Compilation of load spectrum of loader drive axle

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Abstract. In order to study the preparation method of gear fatigue load spectrum for loaders, the load signal of four typical working conditions of loader is collected. The signal that reflects the law of load change is obtained by preprocessing the original signal. The torque of the drive axle is calculated by using the rain flow counting method. According to the operating time ratio of each working condition, the two dimensional load spectrum based on the real working conditions of the drive axle of loader is established by the cycle extrapolation and synthesis method. The two-dimensional load spectrum is converted into one-dimensional load spectrum by means of the mean of torque equal damage method. Torque amplification includes the maximum load torque of the main reduction gear. Based on the theory of equal damage, the accelerated cycles are calculated. In this way, the load spectrum of the loading condition of the drive axle is prepared to reflect loading condition of the loader. The load spectrum can provide reference for fatigue life test and life prediction of loader drive axle.

1. Introduction

The drive axle is an important part of the vehicle and is the last part of the transmission mechanism to connect the tire. The reliability of the drive axle is directly related to the reliability of the vehicle. The influence of acceleration, braking, roadway and other load on the drive axle, especially the construction machinery loader drive axle, is very heavy and complicated. Generally, the load often lead to the fatigue damage such as point erosion, broken tooth of main gear , or the fracture of the planetary frame and the crack of the gear ring. During the driving of the vehicle, the axle fracture will cause the vehicle to slip out of control and cause serious accidents. In order to guarantee the reliability of the drive axle, we often adopt higher safety coefficient to ensure its high strength, reliable operation, long service life, but it consumes more materials, greatly increase the vehicle's weight and fuel consumption\cite{1}.

Therefore, fatigue reliability of drive axle applied load spectrum was analyzed when designed. It is very important engineering significance for the fatigue reliability test after complete prototype manufacture, lightweight, saving resource and energy consumption of the vehicle \cite{1}. Mechanical reliability research is a subject which mainly focuses on the life characteristics of products. Fatigue is the main damage form of mechanical structure and components which work under cyclic loading \cite{10}.

The study of the load spectrum from the 1960s has only begun to deepen in the 1980s. At present in the construction machinery industry, many manufacturers invest a lot of money and technical force...
to carry out experimental research. At present in the construction machinery industry, many manufacturers invest a lot of money and technical force to carry out experimental research. In the field of automobile, aviation and others, the research on load spectrum has achieved certain results. The test torque technology by the method of strain-current collector is applied to the measurement of loader torque load spectrum [3]. Based on the idea of "flight-by-flight" spectrum of aircraft, some authors put forward the "dig-by-dig" spectrum [4] which is in accordance with the characteristics of loader operation. Sonsino C M, Laue S and Bomas H discussed the problems of loading signal test, pretreatment and test bed loading spectrum, and studies the establishment and application of the whole machine or parts from test to multi-working load spectrum [5,6]. As a typical equipment of construction machinery, wheeled loaders are widely used in construction, agriculture, transportation, mining, defense engineering and other fields. In practical application, the loaders’ machine parts, especially the transmission parts, have high failure rate and serious damage. Jilin university takes wheel loader as an example, and studies the test and pretreatment method of the load signal of the transmission system, and gives the method of the transmission load spectrum on the basis of analyzing its load characteristics [7,8]. However, the load spectrum has too many levels, and is alternating loads. So the bench test is too complicated.

This paper set up the application of damage theory, a two-dimensional load spectrum can be converted to one-dimensional load spectrum, then the torque amplification contain to the maximum load torque of main reduction gear, according S-N curve to calculate cycle number. The load spectrum which compiled into drive axle loading situation when loading conditions was given. The feasibility of this method is verified by experiment.

2. Pretreatment of the Load Signal

The load signals test uses ZL50 wheel loader, and the commonly used clay, sand and soil mixture, large stone square and small stone square are selected for the loading materials. The operation model of "v-type six segment" (no load forward - loading full load backward – full load forward - unloading – no load backward) is used in the operation [9]. According to the layout characteristics of the vehicle power transmission system, the engine output speed, drive axle input and output torque and speed parameters are mainly selected to test signals. In order to facilitate the analysis of the loading machine conditions of the data, the gears signal and the oil pressure and displacement signals of the steering cylinder and working cylinder are collected too.

