

Strength Check Analysis for Gear Shaft of Automobile Transmission

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Abstract: As the main drive components of the automobile transmission, the performance of gear shaft plays an important role on transmission performance. Aiming at the existing problems of the traditional strength check method of gear shaft, the objective of this study is to take a five-speed transmission as an example, to accomplish the strength analysis of gear shaft of the automobile transmission based on the MASTA software. Furthermore, the simulation modeling of the transmission is built completely to simulate the actual load conditions and complete the process of analysis for the gear shaft. Analytical results show that all gear shafts can fully meet the strength requirements, in addition to the input shaft which has any further improvements. Hence, it is indicated that a new design concept is put forward, that is, using specialized software MASTA for transmission modeling and simulation analysis can heavily improve the design level of the gear shaft, provide the theoretic basis to analyze the dynamic characteristics of gear shaft as well. Finally, it can provide references for the development and application of gear shaft of the automobile transmission.

Keywords: Automobile transmission, gear shaft, MASTA, strength check

INTRODUCTION

Automobile transmission is a kind of control device used to transmit power, adjust the running speed of automobile and switch the automobile forward and backward. As a core component of automobile, it will have a great effect on the power performance, economy, comfort, noise of the entire automobile. As the main part of the automobile, the purpose of automobile transmission is to match the characteristics of engine to fit the requirements of traveling (Zhang *et al.*, 2006).

The gear transmission mechanism is one of the most widely used transmission mechanism, which can be used to transmit the motion and force between two random shafts in space of transmission, characterizing large power range, high efficiency, accurate transmission ratio, long service life, safe and reliable, has been widely used in various industries (Wang *et al.*, 2010). In which, gear shaft is the main transmission part in the most general machinery and its intensity has a great influence on the service life of the machine. Because the geometric structure of gear shaft is more complex than the ordinary transmission shaft, to determine and check the actual damage location of gear shaft by the conventional method is more cumbersome, it results in a bigger error (Li *et al.*, 2000). In order to provide the theoretical basis for structural design of gear shaft, especially for new structural measures taken for the dangerous position in time, the strength of gear

shaft should be clearly understood after the preliminary structural design is completed. Based on the above situation, this paper uses the transmission system analysis software MASTA to complete the strength analysis and calculation for gear shaft of a certain automobile transmission.

As a powerful, wide coverage, deep technology and strong practicability large-scale special software system, integrated transmission system selection, design, development and manufacturing and other functions, the software MASTA, advanced computer aided design, manufacture and analysis software, was launched by the British professional gear transmission System Technology company (SMT), covering the basic structure, mechanical design, modeling, analysis and imitation, digital simulation and other functional modules. Its 3D feature modeling function is powerful enough to perform the parametric feature modeling and finite element structural analysis of complex transmission parts, to perform the strength checking calculation under the systematical overall deformation conditions, widely used in aerospace, machinery manufacturing and automobile traffic etc (Tian *et al.*, 2011).

Gear shaft is common important equipment in mechanical equipment, its own design rationality affects the safe operation of the entire equipment (Liu *et al.*, 2011). In the past, the general conventional mechanical method is used for the structural design of

shaft, but the traditional method is to simplify the actual structure and loads reasonably according to the mechanical model and then to perform theoretical calculation, if there are some complex changes in certain parts of the shaft, the stress and strain distribution law on these parts cannot be fully grasped (Zheng and Hou, 2007). The research object of this paper is gear shaft of a certain automobile transmission, as the important part of the whole equipment. As the structure of gear shaft is more complex, including local keyway, shoulder and other special shape, these sites will be easy to appear the phenomenon of stress concentration, it is very difficult to accurately grasp the law of stress and strain with the help of the conventional method. Therefore, by means of the professional transmission system analysis software MASTA, we use its powerful parametric function to establish the standard in volute cylindrical gear shaft parametric model and then import them into MASTA simulation module for CAE analysis, simultaneously considering local complex parts, to study the distribution regularity of stress and strain of gear shaft and finally obtain the static strength and fatigue strength of gear shafts of the automobile transmission, which verify the rationality of the theoretical analysis and calculation. In general, the results of CAE analysis will provide detailed theoretical basis for the structural design and safety work of gear shafts of the automobile transmission.

METHODOLOGY

The function and design requirements of gear shaft: All rotating parts of the transmission are installed in gear shaft and also positioned by each other through gear shaft. As to the automobile transmission, on the premise of meeting the stiffness and strength of gear shaft, we should try to achieve the purpose of reducing the shaft weight, material saving and rational design of the shaft diameter, so as to provide more space for the design of rotating parts on gear shaft. In addition, the reduction of the shaft diameter can reduce the moment of inertia of synchronizer, thereby facilitating the synchronization ability and shift function of synchronizer.

The gear shaft of transmission not only bears the work torque, but also be subjected to the bending moment induced by the circumferential force, radial force and axial force from gear meshing on the shaft. Therefore, the gear shaft should have enough strength and stiffness, if its stiffness is insufficient, large deformation will be generated under the action of load in transmission, thus affecting the normal gear meshing and then resulting in noise, meanwhile, reducing the strength of gear, wear resistance and service life, etc., (Hu *et al.*, 2010).

The structural design of gear shaft of transmission mainly considers the structure form of gear

shaft, consisting of the length and cross sectional diameter of gear shaft, the shaft strength and rigidity, as well as the type and size of shaft spline. In addition, it satisfies structure layout of the transmission. Only in the full consideration of machining process and assembly process, can we finalize the design solution of gear shaft of transmission (Tian *et al.*, 2010).

