Statics analysis for automotive rope-wheel glass regulator

Mingzhang Chen¹², Xiaoshuang Xiong³⁴*, Wuhao Zhuang¹², Zhongbao Chen¹²

¹School of Automotive Engineering, Wuhan University of Technology, Wuhan 430070, PR China
²Hubei Key Laboratory of Advanced Technology for Automobile Components, Wuhan University of Technology, Wuhan 430070, PR China
³Hubei Key Laboratory of Digital Textile Equipment, Wuhan Textile University, Wuhan 430200, PR China
⁴School of Mechanical Engineering and Automation, Wuhan Textile University, Wuhan 430200, PR China

*Corresponding author’s e-mail: 986960577@qq.com

Abstract: Analyzing strength, stiffness, fatigue and wear of automotive rope-wheel glass regulator (glass regulator for short) and optimizing structure of glass regulator benefit improving working stability. Before analyzing strength, stiffness, fatigue and wear, statics analysis is necessary to be taken for investigating stress and displacement of key parts. Statics theoretical and finite element analysis of glass regulator in three kinds of working conditions (locked-rotor on the top dead center, locked-rotor on the bottom dead center, normal working) are taken. Results suggest that concentrated stress and large displacement mainly exist on guide rail. The concentrated stress also exists on slider, guide pulley and motor plate, but maximum stress value and large displacement risk on them are small. Statics analysis provides analysis of strength, stiffness, fatigue and wear with support on data and offers driving data for optimizing structure of glass regulator.

1. Introduction

Glass regulator acts as a functional component for adjusting door glass, and its working stability affects comfort and safety of driver [1]. Strength, stiffness, fatigue and wear of key parts in glass regulator affect working stability of glass regulator. In order to improve working stability of glass regulator, statics analysis of key parts is required to obtain stress and displacement performance of parts. According to stress and displacement performance, strength, stiffness, fatigue and wear of parts are analyzed. Analysis of strength, stiffness, fatigue and wear is good for obtaining structure optimization of glass regulator and improving working stability of glass regulator.

At present, some scholars have done some researches on structure, fault analysis, fault maintenance and structural optimization of glass regulator. In terms of researches on structure of glass regulator, [2-7] studied structures of different kinds of glass regulators and analyzed advantages and disadvantages of different kinds of glass regulators. In aspect of fault analysis and fault maintenance of glass regulator, [8-13] analyzed fault on door glass regulator and influences of external water cutting, glass mounting holes, rail and suds on fault of glass regulator, and put forward some measures for fault maintenance. In terms of structural optimization of glass regulator, [14-19] proposed some structural optimization schemes for parts in glass regulator to improve working stability of glass regulator.
regulator. However, the structural optimization schemes of glass regulator proposed in these studies are mainly to optimize structure of some parts of glass regulator, based on analysis of increase in stress caused by structure of these parts. By contrast, through statics analysis of glass regulator, strength, stiffness, fatigue and wear of key parts of glass regulator can be judged from stress and displacement performance. Then, structure of parts with a greater threat can be optimized, which can improve stability of glass regulator more effectively. Therefore, it is necessary to carry out statics analysis on key parts of glass regulator, which provides a research foundation for later structural optimization to improve working stability of glass regulator.

In this paper, four key parts and three key working conditions of glass regulator are introduced. In three working conditions, statics theoretical analysis of four key parts is carried out. Statics theoretical analysis results act as input conditions and are adapted in statics finite element analysis. Statics analysis results of glass regulator suggest that stress concentration and larger strain exist on guide rail. Stress concentration also exists on slider, guide pulley and motor plate, but maximum stress value and risk of larger displacement are small. Statics analysis of glass regulator provides data support for strength, stiffness, fatigue, and wear analysis of glass regulator, as well as driving data for subsequent structure optimization of glass regulator. Statics analysis of glass regulator can provide reference for investigation of other types of regulators.

