The Test Bench Design of Metro Gearbox Simulation Operation Condition

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Abstract. The axle gearbox is the last one of the key parts of metro transmission system. Metro gearbox test rig with line stocks is important process equipment of running in gear box testing and fault diagnosis. This paper describes the selection subway gearbox operating conditions simulation test bench design scheme, and analyzed. the key technologies including design and design load on the system power loading device. For vibration signals measured, this paper introduces a reasonable data processing and fault diagnosis. Gearbox test rig operating conditions can train drive system condition monitoring and fault diagnosis, the safe operation of the train has obvious practical significance.

Keywords: fault diagnosis, gearbox test bench, hydraulic loading, operating conditions

0   Foreword

As an important component in present urban public transport, safety and reliability is very important for the metro. Gearbox drive system is an important component of metro vehicles, the traction motor output torque is transmitted to the gear wheel on the subway, the operating condition of the gearbox is directly related to the safe operation of the vehicle. This paper first describes the overall design of the test bench, Then focus on the key design of the force loading system and drive and load system. Currently gearbox test rig are based on the torque load in the form of analog load, the design of the experiment station directly to the load applied to the gear shaft, simulate the interaction of wheel and rail. Finally, conducted a spectral analysis and fault diagnosis for the gearbox running-in vibration test data obtained.
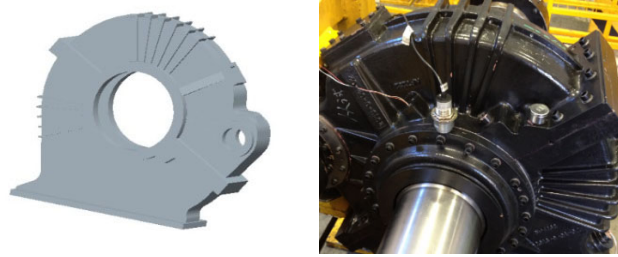
1   The Functions of the Metro Gearbox Test Rig

According to the vehicle gear box test need, the simulated test shall meet the following basic requirements [1]:
   1. The test bed can simulate the subway drive performance.
   2. The test bed can simulate various operating conditions.
   3. The bench can at full power in any speed and torque in full speed range to simulation operation (Fig. 1).

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**Fig. 1.** Three-dimensional model of the gear box and assembly gearbox

2   The Overall Design of Metro Gearbox Test rig

2.1   The Simulation and Testing Scheme of Metro Gearbox Test Rig Working Condition

This simulation test bench is design as electric power closed test bench. The test bench mainly make up with the traction motor, load motor, gear box, hydraulic loading equipment and other mechanical fittings of a closed machine system. The load motor connecting gear box driven gear side, drive motor connecting gearbox driven gear shaft. Experiment by adjusting the drive motor and the load motor torque and speed analog gearbox loading conditions, load test rig driven shaft respectively the horizontal and vertical forces to simulate the gear box in the lateral and vertical working conditions.

By a variable speed motor traction drive gear box, transmission box and the gear box by coupling a small shaft, and then drive axle rotation.

As shown is mechanical closure for gearbox test rig schematic diagram (Fig. 2): (1) The drive motor; (2) Coupling; (3) Torque- Speed Sensor; (4) Gearbox; (5) The vertical force loading device; (6) The lateral force loading device; (7) torque loading device
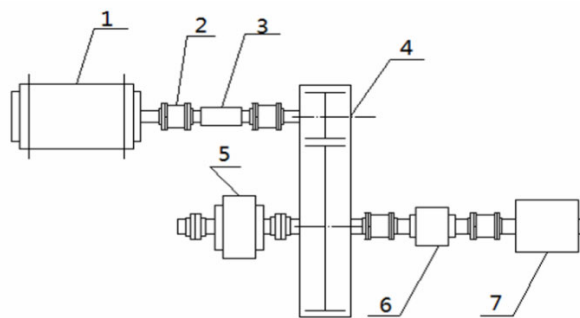
Fig. 2. The mechanical closure for gearbox test rig schematic diagram

This test rig installed six temperature sensors were used to detect the size of the gear shaft bearing temperature. Also in the size of the gear shaft is mounted at each vibration sensor for detecting an acceleration vibration gearbox. By detecting the gearbox in the case of different speed and different load bearing temperatures and the amount of vibration to determine whether a faulty gearbox. To study the different conditions [2] for gearbox vibration of research methods used in the experiment are as follows:

(1) Load torque constant, by continuously improving gearbox speed record at different speeds corresponding sensor values, analysis speed gearbox for vibration.