Because of the whole test system circuit winding through the engine, controller, battery, in the working process, these factors such as electricity, magnetic and heat can cause interference to the test signal. It is necessary to pretreat the original load signal preprocessing, such as to remove trend term, singular value, noise signal to improve the signal-noise ratio of the load signal goal and to create conditions for subsequent data statistical analysis.

When the vehicle loading, transmission parts work in frequent braking, forward and impact conditions. The measured torque signals include the periodic torsional vibration signals of the engine and the periodic meshing of the transmission gears. It is clear that some of the torque signals have peak value. There is a trend item in the strain signal that causes it to drift. These two situations are the most common problems in data processing. Through the signal processing software, the appropriate digital filter is selected to remove the drift of the signal and the interference signal mixed in the load signal.

According to the frequency-domain analysis, the signal is filtered to eliminate the unwanted frequency components. The filter is divided into low pass, high pass, band pass and band stop filter according to amplitude frequency characteristics. Through self-power spectrum analysis for each test condition, each channel signal, the conclusion is obtained that the operation load of loader is typical low frequency signal, and the signal energy is concentrated within 5Hz. So low-pass filter can be used to remove high-frequency noise, the threshold to take 1-5Hz. After signal filtering, as shown in Fig 2.
In a random signal, there is a nonlinear component with slowly changing and longer period than the recording length. It was caused usually by zero drift of a sensor or instrument, improper installation of sensors (such as loosening, connect-lines shaking, etc.), instability of low frequency performance outside the frequency range of the sensor or the surrounding environment interference caused by the signal waveform shift. The overall bias method is adopted to eliminate trend items directly for data overall drift data. Offset correction is used to make the data initial point and the end point consistent for linear variation of the trend term. When the trend item is more complex nonlinear, the measured data can be segmented to remove the trend term. Wavelet analysis can also be used for the removal of trend terms. In wavelet transform, the larger the scale of decomposition, the lower the frequency of decomposition signal. After removing the trend item, as shown in Fig 3 and Fig 4.

Abnormal value that do not conform to the changing law usually caused by the transmission errors of test system, channel noise and interference from some external environment factors are removed from the data. The main methods to remove outliers include amplitude threshold detection, gradient threshold detection, standard deviation detection, wavelet analysis, etc.. Abnormal signals can be detected by probability density analysis and frequency spectrum analysis. Intermittent noise spikes can be eliminated by low pass filtering, with a threshold of 1.5Hz. Amplitude threshold method, gradient threshold method and standard variance method are often used to remove outliers in large amplitude interference. Before and after removing the singular values, the effect is shown in Fig 4 and Fig 5.

3. Compilation of Load Spectrum of Transmission System

According to the fatigue damage principle, small cycles of 10% of the random load range (maximum stress amplitude-minimum stress amplitude) which will not cause fatigue damage could be deleted.[10] So in this process, wavelet compression method is used to compress the small load cycles, so that a large number of invalid load cycles are deleted, so as to improve the efficiency of statistical counting. At present, statistical counting methods include peak count method, step count method, amplitude count method, rain flow counting method, and so on. As the result of the rain flow counting method is consistent with the hysteresis loop of the stress strain, the rain flow counting method is used to count the cycles in this paper.
When the rain flow counting, test data of these four materials (clay, sand and soil mixture, large Stone Square and small Stone Square) were counted respectively. The mean-amplitude matrix corresponding to four kinds of materials is obtained. The specific value of loading one material is shown in Table 1, and the negative value represents the reverse of the torque.

| Mean(Nm) | Amplitude(Nm) | -962.6 | -463.3 | 36 | 535.3 | 1034.6 | 1533.9 | 2033.2 | 2532.5 |
|----------|---------------|--------|--------|----|-------|--------|--------|--------|--------|
| 284.7    | 44            | 616    | 843    | 238| 70    | 60     | 62     | 123    |
| 593.8    | 3             | 25     | 58     | 32 | 4     | 8      | 7      | 7      |
| 902.9    | 0             | 6      | 61     | 11 | 0     | 1      | 0      | 0      |
| 1212.0   | 0             | 0      | 8      | 11 | 1     | 0      | 0      | 0      |
| 1521.1   | 0             | 0      | 4      | 9  | 3     | 0      | 0      | 0      |
| 1830.2   | 0             | 0      | 0      | 10 | 24    | 0      | 0      | 0      |
| 2139.3   | 0             | 0      | 0      | 19 | 17    | 0      | 0      | 0      |
| 2448.4   | 0             | 0      | 0      | 9  | 0     | 0      | 0      | 0      |

