DOI: 10.3901/CJME.2014.0909.147, available online at www.springerlink.com; www.cjmenet.com; www.cjmenet.com.cn

Design and Analysis of the Gemini Chain System in Dual Clutch Transmission of Automobile

CHENG Yabing[1, *], GUO Haitao[1], FU Zhenming[2], WAN Nen[1], LI Lei[1], and WANG Yang[1]

1 *College of Mechanical Science and Engineering, Jilin University, Changchun 130022, China*
2 *Qingdao CHOHO Industry Limited Company, Qingdao 266705, China*

Received May 5, 2014; revised August 28, 2014; accepted September 9, 2014

Abstract: Chain drive system is widely used in the conditions of high-speed, overload, variable speed and load. Many studies are focused on the meshing theory and wear characteristics of chain drive system, but system design, analysis, and noise characteristics of the chain drive system are weak. System design and noise characteristic are studied for a new type Gemini chain of dual-clutch automatic transmission. Based on the meshing theory of silent chain, the design parameters of the Gemini chain system are calculated and the mathematical models and dynamic analysis models of the Gemini chain system are established. Dynamic characteristics of the Gemini chain system is simulated and the contact force of plate and pin, plate and sprockets, the chain tension forces, the transmission error and the stress of plates and pins are analyzed. According to the simulation results of the Gemini chain system, the noise experiment about system is carried out. The noise values are tested at different speed and load and spectral characteristics are analyzed. The results of simulation and experimental show that the contact forces of plate and pin, plate and sprockets are smaller than the allowable stress values, the chain tension force is less than ultimate tension and transmission error is limited in 1.2%. The noise values can meet the requirements of industrial design, and it is proved that the design and analysis method of the Gemini chain system is scientific and feasible. The design and test system is built from analysis to test of Gemini chain system. This research presented will provide a corresponding theoretical guidance for the design and dynamic characteristics and noise characteristics of chain drive system.

Keywords: Gemini chain, system design, noise characteristic, dynamic characteristic, transmission error

1 Introduction

Transmission system is the core component of the automotive powertrain. Its excellent performance and perfection, play decisive roles in the automobile power performance, economy, comfortable and reliability. Dual clutch transmission(DCT) can transmit power without interruption. Thus the shift time is shortened and the shift quality is effectively improved. DCT has inherited many advantages of the manual transmission, such as high transmission efficiency, compact installation space, light weight, low cost etc. So it is the development direction in the automatic transmission industry.

DCT available in automotive technology is shown in Fig. 1. The round pin silent chain transmission system is applied in the chain transmission system studied in this paper.

Up to now, many scholars have done a lot of research in related areas. Based on the meshing theory of silent chain and sprocket, MENG Fanzhong, et al[1–4], presented a method which can calculate the parameters of plate and sprocket. The meshing design system of chain plate-sprocket-hob when plate and sprocket is meshing was studied in those papers. And the multivariate variation characteristic of silent chain plate and sprocket is expounded. Based on the silent chain simulation models, FENG Zengming, et al[5–6], researched the meshing characteristic of chain drive system by analyzing the contact force and stress of plate and pin in different meshing period. Based on the abrasion test of chain drive system, CHENG Yabing, et al[7–9], studied the abrasion position surface morphology of plate, sprocket and pin. The transverse fluctuations of axial moving of silent chain using multi-body dynamics was analyzed by ZHANG W M, et al[10]. The wear characteristics of automotive chain drive system from the microscopic view and analyzed the force characteristics of chain plate and pin at the Nano-level was studied by LI Baolin, et al[11]. Microstructure and performance of contact surfaces of the tooth chain plate after quenching in the microscope was researched by FU Zhenming, et al[12]. Dynamic response of the chain transmission system in composite and alternating conditions was studied by XU Lixin, et al[13]. Based on the meshing mechanism of chain plate and sprocket with involute tooth proposed by XUE Yunna, et al[14–15], WANG

* Corresponding author. E-mail: chengyb@jlu.edu.cn
Supported by National Natural Science Foundation of China(Grant No. 51305154), and Jilin Provincial Science and Technology Development Program: Automobile Coordinated Action, China(Grant No. 20116004).

Yong, et al[16], analyzed the modification coefficient of sprocket while the chain plate and sprocket meshing. They have achieved the change rules of different tooth profile from the modification coefficient changes. New double-pitch rocker-pin silent chain for conveyors and sprocket tooth profile were studied by WANG Wencheng, et al[17], SUN Wei, et al[18], they proposed a new type of double-pitch rocker-pin silent conveyor chain and studied sprocket tooth profile and involute sprocket tooth profile for effects on dynamic tension of chains in the silent chain drive.