2. Analysis of structure and working condition of glass regulator

As a functional component in car door system, glass regulator can ensure glass to rise and fall smoothly and stay in any position. According to specific structure, glass regulators can be divided into three types: fork-arm type, soft-shaft type and rope-wheel type.

In this paper, a certain type of single track rope-wheel glass regulator in Wuhan Donghuan Body System company is regarded as research object. Structure of glass regulator is shown in Fig. 1. Main parts of single track rope-wheel glass regulator include guide rail, slider assembly, guide pulley, motor assembly, upper and lower wire rope assembly. Motor is installed on inside plate of door through motor base plate. Winding wheel is fixed on output shaft of motor, and guide rail is installed on inside plate of door through upper and lower bolt fixing holes. Statics analysis of glass regulator mainly analyzes four key parts: guide rail, slider assembly, guide wheel and motor base plate.

Fig.1. Structure of single track rope-wheel glass regulator.

Guide rail is a sheet part with flanging structure near the mounting hole. During normal working condition, stress concentration tends to occur on flanging part of guide rail. When motor is locked-rotor, great deformation is likely to occur near guide pulley and flanging structure. Permanent plastic deformation will occur and lead to cracking at flanging structure. Therefore, stress and
displacement performance of guide rail in different working conditions are focus of analysis. According to analysis results, performance and failure of guide rail can be judged.

Slider assembly is a lifting mechanism. Slider assembly consists of a slider and a glass mounting frame. Wire rope drives slider assembly to lift, and glass in the door frame will lift. Glass mounting bracket is embedded as insert slider. Plastic slider is a key part of slider assembly, which is an easy failure part of regulator system.

Guide pulley is made of polyformaldehyde. During normal operation of glass regulator, wire rope interacts with guide pulley, causing wear of guide pulley.

One back and forth operation of glass regulator will experience three working conditions: normal working condition, locked-rotor on top dead center, and locked-rotor on bottom dead center.

As shown in Fig. 2(a), glass regulator is in the condition of top dead center, slider will continue to rise and be blocked when the slider drives the glass running to the top dead center, and motor will be locked at this moment. Motor current and tension on wire rope will increase sharply. In this condition, the guide rail suffers maximum stress. As shown in Fig. 2(b), glass regulator is in the condition of bottom dead center, slider drives glass to bottom dead center. Lower end face of slider supports down turning side of guide rail, which causes slider to continue to fall. Motor current increases sharply, and tension on wire rope increases significantly.

When the glass regulator is in normal upward operation and slider is in middle position of guide rail, motor current is stable and wire rope tension is small.

3. Theoretical statics analysis of glass regulator

When glass regulator is locked-rotor on top dead center, relationship between tensions of upper and lower wire ropes is shown in Eq. (1):

\[ F_{up} R - F_{down} R = T \eta \]  

(1)

Where, \( F_{up} \) and \( F_{down} \) are upper and lower wire ropes tensions, respectively; \( R \) is radius of winding wheel (20mm); \( T \) is locked-rotor torque of motor (10.8Nm); \( \eta \) is efficiency (0.8); \( F_{down} \) is spring force (36.6N). Introducing all data into Eq. (1), it can be calculated that \( F_{up} \) is 468.6N.

When glass regulator is locked-rotor on top dead center, the included Angle of wire rope of upper
guide pulley is $70^\circ$, the included Angle of wire rope near lower guide pulley is $90^\circ$. Resultant force of wire rope on upper guide pulley is 768N, and resultant force on lower guide pulley is 52N, shown in Fig. 3.

When the glass regulator is locked-rotor on bottom dead center, relationship between tensions of upper and lower wire ropes is shown in Eq. (2):

$$F_{up}R - F_{down}R = T \eta$$

Where glass regulator is locked-rotor on bottom dead center, $F_{up}$ is spring force (36.6N), and Eq. (2) is used to calculate $F_{down}$ (468.6N). The included Angle of wire rope of upper guide pulley is $65^\circ$, and that of lower guide pulley is $95^\circ$. Resultant force of wire rope on upper guide pulley is 60N, and resultant force on lower guide pulley is 633N, shown in Fig. 4.

