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Research on fault diagnosis method of radar antenna transmission gear based on motor current characteristics

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Abstract—In order to complete the monitoring and early warning of radar antenna transmission device with more and more frequent faults, a gear fault judgment method suitable for radar equipment is proposed in this paper. According to the fault characteristics of radar antenna transmission gear, the motor current frequency difference of transmission mechanism under normal and fault conditions is compared, and the simulation experiment is completed. The simulation results verify the feasibility and correctness of this method.

1. Introduction

The increase of modern military combat readiness training tasks greatly prolongs the start-up time of radar equipment. The radar equipment of many radar stations has been on 24-hour combat readiness for a long time. The long-term high-load working state has led to the increasing failure rate of radar antenna transmission devices. In the actual work of the army, the fault diagnosis of the antenna transmission mechanism still adopts the traditional way of manual inspection. Limited to the working conditions, the radar technician or operator can only rely on whether the sound of antenna rotation is continuous to judge the working condition of the antenna transmission mechanism. This method has two disadvantages: ① the sound of gear fault is easy to be submerged in the transmitter In the noise generated by air conditioning radiator and shelter power station, it is more difficult to predict the fault simply by hearing; ② The fault is found to be relatively late. When the fault is found by hearing, the antenna transmission mechanism is often seriously damaged, which can not be effectively identified for some minor damage of gears, and can not be repaired in many cases.

At present, the research on gear fault diagnosis has achieved some results. According to whether it is based on motor drive system, it can be roughly divided into two categories: one is the need to install additional mechanical sensors, such as vibration diagnosis method and noise analysis method; On the other hand, the gear fault information can be obtained by using the motor driver itself as the sensor without installing additional sensors, such as motor current characteristic analysis method, load torque characteristic analysis method and motion error identification method. The vibration diagnosis method using Hilbert Huang transform is not mature in theory, such as edge effect, boundary crossing problem and stop criterion, which needs to be developed and improved; The vibration diagnosis method based on wavelet analysis has been applied earlier and the theory is relatively mature. With the development and improvement of vibration signal processing technology, it has ideal detection results for various common gear faults such as broken teeth, pitting and tooth surface gluing. However, it is inconvenient to install vibration sensors on radar equipment, The installation position of the sensor will also affect its sensitivity to vibration signals; the noise analysis method also needs the help of various sound sensors with high tightness. At the same time, because the working environment of gears is usually full of industrial noise and the noise signal is a non-stationary signal with very low signal-to-noise ratio, the noise analysis method is less used than the vibration diagnosis method.

Through the comprehensive analysis of the literature and the current situation of radar actual installation, the gear fault characteristic analysis method based on motor current is most suitable for radar actual installation. This method is easy to obtain the current signal and will not interfere with the original system without damaging the original circuit structure. In this paper, the stator current signal of the motor is used as the analysis starting point, the corresponding relationship between the dynamic characteristics of the mechanical equipment driven by the asynchronous motor and the fault is studied, the mathematical model of gear transmission is established, and on this basis, the fault simulation is carried out to verify the feasibility of fault diagnosis based on the stator current characteristics of the motor, it provides a reliable method for monitoring the normal operation of radar antenna transmission device.

2. Fault characteristic analysis of radar antenna transmission gear system

Gear is an important part of the the radar antenna drive system and the basic unit driving the radar antenna to rotate and pitch. Whether the gear is complete and normal directly affects whether the radar can complete the combat readiness duty task.

