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A Brief Discussion on the Research Progress of the Theory of Dynamic Vibration Reduction with Time Delay

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ABSTRACT

In practical application, the phenomenon of time delay inevitably exists in all kinds of systems. Although the time delay is small, it has a certain influence on the stability and control performance of the control system. In this paper, the rise and development of the time-delay dynamic vibration reduction theory are summarized. Since the time-delay vibration reduction technology was proposed, scholars have conducted a lot of theoretical research, and the research field has expanded from the linear system when it was first proposed to the nonlinear system, and achieved good research results. At present, the main research methods of linear or nonlinear ordinary differential equations with time delay can be divided into time domain method and frequency domain method. The dynamics research of this kind of system mainly focuses on stability analysis, perturbation technology, Holp bifurcation, chaos and so on. The research shows that both linear and nonlinear systems have good application value in vehicle engineering. By selecting reasonable time-delay control parameters, the vehicle body vibration can be greatly suppressed.

Keywords: active control; Time-delay dynamic vibration absorber; Time delay control parameters; Stability switching

INTRODUCTION

With the development of economy and social progress as well as the improvement of people's living standards, cars are becoming more and more popular in people's travel. At the same time, people put forward more and more high requirements for the dynamic performance of the car, such as driving comfort, ride comfort, safety and handling stability, and the quality of these dynamic performance directly depends on the suspension system of the car. Due to the uneven road surface and some rotating parts, the vibration of the vehicle will be stimulated, and the vibration will be transmitted to the cargo and passengers through the suspension, affecting the integrity of the cargo and passenger comfort. At the same time, the vibration of the car will be transmitted to the car parts, destroy the precision and structure of the parts, reduce the use of life of the car. Therefore, how to reduce the body vibration has become a hot topic for experts at home and abroad. Research on vibration damping theory and improve the performance of the suspension system has become an effective measure to improve the dynamic performance of the vehicle.

The main function of automobile suspension is to ease the impact caused by uneven road surface and improve the comfort and safety of passengers. Because the damping and stiffness of the traditional passive suspension are determined according to the structural parameters or the optimization design method, the dynamic performance of the vehicle will be affected to a certain extent. Compared with the passive suspension system, the dynamic performance of the active suspension system has been greatly improved, and the adaptability to different road surfaces has also been greatly improved. Therefore, the active suspension has become the main development trend of the suspension system. Specifically speaking, the active suspension technology mainly has two aspects, that is, the actuator control algorithm. The actuator comprises electrical and hydraulic control damping elements, force generators and related sensors and other mechanical structures and electronic components; Control algorithm [1] is the most critical factor to determine the vibration reduction effect of active suspension system. The study of control algorithm mainly studies the dynamic characteristics of suspension system from the aspects of ride comfort, handling stability and energy consumption. Active suspension control theory is essentially a combination of classical control theory, modern control theory and vehicle dynamics theory. In the past decades, many scholars at home and abroad have carried out a large number of studies on active suspension control theory. The influential foreign scholars include Karnopp, Thompson, Crolla and Langlois et al [2], and the control theory studied involves preview control, variable structure control, stochastic optimal control, ceiling control, etc. With the development of modern control theory, adaptive control, fuzzy control and neural network control have been gradually applied to the design of vehicle active suspension. Domestic research on active suspension system mainly focuses on theoretical analysis and feasibility test study [3].

At first, researchers took time delay as a negative factor into consideration. Later, they found that adding time delay as an active control to active suspension could achieve a good vibration reduction effect, and cleverly used time delay to control the dynamic behavior. In addition, due to the inherent damping effect of the time delay itself, the phase can be changed, and the vibration of the system can be reasonably reduced by using the time delay. The time-delay vibration reduction theory has been studied for many years.

It has become a hot research topic to introduce time-delay feedback theory into active suspension to improve the vibration reduction performance. The application of time-delay feedback control in active suspension, because of the introduction of new active control parameters, makes the system controller adjustment has greater flexibility, and has a more ideal vibration reduction effect, has a better practical significance to improve the dynamic performance of the vehicle.

DEVELOPMENT OF LINEAR TIME-DELAY DYNAMIC VIBRATION REDUCTION THEORY

Dynamic shock absorber theory has been developing for decades. Long ago, people developed various shock absorbers, among which the representative is dynamic shock absorber. The traditional passive dynamic vibration absorber has become the main object of various applications because of its simple structure, easy to design and manufacture, and obvious damping effect. It connects the auxiliary mass to the object vibration system through the elastic element. Its vibration damping mechanism is not realized through the energy consumption, but through the dynamic action of the auxiliary mass, which makes the elastic element produce the same or opposite force as the excitation in the main system, so as to realize vibration damping. The traditional passive dynamic vibration absorber also has obvious defects, that is, when the excitation frequency is equal to the natural frequency of the main system and resonates, the vibration reduction effect of the dynamic vibration absorber has practical significance. When the natural frequency of the dynamic vibration absorber is adjusted to be different from the excitation frequency, the dynamic vibration absorber cannot absorb and reduce the vibration well. In order to broaden the working frequency band of the vibration absorber and improve the vibration reduction effect of the vibration absorber, Xu Zhenbang et al [4] developed a mechanical frequency adjustable dynamic vibration absorber by adjusting its own geometric parameters to adjust its natural frequency, and designed the corresponding control method, and the experimental platform shows that the vibration reduction effect is good.

With the development of active vibration control technology, more and more studies show that delay feedback can also be used as an active control item in active vibration control technology, reasonable use of time delay can improve stability and vibration control effect. In the 1990s, the famous scholars Olgac and Holm-Hansen [5] introduced time-delay displacement feedback into the traditional dynamic vibration absorber for the first time to reduce the vibration of the main system as partial state feedback, so it is called time-delay passive vibration absorber. The advantage of the time-delay dynamic vibration absorber is that it eliminates the vibration of the main system over a very wide frequency range and can be adjusted in real time. This feature enables the absorber to eliminate the dynamic response of the main system under different frequency harmonic loads. Subsequently, Olgac and Holmhansen [6] studied the stability of the combination of the main system and the time-delay vibration absorber by using the Modified Nyquist method and the Root Locus analysis, and especially studied the vibration reduction performance of the excitation frequency varying with time. Through numerical simulation, the validity of Nyquist criterion is proved, and the advantages of this absorption technique over traditional vibration absorber are demonstrated in the case of time-varying excitation frequency, and the absorption of time-varying excitation can be tuned quickly.

DEVELOPMENT OF MULTI-FREQUENCY AND VARIABLE FREQUENCY TIME-DELAY DYNAMIC vibration reduction theory

Previous work is based on the vibration system of a single frequency external excitation to reduce vibration, but when the vibration system is subjected to two different frequencies of external excitation how to reduce vibration? Olgac and Elmali et al [7] first thought of this problem and proposed two methods. The first method is the dual utilization of single-frequency time-delay dynamic vibration absorber, that is, two time-delay shock absorbers are used to eliminate the vibration caused by two excitation frequencies respectively. The advantage of this approach is that the frequency adjustment can be implemented through decoupling control, which may be a preferred mode of operation, especially in the case where the two most harmful excitation frequencies vary over time. However, the stability analysis of this method is not simple, because there are two different time-delay feedbacks, the installation of two time-delay dynamic vibration absorbers cannot be collinear, and the improved Nyquist criterion is of no help. Another method is to design a linear time-delay dynamic vibration absorber with fixed frequency modulation. By adjusting the feedback gain and time delay, the substructure of the vibration absorber can display two resonant frequencies simultaneously. That is, it acts like a fixed frequency combination on a time-delay dynamic vibration absorber. Taking double harmonic excitation single mass damper as an example, the stability analysis and design analysis are carried out. By innovatively studying the feedback gain coefficient and time delay, the vibration of the main system can be completely eliminated, and the vibration reduction problem of the main system in the case of dual-frequency coupling is solved. Jalili and Olgac [8] verified an elastic beam experiment based on the vibration reduction mechanism of a fixed frequency modulated linear time-delay dynamic vibration absorber, and obtained a good vibration reduction effect. Subsequently, Olgac and Huang [9] considered a multi-frequency vibration absorber, and placed a multi-degree-of-freedom passive shock absorber and a time-delay dynamic vibration absorber for tuning on the main system. When the external excitation frequency contains two time-varying frequencies, the vibration of the main system can be completely eliminated by using appropriate time delay and feedback gain in the feedback. In 1999, Renzulli [10] et al. proposed a new tuning algorithm, the robust control algorithm, which can adjust the feedback gain and delay in real time under the condition of time-varying external excitation frequency.

The above-mentioned damping principle is to absorb the vibration energy of the main system through the resonance of the shock absorber. Through a series of studies, it is found that no matter the external excitation frequency is single frequency or dual frequency, no matter it is constant or changing with time, it can only work under a certain external excitation frequency. However, in practice, there are many kinds of harmonics within a certain range of external excitation frequency, so the time-delay dynamic vibration absorber cannot meet its requirements. Jalili and Olgac [11] on the basis of the time-delay dynamic vibration absorber which is used to improve, in this article, put forward the specific frequency range delay feedback of shock absorber that is optimized by nested identification and control program. The shock absorber minimizes the vibration of the main system at the peak response frequency. The olgac team's research on the delay damper shows that the delay damper has many advantages over the dynamic absorber, such as adjusting the damping band width in real time, being easy to implement and being adaptable to variable frequency excitation.

TIME-DELAY STABILITY INTERVAL ANALYSIS

The time-delay problem in vibration control system has also attracted the attention and research of relevant domestic scholars.

Zhao Yanying and Xu Jian [12] studied the vibration and stability behavior of time-delay dynamic vibration absorber by using the direct method, and obtained the time-delay stability region and instability region of main system and dynamic vibration absorber under a certain feedback gain coefficient. In this time-delay stability interval, the dynamic vibration absorber can effectively absorb the vibration of the main system, and the correctness of the theoretical analysis is verified by numerical simulation. Zhang Wenfeng et al [13] used numerical method to study the 1/4 time-delay vibration reduction model with "ceiling" damping control, and gave the full time-delay stability interval under different "ceiling" damping control gain and the critical time-delay of system instability. Subsequently, Zhang Wenfeng and Hu Haiyan [14] studied the LQ control suspension with time delay, and adopted the generalized Sturm criterion for the first time to give the full time-delay stability region under different control gains. Wang Zaihua and Hu Haiyan [15] used the stability switching method to analyze the stability of time-delay systems, and analyzed the time-delay stability interval by judging whether the polynomial equation has positive real roots and the number of real roots.

THEORETICAL AND EXPERIMENTAL ANALYSIS OF LINEAR DELAY VIBRATION REDUCTION

In recent years, Sun and Xu [16] based on the 2-DOF model of the main system and the time-delay dynamic vibration absorber, designed a controllable mechanical device to realize the time-delay feedback control, and obtained the value of the inherent time-delay in the feedback control loop through hammering test. The experimental results and theoretical analysis show that the time-delay vibration absorber can effectively suppress the vibration of the main system, and when the passive vibration absorber fails, the time-delay vibration absorber can effectively improve the suppression performance. Subsequently, Xu and Sun [17] proposed a time-delay vibration absorber with acceleration feedback control, which changed the passive vibration absorber into a time-delay vibration absorber and was used to reduce the vibration of a single-degree-of-freedom system under fundamental excitation. By designing an experimental device to observe the performance of the time-delay vibration absorber, the analysis and experimental results show that when the time-delay vibration absorber has a damping frequency band and the passive vibration absorber is ineffective, the vibration of the main system can be effectively suppressed by selecting the appropriate feedback gain coefficient and the value of the time-delay.Hu et al [18] studied the multi-objective optimization of the time-delay dynamic shock absorber by taking the linear 2-DOF system with random excitation as the object and using the continuous time approximation method to analyze the stability of the time-delay. The target function of the delay system is the peak frequency response of the structure, the vibration energy and the control force of the main structure. Zhao [19] proposed a time-delay dynamic shock absorber for 2-DOF torsional vibration system, focusing on the optimal design of control parameters of the time-delay dynamic shock absorber for active system. The genetic algorithm is used to obtain the optimal feedback gain coefficient and delay value, so that the system has a good damping effect over a wide range of external excitation frequency. The time-delay problem in vibration control system also caused the attention of many scholars, domestic Xu Jian, Zhao Yanying [20]-[23] to delay and delay linear dynamic vibration absorber which is used to research results show that the nonlinear dynamic vibration absorber which is used in the system stability in the region, on the premise of guarantee the stability of system, the main system of vibration can be delay effective dynamic vibration absorber which is used to restrain, Further study shows that the stability control range of the nonlinear dynamic vibration absorber is wider than that of the linear dynamic vibration absorber.