In order to ensure the normal work of gear shaft under the specified service life, usually to follow the following principles of design:

- Reasonable selection of suitable materials, blank form and heat treatment method according to the work condition of gear shaft
- Reasonable stress condition of gear shaft to improve the strength and the stiffness of gear shaft
- To meet the requirement of processing technique, that is to say, the gear shaft shall facilitate the processing, heat treatment, assembling and disassembling, inspection and repair, etc.
- The parts of gear shaft required for accurate positioning, firm and reliable
- To reduce the stress concentration as far as possible in order to improve the fatigue strength of gear shafts
- The diameter and the length of each part of gear shaft should be reasonable

Preliminary sizing of the gear shaft: When structure scheme of the transmission, basic parameters of gears and the layout of gears, bearings and synchronizers and other parts are determined, the design sketches of the transmission can be completed and the length of gear shaft of the transmission can also be preliminarily determined (Liu, 2001).

Because the radial length of gear shaft has great influence on the stiffness of gear shaft, in order to meet the stiffness requirements, the length of the shaft should keep a harmonious relationship with the diameter of the shaft. The diameter and the supporting length of gear shaft can be selected according to the following formula.

With regard to the input shaft and middle shaft:

$$\frac{d}{l} = 0.16 \sim 0.18 \quad (1)$$

With regard to the output shaft:

$$\frac{d}{l} = 0.18 \sim 0.21 \quad (2)$$

The diameter of the shaft is related to the torque transferred by the shaft, so it also has a certain relationship with the center distance of the transmission. For three-shaft transmission, the maximum diameter of the output shaft and the middle shaft can be preliminarily determined according to the following formula:

$$d = (0.45 \sim 0.60)A \text{ (mm)} \quad (3)$$

The diameter of the spline segment of input shaft can be preliminarily determined by the maximum torque of the engine according to the following formula:

$$d = (4 \sim 4.6) \sqrt[3]{M_{e\max}} \text{ (mm)} \quad (4)$$

where,

$M_{e\max}$ = The maximum torque of the engine, N. m

A = The center distance of the transmission, mm

Meanwhile, preliminary sizing of the diameter of gear shaft should also consider the structure layout of the transmission, bearings spline and an elastic retainer ring and other factors and then should be amended in accordance with the checking results of the strength and stiffness of gear shaft.

The traditional analysis method of gear shaft: When the strength and stiffness of gear shaft were calculated, first of all, it is necessary to analyze the applied force from parts of other shafts and supporting reaction force, especially gear meshing force; secondly, because the applied force and supporting reaction force exerted on the shaft are all different when the transmission is in different gear, the strength and stiffness of gear shaft under different gears should be calculated respectively. For the calculation of support reaction force applied to gear shaft, the calculation should start from the output shaft and turn on the intermediate shaft and then the input shaft. As the same time, gear shaft can be regarded as the hinge supporting beams in the process of calculation and the calculating torque of input shaft can be thought of as maximum torque of the engine (Cheng, 2007).

Circumferential force F_t , radial force F_r and axial force F_a from gear meshing can be obtained according to the following formula:

$$F_t = \frac{2M_{e\max} \cdot i}{d} \quad (5)$$

$$F_r = \frac{2M_{e\max} \cdot i \cdot \tan \alpha}{d \cdot \cos \beta} \quad (6)$$

$$F_a = \frac{2M_{e\max} \cdot i \cdot \tan \beta}{d} \quad (7)$$

where,

i = Computational gear ratio

d = Pitch radius of computational gear

α = Pressure angle in the node

β = Spiral angle

$M_{e\max}$ = Maximum torque of the engine, that is, computational torque of Input shaft, N.m

Strength checking of gear shaft should be carried out in consideration of the combined action of bending moment and torque (Xu, 1981). Radial force F_r and axial force F_a exerted on gear shaft cause the shaft from bending deformation in the vertical plane and some degree of vertical deflection f_c ; at the same time, circumferential force F_t causes the shaft from bending deformation in the horizontal plane and some degree of horizontal deflection f_s . After the calculation of the vertical counterforce and horizontal counterforce of each pivot point, the corresponding vertical bending moment M_c and horizontal bending moment M_s can be obtained, so the stress σ (MPa) of gear shaft under the combined action of bending moment and torque can be obtained by the following formula:

$$\sigma = \frac{M}{W} = \frac{32M}{\pi d^3} \leq [\sigma] \quad (8)$$

where,

$$M = \sqrt{M_c^2 + M_s^2 + T_j^2}$$

T_j = Computational torque, N. m

d = The diameter in the computational section on gear shaft, mm

W = Coefficient of bending section, mm³

M_c = The vertical bending moment in the computational section on gear shaft, N.m

M_s = The horizontal bending moment in the computational section on gear shaft, N.m

$[\sigma]$ = Permissible stress, MPa

MASTA modeling of transmission system:

General instructions of modeling process: According to 2D drawing and 3D models of a certain transmission as the research object, provided by the technical departments, the project has established a complete detailed MASTA model. The model includes gears, gear shafts, cylindrical roller bearings, tapered roller bearings, needle roller bearings, clutches, synchronizers and shell. We will put the whole transmission system as a whole to undertake systems analysis, to get system global stiffness and then to obtain static strength and fatigue strength of gear shaft, as well as bearing dislocation and service life, etc.

Material settings of gear shaft: According to the design drawings, 20CrMnTi was selected as the material of gear shaft of automobile transmission because it possesses better mechanical properties. The elastic modulus of the material is 207 GPa, material density is 7800 kg/m³, Poisson's ratio is 0.3, tensile strength is 1100 MPa, yield strength is 850 MPa, fatigue strength limit is 525 MPa. The gear shaft is mainly under self-weight and is used to transmit power.