(2) To maintain a constant speed driven gear shaft, through continuous improvement of load torque, recorded at different moments corresponding virtual value vibration velocity analysis load torque to the gear box vibration.

(3) Maintaining a constant torque and rotational speed, lateral force by changing the gear shaft suffered, recording and analyzing the lateral force to the gear box vibration.

2.2   The Load Scheme of Gearbox Test Rig Test Conditions

As shown in the hydraulic loading program gearbox test rig simulated load (Fig. 3). Vertical force loading program designed door structure, fixed beam gantry framework for steel frame. Fixed transom

door frame with steel plate welded box-type structure, in order to ensure steel frame has sufficient strength and stiffness, so that does not satisfy the steel frame plastic deformation under 600KN static pressure conditions, and to ensure that a trace amount of elastic deformation under the circumstances It does not affect the detection accuracy. It is mainly composed of the main beam, column components. Loading device simulated load acts directly on the large gear shaft. And each of the vertical and horizontal placement of a loader to simulate the vertical and lateral loads generated by the actual operation of the train. This device is a fixed device, in order to facilitate oil cooling, selected as the open-loop system, the work of the media selected as the N46 anti-wear hydraulic oil [2]. Then detects the amount of output feedback to control the flow and pressure of the hydraulic system in order to achieve an output control of the implementation of the output member. Hydraulic loading device requires only vertical or lateral achieve load, variable output pressure, so choose a single output rod piston cylinder. The entire hydraulic system is a variable speed pump volume, pump selection variable type axial piston pump, and through the use of proportional solenoid to achieve closed-loop control system.

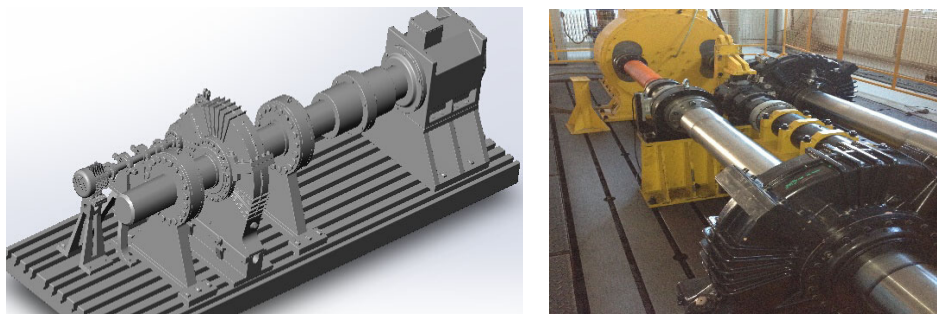Taking into account the actual operation, the design of the axle static load test set as 150KN [3].

Fig. 3. the gearbox test rig 3D simulation figure and physical picture

2.3   The Design of Hydraulic Loading System

Vertical force hydraulic loading system design requirements. Member of static load test system hydraulic system to achieve power source, hydraulic cylinders provide maximum pull pressure 150KN of. Hydraulic cylinders, frames, etc. installed in the member static load platform, based on the specimens by the head and tail stretching jig fixed installation, use sensors to measure the amount of load 150KN, member of static load test system hydraulic flow and load control proportional valve control. Design loading system should be able to meet the design expectations of bogie axle lateral and vertical loading test and the mechanical structure with sufficient rigidity and strength. As shown is overall hydraulic loading system solutions (Fig. 4).
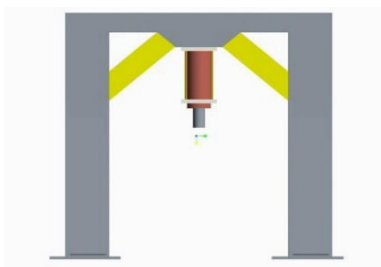

Fig. 4. The effect diagram of hydraulic loading system

The vertical design of hydraulic loading system. Member static load test system based on the overall design of the functional requirements of the test bed, the system main components: static loading platform base member, the mechanical structure-reaction force frame, head and tail stretching jig, pre-stretching device; power--150KN part of the hydraulic system; test section--150KN sensor; control system-proportional valve control. The equipment installed two clamping cylinders, also known as double-acting actuators, cylinder stroke 400mm, single cylinder is greater than the maximum output pressure 100KN, cylinder built-in import displacement sensors, force sensors piston rod end connector imports. Electro-hydraulic clamping cylinder intelligent servo control method can achieve load control

and displacement control, partial load conditions can be simulated vehicle load coordination.