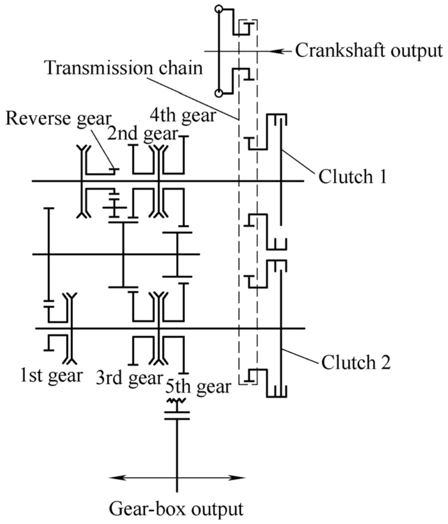


Fig. 1. Schematic of DCT transmission system

Many other famous scholars have conducted in-depth research in the chain transmission related fields. PERAIRA C M, et al[19], presented a method to establish multi-body dynamics model of a chain drive system with geometric mathematics, and analyzed the link velocity, acceleration, force and trajectory. YOUNG J D, et al[20], proposed an arrangement of a non-symmetric and alternating engagement tooth profile, and a method for installing the damping rubber ring in the outside sprocket to reduce meshing impact and vibration of roller chain drive system. FUJIMOTO N, et al[21], developed a method to achieve chain noise reduction by changing meshing tooth profile of the plate and the chain sprocket. MATSUDA A[22] presented a new silent chain and developed a silent chain with double-sided engagement, which can achieve multi axis drive in space. Based on by TROEDSSON I, et al[23], presented a mathematical model, and developed a mathematical model. By this model, oscillation and force of the chain transmission system can be calculated directly. The chordal action and transmission errors of a simple silent chain system was investigated by HUANG C, et al[24], they analyzed the chordal action based on the tooth contact analysis of the chain with the driving sprocket.

DCT transmission system studied in this paper is a new type Gemini chain system of DCT based on an improved DCT chain transmission system. Based on the meshing theory of silent chain, a new Gemini chain transmission system is designed and the dynamic analysis model is established. Based on RecurDyn software, the dynamic characteristics are analyzed and evaluated. The noise characteristics of the Gemini chain transmission system are analyzed through noise experimental. The innovation of this paper is the first time combined the design, simulation analysis and noise experimental which can improve the design and simulation. We can verification the rational of design through simulation analysis and experimental.

2 Mathematic Modelling Established

2.1 Parameters design of plate

According to the meshing theory of silent chain and sprocket and the design conditions of Gemini chain system in dual clutch transmission, the plate design of the DCT Gemini chain transmission system is shown in Fig. 2. The main parameters are: hole pitch a, apothem f, half angle of tooth profile α.

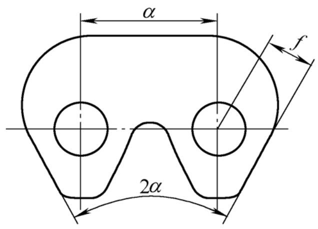


Fig. 2. Plate parameter

The hole pitch a=7.92 mm, apothem f=3.168 mm, the half angle of tooth profile α=30° .

2.2 Parameters design of sprocket

The sprocket design of the DCT Gemini chain transmission system is shown in Fig. 3. The main parameters are: teeth number Z, pitch p, pitch diameter d, tip diameter d_a and root diameter d_f, measurement over pins M_R, measuring pin diameter d_R. The Gemini chain system consists of crankshaft sprocket(Gemini sprocket), clutch sprocket 1，clutch sprocket 2，chain 1 and chain 2. The design parameters of sprockets are shown in Table 1.

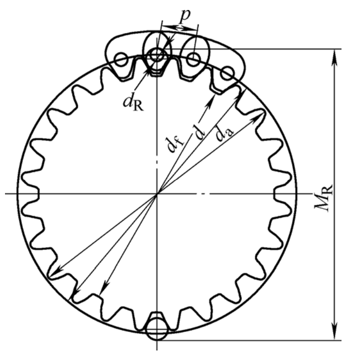


Fig. 3. Sprocket parameter

Table 1. Design parameters of sprockets

Parameter	Gemini sprocket	Clutch sprocket 1	Clutch sprocket 2
Tooth number Z	24	42	56
Pitch p/mm	8.0	8.0	8.0
Pitch diameter d/mm	60.5	105.8	141.1
Root diameter d_f/mm	51.2	96.3	131.7
Tip diameter d_a/mm	59.4	105	140.4
Measurement over pins M_R/mm	63.2	109	144.4
Measuring pin diameter d_R/mm	5.0	5.0	5.0

2.3 Parameters definition

(1) According to the design requirements, the speed range of Gemini sprocket is defined from 0 to 6500 r/min.

(2) The number of whole chain links must be calculated in the process of design and calculation of DCT Gemini chain system. By calculation, the number of chain links between Gemini sprocket and clutch sprocket 1(chain1) is 70, the number of chain links between Gemini sprocket and clutch sprocket 2(chain 2) is 88.