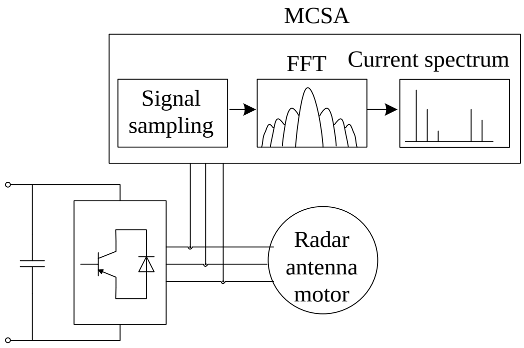


Fig. 1 diagnosis scheme based on radar motor stator current characteristic analysis

The radar antenna drive system is mainly composed of radar antenna motor, coupling, gearbox and various antenna loads. The gear box contains multiple pairs of gear pairs. According to the logarithm of the gear pairs, the gear box can be divided into single-stage gear box and multi-stage gear box. This paper takes the single-stage gearbox as the research object to study and analyze the gear failure of the radar antenna transmission system, that is, the gearbox only contains a pair of gear pairs, and the gears are all spur gears.

2.1 Characteristic Analysis of Gear Meshing Stiffness

In the radar antenna transmission system, the stiffness excitation caused by the elastic deformation of the gears in the gearbox directly affects the meshing of the gears. When the gears rotate in contact, the meshing of the single-tooth pair and the double-tooth pair occurs alternately, and the gears rotate during the rotation process. The contact situation of the gear will change periodically with the rotation of the gear. Since the rigid deformation of the two tooth pairs during the contact period of the gear is not the same, there will be a step change, as shown in the Fig. 2:

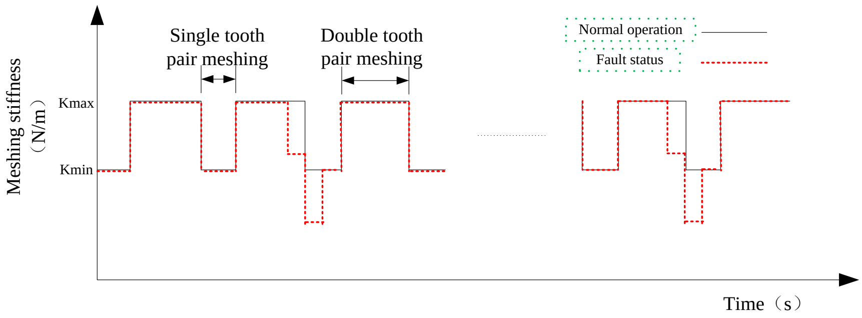


Fig. 2 Schematic diagram of time-varying meshing stiffness

2.2 Analysis of the Variation between Motor Load Torque and Motor Current

During the operation of the radar antenna transmission system, it is assumed that the electromagnetic torque of the transmission is T_e, the load torque is T_L, the moment of inertia is J, the motor speed is ω_m, and the friction coefficient is B. According to the dynamic principle of motor transmission, we can get the following correspondences:

$$T_e - T_L = J\frac{d\omega_m}{dt} + B\omega_m$$

When the gear in the gearbox fails, the load torque T_L will be superimposed with a periodic fluctuation interference, and the final speed of the gear rotation will reach a dynamic balance in the presence of the fluctuation component. The electromagnetic torque T_e in the above equation, the load torque T_L and the motor speed ω_m will each superimpose a constantly changing component, which satisfies the following correspondence:

$$\begin{cases} T_e = T_{e0} + \Delta T_e = T_{e0} + \sum_i T_{ei}\cos(2\pi f_i t + \varphi_{ei}) \\ T_L = T_{L0} + \Delta T_L = T_{L0} + \sum_i T_{Li}\cos(2\pi f_i t + \varphi_{Li}) \\ \omega_m = \omega_{m0} + \Delta\omega_m = \omega_{m0} + \sum_i \omega_{mi}\cos(2\pi f_i t + \varphi_{mi}) \end{cases}$$

The steady-state DC component is as follows:

$$T_{e0} - T_{L0} = B\omega_{m0}$$

The added variation components after analysis are:

$$\Delta T_e - \Delta T_L = J\frac{d\omega_{mosc}}{dt} + B\omega_{mosc}$$

In the two formulas, T_{L0}, T_{e0} and ω_{m0} respectively represent the average value of load torque, electromagnetic torque and rotational speed, ΔT_e, ΔT_L, $\Delta\omega_m$ and are the periodic fluctuations of each variable.