Calculating a driving force hydraulic cylinder [4]

$$F0 = F / \eta m. \tag{1}$$

Stage hydraulic cylinder total load

$$F = Fm + Ff + Fa. \tag{2}$$

Take 150 KN hydraulic cylinder mechanical efficiency ηm is 0. 90, Fm workloads, Fa inertial load, Ff is the frictional resistance load, Fa will not consider, for Ff, due to the tension specimens through the wheel and bracket rail contact rolling friction, friction is very small, negligible. Therefore, the driving force of the hydraulic cylinder is set as $F0 = 1.67 \times 10^5 N$. Similarly, 1.5t pre-tensioning cylinder driving force set as $1.67 \times 10^4 N$.

Hydraulic cylinders parameter calculation

The hydraulic - Nominal series of standards (GB / T 2346), taking into account the need to output 150 kN of force, and the practical application of the pressure range, first select the operating pressure of the hydraulic cylinder 31.5 MPa. Use a single hydraulic cylinder rod. Calculation cylinder diameter D and piston rod diameter d. The maximum load F is $1.67 \times 10^5 N$.

Take back pressure P_2 to 1 MPa, take d / D between 0.54-0.5. Then take the data into formula [5]

$$D = \sqrt{\frac{4F}{\pi P_1 \left\{ 1 - \frac{P_2}{P_1} \left[1 - \left(\frac{d}{D} \right)^2 \right] \right\}}} = 83.30 mm. \tag{3}$$

The hydraulic cylinder bore size series of standards (GB / T2348-1993), taking into account the smooth and lighten crawling, use big bore sport, rounded inner diameter of 100 mm. d / D selected as 0.4, according to the outer diameter of the cylinder rod series Standard (GB / T 2348-1993), and the rod chamber into the oil chamber as to take into account the tensile test, the output power must reach more than 150 kN, rod diameter d = 40 mm, piston rod thread option M36 × 4. When the actual calculation of rod chamber into the oil chamber, the output force is

$$F = P_1 \times (D^2 - d^2) \pi / 4 = 208 \, kN > 150 \, kN. \tag{4}$$

Meet the requirements.

Cylinder barrel end selection flange connection flange 840 mm, made of 16Mn or Q345B.

The design of reaction force frame [6]. The main function of the anti-force framework is to assume 150 KN load reaction force, as well as installation of hydraulic cylinders, sensors and pre-stretching mechanism. Frame is bolted to the floor platform, based on the reaction force frame consists of several parts, each part by the plurality of steel plates welded materials are used Q235A, its elastic modulus E = 210 GPa, Poisson's ratio μ = 0.3, density ρ = 7 850 kg/m^3.

To improve material utilization, reduce footprint, this counter-force framework designed for a fish plate structure (Fig. 5).
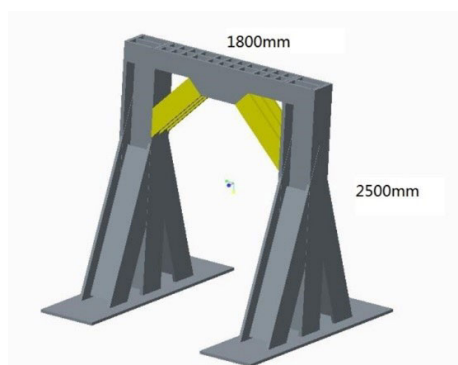

Fig. 5. Model Figure using the workbench free meshing reaction force element simulation framework

Modeling process, simplify swap calculation has little effect on the model structure. The actual form of the constraint reaction force frame by the fixing plate when the whole device is fixed on a concrete base, fixed base plate to simulate fully constrained, the load applied to the central plate in the beam, to 150KN (Fig. 6).
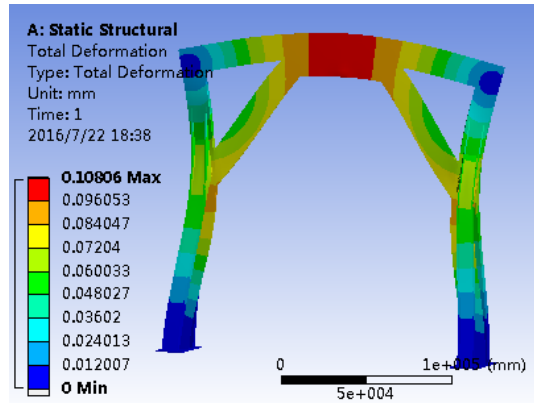
Fig. 6. Simulation results show that the model is shaped into a maximum 0.11mm, static strength to meet the requirements, and the larger safety factor. Not repeat superfluous state here.

