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Research Article

Active Vibration Control of Robot Gear System Based on Adaptive Control Algorithm

Dayu Zhang [1] and Cong Guan [2]

[1] *Graduate School of Science and Technology, Gunma University, 1-5-1 Tenjincho, Kiryu 376-8515, Japan*
[2] *School of Artificial Intelligence, Nanjing University, Nanjing, Jiangsu 210023, China*

Correspondence should be addressed to Cong Guan; 14521209@xzyz.edu.cn

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With the aim of solving the errors of gear transmission system in the actual manufacturing process, processing and installation, and solving the the vibration and noise of the gear system caused by the deformation brought about by external excitation such as motor load and actuator, which seriously threaten the safety and stability of unit equipment, a novel active vibration suppression structure of multistage gear system with built-in piezoelectric actuator is designed to generate active control force, and it can be used on the shaft. An active controller is designed and established using FxLMS adaptive algorithm. The results of this method show that by measuring the vibration signal system, the base frequency of the high-speed gear pair is 310 Hz, and the basic frequency of the low-speed gear pair is 192 Hz. I had the adaptation snare go for almost 0.5 seconds, with a difference of 0.52%. Adaptive Trap II reached in 1 second, with a difference of 0.96%. In the active vibration suppression test, the basic frequency of the high-speed gear pair is 804 Hz, and the basic frequency of the low-speed gear connector is 500 Hz. Using the FxLMS adaptive algorithm, it is able to effectively suppress the frequency vibrations of the high-speed dual-gear and low-speed dual-gear coupling systems of multispeed gears. After being controlled by FxLMS algorithm at the second frequency of the high-speed gear, the vibration reduction is about 10 dB at the third frequency of the low-speed gear. The vibration reduction is also approximately 7 dB. This has proved that a new experiment of industrial safety can be used to accelerate the movement of gear vibrations using the FxLMS adaptation algorithm.

1. Introduction

As one of the most widely used forms of transmission, gear transmission can achieve constant transmission ratio transmission for its compact structure and the reliable transmission, which is widely used in machinery, automobile, aerospace, metallurgy, mining, robot, and many other fields. It becomes an indispensable part of major rotating machinery and power transmission devices. However, due to the change of system external load and the errors in the process of gear manufacturing and rodent impact, gear transmission in operation may cause vibration and noise in the actual process of gear engagement. It is not only related to the working life of mechanical parts, but also affects people's daily life and work. Therefore, the vibration control problem of gear transmission system has become one of the key technical research hotpots in the field of vibration control [1].

The vibration of the gear transmission system will not only cause noise, but also cause the serious impact on the smooth operation and service life of other transmission parts. It even causes the immeasurable loss. In terms of mechanical equipment, gear failure can cause serious machine failure and the component damage. For example, the main transmission device of the traditional helicopter is generally composed of multistage gear transmission system, which is located at the top of the cabin. The vibration of autonomous transmission system will reduce the comfort of cabin crew, causing fatigue and affecting work safety and efficiency. The precision of the important precision instrument will be affected, reducing reliability and causing a serious threat to flight safety [2].

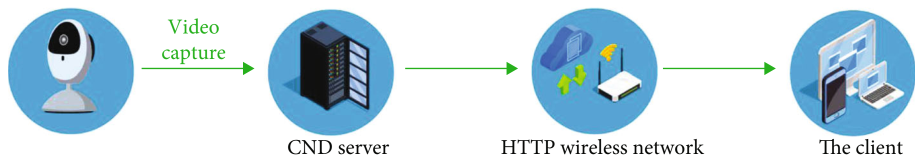

Figure 1: Adaptive control algorithm.

