Mechanical resonance suppression method of Naval Gun servo control system based on Notch Filter

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Abstract: The naval gun servo system requires high dynamic tracking accuracy. In addition, the resonance point of the system changes at any time due to the influence of sea weather and wind waves. Therefore, the traditional off-line detection method of resonance point is not suitable for naval gun servo system. According to the characteristics of naval gun servo system, an on-line resonance suppression method based on notch filter is designed in this paper. The resonance frequency point is detected by fast Fourier transform, and then the notch filter is adjusted on-line parameters. The simulation results show that this method can suppress the resonance problem of naval gun servo system on line.

1. Introduction
In naval gun servo system, the load with large moment of inertia is usually equipped, and the limited rigidity of the transmission shaft causes angular deviation, so the existence of mechanical resonance is inevitable. Compared with other servo systems, the working environment of naval gun servo system is worse, and the required dynamic tracking accuracy is higher. However, the jitter phenomenon caused by mechanical resonance at the end of the load will seriously affect the tracking performance and firing accuracy of naval gun. The mechanical resonance frequency of naval gun servo system will change due to swaying caused by sea waves and vibration caused by firing, etc. It is difficult to predict accurately in the early design. Therefore, in order to improve the tracking performance and firing accuracy of naval gun servo control system, it is very necessary to study the resonance suppression of naval gun servo control system.

At present, there are mainly three methods to suppress mechanical resonance: one is to optimize mechanical design, which belongs to the mechanical field and will not be discussed too much here; The second is to actively change the parameters or control structure of the controller to eliminate the resonance effect, but the design of the controller is relatively complex and requires a large amount of calculation, or because of other practical difficulties, many researches are still at the laboratory simulation stage. Although the simulation experiments have been verified, they have not been put into practice too much in practical application engineering. Thirdly, the notch filter is added to suppress the noise. The method is simple and easy to implement. The design requirements are relatively low. Documents [1] to [3] analyze and summarize the defects of the traditional resonance suppression method of the intermediate frequency adaptive notch filter, and introduce a self-correcting low-pass filter into the speed feedback path; Documents [4] to [6] have designed filters with self-tuning parameters, which can achieve better effect on resonance suppression. Literature [7] according to the requirement of the servo system's computation and real-time performance, a mechanical resonance frequency detection method based on sliding DFT algorithm is given, and compared with the traditional fast Fourier transform detection method. Based on notch filter, this paper designs an algorithm to extract resonance frequency and a method to suppress resonance on line, and simulates with MATLAB.
2. Mechanical resonance characteristic analysis

Generally, the motor and the load can be regarded as a double inertia system, while the mechanical resonance occurs between the motor and the load.

![Fig. 1 dual inertia system](image)

The system state can be described by the dual inertia system model (the model is shown in fig. 1):

\[
R_a i + L_a \frac{di}{dt} + K_e \dot{\theta}_m = u_m \tag{1}
\]

\[
T_m = K_i i \tag{2}
\]

\[
j_m \ddot{\theta}_m + B_m \dot{\theta}_m = T_m - T_1 \tag{3}
\]

\[
T_1 = K_s (\theta_m - \theta_1) \tag{4}
\]

\[
j_1 \ddot{\theta}_1 + B_1 \dot{\theta}_1 = T_1 - T_d \tag{5}
\]

Where:
- \(R_a\) is armature resistance;
- \(L_a\) is armature inductance;
- \(i\) is armature current;
- \(K_e\) is the back electromotive force coefficient;
- \(\theta_m\) is the rotation angle of the motor;
- \(u_m\) is armature voltage;
- \(T_m\) is the output torque of the motor;
- \(K_i\) is the electromagnetic torque constant;
- \(j_m\) is the moment of inertia of the motor;
- \(B_m\) is the viscous damping coefficient at the motor end;
- \(\theta_1\) is the load angle;
- \(K_s\) is the mechanical rigidity of the rotating shaft;
- \(j_1\) is the moment of inertia at the load end;
- \(B_1\) is the viscous damping coefficient at the load end;
- \(T_d\), \(T_1\) and \(T_2\) are disturbance torque (including friction torque, coupling torque and external disturbance torque).

Formulas (1) to (5) can be simplified to obtain the relationship between motor torque and motor rotation angle

\[
\frac{\theta_m(s)}{T_m(s)} = \frac{j_1 s^2 + B_1 s + K_s}{s(K_1 s^3 + K_2 s^2 + K_3 s + K_4)}
\]

Where: \(s\) is Laplace operator; \(K_1 = j_m j_1\); \(K_2 = j_m B_1 + j_1 B_m\); \(K_3 = j_m K_s + j_1 K_s + B_m B_1\); \(K_4 = B_m K_s + B_1 K_s\).

The viscous damping between the motor end and the load end is very small and can be ignored. The relationship between the motor rotation angle and the motor torque is as follows:

\[
\frac{\theta_m(s)}{T_m(s)} = \frac{j_1 s^2 + K_s}{s(j_m j_1 s^3 + j_m j_1 s^2 + j_1 K_s s + j_m j_1)}
\]

The poles in the equation generate resonant frequencies, i.e.

\[
\omega_n = \sqrt{\frac{j_1 + j_m}{j_m j_1 K_s}}
\]

It can be seen from the above formula that the mechanical resonance frequency of the system is determined by the rotational inertia of the system and the mechanical rigidity of the rotating shaft.

3. On-line suppression of mechanical resonance

3.1 Online Identification of Resonance Frequency

On-line suppression of resonance frequency is mainly divided into four steps: sampling, FFT analysis, resonance frequency extraction and notch filter function. After the mechanical resonance automatic
suppression function is added to the system, the cross-axis current signal entering the steady state is sampled. Each speed loop sampling period completes one cross-axis current signal sampling, and each sampling data is stored in a register for overall calculation. When the number of sampling points reaches a predetermined number of points for fast Fourier operation, the sampling is finished and FFT analysis is started. After spectrum information is obtained, a frequency extraction algorithm is used to extract and calculate resonance frequency points, and filter parameters are configured through the obtained frequency point information to achieve the purpose of suppressing resonance.

FFT analysis can be divided into two categories. Time extraction method and frequency extraction method are adopted in this paper. The frequency extraction method is not decomposed according to odd and even numbers, but is decomposed in half in front and back order. In this way, the DFT of n points is decomposed into front and back parts. The frequency extraction method of decomposing one n point into two N/2 point DFT is shown in fig. 2.

![Fig. 2 FFT frequency extraction method for n points](image)

\[
X(k) = \sum_{n=0}^{N-1} x(n)W_N^{kn} = \sum_{n=0}^{N-1} \left[ x(n) + (-1)^k x \left( n + \frac{N}{2} \right) \right]W_N^{kn}, \quad N = 2^k
\]

When k is even, k=2r,

\[
X(k) = \sum_{n=0}^{N-1} \left[ x(n) + x \left( n + \frac{N}{2} \right) \right]W_N^{2r} = X_1(r)
\]

When k is odd, k=2r+1,

\[
X(k) = \sum_{n=0}^{N-1} \left[ x(n) - x \left( n + \frac{N}{2} \right) \right]W_N^{(2r+1)n} = X_2(r)
\]

3.2 Frequency extraction algorithm

The frequency spectrum of the rotational speed error signal is analyzed by FFT, and then the resonant frequency is obtained by designing a frequency extraction algorithm of the response. The basic steps are as follows:

Firstly, the amplitude A(n) corresponding to the frequency points in the spectrogram is obtained. If the amplitude is greater than the threshold set by the system, the value is regarded as the effective amplitude, otherwise it is regarded as invalid noise. When A(n) is a valid value, we temporarily store A(n) in the space of the variable t if any amplitude A(n) is greater than the amplitude of the previous point and greater than the amplitude of the latter point are all valid. After that, a loop statement is executed, and the condition for ending the loop is n = n. According to the amplitude of the resonance point stored in the variable and the n value corresponding to the resonance frequency, the resonance frequency can be obtained: \( f = \left( n - 1 \right) \frac{f_s}{N} \) (fs is the sampling frequency, n is the sampling point). Then the corresponding filter parameters are set according to the calculated resonant frequency.
The algorithm can identify the largest resonance point of the system. The identification accuracy is related to the number of sampling points. The more sampling points, the more accurate the resonance frequency identified by FFT. However, due to the storage and calculation capability of the main control chip, the number of sampling points should not be too large. In actual servo systems, the resonant frequency point may not be unique, but this algorithm can only suppress one resonant point, and improvement will be considered later.

3.3 Design of Notch Filter

For the suppression of mechanical resonance, notch filter is a relatively simple and easy-to-operate method.

The commonly used notch filter is an improved double-T network notch filter, and the transfer function is:

\[ Q_1(s) = \frac{as^2 + cs + 1}{as^2 + bs + 1} \]

Where \( a = \frac{1}{\omega_0^2} \), \( b = \frac{K_1}{\omega_0} \), \( c = \frac{K_2}{\omega_0} \), \( \omega_0 \) is the operating frequency of the notch filter; \( K_1 \) and \( K_2 \) are notch bandwidth parameters and notch depth parameters of notch filter respectively.

The following is Bode diagram of notch filter when different notch depth parameters (Fig. 3) and notch width parameters (Fig. 4) are selected:

Fig. 3 When the notch width parameter \( K_1 = 20 \), the notch depth parameter \( K_2 \) selects bode plots of 0.1, 0.5, 0.9, and 1 respectively.
Fig. 4  When the notch depth parameter $K_2 = 0.5$, the notch width parameter $K_1$ selects bode plots at 10, 20 and 50 respectively.

As can be seen from the above figure, when the depth coefficient is constant, the width coefficient becomes larger and the notch at the notch frequency point corresponding to Bode diagram becomes larger, and the change of phase angle tends to be smooth. However, a large notch width coefficient will cause some distortion of non-resonant signals, which is undesirable in system design. When the width coefficient of the notch filter is unchanged, with the increase of the depth coefficient of the notch filter, the notch depth at the notch frequency point corresponding to Bode diagram increases, the frequency amplitude attenuation increases, and the phase angle changes tend to be sharp. Proper increase of depth coefficient will increase the attenuation degree of resonance point amplitude, but it will also increase the difficulty of realization. In addition, when the notch depth coefficient $K_2$ is between 0 and 1, the notch filter can effectively attenuate amplitude frequency points in the shape of a depression, thus achieving the effect of suppressing resonance. However, when $K_2$ exceeds the interval of 0 to 1, the frequency amplitude diagram of the notch filter forms a convex shape. At this time, the amplitude of the frequency point cannot be attenuated, and the notch filter will lose its notch effect. Therefore, $\omega_n$ can be set as the frequency value of the resonance point, and the notch filter can be designed by selecting appropriate parameters $K_1$ and $K_2$ according to the resonance frequency.

4. Simulation results
Build a simulation model on MATLAB R2015a as shown in the following figure:
The following figure shows the speed response without notch filter (Fig. 6) and with notch filter (Fig. 7).

From the simulation results, it is known that before the notch filter is added, the system's speed response curve oscillates greatly. After the notch filter is added, the oscillation of the system response has obvious attenuation, which indicates the effectiveness of the algorithm.
5. Conclusion
In this paper, aiming at the characteristics of naval gun servo control system, which requires high
dynamic tracking accuracy and is easy to be affected by sea waves and shooting vibrations, the motor
and load are first modeled as a dual inertia system, the causes and mechanism of mechanical resonance
are analyzed, then FFT analysis and corresponding frequency extraction algorithm are used to identify
resonant frequency, and notch filter is used to suppress mechanical resonance. Finally, the simulation
verifies the availability of the method. Under the condition of changing resonant frequency, the system
can quickly suppress mechanical resonance and meet the demand of online application.

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