Research Article

Research on Flow Characteristics of a Variable Mach Number Aerodynamic Test Device by a Rotating Profile

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Received 17 December 2021; Accepted 15 February 2022; Published 16 March 2022

Academic Editor: Linda L. Vahala

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In the development process of aircraft, it needs to be tested in different incoming flow environments. Therefore, the test equipment that can provide a wide Mach number range and a fast-response flow field has always been a research hotspot. In this paper, a variable Mach number aerodynamic test device by a rotating profile is constructed with a divergent nozzle. The flow field parameters of the device are calculated by numerical simulation. The influence of the initial divergent half-angle of the cubic curve profile and the profile rotation mode on the test area is analyzed by using the flow quality evaluation method. The results show that when the incoming flow Mach number is 1.5 to 3.0, by adjusting the incoming flow Mach number and the expansion ratio of the test device, the Mach number in the test area can change continuously from 3 to 5 and the atmospheric environment at an altitude of 11 km to 20 km can be simulated. The test device composed of the cubic curve profile with the same initial divergent half-angle as the original straight line has a better flow quality. The both-side rotation mode can ensure the symmetry of the flow direction better than the one-side rotation mode.

1. Introduction

Since the Second World War, with the breakthrough and improvement of rocket engine and turbojet engine technology, the speed of rockets and other aircraft has increased rapidly and supersonic weapons have appeared. In the development process of aircraft, it needs to be tested in different incoming flow environments, which puts forward new challenges to ground test equipment. The wind tunnel with the fixed profile can only simulate the incoming flow with a fixed Mach number. The demand for variable Mach number needs to be realized by replacing the device. But the operation is complex, which greatly reduces the operation efficiency, and cannot simulate the real speed changing process of aircraft. Therefore, the test equipment which can provide a wide Mach number range and fast response flow field has always been a research hotspot.

At present, in the wind tunnel experiment, the flexible plate nozzle is a common choice to achieve a variable Mach number [1–3]. The bending shape of the flexible wall is controlled by the movement of the actuator to make it consistent with the theoretical aerodynamic profile of the nozzle. And the nozzle profiles with different test Mach numbers are obtained. However, the structure of such a variable Mach number mode is complex and cannot quickly realize the demand of the variable Mach number.

In addition, there is a variable Mach number nozzle scheme, which does not change the nozzle profile. The nozzle wall can rotate around the fixed axis of the nozzle outlet by the movement of the actuator connected with it. In this way, the nozzle inlet area is changed while the nozzle outlet area remains unchanged. The expansion ratio is changed and a variable Mach number flow field is formed behind. This scheme is easy to control with a fast response flow field and has a good application prospect.

Kitamura et al. [4] in Japan have researched, manufactured, and calibrated a wind tunnel nozzle by a rotating profile, realizing the continuous change of the outlet Mach number in the range of 2–4. Tichenor et al. [5] of Texas A
& M University designed and calibrated a wind tunnel nozzle equipment by a rotating profile, realizing the continuous change of outlet Mach number from 5 to 8. Li [6] designed the aerodynamic profile of a hypersonic nozzle by a rotating profile and calculated the flow field parameters under different Mach numbers by numerical simulation. A flow field with good uniformity can be formed at the nozzle outlet in the range of 4.5–6.5 Ma. Fan et al. [7] built an optimization design platform for the variable Mach number wind tunnel nozzle by a rotating profile in the range of 2–4 Ma and obtained the optimal profile of the wind tunnel nozzle. Based on the former design results, Qi et al. [8] carried out a 3D numerical simulation and experimental calibration for the outlet flow field of the continuously adjustable wind tunnel in the range of 2–4 Ma and obtained the size of the uniform region of the outlet flow field. The designed wind tunnel has good flow field uniformity and can be put into use.

The above researches on variable Mach number wind tunnel nozzles by a rotating profile focus on the Laval nozzle. In this paper, the idea of using the rotating profile nozzle is widened. A divergent nozzle is used to construct the variable Mach number aerodynamic test device by a rotating profile, which can further accelerate the supersonic incoming flow and make the outlet flow Mach number higher and the pressure lower. A test area with a higher Mach number and variable velocity can be formed in the wind tunnel by placing the test device in a low-supersonic wind tunnel with a fixed profile. If the test device is installed on a high-speed motion platform such as the Holloman track sled [9], it can simulate the faster, higher-altitude incoming flow than the motion platform and conduct the test for a longer time on the same length track. It also ensures the cleanliness of the incoming flow, which will not contain the combustion products often found in direct-connect wind tunnels.