Gear transmission is also widely used in cars, such as car gearbox, drive axle, differential, and steering machine. And gear transmission is even also used in many electrical components, such as glass elevator, wiper, and electronic handbrake. The application of gear transmission system in the aviation field is the main transmission system of the US Apache AH-64D attack helicopter. And the application of gear transmission system in the automotive field is the ZF8-speed transmission equipped by the Chrysler 300C. The vibration caused by the gear pair can be transmitted to the supporting structure and the box structure, and then, the noise is transmitted to the outside. Different levels of vibration and noise will be inevitably produced in normal work in the gear system. Therefore, the action of taking effective vibration and noise reduction measures can not only improve the safety and stability of the vehicle, but also meet people's high standards and requirements for car driving safety and comfort.

In the project of "Key Basic Parts and General Parts" of the National Science and Technology Support Plan during the 12th Five-Year Plan, gears and other key transmission basic parts are listed as the key research and support projects. The research on key technologies such as design and manufacturing of science and technology meets the needs of the national development through science and technology. At present, in view of the vibration and noise control problems of the gear transmission system, most researchers are committed to the passive vibration reduction technology research such as improving the processing process and improving the processing precision and wheel tooth repair. The adaptability of the passive vibration control method is poor, and the actual effect of vibration reduction is low. So the limitations of this method are increasingly prominent [3]. With the emergence and application of new multifunctional materials, the rapid development of vibration reduction and noise reduction technology based on active control algorithm is promoted (Figure 1). It can not only achieve a better control effect, but also ensure the controllable stability of the charged system, effectively making up for the insufficient of the passive control method.

Therefore, the vibration control principle of gear transmission system, exploring new methods and designing new schemes, is studied in depth, which is conducive to improving the service life and work stability of mechanical transmission equipment. It has a very critical guiding significance for the development of China's industrial economy.

2. Literature Review

The study of the impact strength of glass has become one of the hot topics of many scientists, because glass plays an important role in the protection of the glass country, industry, and other important applications.

Sun J. was one of the first experts to determine the impact of vibration in transmission gear and introduced a new way to prevent vibrations from spreading through the second gear. The key to this process is the use of a piezoelectric actuator and an analog frequency generator in a vibration control system. Experiments have shown that the vibration reduction can reach 70% [4]. Zhang, J. et al. suppressed the vibration caused by gear engagement by arranging a magnetostrictive actuator acting on the input shaft in the gearbox, which also corrected the dynamic engagement characteristics of the gear. In addition, he used an adaptive feedback controller to output the force that determines the amplitude and phase to drive the actuator on the axis in order to reduce the vibration of the box. And the results showed that the vibration decay at the base frequency was about 20-28 dB [5]. Wang, R. et al. proposed a new control scheme, in which three magnetostrictive actuators are applied directly on the gear body and the actuator generates a circumferential force to suppress the torsional vibration according to the corresponding control strategy. The results of the experiment showed that the vibration decreased by about 7 dB at a base frequency of 250 Hz [6]. Thereafter, Afanas' Ev, V. A., et al. first proposed the idea of lateral vibration control of the gear drive system. The actuator to generate active control force acting on the shaft through additional bearings were adopted, and the active controller based on the LMS method and its improved control algorithm to generate active driving signal was designed. And good control results were obtained [7]. The same approach was used to suppress the vibratory of the rotating machinery by Fukunaga, T.G et al. [8]. Xia et al. fixed the built-in piezoelectric actuator directly on the transmission shaft and also used the FxLMS control algorithm to establish the corresponding active controller. The results of the experiment proved that when the rotation speed was below 180 rpm, the vibration of the plate was reduced by 7 dB [9]. Jiang, S. et al. designed a nonlinear controller which effectively regulates the torque acting on the input shaft gear, which can effectively reduce the impact caused by time-varying engagement stiffness [10]. Major research at home and internationally has found that most studies focus on the theory and process of vibration control at one-phase energy, but there are a few studies on vibration control of secondary and multiphase mechanisms and phase gear transmission system. Thus, this article focuses on modeling, vibration control, and vibration control techniques.