The control section of Vertical hydraulic loading device. Power test bench is provided by a hydraulic control system as shown (Fig. 7). Hydraulic control electro-hydraulic proportional control system mainly consists of proportional valves, hydraulic cylinders, pumps, motors and other components to complete the function of a control signal based on the sample is loaded. The biggest test of test bench system pressure is determined by the diameter and the hydraulic system of the hydraulic cylinder, also characterizes the work capacity test station. Taking into account the working characteristics of the test bed is intermittent work, the use of the test force is 20% to 80%. Therefore, most of the time working at the unloading state, and require test stationary process, reliable, comprehensive consideration, the use of load adaptive hydraulic control system with pressure compensation. Considering the test bench at work, the mechanical properties of the specimen difference is large, sometimes requires light load speed, sometimes requires a slow loading, so the use of double-pump high and low pressure systems, the maximum working pressure relief valve setting system, unloading valve set double pump oil while working pressure. When the system pressure is lower than unloading valve set pressure, two pumps simultaneously supply to the system when the system pressure exceeds the set pressure load discharge valve, oil pressure pump output back into the tank through the unloading valve, Only high-pressure pump oil into the system, thereby reducing the power consumption circuit. In order to achieve speed control into the oil, at both ends of the proportional valve is provided with a pressure valve, so that the inlet pressure remained constant at both ends to ensure the electrical signal into the hydraulic cylinder control oil flow proportional valve input system pressure is proportional with the rising oil source load pressure rises to achieve a load adaptive materials testing hydraulic control system [7].
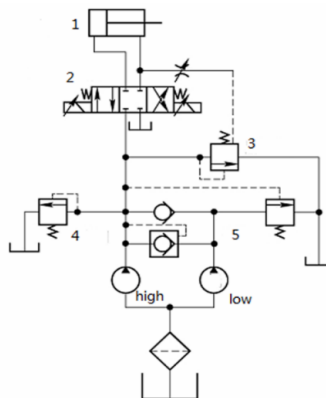

Fig. 7. 1. Hydraulic cylinder; 2. Proportional solenoid valve; 3. Differential pressure valve; 4. Relief; 5. Unloading valve

The loading system design of lateral force hydraulic. In order to simulate subway during running or the like in the wheel-rail suffered lateral force, transverse force loading apparatus design.

The loading device uses hydraulic loading, object is achieved by the loading hydraulic cylinder oscillating reciprocation realization process simulation run in the wheel-rail train suffered lateral force [8]. The loading unit is divided into three conditions, namely no friction state, the state increased friction and the maximum frictional hold.

The lateral force loading system design shown as the simulation diagram (Fig. 8).
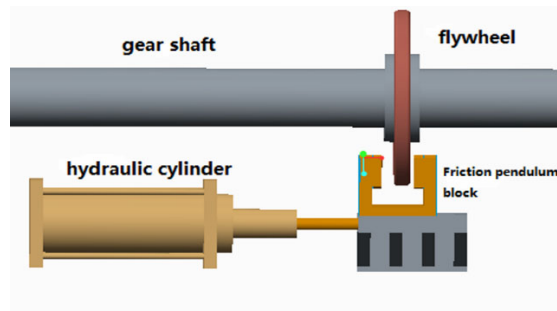
Fig. 8. As the simulation diagram shown, with the cylinder block pendulum action swinging back and forth with the rails provided on the rail stopper to prevent rotation of the flywheel swing excess movement influence

Hydraulic actuator hydraulic cylinder loading system by controlling the hydraulic cylinder rod chamber pressure to achieve the load on the bearing, the force sensor is installed between the piston rod and load bearing loading force can achieve real-time detection. Controllable elements using proportional relief valve, by automatically adjusting the voltage to control the system pressure relief valve, relief valve itself due to the presence of zero leakage and dead zone, the control pressure can not achieve a small pressure. Therefore the design of a damping of loading the system pressure to a minimum load pressure, to achieve a small load loading system, the system loading pressure in the range of 0.2-4 MPa. Action circulatory system are: forward → load → packing → rewind → unloading, using the three-way electromagnetic directional switching valve controls the main action.