SN curve is used to indicate the relationship curve between the fatigue strength and the fatigue life of standard test piece under conditions of a certain cyclic

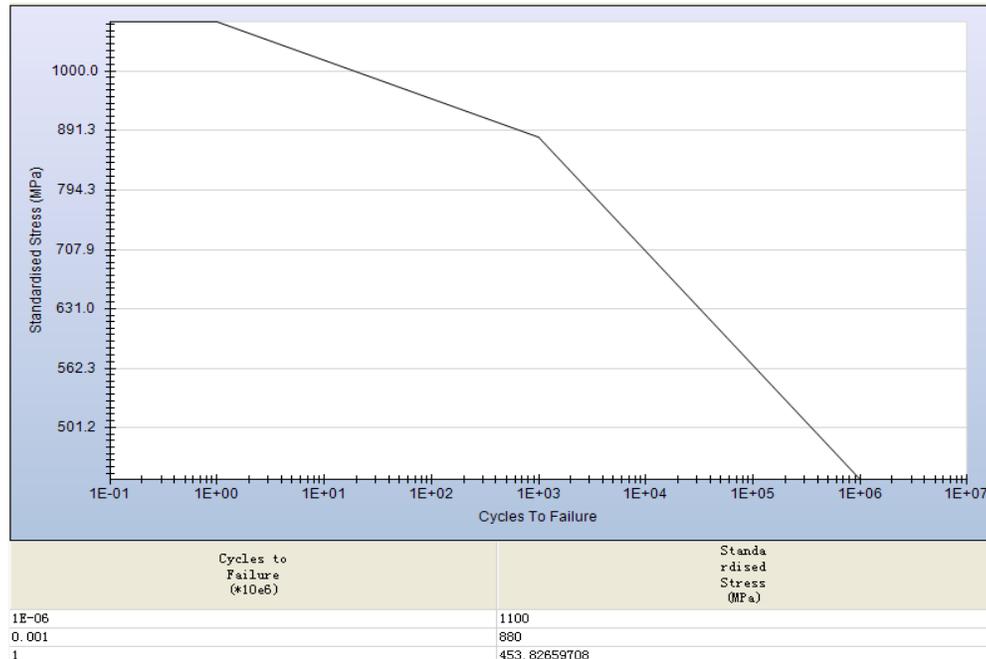


Fig. 1: SN curve of gear shaft

characteristics, also known as stress-fatigue curve, whose longitudinal coordinate is expressed as the fatigue strength of standard test piece of the material and the horizontal coordinate as the logarithmic value of fatigue life \lg^N . What is commonly referred to as SN curve of some material is to shape the raw material into a round rod as standard test piece of the material based on the designated grade of processing precision and heat treatment processes, to get fatigue life under different loads, such as tensile, compression, bending and torsion, so as to obtain a corresponding curve. Therefore, considering that different parts have different shapes, the processing precision and the heat treatment process is not the same, their SN curves are also different certainly.

SN curve of the gear shaft studied in this paper is shown in the Fig. 1.

Establishment of gear shaft: In the software of MASTA, the structure of gear shaft is divided into two types: one is that the structure characteristics of gear shaft is symmetric, called the standard shaft; another is that the structure characteristics of gear shaft is asymmetric, called the special-shaped shaft, commonly including planet carrier, irregular wheel spoke, etc. Standard shaft can be established in the design module of the MASTA software and special-shaped shaft must be completed with the aid of the flexible structure module of the MASTA software.

The automobile manual transmission studied in this paper belongs to the rear drive transmission, which itself has no differential part, so the three shafts are standard parallel shaft, can be directly established in the design module of the MASTA software. First of all, a

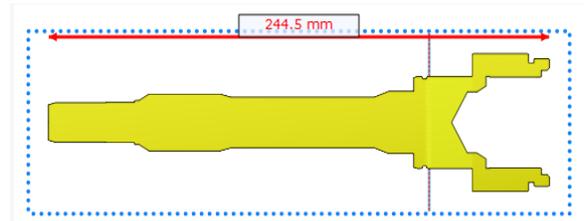


Fig. 2: The input shaft model of the manual transmission

principal shaft needs to be created and then add the exterior features on the shaft in order, including the shaft diameter, inner hole, the stepped surface and the inclined surface on each of the shaft section; secondly, defining the shaft surface roughness, grooves, radial holes, the stress concentration factor and other detail features.

The input shaft model of the manual transmission is shown as Fig. 2. As can be seen from the Figure, this model involves the outer contour of the shaft, inner hole, stepped surface, surface roughness and the radial hole, etc.

According to the above mentioned method, we can establish the models of the middle shaft and the output shaft respectively as shown in Fig. 3 and 4.

The positioning of gear shaft: The left end of input shaft is acted as a reference to determine the space position of the output shaft, the middle shaft and reverse gear idler shaft, as shown in Fig. 5.

Gear modeling: In the software of MASTA, transmission gear is completely defined through its

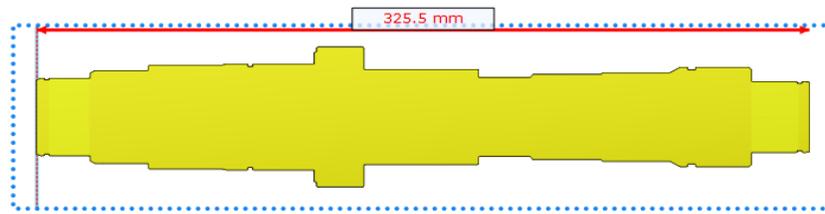


Fig. 3: The middle shaft model of the manual transmission

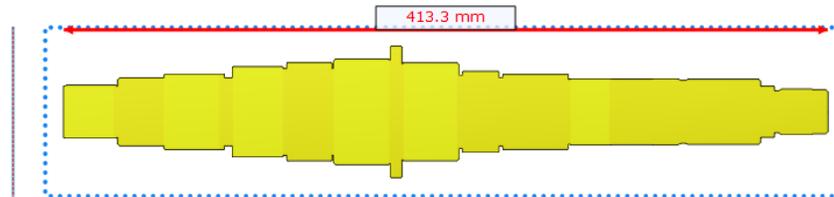


Fig. 4: The output shaft model of the manual transmission

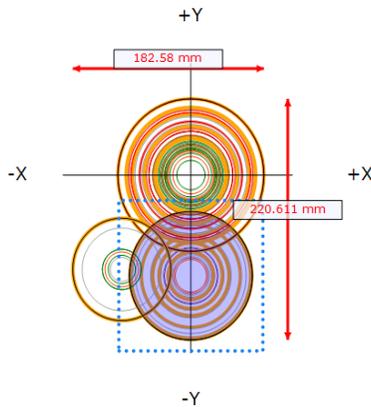


Fig. 5: Space position of gear shaft

parameters, so as to generate automatically the two-dimensional and three-dimensional models of gear. Gear parameters consist of tooth number, modulus, tooth width, displacement coefficient, helix angle and pressure angle and other basic parameters as well as the pitch circle diameter, base circle diameter, tooth root transitional circular arc fillet radius, addendum chamfer and other external dimensions.