(3) Relative coordinate centers of the three sprockets are: the Gemini sprocket(0, 0, 0), clutch sprocket 1(75.79, 76.94, 0), the clutch sprocket 2(203.79, 76.94, 0)。

(4) According to above calculation, the length of the chain 1 is L_1=0.55 m. The length of chain 2 is L_2=0.70 m[22–23]。

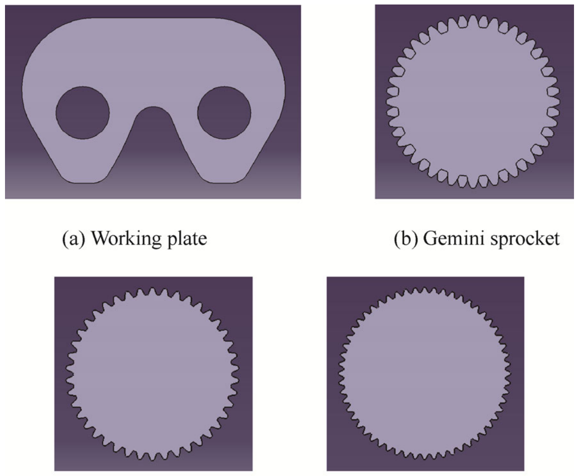
3 System Dynamic Characteristics Analysis

3.1 System dynamic model

According to the above parameters calculation of Gemini plate and sprockets, the three-dimensional(3D) model was established in CATIA as below. The plate 3D model is shown in Fig. 4(a) with plate material 50CrVA. The pin diameter is 2.98 mm with pin material 20CrMnMo. The 3D model of Gemini sprocket is shown in Fig. 4(b). Its teeth number is 24 and the working tooth profile is involute with sprocket material 40Cr. The 3D model of clutch sprocket 2 is shown in Fig. 4(c). The tooth number is 42 and the working tooth profile is involute with sprocket material 40Cr. The 3D model of clutch sprocket 1 is shown in Fig. 4(d). The tooth number is 56 and the working tooth profile is involute with sprocket material 40Cr. The material properties are shown in Table 2.

3.2 System dynamic characteristics

According to the structure and layout of the dual clutch, the Gemini chain transmission system showed in Fig. 5 is simulated. The force and torque have been transferred through two different chains. The driving sprocket is Gemini sprocket which phase difference is half of the tooth profile angle. The meshing noise and vibration can be reduced effectively through adjusting rhythm and frequency.



(a) Working plate (b) Gemini sprocket

(d) Clutch sprocket 1 (d) Clutch sprocket 2

Fig. 4. 3D model of chain plate and sprockets

Table 2. Material properties of Pin, Sprocket and Plate

Material	Tensile strength/ MPa	Yield strength/ MPa	Hardness/ HB
40Cr	⩾980	⩾785	⩽207
50CrVA	⩾1274	⩾1127	⩽321
20CrMnMo	⩾1175	⩾885	⩽217

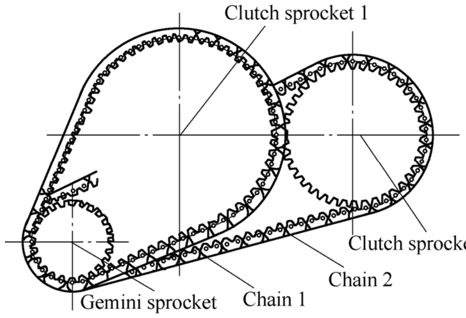


Fig. 5. Gemini chain system

3.2.1 *Contact force of pin and plate*

The contact force of the pin and the plate in meshing process between plate and 3 sprockets is shown in Fig. 6.

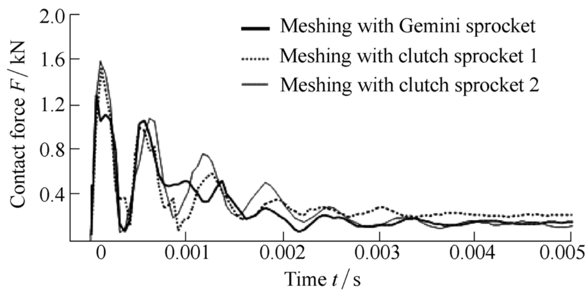
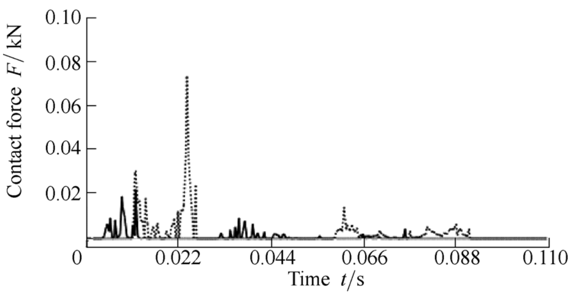


Fig. 6. Contact force of the pin and plate

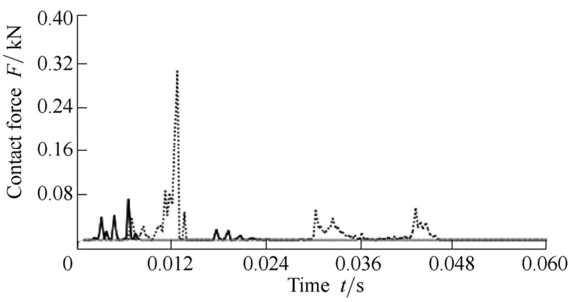
The contact forces of pin and plate changes periodically while meshing. The initial impact of meshing is serious and the contact force is big. The maximum contact force was 1612 N. Early analysis showed that, this contact force was caused by the gap existing in whole assembly and the contact instantly of the plate and pin before meshing. With the meshing further, the plate and pin are seated on sprockets and the contact force decreases gradually.