Packing process is achieved by the use of the check valve at a given pressure of work, when the system implementation dwell, the pump can be unloading and loading process, the main change in pressure, so a quantitative pump oil supply requirements can be realized. The system uses two circuits, respectively, through the loop and proportional damping down loaded pressure relief valve direct control loop, two loops can reduce energy consumption, the hydraulic loading system works as shown (Fig. 9).
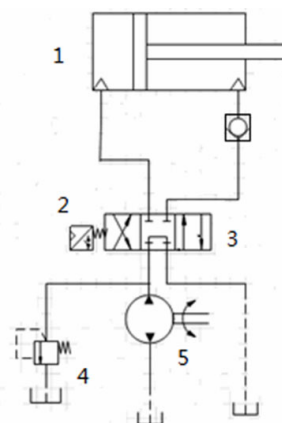
Fig. 9. 1 hydraulic cylinder; 2 electromagnetic proportion value; 3 4 of the 3-way value; 4 overflow value; 5 pump

2.4 The Design of Drive and Load System

Rail vehicles in operation, the force to be hampered by its movement, which is the running resistance.

Since the rail vehicle a very complex system, which runs on the track, but also the different stages of high-speed operation such as occurrence of coupling between the surrounding environment, many factors it will have a huge impact, but also trains start running and steady speed resistance has a greater difference, so that a rail vehicle running resistance change is more complex.

To achieve traction motor load simulation, shall implement the experimental platform formula [9]

$$T_m - \hat{T}_L = \frac{\hat{J}(d\omega_m)}{dt} \cdot \cdot \qquad (5)$$

Where T_m traction motor torque, $\hat{T}_L$ load simulation torque (the load torque and rigidity part of the load torque and inertia), $\hat{J}$ is the load inertia simulation (motor inertia inherent inertia loads and the remaining conversion inertia and), ω_m with traction motor actual speed.

Test rig driven selection of 315KW YTSP series inverter AC variable speed three-phase asynchronous motors, model YTSP355L-4. Frequency control system of choice is SIMOVERT MASTERDRIVES 6SE7 series vector control of three-phase voltage source AC drive system cabinet, by adjusting the output frequency to regulate motor speed. The cabinet when work performance is very stable and reliable, high driving efficiency, simple control, variable speed, can realize reversing, and braking resistor installed, you can self-locking when the motor into overdrive.

During test research is needed on the system load is applied to simulate the actual operation of the work of the gearbox. Experiment common load is applied methods are mechanical and hydraulic two, in which the mechanical torque generated during the loading process is relatively small, easy to adjust; hydraulic loading process can produce large torque, and can be freely adjusted. The bench used in Germany GAT produced by hydraulic rotary torque load, model VMC2500-100, adjusted to meet the high precision, high frequency load and speed requirements. The loading structure shown in Fig. 10.
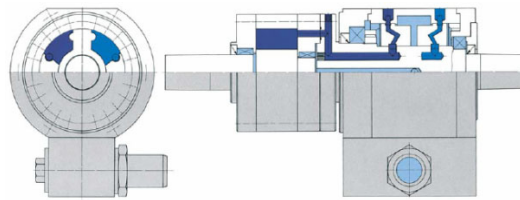

Fig. 10. Loading structure

3   Acquisition and Processing Method of Fault Signal [10]

By testing of gears and a vibration signal of bearings into different categories to collect and store, and then stored to the effective processing and analysis as well as extracting characteristic parameter signal for your computer, which can be done on the gear and operation of the bearing in real time monitoring and timely processing target failure [11]. City rail vehicle gearboxes preliminary analysis of the signal as shown below. By channel acceleration sensor data collected after fusion as follows (from Fig.11 to Fig.15).
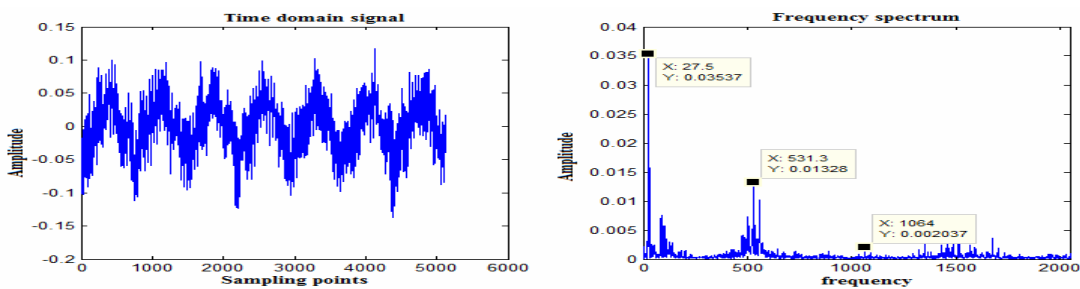