Normal working conditions of glass regulator include two working conditions: adjusting spring is pressed and adjusting spring is not pressed.

If the adjusting spring is pressed, tensions of upper and lower wire ropes will satisfy Eq. (3):

$$F_{max} + F_{down} = 2F_0$$
$$F_{up} = F_{down} + G + F_{zu}$$

Where $F_{max}$ is adjusting force(80N), $F_{up}$ and $F_{down}$ are upper and lower wire ropes, $F_0$ is initial spring tensioning Force, $G$ is gravity of glass(26N), $F_{zu}$ is friction resistance (40N). Fig. 5 shows force diagram of slider during its extension process. $F_0$ is initial spring tensioning force (65N). Introducing $F_{max}$, $G$, $F_0$ and $F_{zu}$ into Eq. (3), it can be calculated that $F_{up}$ is 116N and $F_{down}$ is 50N.
If the adjusting spring is not pressed, tensions of upper and lower wire ropes will satisfy Eq. (4):

\[ F_{up} + F_{down} = 2F_0 \]
\[ F_{up} = F_{down} + G + F_{zu} \quad (4) \]

Where gravity of glass (G) is 26N, initial tensioning force of spring (F_0) is 50N and frictional resistance (F_{zu}) is 30N. It can be calculated that F_{up} is 78N and F_{down} is 22N.

Forces on wire rope, adjusting spring and guide pulley are obtained in statics theoretical analysis of glass regulator. The forces are regarded as loads on glass regulator in statics finite element analysis of glass regulator.

4. Statics finite element analysis of glass regulator

4.1. Mesh division and load application

In statics finite element analysis, guide rail adopts hexahedral solid element. Division method is to import 3D model of guide rail into Hypermesh software and divide mesh. Local enlarged model of guide rail mesh is shown in Fig. 6. Overall element size of guide rail is 2mm, and element size of stress concentration area on local upper and lower dead points is 1mm.

Upper and lower guide pulleys are fixed on guide rail, and force generated by upper and lower steel wire ropes is transferred to guide rail through guide pulley. Load on guide rail is resultant force of upper and lower wire ropes on guide pulley. Load on guide rail in different working conditions is shown in Table. 1:
Table 1. Applied load on guide rail in different working condition.

| Working condition               | Upper guide pulley load/N | Lower guide pulley load/N |
|---------------------------------|----------------------------|----------------------------|
| Locked-rotor on top dead center | 768                        | 52                          |
| Locked-rotor on bottom dead center | 60                        | 633                         |
| Normal operation                | 140                        | 52                          |

According to the geometric features and stress conditions of slider, it was decided to separate main stress and contact areas from other areas, and divide them into C3D8R hexahedral mesh elements, while rest areas were divided into C3D4 mesh elements, shown in Fig. 7.

![C3D8R hexahedral mesh elements](image)

Fig. 7. Finite element mesh division of slider.

Load on slider is pulling force of upper and lower wire ropes on slider, shown in Table 2:

Table 2. Applied load on slider in different working condition.

| Working condition               | Pulling force of upper wire rope/N | Pulling force of lower wire rope/N |
|---------------------------------|-----------------------------------|-----------------------------------|
| Locked-rotor on top dead center | 468.8                             | 36.6                              |
| Locked-rotor on bottom dead center | 36.6                           | 468.8                             |
| Normal operation                | 100                               | 36.6                              |

Contact element of guide pulley is C3D8R, non-contact element of guide pulley is C3D4, and element of wire rope is C3D8R. Load on guide pulley of glass regulator in different working conditions is shown in Table 3:

Table 3. Applied load on guide pulley in different working condition.

