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Research Progress of Stewart Vibration Isolation Platform

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Abstract. Many fields, such as optics, aerospace, ultra precision machining, etc., have high requirements for vibration in all directions of the system. Stewart platform is widely used in multi degree of freedom active vibration isolation. This paper summarizes the Stewart vibration isolation platform. Firstly, it introduces the structure of Stewart vibration isolation platform, including various configurations, flexible kinematic pairs, actuators, etc., and summarizes the influence of different structures on vibration isolation and practical applications. Then the modeling of Stewart platform is introduced, and various modeling methods, advantages and disadvantages are summarized from the aspects of kinematics and dynamics. Thirdly, the active vibration isolation control technology is introduced, and the application and development of the main control methods are summarized. Finally, combined with the development of Stewart vibration isolation platform in recent ten years, this paper points out the shortcomings of existing research and the direction of improvement.

Keywords. Stewart platform, active vibration isolation, actuator, kinematic model

1. Introduction

In 1947, Gough and Whitehall [1] pioneered the Gough Whitehall platform, a six degree of freedom parallel mechanism, which is used to detect the compression of automobile tires in all directions. In 1965, the German scholar Stewart put forward a parallel mechanism flight simulator [2] with six degrees of freedom motion capability. This mechanism includes two upper and lower platforms (commonly referred to as load platform and base platform) and six retractable supporting rods. The rods are connected with the platform through spherical joints. This mechanism is named Gough Stewart Parallel system, or Stewart platform for short. Stewart platform can be divided into three forms as shown in figure 1 according to different hinge links, namely 6-6 structure, 6-3 structure and 3-3 structure [3].

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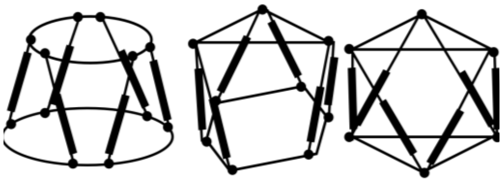


Figure 1. Stewart platform configuration.

Stewart platform has the characteristics of stable structure, large bearing capacity and high precision [4], so it is widely used. It is mainly divided into two categories: one is used as robot actuator or motion simulation device [5-9], and the other is used as precision vibration reduction and isolation device.

In the aspect of vibration isolation application, Geng, Z.J [10] 1994 studied the cubic Stewart vibration isolation platform through robust adaptive algorithm combined with magnetostrictive actuator, and the maximum attenuation is 30dB. Stewart platform is most commonly used in vibration reduction of satellite components. The U.S. Army engineering company cooperates with JPL [11] to develop a cubic Stewart platform structure to isolate the vibration of the satellite momentum wheel, using force feedback signals. Hood Company and Washington University [12] jointly developed a cubic Stewart Platform Based on voice coil motor. The platform increases the displacement of voice coil motor, and uses flexible links, including positioning and vibration reduction, to reduce vibration by 20-25db in the range of 5-20Hz. The vibration isolation application of Stewart platform was first proposed in China in 2006 [13]. In 2007, Harbin Institute of technology [14] developed the cubic Stewart platform for the vibration isolation of the whole satellite system. The piezoelectric actuator is used to design the robust control, which has a good effect on the closed-loop feedback. Changchun Institute of optics, precision mechanics and physics, Chinese Academy of Sciences [15] designed an active vibration isolation system for space optical remote sensor. Beijing University of Aeronautics and Astronautics [16] aimed at the precision load on the vehicle, designed the high-performance actuator of the Stewart platform, and laid the foundation for in-depth research.

Based on Stewart's six dimensional vibration isolation technology, this paper summarizes its structure development, system dynamics modeling method, matched actuator development, vibration isolation control method as the main analysis objectives, and provides some thoughts for the development direction.

2. Research on Stewart Platform Structure

2.1. Stewart Platform Configuration Development

Many domestic and foreign scholars have optimized the Stewart platform configuration. In 1988, Behi proposed [17] a three legged PRPs (prismatic, revolutionary, spherical joint) mechanism; In the same year, Hudgens and Tesar [18] proposed a mechanism with six telescopic legs, each of which is composed of a four-bar mechanism. Kevin cleary and Thurston brooks [19] designed a four degree of freedom platform composed of three outriggers.

In 2002, Professor Longhui Chen [20] made mechanism singularity analysis for Stewart Parallel structure, and used kinematics method to analyze and determine 7 types and motion properties of Stewart singularity. Yang et al. [21] carried out dynamic isotropic design for the six flexible modes of Stewart cubic configuration with geometric parameters, mass parameters and inertia parameters as variables, adopted force feedback vibration isolation decoupling control for the six degrees of freedom, and designed a decentralized active controller. Xiaofang Li [22] used genetic algorithm to analyze the mass ratio, damping ratio and natural frequency ratio of the platform, and obtained the result that the harmonic peak value of the outrigger amplitude frequency curve was the smallest. The five parameters of Stewart platform, including the diameter of the upper and lower platform, the angle between the short sides of the upper and lower hinges, and the platform height, are the main influence of the platform's displacement, velocity, acceleration and other motion indicators. Chaoxin Wang [23] analyzed the modal shape of the system by using the method of subsystem frequency response function synthesis for the Stewart vibration isolation platform, and improved the overall stiffness and modal shape by changing the size of the platform and outriggers. University of Chinese Academy of Sciences [24] used simulation calculation optimization to increase the angular deflection for these five parameters. Li [25] used the homogeneous Jacobian matrix formula of dual quaternion to optimize the design of Stewart platform vibration isolator to reduce the coupling degree and obtain the optimal configuration of 3-3 SPS mechanism.

2.2. Stewart Link Development

In the field of micro vibration, due to the return clearance, friction, crawling and other factors of the traditional spherical joint, the vibration isolation effect is greatly affected, and the influence of wear and lubrication should also be considered. For high-precision devices and other micron level vibrations, flexure hinges overcome the above shortcomings. The design of sexual hinge shall meet the following requirements:

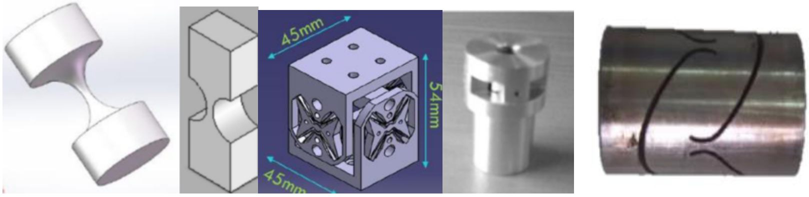
(1) High axial stiffness: it can stably transmit the driving force of outrigger to the moving platform.

(2) Low bending stiffness, low torsional stiffness: for the replacement of spherical flexure hinges, both are required; For Hooke hinge and other two degree of freedom hinges, only low bending stiffness is required, and the torsion angle can be ignored. This performance index is very important for precise vibration isolation in low displacement situations with small radian, and it is an important index to ensure the control force to achieve vibration isolation.

(3) High shear stiffness: increasing the local mode of the outrigger can improve the vibration isolation performance.

(4) Zhu Shi [26] designed the universal flexure hinge according to the requirements of Stewart platform dynamics index strength, as shown in figure 2(a), analyzed the influence of the notch thickness of the universal flexure hinge on the material strength, and met the vibration isolation requirements of optical remote sensing. Yijing Luo [27] designed the flexure hinge with circular arc flexure hinge for Stewart platform and verified its safety, as shown in figure 2(b). Jian Jiao [30] designed the flexible ball hinge, and its mechanical properties were verified by simulation and test. The average drop in the vibration isolation experiment was more than 5dB, indicating that the load of the flexible Stewart Parallel Platform also has a good active control effect. Han Li [28] combined the butterfly flexible mechanism as shown in

figure 2(c) with Hooke hinge to design a flexible Hooke hinge with two degrees of freedom, with a maximum stroke of 10.Chaoxin Wang designed the flexible hinge of equivalent spherical joint, as shown in figure 2(e). The deformation in the x-axis direction reached 33 μm, the maximum displacement of the platform reached 11 μm, and the bending strength met the use requirements.



(a) (b) (c) (d) (e)

Figure 2. Several flexible kinematic pairs.

John E [29] considered the influence of flexure hinge on motion, took the acceleration factor of hinge into dynamics, adopted feedback compensation, and proposed flexure hinge design criteria to prevent insufficient hinge stiffness and increase dynamic complexity. Ahmed [30] used the flexible hinge when building the Stewart vibration isolation platform in 2003, as shown in figure 2(d). By analyzing the natural frequency of the hinge joint, it is concluded that the small stiffness will lead to the decline of the closed-loop performance. Kang, B. H [31] designed a precision motion platform based on flexible joints with the motion range and stiffness as performance indicators and the maximum node stress and design parameter bounds as constraints. Ranganath, R. [32] improved the Stewart type force sensor by replacing the ball joint with a flexible hinge, and obtained similar results while avoiding the effects of clearance and friction.

3. Actuator Technology

With the cross development of materials, chemistry and machinery, actuators used for active vibration isolation are not limited to motors. Nowadays, intelligent materials are booming, mainly including piezoelectric, giant magnetostrictive, memory alloy, magnetorheological / electrorheological, polymer and other materials. Compared with traditional devices, they have overcome the problems of motion amplitude gap, friction, wear and other problems, and in terms of accuracy, bearing capacity the vibration isolation frequency band has been significantly improved. The amplitude and frequency band of Stewart platform vibration isolation are often different according to different practical applications. The selection of actuator shall consider its output performance, including whether the output force, displacement, speed, acceleration, etc. meet the application occasions of vibration isolation. Table 1 summarizes the performance of the main actuators today. According to the feedback physical quantity or control mode, the appropriate type should be selected according to the cooperative actuator principle. At the same time, the actuator should also be easy to drive, suitable in size, easy to assemble; less affected by temperature, and has the appropriate motion frequency band. The power, stiffness, economy and other conditions should also be considered.

Table 1. Summary table of vibration isolating actuator.

Actuator	Characteristic	Application scenario	Feedback mode	vibration isolation bandwidth (Hz)
Electromagnetism actuator	Fast response, wide working frequency band, medium displacement, large output force, and mature technology	Wide range, high precision, vibration isolation frequency bandwidth	Force Speed Accelera-tion	5~200
Piezoelectric actuator	Fast response, small output force, small displacement, high energy conversion efficiency, hysteresis, and high requirements for the algorithm	Occasions with high precision, low frequency and low bearing capacity	Force Accelera-tion	5~200
Magnetostrictive actuator	Fast response, wide working frequency band, large output force, large shape variable and strong nonlinearity	High frequency, bearing capacity general vibration reduction occasions	Force Accelera-tion	10~100
Pneumatic / hydraulic actuator	The response speed is slow, the output of force and displacement is large, the hysteresis phenomenon is obvious, and the auxiliary equipment is complex	Application of low frequency vibration isolation for large mechanisms	Accelera-tion	0~50

3.1. Electromagnetic Actuator

In terms of electromagnetic vibration isolation, voice coil motors (VCM) are mainly used. It is a DC servo motor based on Ampere force. It has linear drive and PWM drive methods. It has the characteristics of simple structure, easy control, small size, high acceleration and fast response [33], and is widely used in the fields of precision positioning and active vibration reduction [34]. The United States, Japan, Britain, China and other countries have carried out a series of research on voice coil motor. In 1995, JPL laboratory in the United States developed a six degree of freedom flexible spring vibration isolation platform for satellite vibration isolation. The dynamic displacement of voice coil motor is 0.25mm. The acceleration feedback method is used to isolate vibration at 3~60hz, which improves the control speed and robustness. The vibration isolation effect of cubic Stewart platform reaches 20dB. The University of Brussels (ULB) [35] in Belgium has designed a cubic Stewart mechanism. The stator and the mover of the voice coil motor of the outrigger mechanism are connected by diaphragm springs. The diaphragm has large radial stiffness, small axial stiffness, 2.5mm axial displacement and 1.5° rotation angle. The vibration isolation effect is effective in 5~400Hz. In 2005, Taiwan scholar Chen et al. Established a vibration isolation platform by using voice coil motor [36], and achieved good dynamic effect in the range of 0~50hz by using the characteristics of notch filter and combining the root locus theorem. In 2009, the Institute of automation of the Chinese Academy of Sciences carried out the research on Stewart vibration isolation platform [37-38]. The voice coil motor combined with robust control neural network control was used to achieve about 45dB vibration isolation effect in the translational direction and about

25dB vibration isolation effect in rotation. Junbing Qian [39] designed a voice coil motor for precise active vibration isolation, and improved the magnetic field structure through two magnetic field air gaps and four permanent magnets to obtain a larger motor thrust constant. At the same time, the equivalent magnetic field of traditional voice coil motor is optimized, and the equivalent model of magnetic source and magnetic circuit is separated by decoupling method, which makes the magnetic field analysis more accurate.