3.2.2 Contact force of plate and sprockets

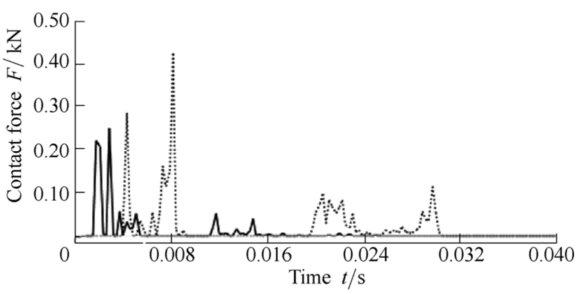
The contact force of links and sprockets in a movement cycle is shown in Fig. 7. The driving speed of Gemini sprocket is separeately 2000 r/min, 4000 r/min and 6000 r/min. The contact forces of chain 1 and chain 2 are represented by the solid line and dotted line. From Fig. 7, we can know, when the speed of the driving sprocket is 2000 r/min, the maximum contact force of chain 1 is 23 N, and the maximum contact force of chain 2 is 76 N, the maximum contact forces of chain 1 and chain 2 are 77 N and 313 N at 4000 r/min, and the maximum contact forces of chain 1 and chain 2 are 246 N and 412 N at 6000 r/min. To sum up, the maximum contact force of chains in the whole duty cycle is 412 N. It is noticed that the contact forces of the plates and sprockets increases with the speed increasing. The contact force is much higher mainly because the meshing impact is bigger while the plate begin to engage with the driving sprocket. The wear of the driving sprocket was so serious that we should investigate the material selection of driving sprocket in design.



(a) Contact force of 2000 r/min



(b) Contact force of 4000 r/min

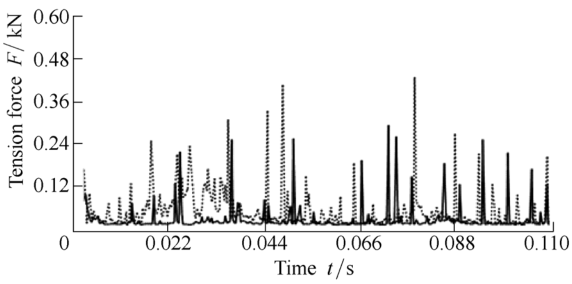


(c) Contact force of 6000 r/min

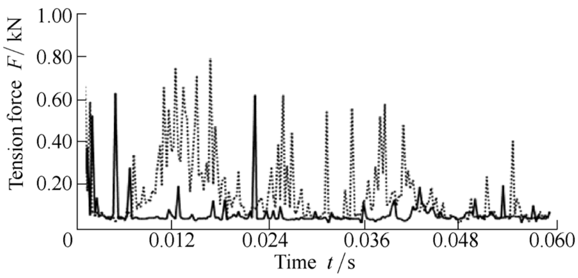
Fig. 7. Contact force of plates and sprockets under different speeds

3.2.3 Tension force

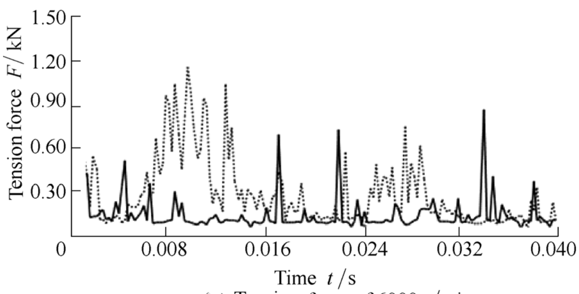
The tension force of the links in the driving process includes effective circumferential tension caused by inertial centrifugal force and catenaries caused by gravity. The tension force of links in one movement cycle is shown in Fig. 8. The driving speed of Gemini sprocket are 2000 r/min、4000 r/min and 6000 r/min. The tension force of link 1 and link 2 are represented separately by the solid line and dotted line. From Fig. 8, we can know, when the speed of the driving sprocket is 2000 r/min, the maximum tension forces of link 1 and link 2 are 300 N and 442 N. When the speed is 4000 r/min, the maximum tension forces are 623 N and 799 N, and the maximum tension forces are 1147 N and 854 N when the speed is 6000 r/min. The theoretical tension force of one single chain is 835.5 N, so the difference between analysis result and theoretical calculation is not obvious. The theoretical tension force for single chain is 6050 N, but the analysis result is 1147 N which is much less than the theoretical one. Small force, impact and vibration proved the driving process is smooth. It is still shown in Fig. 8, the chain tension grows higher with sprocket speed increasing.