2. Research Methods

The goal of the research is that, when the incoming flow Mach number is 1.5 to 3.0, by using the variable Mach number aerodynamic test device by a rotating profile, the Mach number in the test area can change continuously from 3 to 5 and the atmospheric environment at an altitude of 11 km to 20 km can be simulated.

Firstly, a variable Mach number aerodynamic test device by a rotating profile is constructed with a divergent nozzle. To form a high-quality flow in the test area, the flow field parameters of the test device are calculated by numerical simulation and the influence of different profile curves and profile rotation modes of the divergent section on the test area is analyzed. Referring to the evaluation indexes of the flow quality in wind tunnels, a flow quality evaluation method is proposed to compare the flow quality among different schemes.

2.1. Physical Model of the Test Device. The principle of the variable Mach number aerodynamic test device by a rotating profile is shown in Figure 1. An actuator is installed on the divergent section. With the movement of the actuator, the
Figure 4: Boundary conditions.

Figure 5: Grid divisions.

Figure 6: Mach number counters of the flow field under different grid quantities.
The divergent section can rotate around the rotating shaft and the expansion ratio and the flow Mach number behind will be changed. The expansion ratio can vary from 2.5 to 5.0. The width of the horizontal section is 1000 mm and the length is 500 mm. To prevent the length of the divergent section from being too long, the divergent section is designed when the expansion ratio is the minimum value of 2.5. The divergent half-angle is 6.1° [9], and it can be calculated that the axial length of the divergent section is 2807.17 mm.

Using equation (1), the theoretical Mach number that different incoming flows can reach after being accelerated by the test devices with different expansion ratios can be calculated, which can be compared with the simulation results, as shown in Figure 2.

\[
\frac{A}{A_0} = \frac{1}{Ma} \left[ \frac{2}{k+1} \left(1 + \frac{k-1}{2}Ma^2 \right)^{k+1/2(k-1)} \right].
\]  

Figure 7: Axial static pressure of the flow field under different grid quantities.

Figure 8: The calculation area.
Figure 9: Mach number scatter diagrams of grids in the calculation area.

Figure 10: Mach number scatter diagram of grids in the calculation area (800 mm Cut).

Figure 11: The RMSE of the Mach number in three calculation areas under different expansion ratios.
tail tangent to the horizontal section, such as using a characteristic curve or a cubic curve.

After further inquiries, it is found that the characteristic curve is more suitable for the nozzle with a known throat area and a convergence section. However, there is no throat in this test device and the velocity of the incoming flow is not constant. Therefore, the cubic curve is finally selected, which has fewer design constraints. The cubic curve function and its derivative are as follows:

$$y(x) = ax^3 + bx^2 + cx + d,$$
$$y'(x) = 3ax^2 + 2bx + c.$$  \hfill (2)

To make the equations solvable, only the coordinates of two points and the corresponding slope are needed. Coordinates of the head and the tail of the divergent section are known, and the remaining two variables are the initial divergent half-angle and the tail divergent half-angle of the divergent section. To make the flow in the divergent section flow smoothly to the horizontal section, let the tail of the cubic curve be tangent to the horizontal section, that is, the tail divergent half-angle is $0^\circ$.

There are two schemes for the initial divergent half-angle: the same as the divergent half-angle of the straight profile (i.e., $6.1^\circ$) and $0^\circ$. The former can make the cubic curve profile have a larger radius of curvature and make the flow expansion gentler. The latter can make the inlet flow more uniform. For the convenience of distinguishing, the two shapes of the profile are marked as shape A and shape B. The curves of two cubic curve profiles are shown in Figure 3. It is necessary to analyze the numerical simulation results of the flow field as to which one is better than the other.

In the investigation of literature related to variable nozzles, it is found that in engineering practices, there is also a practice of setting the actuator only on one side of the nozzle \[6\]. Compared with the simultaneous rotation of two profiles, rotating only one profile can reduce the complexity of the actuator control and reduce the development cost. Therefore, after the profile curve is determined, it is necessary to analyze the flow field numerical simulation results of the both-side rotation and one-side rotation schemes to verify whether the one-side rotation has more advantages.