3. Research Methods

3.1. Dynamic Active Control Algorithm of Gear Transmission System. The least mean square algorithm, which can modify

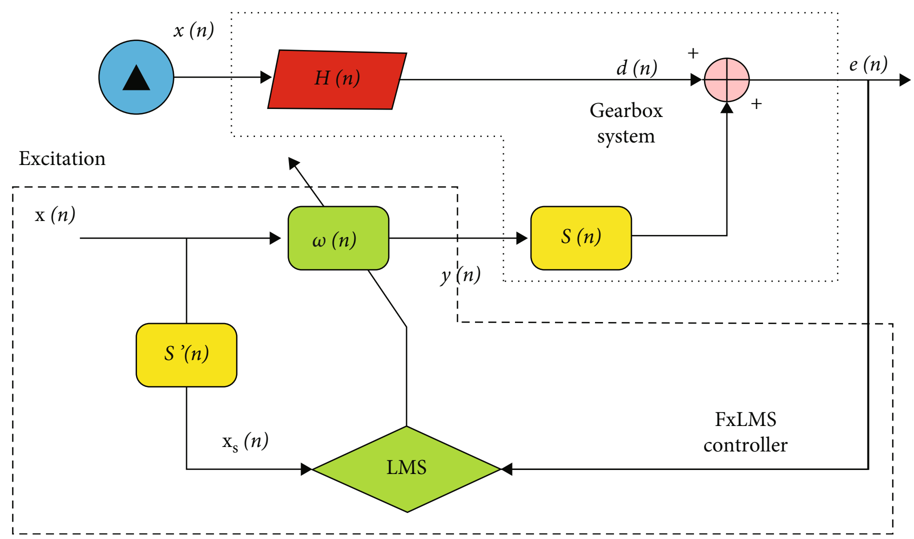

Figure 2: Structural diagram of the FxLMS adaptive algorithm.

the objective function to simplify the gradient vector, is one of the most popular algorithms in adaptive filtering theory and active control research and application, with low computing complexity and easy convergence under steady-state conditions [11].

The principle of active vibration control of the adaptive algorithm method is based on the vibration signal received by the sensor, and the signal is equal to the vibration source and antiphase signal to compensate for the problem. Vibration is directly controlled by adaptive law. A signal equal to the size of the vibration source and opposite to the phase of the vibration source is generated to counteract the harmful vibration. The second channel usually represents the channel from the activator to the fault sensor. The second channel includes the D/A converter, the amplifier, the activator, the physical channel, and the error-sensing main [12]. After filtering the signal used by the second channel, the distribution of the individual values on the autocorrelation matrix of the input signal increases and is not diagonalized. In addition, the integration speed of the algorithm is reduced. To improve the control, it is also possible to introduce a model with a second function to change the signal input and integrate the control algorithm into the solution. In order to improve the control effect, a model with the same transfer function as the secondary channel can be introduced to change the input signal $X(n)$ to ensure that the improved control algorithm can still converge to the optimal solution. The filter using the signal can also be involved in calculating the gradient error. The improved control algorithm is called FxLMS adaptation algorithm [13].

The structure of the FxLMS adaptive algorithm being applied to the active vibration suppression of the multistage gear transmission system is shown in Figure 2. $H(n)$ represents the channel between the excitation source input $x(n)$ and the box vibration $d(n)$. The objective existence of the secondary channel is denoted as $S(n)$. $S'(n)$ represents the estimation model of the secondary channel. The weights w of the adaptive filter are mainly affected by the error signal $e(n)$ and the signal $x(n)$ obtained through the filtering of the secondary channel [14].

The output signal $y(n)$ from the controller actually represents the electrical control signal driving the actuator. And the secondary channel $S(n)$ is modeled with a M step filter (1):

$$S = [S_0, S_1, \cdots, S_{M-1}]. \tag{1}$$

The signal $x_s(n)$ filtered by the secondary channel can be expressed as:

$$x_s(n) = \sum_{i=0}^{M-1} S_i x(n). \tag{2}$$

The force or displacement signal $y_s(n)$ used to characterize the actual control output may be expressed as:

$$y_s(n) = y(n) S_i. \tag{3}$$

The error signal $e(n)$ can be expressed as:

$$e(n) = d(n) - y_s(n). \tag{4}$$

Organize the above formula and form:

$$e(n) = d(n) - w(n)^T x_s(n). \tag{5}$$

As the estimate of the error gradient, the product of $e(n)$ and $x_s(n)$ participates in the weight updating of the FxLMS control algorithm. And the following formula is obtained:

$$w(n+1) = w(n) + 2\mu x_{\hat{s}}(n) e(n). \tag{6}$$

The calculation process of the FxLMS algorithm is shown in Figure 3.