| Working condition               | Pulling force of wire rope/N |
|---------------------------------|-------------------------------|
| 1 Normal rising with spring uncompressed | 22                            |
| 2 Locked-rotor on bottom dead center | 36.6                         |
| 3 Normal rising with spring uncompressed | 78                            |
| 4 Normal rising with spring compressed | 116                          |
| 5 Locked-rotor on top dead center | 468.8                         |
Shape of motor base plate is complex, and large deformation and contact problems will not exist on motor base plate. Therefore, tetrahedral element C3D4 is selected in mesh division of motor base plate. Load applied on motor base plate is tension exerted by outlet ends of two sleeves, and value of tension is 468.6N (maximum tension value of wire rope).

4.2. Finite element analysis results
When glass regulator is locked-rotor on top dead center, stress and displacement of guide rail is the largest. When glass regulator is locked-rotor on top dead center, statics finite element analysis of guide rail is carried out. Stress and displacement nephograms are shown in Fig. 8. Stress concentration and plastic deformation take place on flanging A. Stress value on flanging A is 240.1Mpa, plastic strain value on flanging A is 0.0025mm, and maximum displacement of guide rail is 0.67mm. Finite element analysis results show that greater stress concentration and displacement exist on guide rail when glass regulator is locked-rotor on top dead center. Risk of failure exists on guide rail.

![Stress nephogram (a) and displacement nephogram (b) of guide rail (Locked-rotor on top dead center).](image)

Finite element analysis is carried out on stress and displacement of slider. Maximum stress of slider is distributed on shrapnel. When glass regulator is locked-rotor on top and bottom dead centers, maximum stress value of slider are 80.76Mpa and 79Mpa, respectively. When glass regulator is locked-rotor on top dead center, stress nephogram of slider is shown in Fig. 9. Compared with guide rail, maximum stress value and risk of large deformation are less on slider.

![Stress nephogram of slider (Locked-rotor on top dead center).](image)

Stress and compressive stress of guide pulley in five working conditions (Table 4) are analyzed. In working condition 5, when glass regulator is locked-rotor on top dead center, maximum stress and compressive stress of guide pulley are 44.6Mpa and 63Mpa, respectively. Maximum stress and compressive stress of guide pulley are small, and it is not easy to fail. When glass regulator is locked-rotor on top dead center, stress and compressive stress nephograms of guide pulley are shown in Fig. 10.
Fig. 10. Stress nephogram (a) and compression stress nephogram (b) of guide pulley (Locked-rotor on top dead center).

When glass regulator is locked-rotor on top dead center, stress nephogram of lower seat plate of motor seat plate, displacement nephogram and stress nephogram of motor upper cover plate are shown in Fig. 11, respectively. Maximum stress and maximum displacement of lower seat plate of motor are 62.7Mpa and 0.15mm, respectively. Maximum stress of upper cover plate of motor is 15.6Mpa. Maximum stress and displacement of motor base plate are small, and it is not easy to fail.

Fig. 11. Nephograms of motor bottom plate stress (a), motor bottom plate displacement (b) and motor top plate stress (c).

5. Conclusions

Three working conditions exist during glass regulator working: locked-rotor on top dead center, locked-rotor on bottom dead center and normal working condition. In this paper, statics theoretical analysis and finite element analysis are carried out for investigating static performance of four key parts of glass regulator in three working conditions. Several conclusions can be drawn as follows:

1) When glass regulator is locked-rotor on top dead center, resultant force of wire rope on guide pulley is greater than resultant force of wire rope on guide pulley in other conditions. Stress and compressive stress on guide pulley will not cause great displacement.

2) When glass regulator is locked-rotor on top dead center, stress and displacement on guide rail
are maximum. Great stress concentration exists on flanging and leads to risk of failure.

(3) When glass regulator is locked-rotor, maximum stress of slider is distributed on shrapnel, and maximum stress value is small.

