Application Optimization of Two-Dimensional Nozzle with Alloy Steel Structure in the Supersonic Wind Tunnel

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Abstract

The two-dimensional nozzle is an import part of supersonic wind tunnels to obtain the flow field with designed Mach number, and the structure of nozzles has direct influence on the uniformity of flow field. Usually, for easy construction and convenience in the two-dimensional nozzle, epoxy resin is adopted in the structural design as the material. However, because of the difference linear expansion coefficient between epoxy resin and the steel framework, often the separation appears due to the reason, and the expansion and contract caused by the heat and cold air flows during the operation of wind tunnel, there often appear some cracks on the edges and body of the nozzle made of epoxy resin; due to the large size of particle contained in the air flow, there often appear some nicks on the nozzle contour. The cracks and nicks will bring about shock waves in the flow field which has disadvantageous effect on the quality of flow field. In order to eliminate the shortcoming caused by the epoxy resin, we have comprehensive consideration of various factors in the two-dimensional nozzle design of 1.2m×1.2m supersonic wind tunnel, making the body structure based on alloy steel for the two-dimensional nozzle design, so a nozzle of steel structure is made with exit size of 1.2m×1.2m and Mach number of 3.5. A great deal of experiments have been conducted on the nozzle, and experimental results show that the flow field of the nozzle is always good. In this paper, the design details of two-dimensional nozzle will be described on the basis of the engineering algorithm, and the stress and deformation analysis is calculated by Ansys, and the calculation results show that two-dimensional nozzle with alloy steel satisfies the design conditions. Some typical experimental results of flow fields of the nozzle steel structure are also presented, the nozzle is reliability and easy to use, and the maintainability is very good, the surface strength of two-dimensional nozzle is greatly increased, extend the service life more than 10 years.

Keywords: structure, optimization, two-dimensional nozzle, supersonic, alloy steel

1. Determine the scheme

There are two kinds of supersonic nozzle contours, two-dimensional contour and three-dimensional contour. The two-dimensional nozzle has two parallel planar walls and its other two walls are two-dimensional curve surface, while the wall of three-dimensional nozzle, whose cross section is circular, is a three-dimensional curve surface. The supersonic nozzle is an important part of supersonic wind tunnels to obtain the design Mach number of airflow, and it is already known that the Mach number is determined by the area ratio of nozzle throat to test section, meanwhile the quality of flow field is influenced by the nozzle contour. So the design and processing quality of the nozzle have a decisive influence on the quality of the flow field in the test section[1].

A 1.2 meter magnitude supersonic wind tunnel is adopted two-dimensional nozzle structure, the maximum Mach number of this tunnel is M4.0 and two-dimensional nozzle structure is used in it. Now the wind tunnel has now completed the supersonic flow field debugging and this paper focus on M3.5 nozzle structure optimization. The contour of 1.2 meter magnitude supersonic wind tunnel nozzle is 1.2 meter with width and height of outlet dimension. The nozzle length is 4.8m.

According to the design data about supersonic wind tunnel, the structure of solid-block nozzle is usually made of cast aluminum and epoxy coating. When doing the two-dimensional nozzle design in the wind tunnel, the M3.0 and M4.0 nozzles are both made of epoxy resin in the initial stage. 40 millimeter steel plate welding is used to form nozzle's frame, on which is laid. Finally epoxy coating is used to form the surface of nozzle with mould. The advantage of this structure is that the accuracy is easy to ensure, besides its low cost, it is shown in Fig.1. The disadvantage is that the thermal expansion coefficient between epoxy resin and the steel is very different (The epoxy resin is 56.8×10^{-6} /℃ and the steel is 11.7×10^{-6} /℃). When the wind tunnel is working, the temperature is turn down quickly, causing the appearance of crack when tunnel is working. The crack will propagate if the nozzle is not timely repaired. And also the flow field inevitably contains a large number of foreign particles, which will obtain huge impact and damage when the wind tunnel is working. So the surface of epoxy resin, whose hardness is far lower than steel, may be full of scratch, because of the collision of particles. The cracks and scratches can cause shock wave, bringing adverse effect in the flow field, The nozzle frame and cracks and scratches can be seen in Fig. 2, Fig. 3, Fig .4.