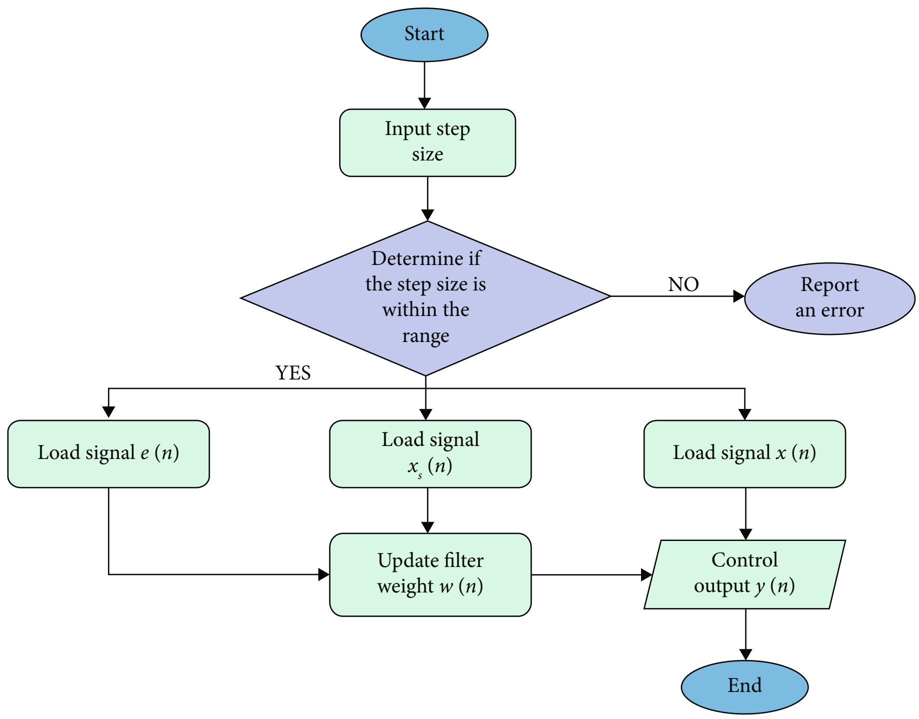

Figure 3: Computational flow chart of the FxLMS algorithm.

3.2. Establishment of Vibration Active Control Cooperative Simulation System of Multilevel Gear Transmission System. The PID controller is widely used in the industrial field for its good stability and strong robustness. As a classical control method, it is still one of the basic applied control methods in the manufacturing field. PID control mainly includes three basic parameters: proportion P, integral I, and differential D. The key to PID control is to adjust the three parameters of the PID controller, so that the output is optimal and the control can achieve the desired control effect [15]. In addition, the stability of the system is mainly affected by control factor P. The key of control factor I is to be used to adjust the system steady-state error. And control factor D is used to control the overall stability of the system and suppress overshoot. The control unit output can be expressed by:

$$u(t) = K_p e(t) + K_i \int_{t_1}^{t_2} e(\tau) d\tau + K_d \frac{de(t)}{dt}, \quad (7)$$

$$e(t) = x(t) - y(t), \quad (8)$$

where $e(t)$ is the error signal, $u(t)$ corresponds to the output of the controller, and K_p, K_i,and K_d correspond to the gains of P, I, and D, respectively.

3.3. Design of the Adaptive Controller. As for the experimental research on active vibration suppression of multistage gear transmission system, the actuator received the instruction from the controller, and the active vibration suppression force output real timely controls the transmission shaft of gear transmission system to suppress the complex vibration at the engagement frequency, so as to achieve the purpose of vibration reduction and noise reduction [16].

In the research of active vibration suppression of gear transmission system, obtaining reference signal plays the important role of vibration suppression. The current frequency estimation methods include spectrum analysis, phase-locking technology, and adaptive trap [17, 18]. Adaptive trap is a digital filter with active conditioning characteristics that can actively adjust with the input instruction. A frequency estimator based on the second order infinite impact response (IIR) adaptive digital trap filter is designed by the LMS algorithm. Due to its simple calculation and strong adaptability, adjusting a single parameter enables frequency estimation. Therefore, it is applied to the acquisition of the reference signal of the secondary gearbox vibration active control system, and then, the two engagement base frequencies are estimated by the vibration acceleration signal.

Set the sinusoidal reference signal as:

$$\mathrm{x}(k) = A \cos(w_0 k + \theta) + v_0(k), (k = 1, 2, \cdots, N), \quad (9)$$

where A is the amplitude of the reference signal, w is the frequency of the reference signal, θ indicates the signal phase, and $v_0(k)$ is the additive Gaussian white noise.

The transfer function of the adaptive filter is shown in:

$$H(z, a) = \frac{N_{(z,a)}}{D_{(z,a)}} = \frac{1 + az^{-1} + z^{-2}}{1 + \rho a z^{-1} + \rho^2 z^{-2}}, \quad (10)$$

where ρ represents the polar radius and determines the width of the notch wave. $a = -2\cos(w)$ is the trap frequency parameter, in which w is the trap frequency of the trap. In the process of the frequency estimation, w will gradually

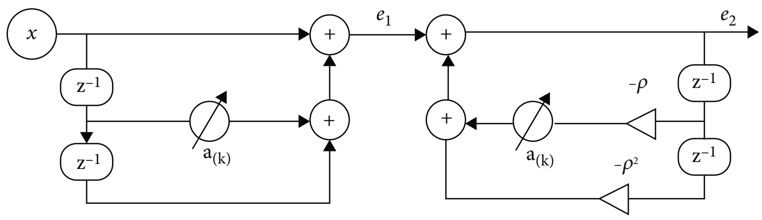

FIGURE 4: The structure of second-order IIR trap.

TABLE 1: Active vibration control effect at the different moving positions of the piezoelectric actuator.

Position controlling means	Position 1	Position 2	Position 3	Position 4
No control	-0.85238 dB	-1.26729 dB	-1.01891 dB	-1.66384 dB
PID	-3.5055 dB	-4.54135 dB	-5.2639 dB	-8.81372 dB
FxLMS	-6.14451 dB	-13.7313 dB	-13.2571 dB	-18.5504 dB

approach w_0, so w can correspond to the estimated frequency of the estimator. The construction of the secondary trap is shown in Figure 4. From the transmission function, signals $e_{1(k)}$ and $e_{2(k)}$ can be expressed in the following formulas after signal $x_{(k)}$ goes through $N(z, a)$ and $H(z, a)$:

$$e_{1(k)} = x_{(k)} + ax_{(k-1)} + x_{k-2}, \tag{11}$$

$$e_{2(k)} = e_{1(k)} - \rho a e_{2(k-1)} - \rho^2 e_{2(k-2)}, \tag{12}$$

$$e_{2(k)} = e_{1(k)} - \rho a e_{2(k-1)} - \rho^2 e_{2(k-2)}. \tag{13}$$

To obtain the best estimated frequency value, the LMS algorithm is adjusted parameter a and the error function is set to $J_{a_{(k)}} = |e_{2_{(k)}}|^2$. And the updated equation of the trap coefficient is shown in

$$a_{(k+1)} = a_{(k)} - \mu \frac{\partial J_{\left(a_{(k)}\right)}}{\partial a_{(k)}} = a_{(k)} - 2\mu e_{2(k)} s_{2(k)}, \tag{14}$$

$$s_{2(k)} = \frac{\partial e_{2(k)}}{\partial a_{(k)}} = x_{(k-1)} - \rho e_{2(k-1)}, \tag{15}$$

where $s_{2(k)}$ is the gradient of the relative coefficient $a_{(k)}$ of the trap output $e_{2(k)}$.