When the gear is mounted on the shaft, as long as the gear position on the shaft is defined, we can choose a different location reference to conveniently position the gear on the shaft.

Bearing modeling: Because the bearing belongs to standard part, the bearing database in the MASTA software has already covered most of products series provided by the bearing manufacturers. In the ordinary course of events, we can select the corresponding bearing from the bearing database. If necessary, we can also add new bearings to the database through setting the bearing's basic parameters such as bearing width,

inner and outer diameter, parameters and shapes of raceways and rollers of bearings.

For example, rolling bearing is used as the front bearing of the middle shaft of the manual transmission as shown in Fig. 6. Other bearings, including needle roller bearing, are selected through the corresponding parameters and models found in the bearing database

Synchronizer modeling: After the basic parameters of synchronizer are input to the corresponding synchronizer module of the MASTA software, the simple model of the corresponding synchronizer will be generated in the software. So it can be assembled to the corresponding gear shaft and then will be connected to the corresponding gear together.

General model of the whole transmission: Aimed at a certain automobile transmission, this study mainly completes the entire transmission system modeling in design module of the MASTA software. The sequence of the entire modeling process in order is to establish the model of all gear shafts and then to determine the space position of these shafts, followed by assembling other parts of gear shaft, such as gears, bearings, synchronizers, etc. According to the detailed parameters of the gear, shaft and bearing and other parts, the transmission simulation model is established in the MASTA software as shown in Fig. 7 and 8.

The load case on the transmission simulation model: When the transmission is in the actual working condition, the loading born by the transmission is changing, embodying that both the torque and the speed are changing, in addition, the usage frequent rate of the different stop positions, that is, the acting time of each stop positions, is not same also. The corresponding relationship among three variables is called the load

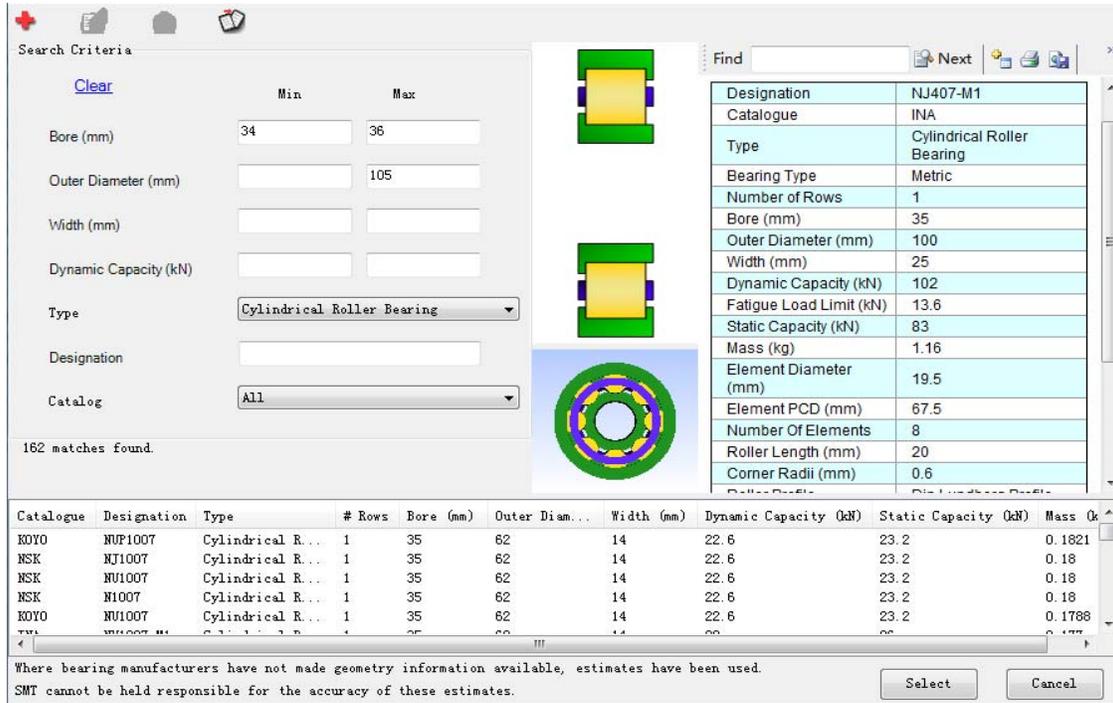


Fig. 6: The select of bearing

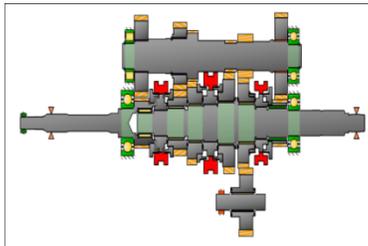


Fig. 7: 2D model view of the transmission

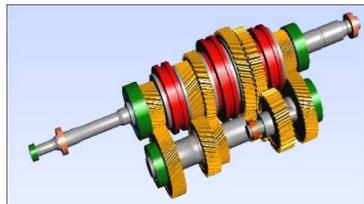


Fig. 8: 3D model view of the transmission (excluding housing)

cases. After clarifying the load cases of the transmission in actual working conditions, we can get the actual stress condition of every component in the whole transmission system under the load cases, so as to obtain the accurate calculation result.