Figure 1. The frame foundation of epoxy resin surface

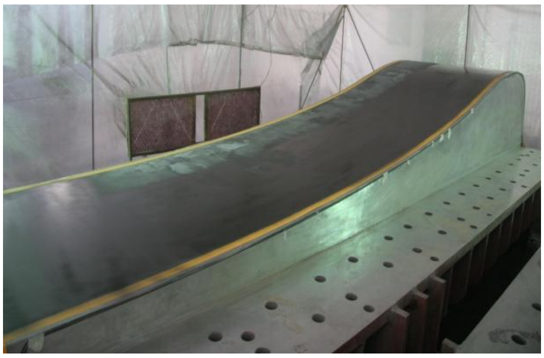


Figure 2. The Forming picture of epoxy resin

Figure 3. The separation between epoxy resin and the frame of nozzle

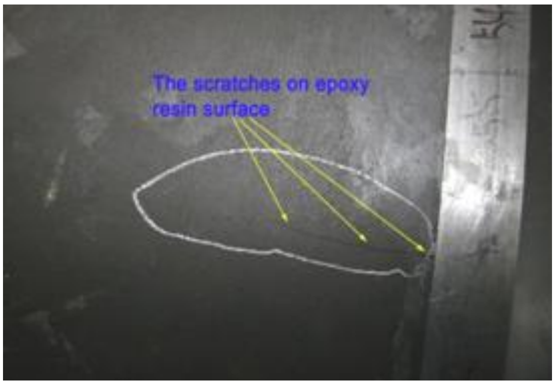


Figure 4. The scratches on epoxy resin surface

In order to eliminate the negative factors, we fully analyzed the reason of the above problems during the designing of the M3.5 nozzle. Based on the original structure of nozzles of M3.0 and M4.0, we optimize the design of nozzle. This two-dimensional nozzle scheme is that the whole nozzle structure uses alloy steel, the curve surface is made of alloy steel plate, and is machining by CNC milling machine can reach 0.03mm and the surface roughness can reach more than 1.6, so the stiffness and strength have been greatly improved. Besides the above improvement, the low cost and simple manufacture are also its advantages. This design method by using alloy steel belongs to domestic initiative.

2. The engineering algorithm

The material of M3.5 two-dimensional nozzle is made of 16MnR, and the material of it whose allowable stress is $[\sigma]=163MPa$. The pressure of two-dimensional nozzle is P1 before the throat and P2 after the throat. The M3.5 nozzle is composed of support ribs intersecting, which is divided into many rectangular plates. Thus each rectangular plate can be seen as fixed edges under uniform load. The structure of M3.5 nozzle is shown in Fig.5.