**2.2. Numerical Simulation Method.** The finite volume method is used to solve the Navier-Stokes equations. And the SST k-\omega model is used as the turbulence model, which has a good effect in calculating air inlet flow fields \[10\]. Since the test device is an axisymmetric structure, the 1/2 model is used as the calculation domain to reduce the calculation time. The boundary conditions are shown in Figure 4. The wall is an adiabatic nonslip wall. All the surrounding boundaries are set as pressure-far-field boundaries except the symmetry boundary below. The incoming static pressure is 0.86 atmospheres and the static temperature is 15°C. The Mach number of the incoming flow is 1.5–3.0. Under the same...
Figure 13: Mach number counters of the flow field of different profiles when the expansion ratio is 5.0.

Figure 14: Axial static pressure of the flow field of different profiles.
(a) Expansion ratio is 2.5

(b) Expansion ratio is 5.0

Figure 15: The RMSE of the Mach number of the flow field of different profiles.

(a) Both-side rotation

(b) One-side rotation

Figure 16: Mach number counters of the flow field of different rotation modes when the expansion ratio is 3.0.
speed of the incoming flow, 6 expansion ratios of 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0 are set, respectively, to simulate the change of the incoming flow speed and the expansion ratio. The turbulence parameters are defaults. The turbulent intensity is 5% and the turbulent viscosity ratio is 10.

To prevent the inaccurate calculation results caused by the small-grid quantity, two grids with the quantity of 92360 and 188137 are prepared. The grids near the wall and the grids in the regions of shock waves have been refined. The grid divisions are shown in Figure 5. The calculation is carried out as an example under the condition that the Mach number of incoming flow is 2 and the expansion ratio is 2.5. It can be seen in Figures 6 and 7 that there is no obvious difference between the two results. To improve the calculation efficiency, the grids with the quantity of 92360 are selected.

2.3. Evaluation Method of Flow Quality in Test Section. The area where the aircraft test article is placed should have good flow quality. To compare the quality among different working conditions clearly, evaluation indexes of the flow quality

Figure 17: Mach number counters of the flow field of different rotation modes when the expansion ratio is 5.0.

Figure 18: Streamlines of the one-side rotation device when the expansion ratio is 5.0.
in the wind tunnel are referred to, one of which is the uniformity of the Mach number in the flow field \[11\]. The uniformity of the Mach number in the flow field can be expressed by the root mean square error (RMSE) of the Mach number of all nodes in the calculation area. The smaller the value, the more uniform the Mach number and the better the quality of the flow field. The calculation formula is as follows:

\[
\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (M_{ai} - M_{ave})^2},
\]

\[
M_{ave} = \frac{1}{n} \sum_{i=1}^{n} M_{ai},
\]

During the calculation of the RMSE of numerical simulation results, there will be a problem that grids of different sizes have the same weight by using the original formula, so it is necessary to weigh grids of different sizes. The modified calculation formula is as follows:

\[
\sigma = \sqrt{\frac{1}{S} \sum_{i=1}^{n} (M_{ai} - M_{ave})^2 * S_i},
\]

\[
M_{ave} = \frac{1}{S} \sum_{i=1}^{n} M_{ai} * S_i.
\]
In the formula, $S_i$ represents the volume of a grid in the calculation area and $S$ is the total volume of all grids in the calculation area.

The Java language is used to read and process the grid information exported by the software during the calculation of the RMSE of the Mach number, which includes the coordinate, volume, and Mach number.

To compare the uniformity of the Mach number in the flow field among different working conditions, it is necessary to calculate the RMSE of the Mach number in the area where the aircraft test article is placed. The calculation area is generally diamond. It is preliminarily set that the axial diagonal length is 1000 mm and the radial diagonal length is 800 mm. The position of the calculation area is shown in Figure 8(a).

Taking the working condition that the expansion ratio is 5.0 and the Mach number is 3.0 as an example, the Mach number scatter diagram of grids in the calculation area is shown in Figure 9(a). It is found that there is a large gap between the Mach number of the area close to the wall and the central area in the calculation area, because the shock wave between the divergent section and the horizontal section passes through the calculation area, which interferes with the flow field.

If the area close to the wall is included in the calculation area, the RMSE of Mach number will be large, which may have adverse influence and draw wrong conclusions comparing different working conditions. Therefore, try to remove the area close to the wall as shown in Figure 8(b). The width of the diamond area is reduced from 800 mm to 600 mm, and the Mach number scatter diagram of grids is shown in Figure 9(b). Through comparison, it is easy to find that the Mach number uniformity is improved.

In addition to reducing the width of the diamond area, it is also a feasible method to directly cut off the area close to the wall, which will not influence the central area. Therefore, try cutting off the area close to the wall as shown in Figure 8(c). The cutting width is 100 mm, and the Mach number scatter diagram of grids is shown in Figure 10. The RMSE of the Mach number in three calculation areas under different expansion ratios is shown in Figure 11.

![Figure 21: Average Mach number in the calculation area under different incoming flow and expansion ratios.](image)

![Figure 22: Altitude (m) corresponding to static pressure in the calculation area under different incoming flow and expansion ratios.](image)
The RMSE of the Mach number in the 600 mm wide area is 25.499% lower than that in the 800 mm area. The average difference between the 800 mmCUT area and the 600 mm area is 3.819%, and the maximum is no more than 7.019%. Obviously, after directly cutting off the area close to the wall, the Mach number uniformity is significantly improved and the RMSE of the Mach number is almost the same as that in the 600 mm wide area. Therefore, the 800 mmCUT area is selected as the calculation area to compare the RMSE of Mach number among different working conditions.

3. Analysis of Simulation Results

3.1. Two Initial Divergent Half-Angles. When the profile has not been rotated inward and rotated to the innermost side, that is, when the expansion ratios are 2.5 and 5.0, the numerical simulation results of two profiles under the 3.0 Ma incoming flow are shown in Figures 12–13.

According to the comparison of the Mach number counters under different expansion ratios in Figures 12–13, since the cubic curve of shape A has a larger radius of curvature, the flow has experienced a gentler expansion process from the inlet and the shock wave at the connection of the divergent section and the horizontal section is weak. The cubic curve of shape B has a slow variation trend in the first half, resulting in it needing to expand to the required width in a short distance in the second half, and the shock wave is stronger.

Therefore, the maximum Mach number of shape B is larger. When the expansion ratio is 2.5, the Mach numbers are 4.099 and 4.265, and when the expansion ratio is 5.0, the Mach numbers are 5.403 and 5.429.

It can also be seen from the variation trend of axial static pressure in Figure 14 that the pressure of shape A decreases faster, the minimum pressure is higher than that of shape B, and a more stable pressure curve can be maintained in the test section.

The RMSE of the Mach number in the flow field with 1.5–3.0 Ma incoming flow is shown in Figure 15. The flow separation occurs when the expansion ratio is 5.0 and the Mach number is 1.5, so it is not calculated. It can be seen that the flow field uniformity of shape A is better under most working conditions. Therefore, it is more appropriate to select shape A as the divergent section profile.

3.2. Both-Side Rotation and One-Side Rotation. Use the cubic curve profile with the same initial divergent half-angle as the straight profile in the previous section. Fix the lower profile, and only rotate the upper profile. Make the expansion ratios consistent with the both-side rotation profile, which is 3.0 and 5.0. When the Mach number of incoming flow is 3.0, the calculation results can be obtained as shown in Figures 16–19.
From the comparison of the Mach number counters under different expansion ratios in Figures 16–17, there is no significant difference in the maximum Mach number of the flow between the both-side rotation device and the one-side rotation device. When the expansion ratio is 3.0, the Mach numbers are both 4.440. And when the expansion ratio is 5.0, the Mach numbers are 5.403 and 5.386.

However, because the one-side rotation device only rotates one side of profiles, a problem of the asymmetric flow velocity will occur, which will adversely influence the test area behind. With the increase of the expansion ratio, the one-side rotation device needs to rotate more angles to make the expansion ratio consistent with the both-side rotation device and such asymmetry will be stronger. The streamlines in the box of Figure 18 can more obviously show the asymmetry of the flow direction on the upper and lower sides. The flow direction on the upper side deviates upward along the axis.

In Figure 19, when the expansion ratio is 3.0, the axial static pressure curves of the one-side rotation device and the both-side rotation device almost coincide. When the expansion ratio is 5.0, the pressure curve at the inlet experiences a sharp rise and fall process because the head of the upper profile of the one-side rotation device contacts the axis. But the variation trend in the test section behind is the same as that of the both-side rotation device. The phenomenon can show that the difference between the both-side rotation device and the one-side rotation device cannot be measured only by the flow Mach number and the symmetry and the uniformity of the flow also need to be compared.