Load cases are mainly used to define the input conditions of the proposed model, which can be load cases under actual working conditions or load cases of bench test. In the MASTA software, the working condition usually refers to torque, rotating speed and

acting time under the action of a certain power flow, while the load cases are the combinations of different working conditions. Therefore, before the definition of load cases, we need to define the input and output power flows for the proposed model.

The automobile manual transmission has five forward gears and one reverse gear, considering that each gear corresponds to a working condition, it is necessary to define six working conditions. Only when we specify the name, acting time or cycle number, rotating speed, torque or power for each working condition, can the definition of the whole working condition be considered to be complete. The load cases used by the article are consistent with the ones in the fatigue life test of the gear assembly, as shown in Table 1.

THE STRENGTH ANALYSIS OF GEAR SHAFT

Compared to the traditional checking method on the shaft, which calculation is too complex and be inaccurate, the use of MASTA not only can conveniently analyze the deformation, stress, torque and bending moment of gear shaft under the action of load cases, but also can carry on fatigue life analysis of gear shaft, get the injury rate of the dangerous sections of gear shaft.

In the MASTA software, if the allowable fatigue safety coefficient of gear shaft obtained by simulation analysis after loaded is greater than 1, it is available to

Table 1: Load cases of the transmission

Design state	Load case	Duration (h)	Power load	Speed (rev/min)	Torque (Nm)	Power (kW)
3 rd design state	New statistic load 100%	70.25	Input power load	2000*	280*	58.6431
			Output power load	1186.5079	-471.9732	-58.6431
4 th design state	New statistic load 100%	0	Input power load	2000*	280*	58.6431
			Output power load	2000	-280	-58.6431
5 th design state	New statistic load 100%	63.58	Input power load	2000*	280*	58.6431
			Output power load	2622.8070	-213.5117	-58.6431
R design state	New statistic load 100%	2	Input power load	2000*	280*	58.6431
			Output power load	-437.1345	1281.0702	-58.6431
1 st design state	New statistic load 100%	16.86	Input power load	2000*	280*	58.6431
			Output power load	395.5026	-1415.9198	-58.6431
2 nd design state	New statistic load 100%	36.04	Input power load	2000*	280*	58.6431
			Output power load	693.6508	-807.3227	-58.6431

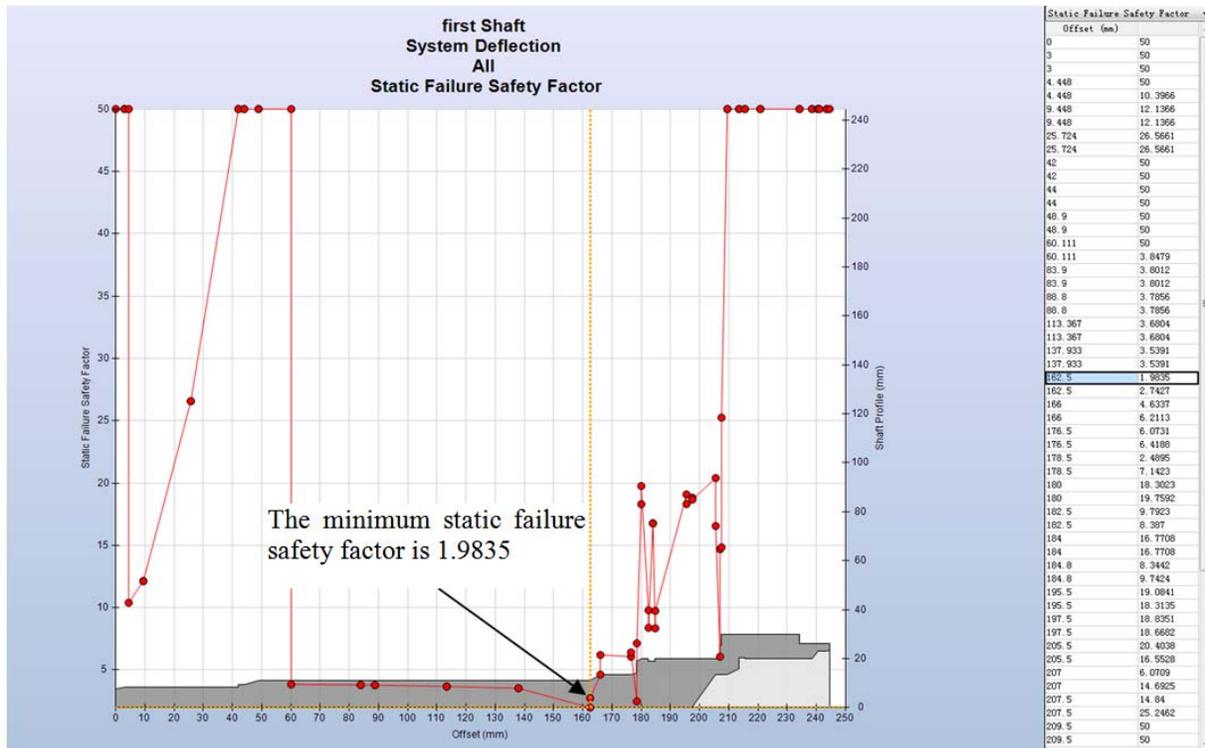


Fig. 9: Static failure safety factor of input shaft

meet the design requirements, if not satisfied; the reasons of the fatigue failure should be concretely analyzed.

The analysis results of input shaft under load cases are shown in Fig. 9 and 10, we can find that the minimum static failure safety factor is 1.9835 and the minimum fatigue safety factor is 2.1358, which all occur in about 162.5 mm from the left end of input shaft. Analytical data indicates that input shaft can fully meet the strength requirements.