(a) Tension force of 2000 r/min



(b) Tension force of 4000 r/min

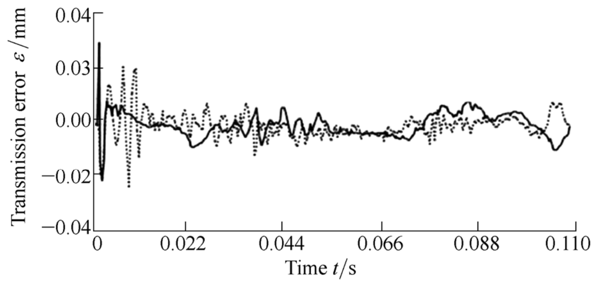


(c) Tension force of 6000 r/min

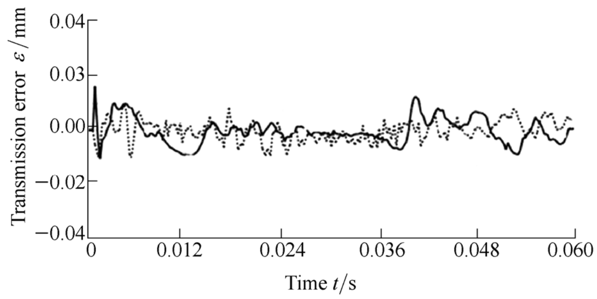
Fig. 8. Tension force under different speeds

3.2.4 Transmission errors

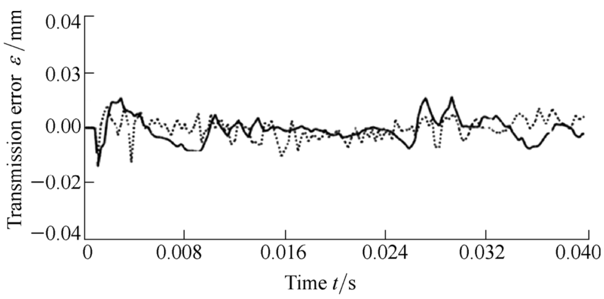
Fig. 9 shows the transmission errors of two different clutch sprockets when Gemini sprocket with sprocket speed in 2000 r/min, 4000 r/min and 6000 r/min. Unexpected transmission error must be inevitable because two hanging chains couldn't work so synchronized. The system performance quality can be tested by analyzing transmission error. The solid line represents the transmission error of the chain 1 and the dotted line for chain 2. Due to assembly clearance, meshing in initial stage is not stable, so the data is used to calculate transmission error when meshing is stable. It is noticed that the transmission error of chain 1 is the 0.96% and 0.86% for chain 2 at 2000 r/min. The transmission error for chain 1 is 1.20% and 0.86% for chain 2 at 4000 r/min. The transmission error for chain 1 is 1.10% and 0.74% for chain 2 at 6000 r/min speed. Generally, maximum transmission error is 1.20% which is less than national industrial of 3%. This is proved that the transmission error of the Gemini chain meets design requirements.



(a) Transmission error of 2000 r/min



(b) Transmission error of 4000 r/min

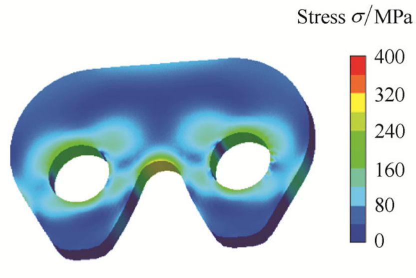


(c) Transmission error of 6000 r/min

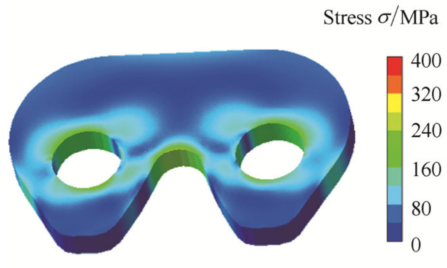
Fig. 9. Transmission errors of the Gemini chain system under different speeds

3.2.5 Meshing stress of plate

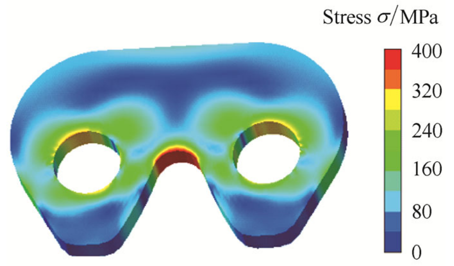
The meshing stress nephogram of the plate and the sprocket is shown in Fig. 10. The horizontal pulling force is the mainly force before meshing and the force of the plate gradually become smaller due to the contact with the sprocket while meshing. The sprocket shared part of tension and the contact force of the plate and pin. As can be seen from Fig. 10 that the maximum stress of plate is 282 MPa for Gemini sprocket, 257 MPa for clutch sprocket 1 and 350 MPa for clutch sprocket 2. To sum up, the maximum stress of plate is 350 MPa which is far less than the yield strength of 1127 MPa, the material strength of the plate meets the design requirements.



(a) Meshing with Gemini sprocket



(b) Meshing with clutch sprocket 1



(c) Meshing with clutch sprocket 2

Fig. 10. Stress nephogram of plate

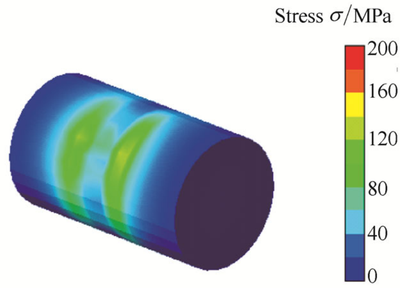
3.2.6 Meshing stress of pin

The pin is contacting with the chain plate in whole engagement process. The maximum stress of pin while the plates meshing with Gemini sprocket is 132 MPa as shown in Fig. 11(a), and the maximum stress of clutch sprocket 1 pin is 154 MPa as shown in Fig. 11(b). The maximum stress of pin while plates meshing with clutch sprocket 2 is 186 MPa as shown in Fig. 11(c). To sum up, the maximum stress of the pin is 186 MPa which is far less than the yield strength of 885 MPa. The strength of the pin meets the design requirements.