Finally, a load spectrum with sufficient representativeness is constructed and synthesized under different material conditions investigated. The processing steps of different materials operating load cycle are as follows:

1. According to the earlier investigation, the proportion coefficient $K_j$ of different materials is expanded to 1000 shovel cycles the proportion of various materials $N_i=1000 \times K_j$;

2. According to the result of rain flow count, the actual load frequency, $P_i$ and time $T_i$ of each material are calculated;

3. The effective number of shovels for actual testing of various materials $n_i$ is counted. Then the synthetic coefficient $K=N/n_i$ of various materials is obtained.

4. The calculation of the load frequency $P$ after 1000 shovel cycles synthesis is shown in formula (1):

$$P = \sum_{i=1}^{n} P_i \times K_i \quad (1)$$

The $n$ in the formula is the number of shovel materials.

According to the operating conditions of the loader, the actual test results can be used as the actual digging cycles. The number of digging cycles of each working condition is calculated when the digging cycles extend to 1000. This is shown in table 2.

The data collected in the data acquisition process of the expansion of 1000 digging cycles is often limited, and it is not sufficient to represent the occurrence of the few maximum loads in the actual parent. From a statistical point of view, the $10^6$ cycles are representative enough for the full load, including the most severe cases, which have rarely occurred. It’s the equivalent of a fatigue life cycle. Therefore, the cumulative frequency of synthesis must be extended to $10^6$ cycles, so as to get a more realistic site load process in the total life span, and the specific calculation method references [8]. Table 3 is a two-dimension load spectrum for the full life cycle of the drive axle.
Table.2 The number of digging cycles

| serial number | Material                | Ratio($K_j$) | need digging cycles($N_i$) | actual digging cycles ($n_i$) | composite coefficient($K_i$) |
|---------------|-------------------------|--------------|----------------------------|-------------------------------|-----------------------------|
| 1             | small Stone Square      | 0.2          | 200                        | 115                           | 200/115                     |
| 2             | large Stone Square      | 0.1          | 200                        | 96                            | 100/96                      |
| 3             | sand and soil mixture   | 0.4          | 300                        | 100                           | 400/100                     |
| 4             | clay                    | 0.3          | 300                        | 79                            | 300/79                      |

The basic principle of loading spectrum preparation for fatigue test is to ensure that the load applied according to the loading spectrum is consistent with the actual load of the loader. That of compiling the program loading spectrum is to ensure that the load applied according to the load spectrum is consistent with the actual field load, and is able to approach the actual load to the maximum extent\[11\-12\]. After determining the positive and negative rotation of the transmission shaft, the load spectrum classification number and the removal of the small load threshold, the loading spectrum of the fatigue test of the driving axle is worked out. According to the conditions of the fatigue test equipment and the strength of the drive axle, the loading spectrum of the strengthening fatigue test can be worked out in accordance with the actual load information of the loader, so as to speed up the fatigue test process of the drive axle assembly.

The fatigue life represented by the loading spectrum of a strengthened fatigue test should be consistent with the loading spectrum of fatigue test. Specific methods are as follows:

1. According to table 4, the upper and lower limits of each stage load are found: $S_{\text{imin}} = S_{\text{im}} - S_{\text{ia}}$ , $S_{\text{imax}} = S_{\text{im}} + S_{\text{ia}}$ \[2\]

   $S_{\text{imin}}$, $S_{\text{imax}}$ are the lower and upper bound of the stage i load respectively, and the $S_{\text{im}}$, $S_{\text{ia}}$ are the mean and magnitude of the I load respectively;

2. According to the upper and lower bounds of each level load for maximum $S_{\text{max}}$ and minimum $S_{\text{min}}$ load, then the interval[$S_{\text{imin}}$, $S_{\text{imax}}$] is divided into 8 parts, and each part is equal to \( (S_{\text{max}} - S_{\text{min}}) / 8 \) marked $\Delta$;

3. According to the mean of each level load, load spectrum is divided into 8 intervals equaled marked $[S_{\text{im}} - \Delta / 2\,,\, S_{\text{im}} + \Delta / 2]$;