The analysis results of output shaft under load cases are shown in Fig. 11 and 12, we can find that the minimum static failure safety factor is 1.3125, which occurs in about 334.2 mm from the left end of output shaft and the minimum fatigue safety factor is 1.0362, which occurs in about 211.1 mm from the left end of output shaft. Analytical data indicates that, because the

minimum fatigue safety factor is slightly larger than 1, there is excessive stress somewhere on output shaft, which will seriously affect the service life of output shaft. Therefore, it is necessary to have any further improvements in the output shaft.

The analysis results of middle shaft under load cases are shown in Fig. 13 and 14, we can find that the minimum static failure safety factor is 2.8003 and the minimum fatigue safety factor is 1.329, which all occur in about 240 mm from the left end of middle shaft. Analytical data indicates that middle shaft can fully meet the strength requirements and certain safety margin is left in the static failure safety factor of middle shaft.

The analysis results of reverse gear idler shaft under load cases are shown in Fig. 15 and 16, we can find that the minimum static failure safety factor is

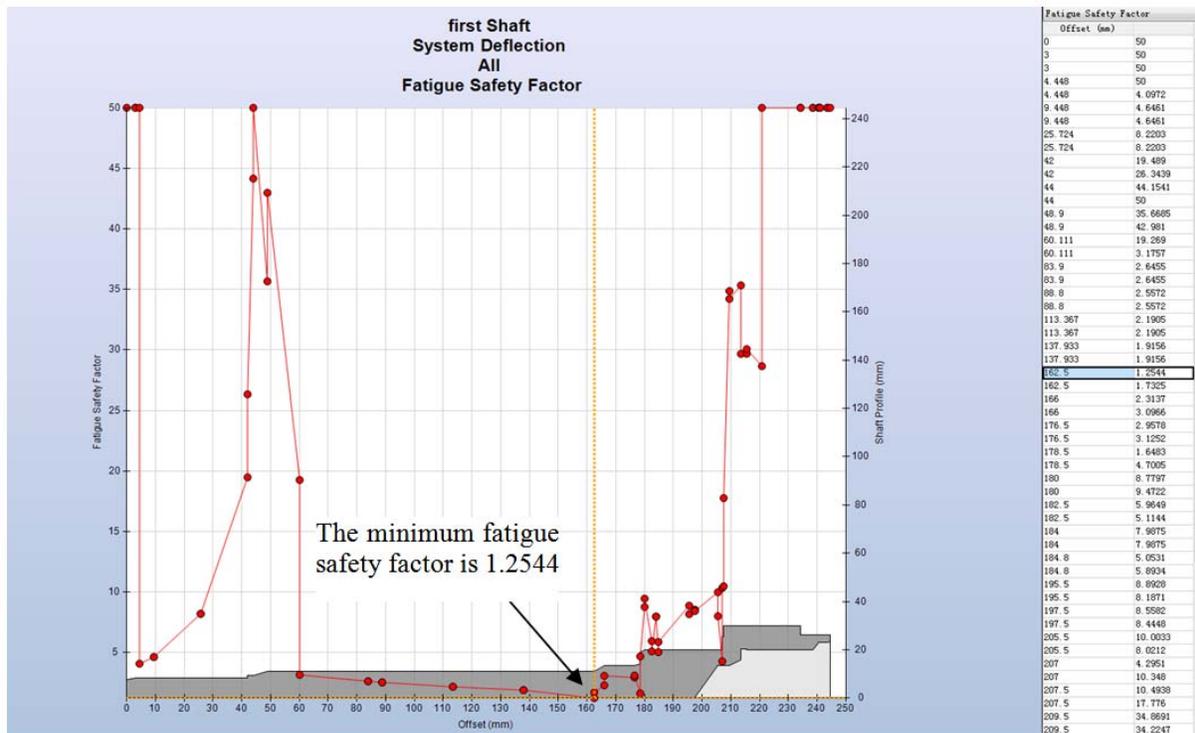


Fig. 10: Fatigue safety factor of input shaft

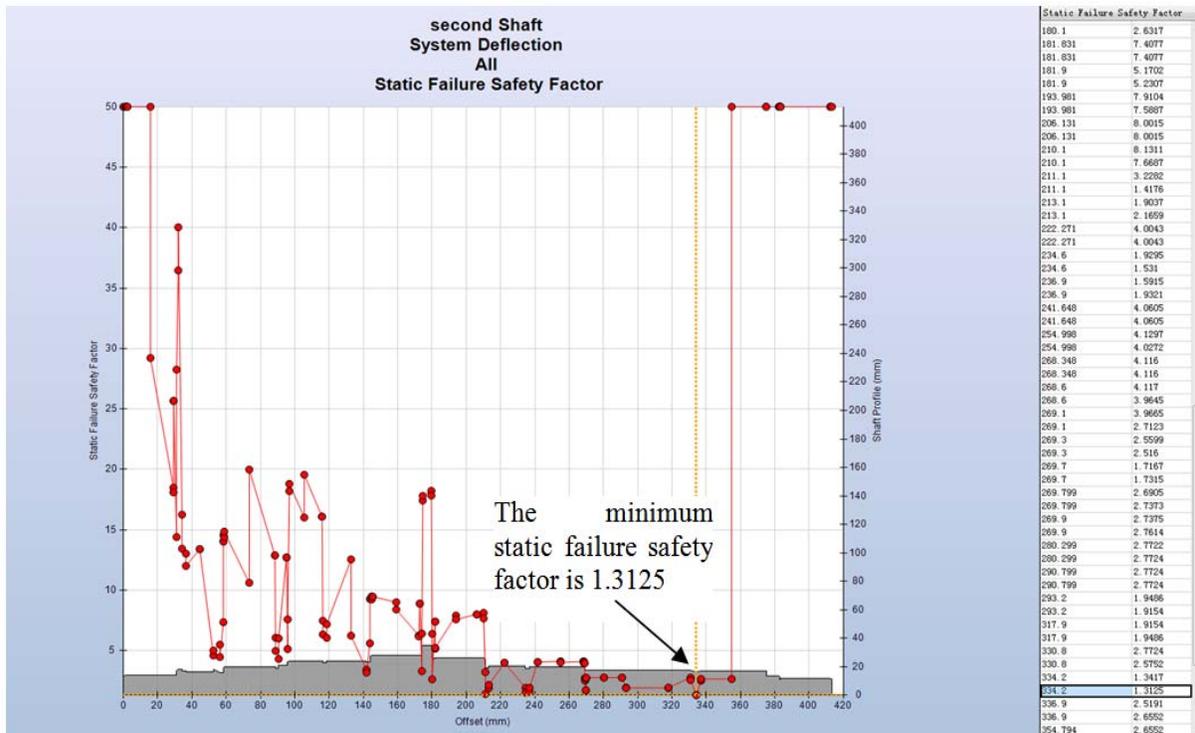


Fig. 11: Static failure safety factor of output shaft

0.0204 and the minimum fatigue safety factor is 1.329, which all occur in about 71 mm from the left end of reverse gear idler shaft. Analytical data indicates that

reverse gear idler shaft can fully meet the strength requirements and sufficient safety margin is left in the static failure safety factor of reverse gear idler shaft.