Assuming that the motor used in the radar antenna drive system is a permanent magnet synchronous motor, the torque equation under the vector control mode with $i_d = 0$ should satisfy the following correspondence:

$$T_e = p\Psi_f i_q$$

In the formula p and Ψ_f are constants. Based on the above expressions, it can be seen that in addition to the DC component i_{q0} in i_q, the cosine components i_{qi} containing their respective frequencies will also be superimposed, and they satisfy the following correspondence:

$$i_q = i_{q0} + \sum_i i_{qi} \cos(2\pi f_i t + \varphi_{qi})$$

In the above formula, i_{qi} corresponds to the amplitude of the variable at various frequencies; φ_{qi} is the corresponding phase. Use the inverse transformation matrix of the principle of conservation of amplitude to transform the current in the dq coordinate system into the abc three-phase coordinate system:

$$\begin{cases} i_a = -i_q \sin\theta \\ i_b = -i_q \sin(\theta - 120^\circ) \\ i_c = -i_q \sin(\theta + 120^\circ) \end{cases}$$

The rotor position satisfies the following equation:

$$\theta = \theta_0 + \int p\omega_m dt = \theta_0 + p\omega_{m0} t + \sum_i \frac{p\omega_{mi}}{2\pi f_i} \sin(2\pi f_i t + \varphi_{mi}) = \theta_0 + 2\pi f_e t + \theta_{tz}$$

In the above formula θ_0 represents the initial angle of motor rotor; f_e is the fundamental frequency corresponding to the stator current of synchronous motor during the rotation of motor rotor; θ_{tz} represents the modulation component corresponding to the angular velocity change caused by gear failure. Then formula 6 can be transformed into:

$$\begin{aligned} i_q &= i_{q0} \cos(2\pi f_e t + \theta_0 + \theta_{tz} + \frac{\pi}{2}) + \\ &\frac{1}{2}\sum_i i_{qi} \left[\begin{aligned} &\cos\left(2\pi(f_e + f_i)t + \varphi_{qi} + \theta_0 + \theta_{tz} + \frac{\pi}{2}\right) \\ &+\cos\left(2\pi(f_e - f_i)t - \varphi_{qi} + \theta_0 + \theta_{tz} + \frac{\pi}{2}\right) \end{aligned} \right] \end{aligned}$$

From this formula, it can be seen that the change of stator current caused by gear fault is modulated by amplitude and phase angle at the same time. However, the speed of the motor is controlled by a closed loop during the actual operation, so the cosine component in ω_m is very small, and the influence of the phase angle is generally ignored. At the same time, for the research, the frequency characteristic quantity obtained by the Fourier transform has practical significance only if the value is positive, so it can be judged whether the gear fault occurs according to the symmetrical frequency characteristics appearing on both sides of the fundamental frequency on the frequency spectrum of the motor stator.

3. Simulation analysis of radar antenna transmission gear fault diagnosis

As shown in the fig.3, this paper builds a simulation model of the gear fault of the radar transmission based on the permanent magnet synchronous servo motor, and simulates the normal and fault states of the gear by controlling the gear fault subsystem.

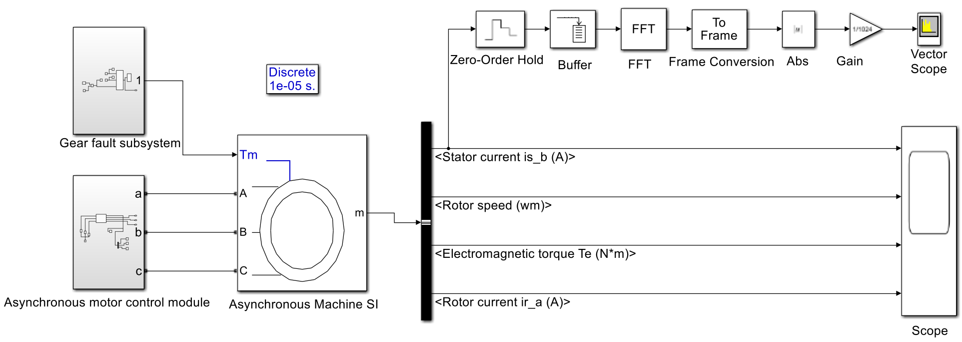


Fig. 3 fault simulation model of radar antenna transmission gear

The parameters in the simulation are shown in the table below. The unit of the ordinate in the motor electronic current spectrum diagram is decibel (dB), and the current is sampled in a whole cycle during sampling.

Tab.1 Main parameters of permanent magnet synchronous motor

Parameters	Value
Rated power/W	750
Rated torque/N·m	2.4
Rated current/A	2.8
Rated speed/(r/min)	2800
Moment of inertia of motor shaft/(kg·m^2)	0.0001
Load inertia/(kg·m^2)	0.0003
Motor pole pairs/pcs	3

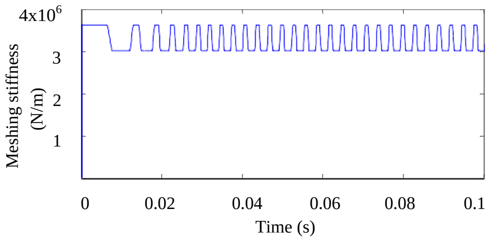
In the simulation, the speed of the motor is set to 1000r/min, and the reduction ratio of the motor is 1.5, then there are the following equivalent relationships:

$$f_e = \frac{n_1 \cdot p}{60};\ f_{r1} = \frac{n_1}{60};\ f_{r2} = \frac{n_2}{60};\ f_m = f_{r1} \cdot z_1$$

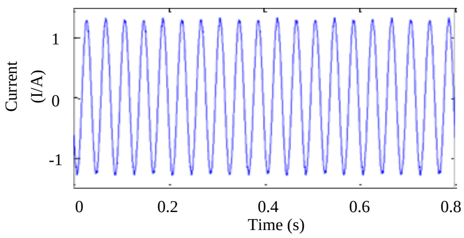
In the above formula f_e is the stator current fundamental frequency, f_{r1} represents the rotational frequency of the driving wheel, f_{r2} represents the rotational frequency of the driven wheel, and f_m represents the meshing frequency.

3.1 Simulation analysis of the normal working gear characteristics of the radar antenna transmission device

When the device is working normally, the stiffness running curve of the gear is shown in Fig 4(a), which is a rectangular wave curve with regular shape, and the waveform of the stator current is shown in Fig 4(b).



（a）Meshing stiffness waveform



(b)Motor stator current waveform

Fig. 4 meshing stiffness and stator current waveform when the gear is intact

In the initial stage of the stiffness curve, the period becomes shorter and shorter, corresponding to the process of increasing the motor speed. The stiffness curve changes frequency faster and faster as the motor speed increases. In the middle and later stages, since the motor speed is constant, the meshing frequency also remains unchanged. The time domain waveform of the motor stator current is shown in Fig 5(b).

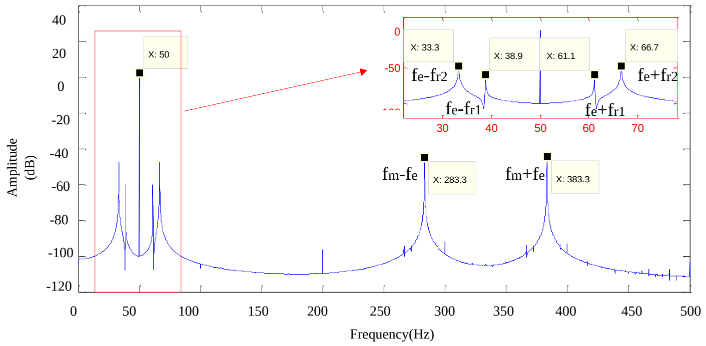
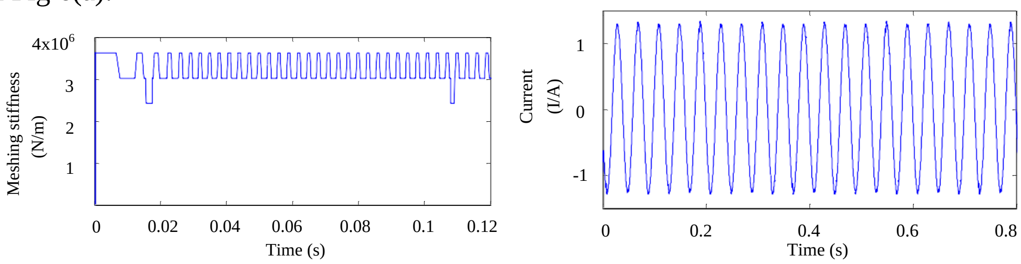