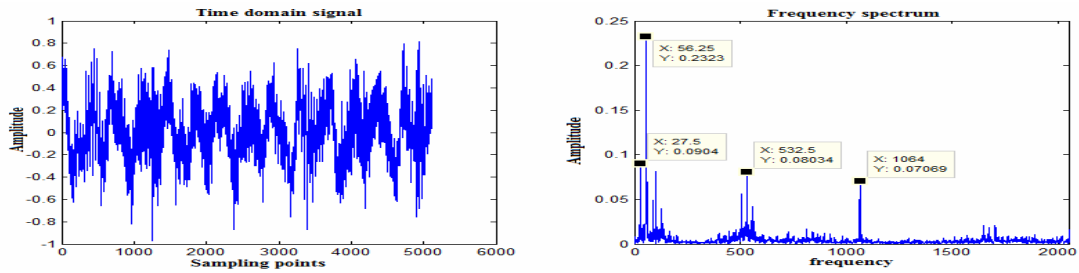**Fig. 11.** Time domain and frequency spectrum when No fault

Fig. 12. Time domain and frequency spectrum when tooth wear
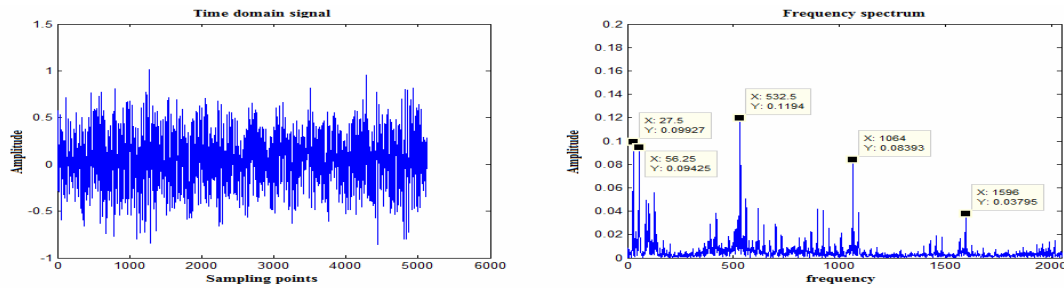

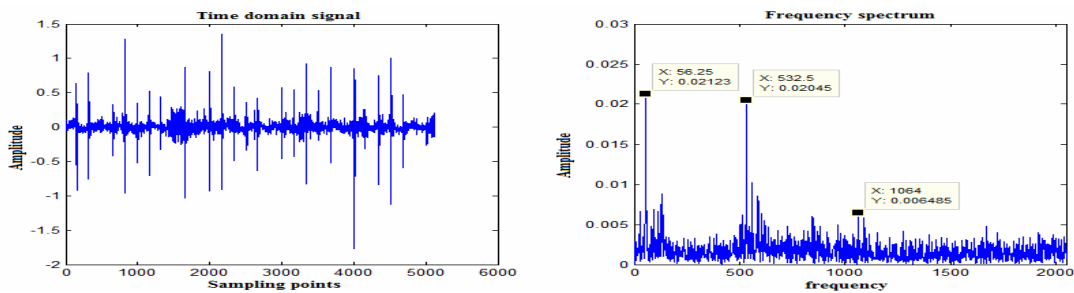**Fig. 13.** Time domain and frequency spectrum when broken tooth