DEVELOPMENT OF NONLINEAR TIME-DELAY DYNAMIC VIBRATION REDUCTION THEORY

Thanks to the development of nonlinear dynamics, more and more researchers have introduced the time-delay vibration absorber into the nonlinear system to study whether the nonlinear system can have a better effect on vibration control. Zhao Yanying and Xu Jian [24] introduced time-delay state feedback into the nonlinear system and studied the damping effect of the nonlinear time-delay dynamic absorber on the main system. The results show that for a given feedback gain coefficient, there is a delay damping interval and a "maximum damping point" in the interval under the stable condition. For different feedback gain coefficients, the amplitude of the "maximum damping point" is different, so there is an optimal set of feedback gain coefficients and delays that can stabilize the system and minimize the amplitude. In the following part, the paper conducts numerical verification and finds that the amplitude of the main system can be reduced by 90% compared with that of the passive suspension under the delay feedback gain, which also indicates that the delay feedback control has a very good effect on the vibration reduction of the nonlinear system. Subsequently, Zhao and Xu et al [25] studied the influence of time-delay feedback on nonlinear vibration and suppressed the vertical displacement vibration of a 2-DOF nonlinear system with external excitation. The results show that when the main resonance and 1:1 internal resonance occur in the system at the same time, the appropriate feedback gain coefficient and time delay can be selected, and the positive feedback control or negative feedback control can achieve relatively large vibration reduction effect. However, under the action of sometime delays, the damping effect of the system is ineffective, and the system may have bifurcation and chaos. With the increase of the feedback gain coefficient, the dynamic behavior of the system will become very complex. Sun and Xu [26] proposed a time-delay active control combination structure coupled by a shock Absorber and a vibration Isolator, and constructed the vibration control of a absorber-isolator-combined structure. Based on the analysis of the multi-scale control mechanism, the comprehensive effects of nonlinear and time-delay on vibration suppression and energy transfer are discussed in detail, and the vibration control performance under the condition of internal resonance is studied.

CONCLUSION

At present, most of the research on time-delay vibration reduction is on the vibration absorber. By adjusting the feedback gain coefficient and time delay, the natural frequency of the shock absorber is equal to the frequency of the external excitation so as to generate resonance. Through resonance, the external input energy is completely absorbed by the shock absorber, and the vibration of the main system is almost eliminated by using this method. Since the working characteristics of the vibration absorber determine that it mainly works near the resonant frequency, the research on it is also focused on the resonant frequency, but this cannot reflect the advantage of time delay control for random vibration system control.

The advantage of the linear time-delay dynamic vibration absorber is that it can adjust the feedback gain coefficient and the time-delay value in real time according to the external excitation frequency, and can completely eliminate the vibration of the main system in some cases, but the adjustable range of the time-delay is relatively small.

The nonlinear time-delay dynamic vibration absorber has wider damping frequency band than the linear time-delay dynamic vibration absorber. If appropriate active control parameters are selected, the nonlinear system and time-delay can be combined to obtain a wider delay adjustment range, and the vibration reduction effect can be greatly improved. With the development of nonlinear dynamics, the improvement and application of nonlinear vibration reduction methods will be further promoted. Time-delay can also act as a stability switch to control the motion of a system, from ordered motion to complex motion or from complex to ordered motion. In recent years, the trend of time delay is from theoretical analysis to applied research, and the results of the analysis should be applied to real life and work. For example, the time-delay dynamic vibration absorber is applied to the sway of helicopter blades, synchronization of communication delay, and active control of cutting process.

Previous researches on time delay by scholars are relatively complete, and I think there are several points that can be regarded as the key directions of future.

(1) Previous researches are all based on single frequency or superposition frequency, and it is also necessary to study the effect of pavement random excitation on time delay vibration reduction.

(2) There are many researches on Holp bifurcations in time-delay nonlinear systems, but few researches on other bifurcations.

(3) According to the theoretical analysis, the coupling of nonlinear and time delay has a good damping performance, which should be verified by further experiments. However, the experiment of nonlinear control is more difficult, not to mention the time delay, which should be a promising research direction.

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