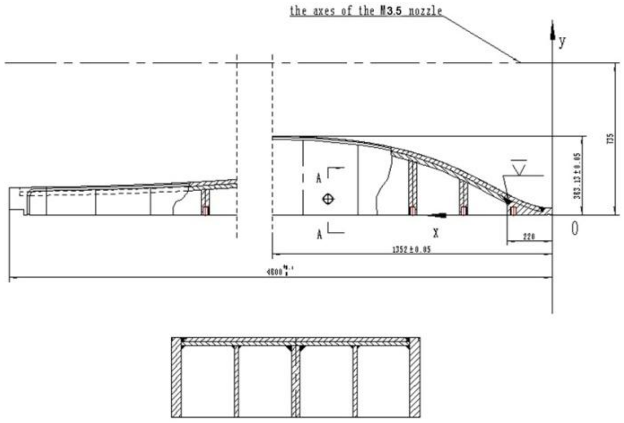


Figure 5. The structure of M3.5 nozzle

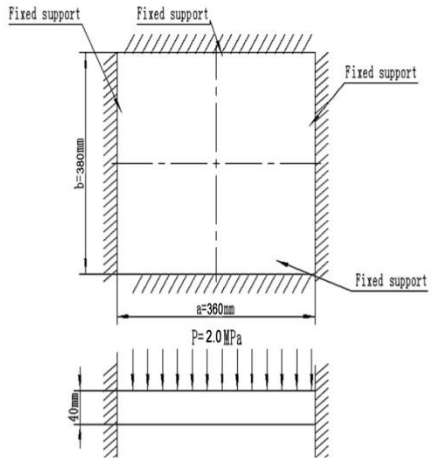


Figure 6. The force of M3.5 two-dimensional nozzle

2.1 Stiffness calculation

Deformation calculation formula for center part: $f=C_3\dfrac{qb^4}{Eh^3}$ （1）

a	Rectangular plate long edge	$a=380mm$
b	Rectangular plate short edge	$b=360mm$
C_3	Rectangular plate coefficient	$C_3=0.0165$
q	The uniform load on plate	$q=2MPa$
E	Modulus of elasticity	$E=206\times10^3 MPa$
h	The thickness of rectangular plate	$h=40mm$

The above data into the formula to be $f=0.0165\times\dfrac{2\times360^4}{206\times10^3\times40^3}=0.042mm$

According to design requirements of 1.2meter wind tunnel, the machining tolerance of M3.5 curve surface nozzle by using steel welded need been controlled within ±0.05mm.The curve surface deflection through machining tolerance calculation is f<0.05mm which comply with the design requirements.

2.2 Strength calculation

The center stress[4] of curve surface panel before throat $\sigma_E=C_4P_1(\dfrac{b}{h})^2$ （2）

a	Rectangular plate long edge	$a=380mm$
b	Rectangular plate short edge	$b=360mm$
C_4	Rectangular plate coefficient	$C_4=0.1602$
q	The uniform load on plate	$q=2MPa$
E	Modulus of elasticity	$E=206\times10^3 MPa$

h The thickness of rectangular plate $h = 40mm$

$$\sigma_E = 0.1602 \times 2 \times \left(\frac{360}{40}\right)^2 = 25.9MPa$$

The center stress of the rectangular plate long edge $\sigma = -C_6 P_1 (\frac{b}{h})^2$ (3)

C_6 Rectangular plate coefficient $C_6 = 0.3324$

The significance of all other symbols are consistent with above symbols

$$\sigma = -0.3324 \times 2 \times \left(\frac{360}{40}\right)^2 = -53.85MPa < 163MPa$$

So the strength is qualified

3. The finite element calculation of two-dimensional nozzle

3.1 Processing

(1) Imported model can be seen in Fig.7, Fig.8.

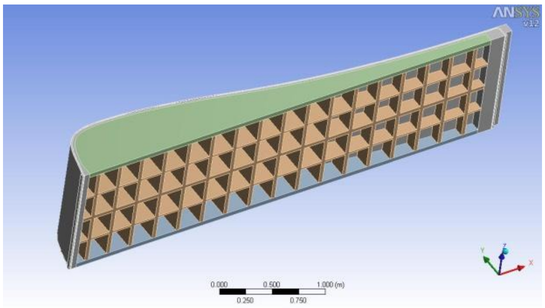


Figure 7. The model of M3.5 two-dimensional nozzle

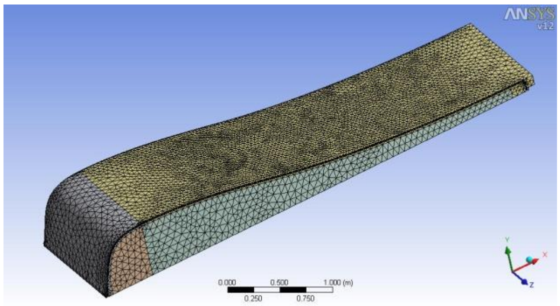


Figure 8. The mesh of M3.5 nozzle

(2) The constraint and load: Considering the actual stress condition on the surface of the nozzle, the bottom of the M3.5 nozzle is received full constraint, the side flange is received Y direction constraint, the surface of entrance and exit is free. The constraint and the load of the structure can be seen in Fig.9, Fig.10.

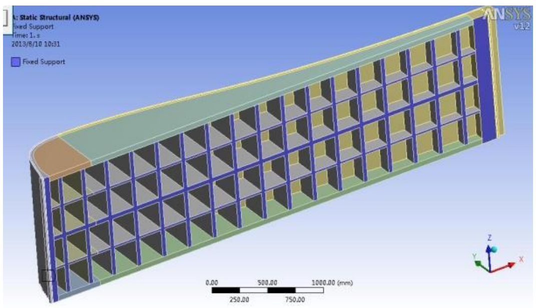


Figure 9. Constraint of M3.5 nozzle

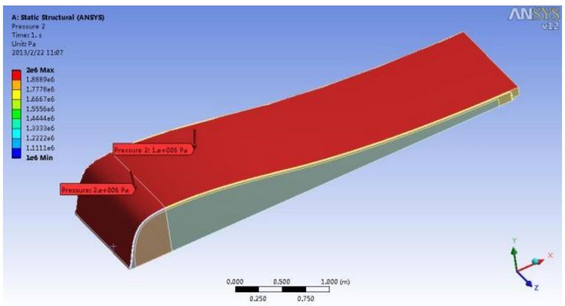


Figure 10. The load of M3.5 nozzle

3.2 Calculation results

The maximum stress value is 44.197MPa which is shown in Fig.11, it appears in the surface panel before the throat which is intersected at the ribs, the whole stress value of M3.5 nozzle is in 0.058 ~ 44.197MPa range, we can see it in Fig.12. The allowable stress value of 16MnR is $[\sigma] = 163MPa$.

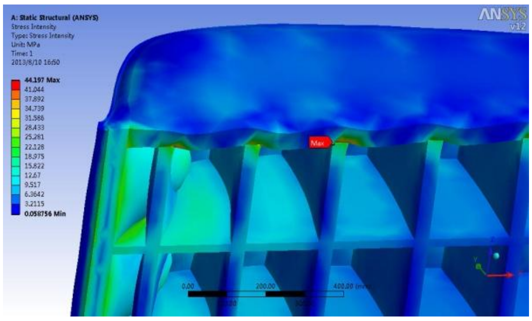


Figure 11. The maximum stress value of M3.5 nozzle

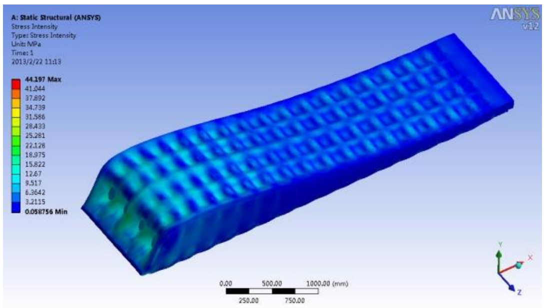


Figure 12. The stress distribution of M3.5 nozzle

Fig.13 shows that the maximum deformation value of the nozzle is 0.05211mm, the value appears in the curve surface before the throat. The maximum deformation value of the nozzle is less than 0.06mm which accords with design rigidity requirements of the nozzle.