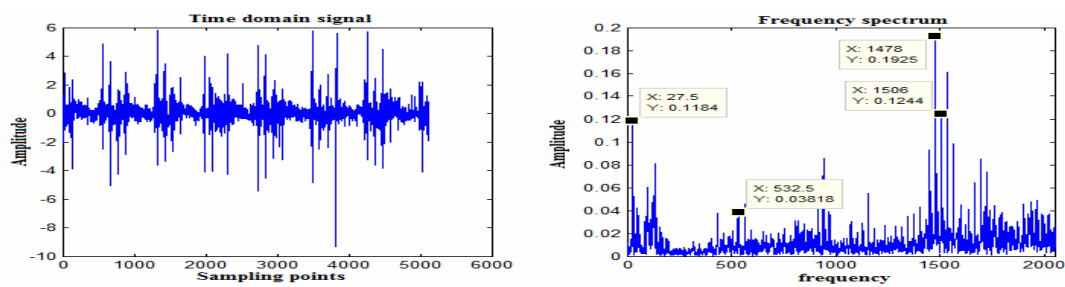**Fig. 14.** Time domain and frequency spectrum when rolling element bearing failures

Fig. 15. Time domain and frequency spectrum when bearing inner ring fault

From the point of view of energy transfer process gearbox vibration is vibration energy propagation process, the energy transfer process will take place in a loss, the vibration amplitude of the input energy is also closely related to the intensity [12]. When the gear transmission fails, it will lead to the emergence of internal cycle power, seriously reduce the transmission performance, this time out of the vibrational energy transferred from the vibration source will change, the external manifestations of vibration strength box structure itself, as well as the energy conversion from the noise to spread around.

From the perspective of modal analysis, the vibration generated in the process of the gear box vibration energy loss, and therefore, the formation of a stable input-output mapping between input power and the gearbox casing vibration signal transmission system. Gear transmission of energy and vibration relationship model shown (Fig. 16) [13].
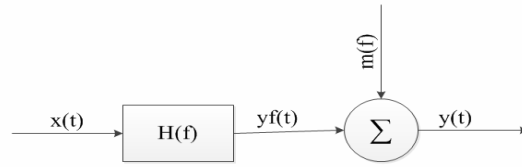
Fig. 16. Gear transmission of energy and vibration relationship model shown

Define the input signal and the output signal of the coherence function is:

$$r_{xy}^2(f) = \frac{|S_{xy}(f)|^2}{S_{xy}(f)S_{yy}(f)} \qquad 0 \le r_{xy}^2(f) \le 1. \tag{6}$$

Where: $S_{xx}(f)|S_{yy}(f)$ are input, the output signal from the power spectral density function $S_{xy}(f)$ for the cross-power spectral density function. Finishing [9]:

$$\begin{aligned} r_{xy}^2(f) &= \frac{|H(f)|^2 \, S_{xy}^2(f)}{S_{xx}(f)S_{yy}(f)} \\ &= |H(f)|^2 \, \frac{S_{xx}(f)}{S_{yy}(f)} \\ &= 1 - \frac{S_{nn}(f)}{S_{yy}(f)} \end{aligned} \tag{7}$$

The above equation: $S_{nn}(f)$ of the noise signal from the power spectral density function; $H(f)$ for the system frequency response function.

Obviously the ideal single-input single-output linear system, since the power spectral density calculation is actually based on the estimated data sequence corresponds to the coherence function is also used in the form of probability and statistics represent the input signal $x(t)$ for a total output signal $y(t)$ ratio of the size of the contribution [14], from the perspective of frequency domain reveals the relationship between the two. the larger coherent value that represents the more evident in the vibration energy at that frequency, and vice versa weak. this angle from classical control theory confirmed related Content vibration mechanism gear analysis, illustrating the close relationship between the energy of the signal and vibration.

5   Conclusion

The test rig can be used to simulate the dynamic characteristics of the locomotive load and full-load weight and other operating conditions of the gearbox. In this gearbox load simulation system, the loading rate of rise of the load were strictly controlled, while the load between the cylinder sleeve with the test pieces have greater flexibility characteristics. Test rig can meet the vertical and lateral loading load should be able to meet simulate actual operating conditions the gearbox. To further analyze the situation gearbox load test abnormal vibration, study or test bench in fault conditions that may exist in different sports problems of gearboxes, require spectrum analysis and fault diagnosis of gearbox load carried. Because when the gearbox load test concentricity error installation may lead to the gearbox vibration values measured too large, so the test rig installation process should be strictly guaranteed concentricity requirements adjacent shaft. Considering the subway safety of vehicle operation, the gearbox before the loading operation, requires a lot of bench for different operating conditions to simulate, analyze the dynamic characteristics of the gearbox, to provide technical support for the development of the gearbox, to achieve gearbox real-time status monitoring and fault timely and accurate diagnosis is important.

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Appendix: Fund Project: