Shape analysis and numerical fitting of boneless wiper reed

Liu Yunpeng¹,a, Xu Jingjing²,b*, Wang Xin³,c
¹School of Mechatronic Engineering and Automation of Shanghai University, Shanghai, China
²School of Mechatronic Engineering and Automation of Shanghai University, Shanghai, China
³School of Mechatronic Engineering and Automation of Shanghai University, Shanghai, China
aemail: liuyunpeng@shu.edu.cn, cemail: 508943094@qq.com,
b*Corresponding Author: bemail: xjj125@shu.edu.cn

Abstract. The boneless reed curve of the car wiper has geometric nonlinearity and variable curvature characteristics. In order to design a geometric curve that satisfies the working performance of the boneless wiper reed, the inverse solution function item in the finite element simulation and the addition of appropriate boundary conditions are used to solve the geometric curve of boneless wiper reed before it is stressed, and verify the accuracy through the known actual reed. To prepare for actual processing, the geometric characteristic parameters of different curves are extracted on the basis of the above. Based on the small deformation linear deflection equation of the beam obtained by the superposition method, a large deformation correction item is added to correct the small deformation equation, and the influence of the length of the wiper buckle on the curve is considered. Construct a correction equation including load requirements, reed geometric dimensions, and material parameters to fit the geometric curve of the boneless wiper reed, so as to provide certain guidance for actual production.

1. Introduction
With the continuous upgrading of the automobile industry, boneless wipers gradually replaced bone wipers and became the upstart of automobile wipers. The boneless wiper is composed of a rubber strip, a built-in wiper blade, a wiper sheath and a plastic buckle. Compared with the boneless wiper blade, the boneless wiper uses a whole steel reed as the main supporting body to transmit force, which makes the boneless wiper work with a high degree of fit, uniform force, and a better wiping effect. At the same time, both in terms of vibration and noise, or in terms of wear life, they are better than bone wipers.

Boneless wiper blades are usually made of high-strength alloy steel, and the thickness is only about one millimeter, so it is usually wrapped with an electroplated layer on its outer surface to make it have better elasticity and wear resistance. As one of the most important components of the boneless wiper blade, the rationality of the design and processing quality of the boneless wiper spring directly determines the performance of the boneless wiper. However, at present, the complete design theory of boneless wiper reeds is basically in the hands of a few large auto parts companies, and it is difficult to obtain them directly from the public literature and books.
The geometric shape of the boneless wiper blade is a curve of variable curvature, and the complex relationship between the curve and the size parameters, material parameters of the boneless wiper blade and the required uniform force load needs to be considered. Drawing on the related literature of sheet design and sheet bending forming: Li Jian et al. [1] conducted a theoretical analysis on the free bending forming and springback process of the sheet, and created the corresponding springback calculation model and mathematical expression. Wang Peilin et al. [2] provided a solution to solve the size of thin-walled parts inversely according to the size obtained by the reverse direction of the strength of the plate.

Since the design of the boneless wiper blade involves geometric nonlinearity, there is no related theoretical formula for direct calculation. Therefore, this paper adopts the finite element reverse analysis method to establish the geometric model of the boneless wiper blade and solve the geometry of the wiper reed in the unloaded state in reverse. Finally, the theoretical reed curve is compared with the standard reed curve to verify its accuracy. In order to facilitate subsequent production and processing, a new deflection equation is constructed by adding large deformation correction items to the small deformation deflection curve equation of the beam and substituting the effect of the wiper buckle length on the curve into the formula. Through this new equation, the geometric characteristic parameters of different curves can be easily obtained.

2. Analysis of the working condition of the boneless wiper reed

When analyzing the working status of the boneless wiper, considering that the radius of curvature of the windshield is generally 4m~7m, the windshield can be approximated as a flat plate for analysis during the loading process of the boneless wiper reed.

As shown in Figure 1, when the boneless wiper is working, the boneless wiper arm applies a vertical load P to the wiper buckle to tightly fit the boneless wiper spring on the windshield of the car. And through a rubber strip wrapped around the reed, it constantly swings back and forth to clean up the water and debris on the glass. According to the performance requirements of the wiper, when the wiper is tightly attached to the glass, its standard uniformity line pressure value q on the glass should be maintained in the range of 0.9g/mm-1.8g/mm.

![Figure 1. Schematic diagram of the working state of the boneless wiper](image)

As shown in Figure 2, the state "A" is the state when the boneless wiper reed is not stressed after processing. Due to the different working conditions, the geometric curve of the reed is unknown. The state "B" is an analysis diagram of the working force of the boneless wiper reed, and the loaded state of the reed is known in this state. Taking the boneless wiper reed as the object of analysis, because the reed receives the concentrated load P transmitted from the buckle and the equalized wiring pressure q transmitted from the laminated glass, it is balanced under the action of two forces. Therefore, the magnitude of these two forces should be the same in magnitude and opposite in direction.

![Figure 2. Schematic diagram of the loaded and unloaded state of the reed](image)

According to the concept of reverse analysis, the process in the unloaded state is solved through the initial geometry that has been deformed under a set of loads. In this deformation process, state "B" is known but state "A" is unknown, which meets the conditions of reverse solution. Therefore in the
simulation design, it is only necessary to input the boundary conditions of state "B" to obtain the original curve of state A, which is the required design curve.

3. Establishment of finite element model and verification of results

3.1. Establishment of finite element model

As shown in Figure 3, through the finite element software, a cuboid solid model with length, width and height of 606mm, 7mm, and 1mm was established according to the actual geometry of the boneless wiper blade. Due to the geometric shape and force of the wiper reeds, the left and right sides are completely symmetrical so a symmetrical solution can be adopted to analyze only half of them to save computing resources. Because the model is relatively simple, hexahedral mesh is directly used for mesh division, and the mesh size is set to 1mm.

Because only elastic deformation occurs during the working load of the wiper reed, no plastic deformation occurs. Therefore, when creating a stress-strain curve, only the yield strength of the material and the elastic modulus $E$ are input to construct a linear relationship. Metal material. When applying boundary conditions, first turn on the inverse solution function in Analysis setting. Since this function is only applicable to a single component, it is impossible to construct the windshield glass. Therefore, when simulating the load state of the reed (Figure 2 State 2), it is necessary to add the uniformly distributed load $q$ in the vertical direction on the lower plane of the reed. In order to prevent the back and forth displacement of the reed during the bending process, the front side of the reed should be impose frictionless support. Since the model adopts a symmetrical model, in order to prevent the mid-plane of the reed from shifting from left to right, the mid-plane should be restrained from displacement to limit its displacement in the X direction. In order to prevent the right edge of the reed from leaving the glass plane, a displacement constraint in the Y direction should be set on the bottom edge of the right side.

By changing the elastic modulus and the uniform linear pressure in the material parameters, the geometric curves required by the wiper reeds under different working conditions can be solved.

3.2. Analyze the influence of the length of the reed snap

According to Figure 4, when analyzing the load on the boneless wiper reed, the load it receives is a concentrated load, but in actual work, the load it receives should pass through a plastic card with a length of B. Buckle to transfer, thus forming a uniform force range.

Considering the influence of the buckle length on the geometric curve of the boneless wiper blade, the equivalent bending moment method can be used to reflect the influence of the buckle length in the uniformly distributed load. As shown in the left figure of Fig. 4, when the reed is subjected to a
uniform force zone with a length of B and a load of q’, the position of the maximum bending moment is in the mid-plane because of symmetry. Let the magnitude of the bending moment be \( M_1 \), and the magnitude can be calculated by formula 1. And the product of B and q’ is equivalent to the product of the corresponding uniform linear pressure \( q_1 \) and the length of the reed L. As shown in the right figure of Figure 4, assuming that the reed is subjected to a concentrated force \( F \), its maximum bending moment position should also be in the middle, so that the size of the bending moment is \( M_2 \), which can be calculated according to equation 2. And the size of \( F \) is equal to the product of the corresponding uniform linear pressure \( q_2 \) and the length of the reed L.

\[
M_1 = \frac{Bq’}{2} * \frac{L}{2} \quad \text{(1)}
\]

\[
M_2 = \frac{FL}{4} \quad \text{(2)}
\]

In order to calculate the bending deformation in the left figure by the model in the right figure, the bending moments in the two cases can be made the same, that is \( M_1 = M_2 \). At this time, the two cases have the same maximum bending moment, but the loads received in the two cases are different, and the corresponding uniform linear pressure \( q \) is also different. Therefore, the uniform line pressure in the left picture can be converted into the uniform line pressure in the right picture, and the influence of the length of the buckle on the geometric curve of the reed can be characterized by the value change of the uniform line pressure and the conversion relationship can be characterized by formula 4.

\[
q’ = \frac{q_1L}{B} \quad \text{(3)}
\]

\[
q_2 = \frac{Bq’(2L-B)}{2L^2} \quad \text{(4)}
\]

3.3. Verification of the accuracy of finite element simulation results
Import the simulation curve into Auto CAD to obtain its geometric characteristic data, and compare the three types of reeds with uniform line pressure of 0.990, 1.155, and 1.320 (unit: g/mm) with the corresponding actual standard reed data and the buckle length is 50mm. The red is the simulated reed curve and the black is the actual reed curve.
Figure 5. Geometry comparison diagram of simulated reed and actual reed

Table 1. The geometric parameters of the simulated and actual reeds

| Uniform line pressure (g/mm) | Actual aspect ratio | Simulation aspect ratio | Error (%) | Actual minimum radius of curvature (mm) | Simulation minimum radius of curvature (mm) | Error (%) |
|-----------------------------|---------------------|-------------------------|-----------|----------------------------------------|--------------------------------------------|-----------|
| q = 1.320                  | 5.321               | 5.323                   | 0.376     | 392.5                                  | 412.3                                      | 5.044     |
| q = 1.155                  | 6.566               | 6.476                   | 1.371     | 416.9                                  | 435.8                                      | 4.533     |
| q = 0.990                  | 7.561               | 7.342                   | 2.896     | 488.6                                  | 502.5                                      | 2.845     |

According to the comparison of the geometric curves of the standard reed and the simulated reed in Figure 5, it can be concluded that the reed curve predicted by the above method basically coincides with the geometric curve of the actual reed. By comparing the core data in Table 1, the aspect ratio error of the wiper reed after molding is within 3%, and the maximum error of the minimum radius of curvature is about 5%, which meets the actual engineering requirements.

4. Construct curve equation to fit reed geometry

4.1. Select the appropriate fundamental equation

In order to facilitate the subsequent actual processing of the boneless wiper reeds, it is very important to quickly extract important geometric feature parameters (radius of curvature, deflection, etc.) through a curve equation. However, the wiper blade curve has the characteristics of large deformation and geometric nonlinearity, and there is currently no clear fitting equation. Therefore, based on the small deformation linear deflection equation of the beam obtained by the superposition method, the large deformation correction item is added to modify, and a new deflection equation is constructed to fit the geometric curve of the boneless wiper reed.

As shown in Figure 6, in this case, the beam is subjected to a uniform load and the geometric deformation is close to the state of a boneless wiper reed subjected to a uniform load.

![Figure 6. Basic equation of small deformation deflection](image)

In the formula: q — Uniform line pressure, unit: N/mm
L — Length of reed, unit: mm
B — Elastic modulus, unit: MPa
I — Moment of inertia of the reed section, unit: mm^4

4.2. Correcting the reed span L

In the small deformation calculation formula, the span value does not change by default, but when the boneless wiper blade is actually loaded, the deformation generated is a large deformation, and the
actual span will inevitably change. Therefore, the influence of different elastic modulus $E$ and uniform linear pressure $q$ on span $L$ must be considered.

In the above-mentioned finite element simulation, a set of experimental data is collected by changing the two parameters of elastic modulus $E$ and uniform line pressure $q$, and then using the data fitting function in MTLAB to construct a relationship to predict the change of span $L$. In the design requirements of boneless wiper reeds, the elastic modulus of the material is generally maintained between 158000-208000Mpa, and the uniform linear pressure is maintained between 0.9-1.8g/mm.