(4) When glass regulator is locked-rotor, maximum stress value and maximum displacement value on motor seat plate are small, and working performance is good.

In this paper, statics analysis of single track rope-wheel glass regulator provides data support for analysis of strength, stiffness, fatigue and wear of glass regulator, as well as driving data for later structure optimization. This paper provides reference for investigation of other types of regulators.

Acknowledgments
The authors would like to thank Independent Innovation Fundation of Wuhan University of Technology (2019IV A102) and China Postdoctoral Science Foundation (2020M672429) for the support given to this research.

References
[1] Zhang H. Structural Design and Simulation of Automobile Electric Glass Lifter [D]. Changsha University of Science and Technology, 2017.
[2] Xiong XS, Hua L, Wan XJ, et al. Wear analysis of an automotive window regulator slider[J]. Proceedings of the Institution of Mechanical Engineers Part J: Journal of Engineering Tribology, 2019, 233(10):1508-1522.
[3] Gao K, Wang Q. The Design Method of Cable-Drum Glass Regulator [J]. Automobile Applied Technology, 2016(05):12-17.
[4] Gao J, Wang X, Liu HX. Arrangement and Design of Fork-arm Glass Lifter Based on Smoothness [J]. Machinery, 2016, 54(04):68-71+73.
[5] Hao SS. Brief Discussion on Design and Arrangement of Rope-wheel Glass Lifter [J]. Management and Technology of SME, 2015(10):266.
[6] Qi HB. Design Method of Boom Glass Regulator [J]. Automotive Engineer, 2014(06):28-30.
[7] Hu JK. Structural Analysis and Simulation of Electric Window [D]. Wuhan University of Technology, 2013.
[8] Zhang H, You WP, You XP. Structural Analysis and Simulation of Automotive Fork-arm Glass Lifter [J]. Highways and Automotive Applications, 2018(01):16-19.
[9] Li BT. Reason Analysis and Solution on Influencing of Riser of Heavy Truck Window [J]. Special Purpose Vehicle, 2015(03):90-92.
[10] Li YR, Hu QL. Analysis and Solution of Glass lifting system of a light truck [J] Light Vehicles, 2014(03):13-17.
[11] Li XJ, Hao FL, Duan DJ. Lavida Car Glass Regulator Trouble shooting [J]. Auto Driving and Service, 2014(01):34-35.
[12] Shi DB. Analysis on Layout and Typical Malfunctions of Single Rope Wheel Auto Window Regulator [D]. Chongqing University, 2015.
[13] Lei YF, Li XF. Fault Analysis and Solution of Four Door Glass of New Bora Automobile [J]. Auto Electric Parts, 2015(11):48-50.
[14] Mao WD, Zhou JF, Wang CW. Investigation and Design of Failure of Automobile Glass Lifting System [J]. Auto Manufacturing Engineer, 2019(09):48-50+53.
[15] Shi XH, Wang XH. Failure Model Analysis and Design Improvements for Rope-wheel Glass Regulator [J]. Agricultural Equipment Vehicle Engineering, 2014, 52(02):52-55.
[16] Luo K, Cheng ZM. Multi-objective Optimization of Glass Lifter Based on Rigid Flexible Coupled Dynamic Simulation [J]. Journal of Mechanical & Electrical Engineering, 2019, 36(08):814-818.
[17] Wu YL. Analysis and Optimization Window Regulator’s Motion Performance Based on Multi-body Dynamic Simulation [D]. Hunan University, 2018.
[18] Huang CT. Lightweight Design for Automotive Window Regulator [J]. Automobile Parts,
[19] Li CD, Meng CY. Structure Research on Automotive Glass Riser with Multi-Objective Genetic Algorithm [J]. Machinery Design and Manufacture, 2016(03):253-256.
[20] Fu GY. Improved Design of a Glass Lifter for Passenger Vehicle [D]. Jilin University, 2018.