Fig. 5 The stator current spectrum diagram when the gear is intact

In the current spectrum at this time, the frequencies of $f_m \pm f_e$ are symmetrically distributed on both sides based on the current fundamental frequency f_e. In the Fig. 5, it can be selected and enlarged by the red selection box to obtain 4 frequency characteristic values, and the corresponding values are marked in The Fig. 5 corresponds to the four frequencies $f_e \pm f_{r1}$ and $f_e \pm f_{r2}$ in the theoretical analysis, which verifies the correctness of the theoretical analysis.

3.2 Simulation analysis of gear characteristics when gear failure occurs in radar antenna transmission

The deterioration of the gear and the fracture of the gear will cause a direct drop in the stiffness curve. Assuming that the driven wheel in the gearbox has extreme broken teeth, the mesh stiffness will be shown in Fig 6(a):



a) Meshing stiffness waveform b) Motor stator current waveform

Fig. 6 meshing stiffness and stator current waveform in case of gear failure

Comparing and analyzing the stator current curves of the gears in Fig 4(b) and Fig 6(b) respectively in the normal state and the fault state, it is found that there is basically no difference between the two, which shows from the side that the fault cannot be detected by the current curve in the time domain. diagnosis.

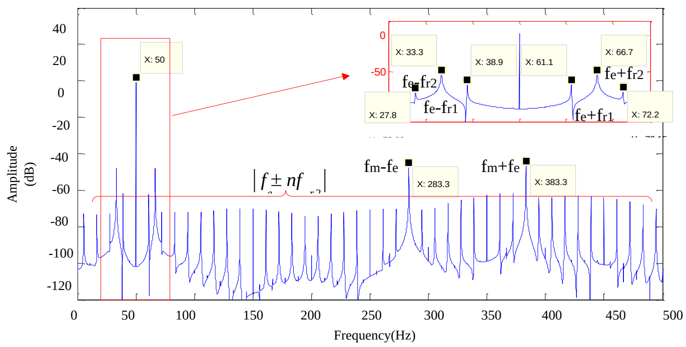


Fig.7 spectrum of stator current in case of gear failure

When the gear is faulty, the frequency components $f_e \pm f_{r1}$, $f_e \pm f_{r2}$ and $f_m \pm f_e$ still exist in the stator current spectrum, but a variable frequency band appears in the frequency spectrum compared with the normal state. Using the red selection box to select the spectrogram on both sides of the enlarged fundamental frequency, four frequency characteristic values can be obtained. These four values represent the frequencies for n=1 and 2 in the formula in the Fig.7, while the cases where n is other values are represented in the sidebands. The above results are consistent with the theoretical analysis, so it can be judged whether a fault has occurred according to whether there is a frequency change in the current spectrum.

4. Conclusion

In this paper, the dynamic modeling analysis of the gears of the radar transmission system is carried out. On this basis, the characteristics of the faults of the gears are mathematically analyzed, and the frequency of the stator current of the normal operation of the gears and the gear faults in the radar antenna transmission device is found. The difference is verified by simulation on the Matlab/Simulink platform. The simulation results show that whether the gear is normal can be judged by whether there are sidebands in the current spectrum of the radar antenna drive motor, which provides an effective fault early warning method for ensuring the normal operation of the radar antenna drive device.

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