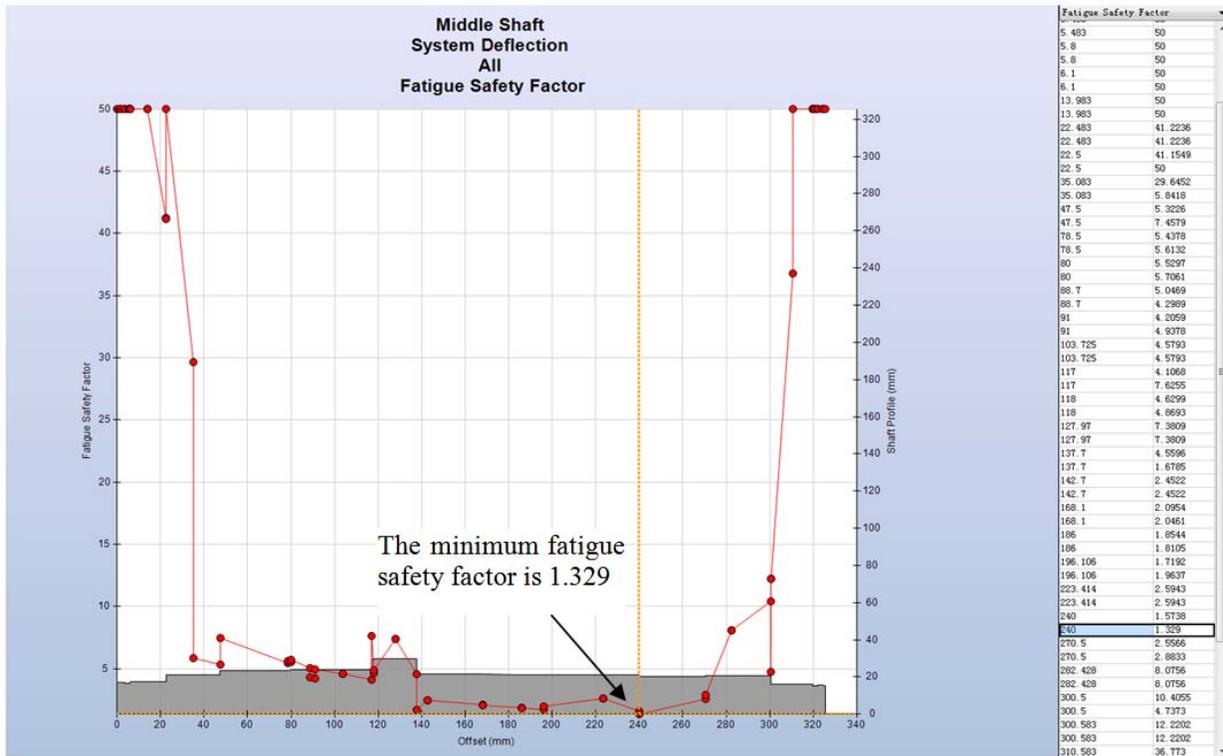


Fig. 14: Fatigue safety factor of middle shaft

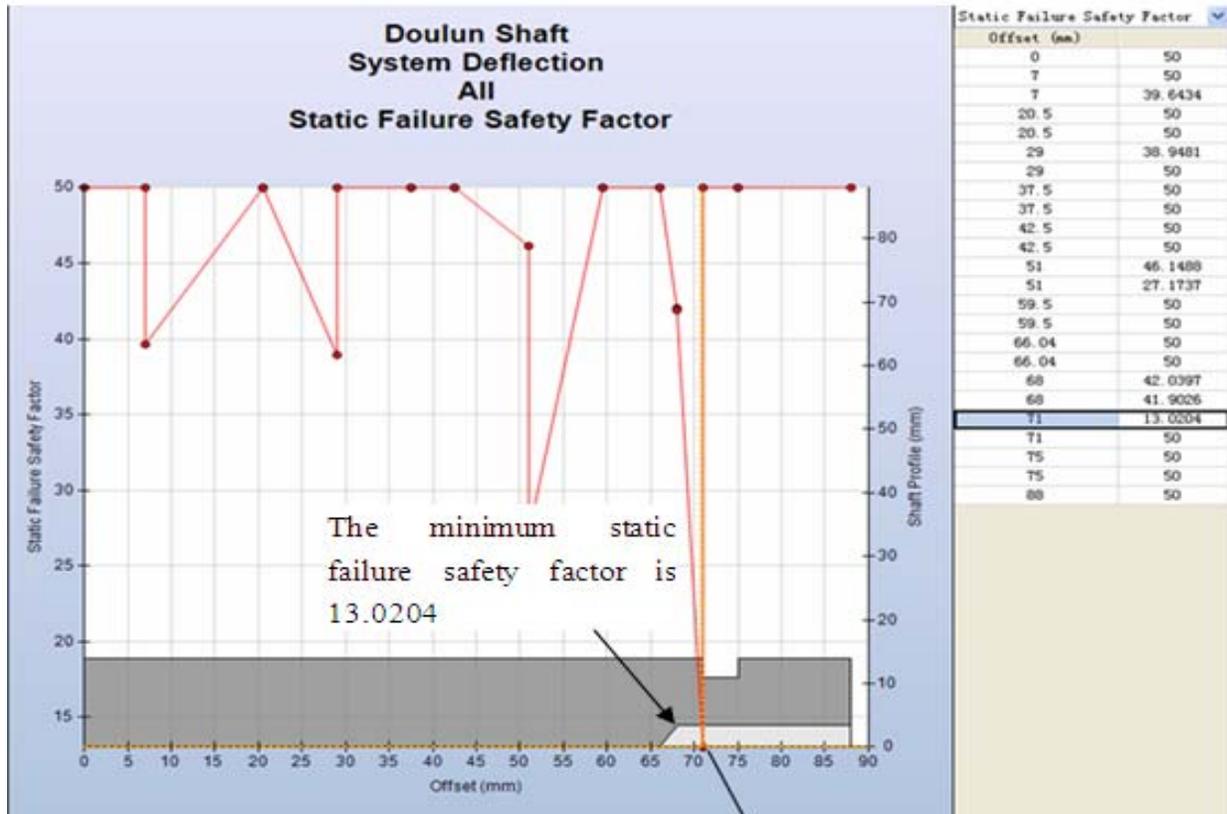


Fig. 15: Static failure safety factor of reverse gear idler shaft

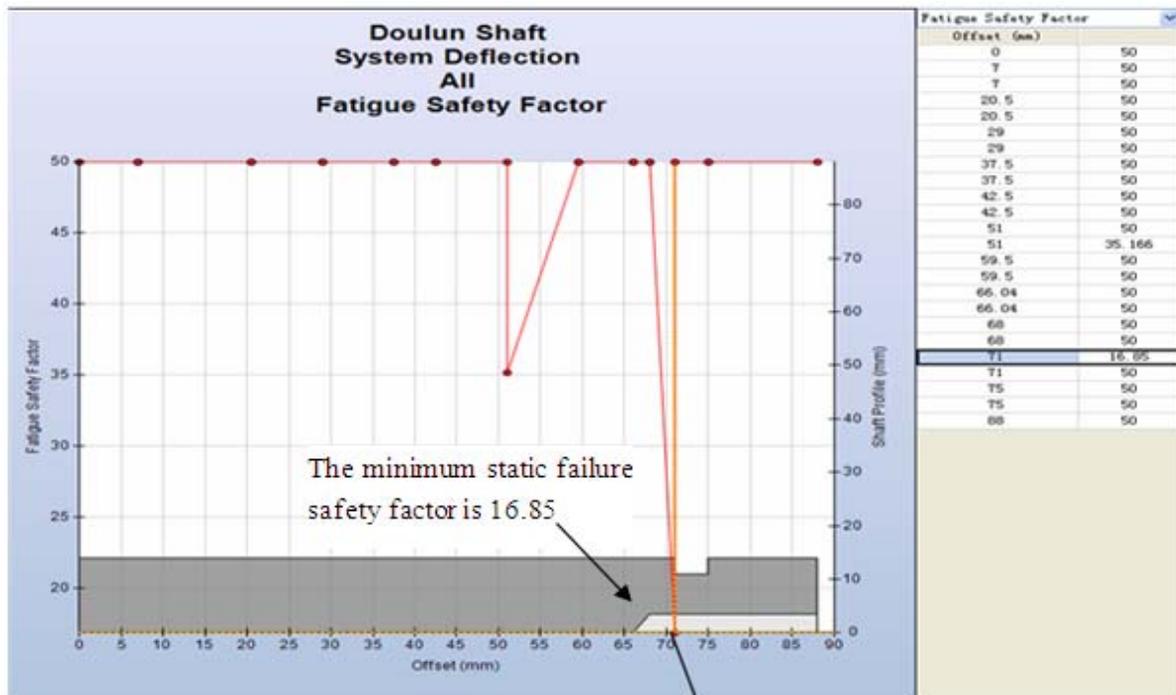


Fig. 16: Fatigue safety factor of reverse gear idler shaft

CONCLUSION

Considering that the structure of gear shaft of a certain automobile transmission, as research object of strain with the help of the conventional method. In this paper, through the strength analysis of gear shaft of the existing automobile transmission with the MASTA software, we can obtain the static failure safety factor and fatigue safety factor of all gear shaft, including input shaft, middle shaft, output shaft and reverse gear idler shaft. Analytical data under load cases indicates that all gear shafts can fully meet the strength requirements, meanwhile, sufficient safety margin is left in the static failure safety factor of reverse gear idler shaft, except that the output shaft need to have any further improvements because of a little too low fatigue safety factor, which will seriously affect the service life of output shaft. Therefore, using MASTA software can effectively perform the strength analysis and optimization design of gear shaft instead of the general conventional theoretical calculation method in the actual manufacturing process, besides, the results of CAE analysis will provide detailed theoretical basis for the structural design and safety work of gear shafts of the automobile transmission.

ACKNOWLEDGMENT

This study was financially supported by Foundation of Educational Commission of Zhejiang Province of China (Y201225934) and the Opening

this study, is more complex, including local keyway, shoulder and other special shape, which will be easy to appear the phenomenon of stress concentration, it is very difficult to accurately grasp the law of stress and Project of Key Laboratory of Testing Technology for Manufacturing Process, (Southwest University of Science and Technology), Ministry of Education (11ZXZK06).

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