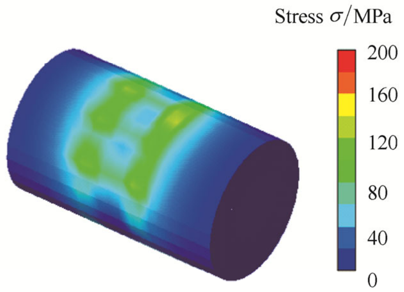
4 Noise Experiments

4.1 Testing instrument

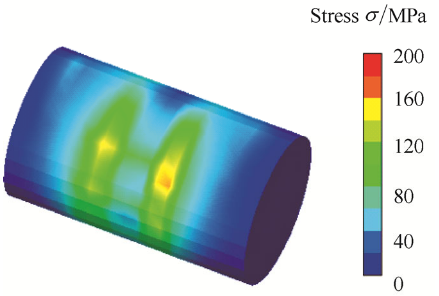
Portable two-channel noise and vibration spectrum analyzer of type AWA6290A is used in the noise experiment. As shown in Fig. 12, it is a kind of multi-channel signal measurement and analysis instrument which can realize real-time measurement of physical quantities, such as noise, acceleration, velocity, displacement and so on.



(a) Meshing with Gemini sprocket



(b) Meshing with clutch sprocket 1



(c) Meshing with clutch sprocket 2

Fig. 11. Stress nephogram of pin

Fig. 12. Two-channel noise and vibration spectrum analyzer of AWA6290A

4.2 Test conditions and parameters

The noise characteristics of the silent chain on DCT are tested under different speeds and load conditions. Test parameters are as follows:

Range of rotational speed of driving sprocket: 0–6500 r/min;

Workload (N): Full load is 500 N; overload is 1000 N;

Tooth number of sprockets: Z_a =24, Z_b =42;

Chain parameters: The pitch is 8 mm; the number of links is 120.

Assembly drawing of test chain and sprockets are shown in Fig. 13.

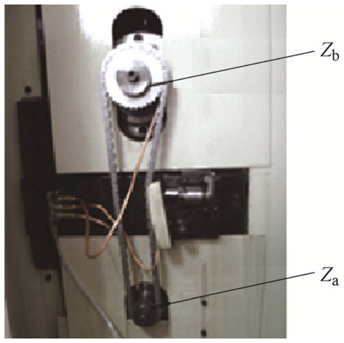


Fig. 13. Assembly drawing of driving-driven sprockets and chain

4.3 Data measurement and analysis

4.3.1 Data measurement

(1) Background noise measurement

In order to meet the accuracy of the test results as far as possible, background noise generated by the surrounding environment is first measured. After removing the chain, the background noise values is measured with other machines indoor working properly[20–21]。Background noise under the different speeds measured is shown in Fig. 14.

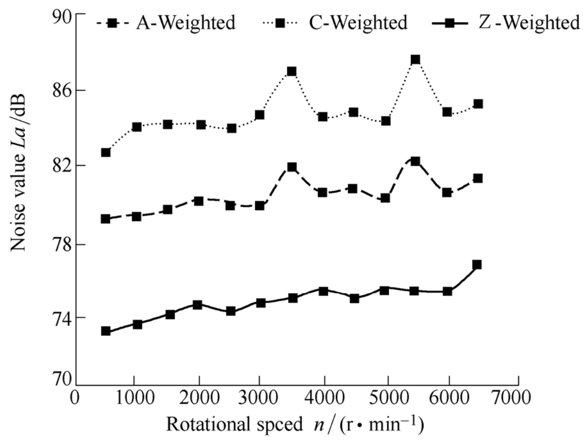


Fig. 14. Background noise under different speeds

(2) Gemini chain noise measurement

After the Gemini chain was installed and all the machines indoor working properly, the mixed noise values of the silent chain were measured.

4.3.2 Results analysis

(1) Noise values analysis of Gemini chain

By correcting A-weighted noise values of the Gemini chain measured under the different loads and speeds, the noise values of the Gemini chain are obtained as shown in Fig. 15. The solid line is the noise values measured under the normal working load(500 N) and the dot line is the noise values measured under the overload(1000 N). As can be seen, the noise values of the Gemini chain is basically consistent and increase along with the rotational speed increasing under the different loads. The maximum noise value is 81.4 dB which is less than national industrial standards of 85 dB, the noise values of the Gemini chain meets design requirements. The noise values of the chain tested generate mutations at the speeds of 1000 r/min, 2500 r/min and 4000 r/min are related to the meshing impact frequency of the test-bed parts.