4. The number of cycles contained in each different interval is equivalent by the S-N curve formula$S_{i}^m * N_i = S_{2}^m * N_2$, and the total cycles is obtained by summation;

5. Each interval multiplied by the expansion factor $\lambda$. So as to the maximum value of the load spectrum is reached to the maximum torque that the main bevel gear of the drive axle receives. According to the equivalent transformation of $S_{1}^m * N_1 = S_{2}^m * N_2$, the total cycles of the corresponding interval was recalculated;

6. In order to keep the number of load cycles in line with the standard QC/T 534-1999 Test evaluation index for automobile drive axle, the load cycle is assumed to be the drive axle main reduction gear mesh once. That is, the input shaft rotates one round.

Table.3 mean-amplitude matrix of total life cycle(number of cycles)

| Mean($N_m$) | Amplitude($N_m$) |
|-------------|------------------|
| -1254.8     | -665.4           |
| -76.0       | 513.4            |
| 1102.8      | 1692.2           |
| 2281.6      | 2871.0           |
| 181.6       | 932              |
| 544.8       | 110717           |
| 364570      | 231870           |
| 40215       | 16816            |
| 23734       | 9184             |
| 908.1       | 18               |
| 1426        | 11426            |
| 22939       | 47227            |
| 6479        | 4302             |
| 4302        | 529              |
| 529         | 680              |
| 908.1       | 0                |
| 230         | 6190             |
| 21579       | 274              |
| 529         | 680              |
| 274         | 0                |
| 1271.3      | 0                |
| 782         | 16362            |
| 1218        | 26               |
| 26          | 0                |
| 16362       | 1218             |
| 26          | 0                |
| 1634.5      | 0                |
| 220         | 8960             |
| 7510        | 11               |
| 11          | 0                |
| 8960        | 7510             |
| 11          | 0                |
| 2361.0      | 0                |
| 0           | 5281             |
| 960         | 0                |
| 0           | 0                |
| 5281        | 960              |
| 0           | 0                |
| 2361.0      | 0                |
| 0           | 297              |
| 0           | 0                |
| 297         | 0                |
| 0           | 0                |

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Finally, the load spectrum of the fatigue test of the drive axle is obtained, which is shown in table 4. It can also be accelerated or decelerated according to the power and heat dissipation conditions of the test motor. The test result is finally calculated according to the cycles of gear meshing.

4. Test verification

Four samples are taken at random, of which two driving axles are tested by standard, that is, the main reduction gear is loaded by the rated torque, and more than 500 thousand cycles are qualified products, and the test results are shown in table 5. The other two tests are carried out on the load spectrum of this paper until the drive axle failure. The test results are shown in table 6.

| Table 4 load spectrum of the fatigue test of the drive axle |
|----------------------------------------------------------|
| state | normalized torque ratio | number of cycles | speed r/min | Load time(s) |
|-------|-------------------------|-----------------|-------------|--------------|
| forward | 0.46 | 28233 | 360 | 4706 |
| | 0.64 | 12539 | 360 | 2090 |
| | 0.82 | 12244 | 300 | 2449 |
| | 1.00 | 21083 | 240 | 5271 |
| | 1.18 | 4258 | 180 | 1419 |
| backward | 0.37 | 44823 | -360 | 7471 |
| | 0.50 | 9578 | -360 | 1596 |
| | 0.64 | 916 | -300 | 183 |

The test results show that the equivalent results of load spectrum test are close to the test results of fatigue reliability standard of automobile drive axle. The rationality and validity of the load spectrum and equivalent processing method are proved. The results of this paper are convenient for the loading operation of the test bench, and can be calculated equivalently with the national standards.

It shows that the load spectrum in this paper has good practicability. It can be used in bench test and anti-fatigue life design of loader drive axle, through actual operation test, data processing and analysis, compilation of load spectrum, equivalent calculation and bench verification.

| Table 5 Results tested by standard |
|-----------------------------------|
| sample numbers | load torque/N.m | meshing times/ ten thousand times |
| 1 | 3500 | 127.1 |
| 2 | 3500 | 144.4 |

| Table 6 Results in this paper |
|-------------------------------|
| sample numbers | load spectrum blocks | meshing times/ ten thousand times |
| 3 | 19.2 | 125.18 |
| 4 | 17.8 | 116.05 |

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