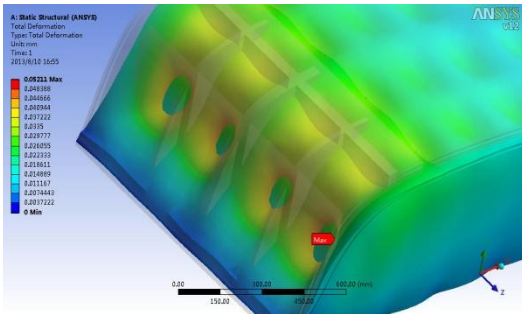


Figure 13. The maximum deformation value of M3.5 nozzle before throat

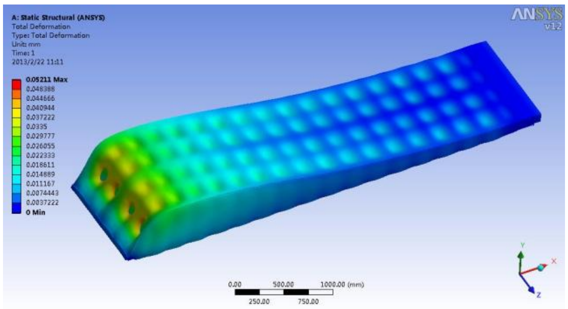


Figure 14. The deformation distribution of M3.5 nozzle

3.3 Analysis of the results

The maximum stress value is 53.85MPa and the maximum deformation value is 0.042mm by engineering calculation method, the maximum stress value is 44.197MPa and the maximum deformation value is 0.05211mm by Ansys calculation method. Comparing one result with another, the difference of the stress value between two methods is 9.653MPa, the difference of the deformation value between two methods is 0.01mm. According to these results, the result of two methods is similar. Comparing the results and it is shown in Table 1.

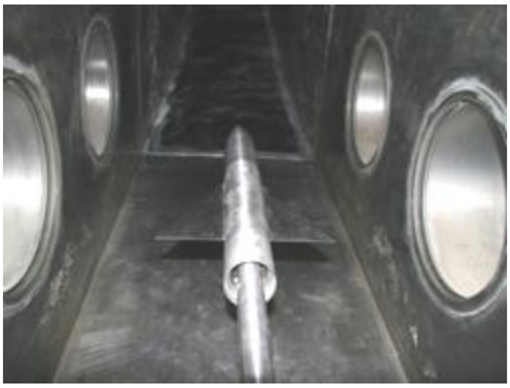
Table 1. Comparing the results

Value / Calculation method	Deformation value(mm)	Stress value(MPa)
The engineering algorithm	0.042	53.85
The finite element calculation	0.05211	44.197
Difference	0.01	9.653

4. Flow field calibration

In the process of practical application, the M3.5 two-dimensional nozzle obtains lots of data from field calibration. The analysis of flow field calibration results are completed in strict accordance with the GJB1179-91" high speed and low speed wind tunnel flow quality standard".

Figure 15. Using alloy steel welded for M3.5 nozzle **Figure 16. The picture of M3.5 nozzle**



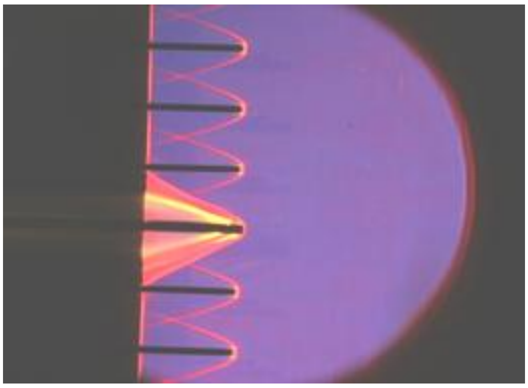


Figure 17. The standard model test of M3.5 nozzle **Figure 18. The press testing**

5. Conclusions

(1) The adoption of alloy steel in the two-dimensional nozzle structure of 1.2 meter supersonic wind tunnel solves the problems of surface cracking, scratches appearing and low surface hardness for the first time. Besides, it can also reduce the manufacturing cost and optimize structure. Comparing the data and it is shown in Table 2.

Table 2. Comparing the data

Name	Manufacturing cost	Surface hardness	Use of time
The nozzle with alloy steel	expensive	hard	long
The nozzle with epoxy resin	expensive	soft	short

(2) M3.5 two-dimensional nozzle is simplifying to the rectangular plate structure, the surface block of supersonic nozzle can be simplified into a flat piece in the engineering calculation for the first time. And the flow field is well, we can see M3.5 nozzle by using alloy steel in Fig.15, Fig.16. Also the test of M3.5 nozzle can be seen in Fig.17, Fig.18. The test result of the two-dimensional nozzle shows that the strength and stiffness of the full steel structure is reasonable and the method of simplifying the surface is feasible.

6. References

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