4. Results Analysis

4.1. Optimization of Piezoelectric Actuator Operation Position. The results of the tests show that a new model in order to generate vibration of various transmission gears is being tested. In other words, the control energy is transmitted through a piezoelectric actuator which acts on the base of the core to break the vibration. At the same time, the location of the piezoelectric activator was examined to find better control [19].

For four different positions of the piezoelectric actuator, the PID control and FxLMS control algorithm can excellently reduce the single frequency vibration of the system at 4 times the engagement base frequency [20]. For position 1, at the target frequency, the vibration can decrease by about 3 dB by the PID control. By being controlled with the FxLMS algorithm, the vibration can decrease by about 5 dB. For position 2, the vibration can decrease by about 3 dB by the PID control. By being controlled with the FxLMS algorithm, the vibration can decrease by about 12.5 dB. Similarly, for position 3, the vibration can decrease by about 4 dB by the PID control. By being controlled with the FxLMS algorithm, the vibration can decrease by about 12 dB. For position 4, the vibration can decrease by about 7 dB by the PID control. By being controlled with the FxLMS algorithm, the vibration can decrease by about 17 dB. Specific comparative analysis of the data is shown in Table 1.

4.2. Acquisition of the Reference Signal of the Adaptive Controller. In the practical experiment research, it is also a key link in the controller design with the FxLMS algorithm as the core to estimate the target signal accurately.

To verify the real-time frequency estimation capability of the adaptive trap device, the experimental equipment is used for the experiment tests and analysis. The prime motor rotation speed is set to 1000 r/min. And the system vibration signal is measured to obtain the vibration time-frequency domain signal as shown in Figure 5 [21]. It can be seen that the actual engagement base frequency of high-speed gear pair is 310 Hz and that of low-speed gear pair is 192 Hz.

The second-order IIR adaptive notch device based on the LMS adaptive algorithm takes the real-time vibration signal as the input signal to realize the online estimation of the gear engagement frequency by adjusting the notch frequency and changes the trap to update the step to improve the estimation speed and accuracy. The two traps are connected in series to form a cascade adaptive trap group based on the LMS algorithm, and the vibration acceleration signal of the secondary gearbox is estimated online to obtain the two engagement base frequency [22]. According to the experimental test data, the cascade adaptive trap designed in this paper can accurately and effectively estimate the corresponding engagement frequency of the system, which proves

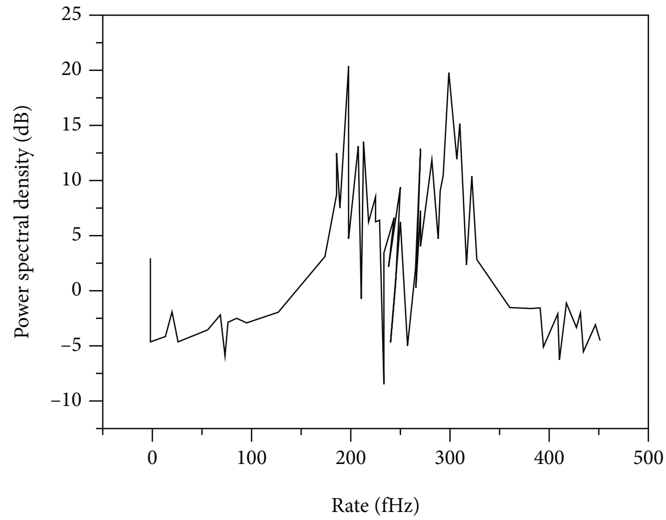

Figure 5: Diagram of vibration and acceleration frequency domain of the gearbox.