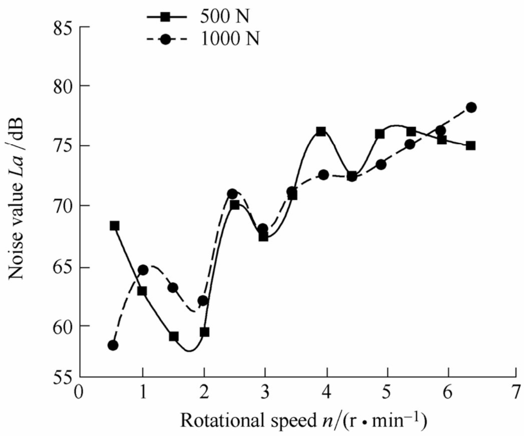
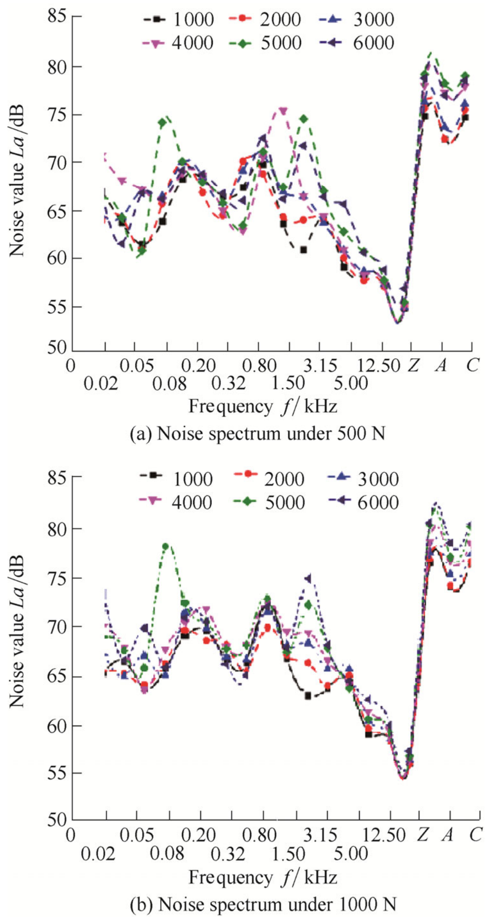


Fig. 15. Noise values of Gemini chain

(2) Noise spectrum analysis of the Gemini chain

The noise spectrum of the Gemini chain under different speeds and frequencies are shown in Fig. 16. Fig. 16(a) shows the noise spectrum of the Gemini chain under the load of 500 N and Fig. 16(b) shows the noise spectrum under the load of 1000 N. Fig. 16 shows that the noise values of the Gemini chain change periodically under the different frequencies. Peaks occurred around in 160 Hz, 800 Hz and 2000 Hz. These frequencies are related to the meshing impact frequencies and structures natural frequencies of the silent chain system.



(a) Noise spectrum under 500 N

(b) Noise spectrum under 1000 N

Fig. 16 Noise spectrum diagram the Gemini chain

5 Conclusions

(1) The main parameters of sprockets and plates are calculated and the system dynamic simulation models are established.

(2) The dynamic simulation analysis is proved that the contact force of plate and pin is cyclical changes and meanwhile the chain tension forces, the contact forces and transmission errors can meet the design requirements.

(3) The result after the flexible processing of plate and pin is proved that the stress of plate and pin is less than the yield strength of materials.

(4) Noise experimental results are proved that the noise values and spectrums of chain drive system can meet the industrial requirements. Therefore, the design of the method is feasible.

References

[1] MENG Fanzhong, LI Chun, CHENG Yabing. Design calculation of common normal line length of Hy-Vo silent chain sprocket[J]. *Journal of Mechanical Engineering*, 2008, 18(23): 2865–2867. (in Chinese)

[2] MENG Fanzhong, LI Chun, CHENG Yabing. Proper conditions of meshing for Hy-Vo silent chain and sprocket[J]. *Chinese Journal of Mechanical Engineering*, 2007, 20(4): 57–59.

[3] MENG Fanzhong, FENG Zengming, CHU Yaxu. Meshing theory and design method of new silent chain and sprocket[J]. *Chinese Journal of Mechanical Engineering*, 2006, 19(3): 425–427.

[4] MENG Fanzhong, CHENG Yabing, QIAN Jiang. Meshing analysis and design method of new Hy-Vo silent chain and sprocket[J]. *Journal of Mechanical Engineering*, 2013, 48(13): 8–12. (in Chinese)

[5] FENG Zengming, MENG Fanzhong, LI Chuntao. The Meshing mechanism and simulation analysis of a new silent chain[J]. *Journal of Shanghai Jiaotong University*, 2006, 39(9): 1427–1430. (in Chinese)

[6] FENG Zengming, DENG Qiang, CAO Di. Research on Rigid-Flexible coupling contact dynamics characteristics of Hy-Vo silent chain and sprocket[J]. *Journal of Mechanical Transmission*, 2012, 36(1): 23–25. (in Chinese)

[7] CHENG Yabing, MENG Fanzhong, XU Hanxue. Experimental study on high speed characteristics of automotive engine Oil-pump chain[J]. *Chinese Journal of Mechanical Engineering*, 2007, 20(1): 36–39.