The RMSE of the Mach number in the flow field with the 1.5–3.0Ma incoming flow is shown in Figure 20. The flow separation occurs when the expansion ratio is 5.0 and the Mach number is 1.5, so it is not calculated. It can be seen that under most working conditions, the RMSE of the Mach number of the both-side rotation device is smaller than that of the one-side rotation device.

Considering comprehensively, the both-side rotation device can ensure the symmetry of the flow direction, which is more suitable as the rotation mode of the test device in this research.

3.3. Relationship between Design Parameters and Flow Parameters in the Calculation Area. The cubic curve profile with the same initial divergent half-angle as the straight profile is selected, and the rotation mode is the both-side rotation. The working conditions with the Mach numbers of 1.5, 2.0, 2.5, and 3.0 and the expansion ratios of 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0 are sorted out, and the simulation results are represented by curves. The average Mach number and the altitude corresponding to static pressure of the calculation area are shown in Figures 21–22.

When the Mach number of the incoming flow is 1.5, there is a detached shock wave in front of the divergent section. And the total pressure loss occurs after the flow passes through the shock wave. When the expansion ratio is 2.5, 3.0, or 3.5, the detached shock exists in the form of an oblique shock wave and the total pressure loss is small. When the expansion ratio is 4.0, 4.5, or 5.0, the detached shock wave is similar to a direct shock wave and the total pressure loss is large. The flow cannot continue to expand in the divergent section, the flow separation occurs, and the uniform test area cannot be formed in the test section, as shown in Figure 23.

According to the relationship between the Mach number of the incoming flow, the shock wave angle, and the flow turning angle, when the half-apex angle $\delta$ of a wedge is constant, there is a minimum incoming flow Mach number: $M_{\min}^\delta$. If the incoming flow $Ma < M_{\min}^\delta$, a detached shock wave will appear. When the incoming flow Mach number is constant, there is also a maximum half-apex angle: $\delta_{\max}^\delta$. If $\delta > \delta_{\max}^\delta$, a detached shock wave will appear. Therefore, to make an attached oblique shock wave appear rather than a detached shock wave at the low Mach number, it is necessary to further reduce the half-vertex angle of the head of the divergent section.

Comparing the average Mach number in the calculation area with the Mach number calculated theoretically, it is found that the former is 3.192% larger than the latter, because the subsequent expansion after the flow leaves the divergent section is not considered in the theoretical calculation.

It can be seen from the curves in Figures 21–22 that when the incoming Mach number is the same, with the increase of the expansion ratio, the average Mach number and the altitude corresponding to static pressure in the calculation area will also increase. By adjusting the incoming flow Mach number and the expansion ratio, the Mach number in the test area can change continuously from 3 to 5 and the atmospheric environment at an altitude of 11 km to 20 km can be simulated.

4. Conclusions

(1) In this paper, a variable Mach number aerodynamic test device by rotating profile is constructed with a divergent nozzle. The flow field parameters of the device are calculated by numerical simulation. The results show that when the incoming flow Mach number is 1.5 to 3.0, by adjusting the incoming flow Mach number and the expansion ratio of the test device, the Mach number in the test area can change continuously from 3 to 5 and the atmospheric environment at an altitude of 11 km to 20 km can be simulated.

(2) In the process of constructing the test device and calculation, the influence of the initial divergent half-angle of the cubic curve profile and the profile rotation mode on the test area is analyzed. The results show that the test device composed of the cubic curve profile with the same initial divergent half-angle as the original straight line has a better flow quality. The both-side rotation mode can ensure the symmetry of flow direction better than the one-side rotation mode.

(3) The flow quality evaluation method is formed. The evaluation indexes of the flow quality in wind
tunnels are referred to, and the original formula is modified aiming at the problem of different mesh volumes in the numerical simulation

(4) There are still some deficiencies in the test device. The oblique shock wave at the inlet of the test device will continuously reflect back and forth on the inner wall, which will make an adverse impact on the test. Therefore, the profile curve of the divergent section can be optimized or a slotted wall can be used as the inner wall to eliminate the shock wave. In the subsequent stage, it will be further researched and a device object will be made for the experiment

Data Availability
No data were used to support this study.

Conflicts of Interest
The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (Program no. 51005179).

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