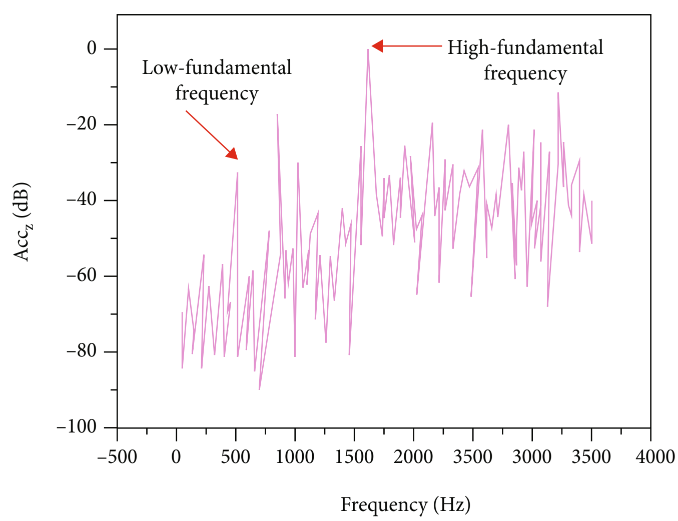

Figure 6: Spectrum diagram of wheel box vibration acceleration signal.

that the proposed frequency estimator is effective in the experimental research.

4.3. Analysis of the Experiment Results of Active Vibration Control of Multistage Gear Transmission System. After developing control logic in the Simulink program for active vibration suppression experiments, a new model of active vibration control of a multistage gear system was developed and tested [23]. The engine speed is set to $n = 2540$ r/min, and the dynamometer load is set to $T = 1$ Nm. Vibration acceleration signals are obtained from the multispeed gear system by receiving data, and the signal processing was indeed shown in Figure 6. Joint frequency and the frequencies of the two forces can be clearly seen. The high-speed dual-gear combination is 804 Hz, and the second to fourth sequences are 1608 Hz, 2412 Hz, and 3216 Hz. A common combination of low-frequency gears is 500 Hz.

As shown in Figure 6, the vibration of the high-speed gear pair is the largest of the second-order double coupling, while the maximum for the lower-speed gear pair is at the third-order double coupling. Therefore, in this paper, the frequency of the gearbox vibration signal is calculated by a two-sequence joint adaptive valve developed by the LMS algorithm, and the frequency signal is provided by the input signal of FxLMS adaptive algorithm and the active vibration control analysis of the corresponding frequency. The benefits of relative vibration control are shown in Figure 6 [24, 25]. The FxLMS adaptive algorithm can handle high-frequency dual and low-speed dual-gear main frequency vibrations in high-speed gear transmission. The frequency of the second phase of the high-speed gear pair is controlled by FxLMS algorithm, and the vibration reduction is approximately 10 dB. At the frequency of the three gears of the lower gear, the vibration reduction using the FxLMS algorithm is approximately 7 dB.

5. Conclusion

In this paper, in order to solve the problem of the complex and time-change vibration caused by the internal engaging excitation in multiphase gear transmission, piezoelectric actuator has been developed to create an active control force that makes the structure of the new active vibration suppression of multistage gear system. The FxLMS adaptive algorithm is designed and active controller used for active vibration suppression of multistage gear transmission. The main activities and research conclusions of the paper are as follows:

(1) Analyze the theory and structure of the FxLMS transition control algorithm in order to generate the vibration of multiple gear transmission, and develop a simulation model for functional vibration control simulation based as FxLMS algorithm. The simulation results show that the FxLMS algorithm can control the vibration of the gear and work efficiently

(2) Obtain a virtual model of a multipower transmission gear developed by ADAMS. After adjusting the functions, the model was sent to Simulink, and the integration for strong vibration suppression was developed using PID and FxLMS algorithms for integration simulation. The benefits of integrated integration have confirmed the functionality of the vibration control model of the new multistage gear. The dynamic position of the internal piezoelectric activator is also optimized. In addition, a comparison and evaluation of the results of multistage gearbox vibration control simulation based on two different control modes of PID and FxLMS algorithms have shown the advantages of control strategy based on FxLMS algorithm

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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