The specific measures are: In order to predict the influence of the uniform linear pressure, keep the elastic modulus $E$ unchanged, and take a value every 0.05 within the parameter range of the uniform linear pressure 0.9-1.8 g/mm. The reed curve is obtained through finite element simulation, the generated curve is imported into CAD, the ratio $k$ of the span $L'$ of the reed to the initial reed length $L$ under different equalizing wiring pressures is measured, and a set of data is obtained. Import the data into MTLAB for numerical fitting.

![Figure 7. Fitting relationship diagram of span L in MATLAB](image)

As shown in Figure 7, the different points in the figure represent the value of the span change rate $k$ under different working conditions. The fitted plane equation can well predict the rate of change $k$ of the span $L$ corresponding to different elastic modulus $E$ and uniform line pressure $q$.

The fitting equation is:

$$k = p_0 + p_1 \cdot x + p_2 \cdot y + p_3 \cdot x^2 + p_4 \cdot x \cdot y + p_5 \cdot y^2$$

(6)

The specific parameters in the fitting equation are shown in Table 2:

| $p_0$ | $p_1$ | $p_2$ | $p_3$ | $p_4$ | $p_5$ |
|-------|-------|-------|-------|-------|-------|
| 0.9168 | 1.697e-06 | -0.2314 | -6.628e-12 | 1.21e-06 | -0.03902 |

Finally, the error of the formula is calculated by formula 6. The maximum error between the predicted span and the simulated span of the equation is 1.79mm when the elastic modulus is 158000Mpa and the uniform linear pressure is 0.9g/mm. The error range is within one percent, which meets the engineering error requirements.

4.3. Add large deformation correction items

The value of the large deformation correction term at a certain position $X_0$ is equal to the ratio $k$ of the deflection $\omega$ of the simulated reed at that position and the calculated deflection $\omega_0$ of the small deformation curve, under the same conditions (same $E$, $q$, $L$). Since the modulus of elasticity is limited to the small deformation deflection curve, the large deformation correction term should include the uniform linear pressure $q$ and the position $x$ of the wiper reed. By collecting the deflection of different line pressure states and different simulation curve positions and according to the small deformation deflection under the same conditions in formula 4.1, the ratio $k$ of the two is calculated, and the numerical relationship between them is fitted by Matlab software.
The specific measures are: take a value every 0.05 within the parameter range of uniform linear pressure (0.9-1.8 g/mm), and other parameters remain unchanged, and the corresponding boneless wiper reed curve is measured by the finite element software. Divide the span L of these curves into 16 equal parts, take the first 8 points due to symmetry, and mark the reed heights corresponding to these equal points; Then substituting these parameters into the small deformation deflection curve, equally divide it into 16 parts and calculate the height of the first 8 points, calculate the ratio k corresponding to the height of the two, and sort out a set of data.

Figure 8. Fitting relationship diagram of large deformation terms in MATLAB

As shown in Figure 8, import these data into MATLAB to adopt a suitable fitting method, and the corresponding fitting item 7 is the large deformation correction item. As shown in Figure 8, the different points in the figure represent the value of the rate of change of deflection k under different working conditions. It is not difficult to see that the fitted plane equation can well predict the deflection change rate k corresponding to different positions x and uniform linear pressure q.

The fitting large deformation term is:

\[ a_1 + a_2 \cdot q + a_3 \cdot x + a_4 \cdot q^2 + a_5 \cdot q \cdot x + a_6 \cdot x^2 + a_7 \cdot q^3 + a_8 \cdot x \cdot q^2 + a_9 \cdot q \cdot x^2 + a_{10} \cdot x^3 \]

(7)

The specific parameters in the large deformation item are as follows in Table 3:

|   | a_1   | a_2   | a_3   | a_4   | a_5   |
|---|-------|-------|-------|-------|-------|
|   | 0.8709| 0.3305| 0.0007463| -0.1862| 0.0005074|
| a_6 | a_7   | a_8   | a_9   | a_{10}|
|   | -7.161e-06| 0.1927| -0.0009547| 3.496e-06| 7.794e-09|

