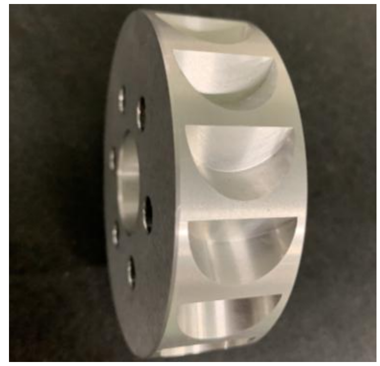

Figure 8. Pneumatic turbine machining physical map

Figure 8 is a physical diagram of a pneumatic turbine machining. Based on the design of the turbine, the pneumatic turbine uses an impact-type pneumatic turbine structure with 16 semi-circular blades circumferentially distributed. Between the constraints of the existing spindle structure, the connection between the pneumatic turbine and the main shaft uses 6 uniform M6 screws to connect the main shaft to transmit power. Considering the quality of the parts as much as possible under the premise of ensuring performance, the pneumatic turbine material is 2a12 aluminum alloy. The alloy is processed on the machining center.

Figure 9. Turbine shell physical map

Figure 9 is a physical view of the turbine casing, the design of which is based on the calculation and design of the pneumatic turbine and the Laval nozzle. The air inlet is divided into a connecting portion and a diversion portion of the Laval tube. Due to the small size of the Laval tube, in order to avoid excessive influence of the excessive length of the flow guiding portion on the air flow speed, the special-shaped housing design is adopted; the diameter of the guiding portion and the pulling method are adopted. The diameter of the outlet of the Vale tube is the same. A gas nozzle is attached to the outer end of the gas outlet to discharge the exhaust gas through the gas pipe. The turbine casing is uniformly distributed with four inlet and outlet ports, and the inlet port position is opposite to the center of the turbine blade, and the outlet port and the inlet port are designed at a certain angle to ensure smooth outflow. The housing is connected to the flange by four M8 bolts, and the material is made of 2a12 aluminum alloy.

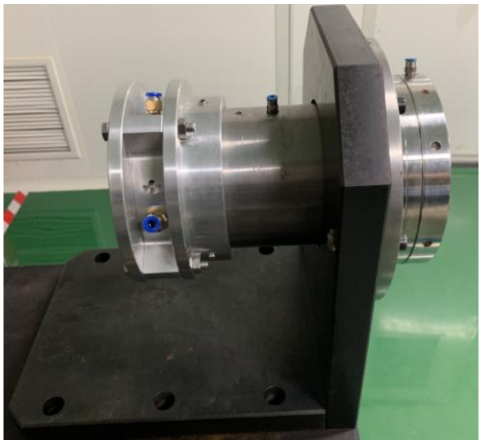

Figure 10. Air floating spindle test bench

Figure 10 is an air floating spindle test bench. The air floating main shaft mainly includes a gas driving portion, a main shaft portion and an air bearing portion. Engineering experiments will be completed on this platform later.

VI. CONCLUSION

In the simplified model establishment, have the following questions to discuss:

In the simplified model establishment, since the theoretical calculation is a one-dimensional non-viscous pipeline flow, considering the increase of the actual gas state loss, the cross-section ratio should be appropriately increased to fully expand the gas. In the theoretical calculation, the wall of the Raphael tube is a smooth curve. Considering the difficulty of processing with a small size, the use of a straight line instead of the actual processing will also make the gas velocity smaller, so the cross-sectional ratio should be appropriately increased. However, the increase in the outlet cross-section leads to an increase in the air consumption per minute. In order to allow the air compressor to continue to supply air for the experiment, the overall size should be appropriately reduced when the cross-section ratio is increased.

In this paper, the mathematical model of Laval nozzle is established, and the calculation method of the parameters of the Laval nozzle is given in detail by appropriate simplification and merging. The problems in the simplification are analyzed, which lays a foundation for the subsequent engineering experiments.

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