[8] CHENG Yabing, MENG Fanzhong, FENG Zengming. Multi-cycle impact were property of automotive engine oil-pump narrow-width chain[J]. *Tribology*, 2009, 29(6): 494–497. (in Chinese)

[9] CHENG Yabing, LIANG Weipeng, FENG Zengming. Study on wear property of automotive chain[J]. *Journal of Mechanical Transmission*, 2012, 36(1): 42–43. (in Chinese)

[10] ZHANG W M. An analysis on vibration of moving silent chain by multi-body dynamics[C]//*ASME 2005 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers*, Long Beach, California, USA, September 24–28, 2005: 1707–1712.

[11] LI Baolin, MENG Fanzhong, QU Shaopeng, et al. Nano-tribology in examination of timing chain of automobile engine[J]. *Lubrication Engineering*, 2006, 181(9): 90–93. (in Chinese)

[12] FU Zengming, JIN Yumo, MENG Fanzhong. Heat treatment process test of 50CrVA steel tooth chain plate[J]. *Heat Treatment of Metals*, 2011, 36(06): 120–122. (in Chinese)

[13] XU Lixin, YANG Yuhu, CHANG Zongyu, et al. Dynamic modeling of a roller chain drive system considering the flexibility of input shaft[J]. *Chinese Journal of Mechanical Engineering*, 2010, 23(3): 367–374.

[14] XUE Yunna, WANG Yong, WANG Xianlun. Engagement theory of silent chain mechanism with involute tooth profile[J]. *Journal of Jiangsu University(Natural Science Edition)*, 2007, 28(2): 104–107. (in Chinese)

[15] XUE Yunna, WANG Yong, WANG Xianlun. Meshing impact mechanism for odontoid chain drive[J]. *Journal of Machine Design*, 2006, 22(9): 37–39.(in Chinese)

[16] WANG Yong, ZHU Dongwei, XUE Yunna. The modal analysis of silent chain drives[J]. *Journal of Mechanical Transmission*, 2008, 31(6): 70–71. (in Chinese)

[17] WANG Wencheng, LIU Xiaolun, LIU Jiajun, et al. Design and experimental analysis of new double-pitch rocker-pin silent chain for conveyors[J]. *Research Journal of Applied Sciences, Engineering and Technology,* 2012, 4(20): 4187–4191.

[18] SUN Wei, LIU Xiaolun, LIU Jianfang. Experimental investigation of sprocket tooth form effect on dynamic tension of silent chain[J]. *Research Journal of Applied Sciences, Engineering and Technology,* 2012, 4(7): 846–850.

[19] PEREIRA C M, AMBROSIO J A, RAMALHO A L. A methodology for the generation of planar models for multibody chain drives[J]. *Multibody System Dynamics*, 2010, 24(3): 303–324.

[20] YOUNG J D, MARSHEK K M, POIRET C, et al. Camshaft Roller Chain Drive with Reduced Meshing Impact Noise Levels[C]//*2003 SAE World Congress,* Traverse City, Michigan, May 5–8, 2003.

[21] FUJIMOTO N, ISHIDA H, MARUYAMA M, et al. Silent chain having improved noise reduction: US, 5267910[P/OL]. 1993-01-29 [1993-12-07]. http: //www.freepatentsonline.com/5267910.html.

[22] MATSUDA A. Silent chain and sprocket having teeth with matching curved surfaces: US, 6168543[P/OL]. 1998-12-01[2001-01-02]. http: //www.freepatentsonline.com/6168543.html.

[23] TROEDSSON I, VEDMAR L. A dynamic analysis of the oscillations in a chain drive[J]. *Journal of Mechanical Design*, 2001, 123(3): 395–401.

[24] HUANG C, LIN K C, KOSASIH L. Kinematic analysis of chordal action and transmission errors of silent chains[C]//*2006 SAE World Congress,* Detroit, MI, United states, April 3–6, 2006.

Biographical notes

CHENG Yabing, born in 1979, is currently an associate professor at *College of Mechanical Science and Engineering, Jilin University, Changchun, China*. She received her PhD degree from *Jilin University, China,* in 2007. Her research interests include simulation analysis and design method of automobile chain transmission system.
Tel: +86-431-85095428; E-mail: chengyb@jlu.edu.cn

GUO Haitao, born in 1988, is currently a master candidate at *College of Mechanical Science and Engineering, Jilin University, Changchun, China*. His major research interests include design and analysis of automobile chain transmission system.
E-mail: +86-13843101886@163.com

FU Zhenming, born in 1965, is currently a professor at *Qingdao CHOHO Industry Limited Company, Qingdao, China.* His research interests include chain system design.
E-mail: fzm8268@163.com

WAN Nen, born in 1988, is currently a master candidate at *College of Mechanical Science and Engineering, Jilin University, Changchun, China*.
E-mail: wannen_2013@163.com

LI Lei, born in 1988, is currently a master candidate at *College of Mechanical Science and Engineering, Jilin University, Changchun, China*.
E-mail: leelei_2014@163.com

WANG Yang, born in 1988, is currently a master candidate at *College of Mechanical Science and Engineering, Jilin University, Changchun, China*.
E-mail: ytuwy@163.com