4.4. Verification of the accuracy of the correction equation

According to the correction term obtained above, the new curve equation is obtained as the following equation 8:

\[ \omega = -\frac{q x}{24El} (L^3 - 2Lx^2 + x^3) \cdot \left( a_1 + a_2 \cdot q + a_3 \cdot x + a_4 \cdot q^2 + a_5 \cdot q \cdot x + a_6 \cdot x^2 + a_7 \cdot q^3 + a_8 \cdot x \cdot q^2 + a_9 \cdot q \cdot x^2 + a_{10} \cdot x^3 \right) \]

(8)

As shown in Figure 9, compare the three theoretical reed data with equalized wiring pressures of 0.990, 1.155, and 1.320 (unit: g/mm) with the corresponding simulation standard reed data, and the buckle length is 50mm. The simulation curve is shown in red and the fitted curve shown in green. It can be seen that the two curves basically coincide. As shown in Table 4, the key geometric data of the reed under different uniform linear pressures are calculated by the above equation, including the
aspect ratio of the wiper reed, the minimum radius of curvature, and compare it with the simulation prediction rain reed to judge its fitting quality. It can be seen that the geometric data fitted by the correction equation is very close to the simulation data. The maximum aspect ratio error is less than one percent, and the minimum curvature radius error is less than five percent, which meets the engineering requirements.

![Graph showing comparison between simulated and actual reed geometry](image)

(a) Uniform line pressure $q = 1.320 \text{ g/mm}$

(b) Uniform line pressure $q = 1.155 \text{ g/mm}$

(c) Uniform line pressure $q = 0.991 \text{ g/mm}$

Table 4. Comparison table of geometric parameters of simulated reed and fitted reed

| Uniform line pressure (g/mm) | Actual aspect ratio | Simulation aspect ratio | Error (%) | Actual minimum radius of curvature (mm) | Simulation minimum radius of curvature (mm) | Error (%) |
|-----------------------------|---------------------|------------------------|-----------|----------------------------------------|------------------------------------------|-----------|
| $q = 1.320$                 | 5.323               | 5.352                  | 0.545     | 412.3                                  | 393.78                                   | 4.492     |
| $q = 1.150$                 | 6.476               | 6.416                  | 0.921     | 445.8                                  | 460.56                                   | 3.331     |
| $q = 0.990$                 | 7.342               | 7.414                  | 0.985     | 502.5                                  | 518.68                                   | 3.212     |

5. Conclusion
According to the actual needs of the boneless wiper blades in actual work, this paper takes into account the material parameters, the load pressure, and the influence of the blade buckle, analyzes the required blade curves under different working conditions, and designs them through finite element simulation. In order to facilitate subsequent production and processing, it is necessary to quickly extract important geometric parameters based on the results of finite element simulation. The following conclusions are made:

(1) Through the analysis of the load on the boneless wiper reeds in operation, the finite element inverse solution function is used to predict the geometric curves required for the wiper reeds under different working conditions. And compared with the actual qualified reed, the geometric curves of the two basically coincide.

(2) Considering that in actual work, the load of the reed is transmitted through the buckle (that is a uniform force zone), so the equivalent bending moment is used to consider the influence of the buckle length.
(3) Through MATLAB software, the span L in the small deformation deflection formula is corrected and a large deformation correction term is added. So a new equation is constructed, which can be used to fit the geometry of the wiper reed under different working conditions curve. After verifying the curve equation, the error meets the engineering requirements. This has played a guiding role in the production of actual boneless wiper reeds.

References
[1] LI Jian, ZHAO Jun, ZHAN Pei-pei, SUN Hong-lei, MA Ru. (2009) Theoretic analysis of forming and springback for sheet metal air bending. J. Journal of Plasticity Engineering 16(04) 1-6
[2] Wang Peilin, Wong Jiancheng. (2020) Research on Reverse Engineering of Thin-Walled Parts Based on Reverse Seeking of Strength Performance. J. Mechanical & Electrical Technology 2020(03) 10-12
[3] Wang Yan, Zhu Xinqing, Hu Jiefei, Cui Ximin. (2020) Research on Numerical Simulation of Continuous Roll Forming Process of Four-roll Plate Bending Machines. J. Journal of System Simulation 30(05) 1772-1780
[4] Hadžić N, Keran Z, Hadjina M, et al. (2019) Analysis of elastic-plastic steel plates forming based on typical shipyard's roller bending machine. J. Ocean Engineering 190 106438