3.2. Piezoelectric Actuator

The principle of piezoelectric actuator is negative pressure effect. When the piezoelectric material is placed in the electric field, it will cause the deformation of the object and produce the phenomenon of elongation or compression. The most commonly used piezoelectric material in Stewart platform is piezoelectric ceramic, which has fast response speed and high precision. Piezoelectric ceramics are also widely used in composite actuators, such as piezoelectric ceramic composite, linear motor, ball screw, etc. [40]. Linear motor and piezoelectric ceramic composite, magnetostrictive actuator and piezoelectric ceramic composite [41]. In 2008, Beijing University of Aeronautics and Astronautics made Stewart vibration isolation platform [42] based on ball screw and piezoelectric ceramic composite actuator. The overall positioning error is less than 1um, and the response is fast and high. The displacement of the piezoelectric actuator used by Chaoxin Wang is 38 μm, and the thrust can reach 1200n. In the micro vibration control, the 30~210Hz active vibration isolation is 10~30dB more attenuated than the passive vibration isolation acceleration. Yushi Li [43] et al. used the active and passive vibration isolation method composed of piezoelectric ceramics and rubber. The translational vibration isolation was reduced by 4~8 μm, the rotational vibration isolation was about, and the vibration isolation effect reached 75%~85%. This method is small in size and light in weight, and is suitable for aircraft shock absorption.

Function in the low-frequency band should be increased as much as possible, so the selected W_1 is a real rational function with low-pass characteristics.

3.3. Giant Magnetostrictive Actuator

The giant magnetostrictive actuator inputs alternating current through the coil to generate a transformed magnetic field, which makes the giant magnetostrictive material (GMM)generate stress and strain, and drives the output rod to move, so as to achieve the effect of vibration reduction [44]. Z. Jason Geng designed a magnetostrictive actuator with a displacement of 127 μm. The method of robust adaptive control is adopted to achieve about 30dB attenuation. Beijing University of Aeronautics and Astronautics designed the Stewart vibration isolation platform through giant magnetostrictive actuator, and gave the solutions of broadband micro amplitude vibration isolation of large load objects and vibration isolation and stabilization of large disturbance engineering objects respectively [45]. Zhongquan Gu, et al. [46] developed a giant magnetostrictive actuator for active vibration isolation. Combined with the feedforward adaptive filtering algorithm, it has verified good robustness, and the frequency response density has been reduced by more than 80%.

In addition, Stewart vibration isolation actuator also has magnetorheological damping vibration isolation [47]. Yong Liao designed magnetorheological damping actuator, with maximum output force of 1.5kn and maximum displacement of 55mm. The change of damping force is controlled through ceiling damping control. In the 3~5Hz resonance region, the translational vibration isolation is 22~40%, and the rotational vibration isolation of XZ axis is about 50%. Stewart pneumatic active vibration isolation has also been studied [48]. Daye Xu selected eight pneumatic actuators to achieve six degrees of freedom fault-tolerant control. The vibration isolation frequency band is 5~50Hz, which significantly suppresses the vibration peak.

4. Stewart Platform Modeling

4.1. Stewart Kinematic Model

Stewart kinematics solution, like other parallel mechanisms, has forward and inverse solutions. Even if the forward solution solves the six coordinates of the moving platform according to the parameters of each leg, the inverse solution solves the input position parameters of the six legs according to the pose of the moving platform.

The reverse solution generally adopts the rotating coordinate system method, and the most commonly used ones are Euler coordinate system or Kardan coordinate system [49], which are in the Cartesian coordinate system. The coordinate axis is rotated step by step to obtain the position and attitude conversion matrix of the moving platform, and then the outrigger vector is obtained according to the upper and lower fulcrum coordinates, and the outrigger speed relationship is established by using Jacobian matrix [50].

There are many studies on the positive solutions of the 6-DOF Stewart platform, and there are at most 40 sets of solutions [51]. As early as 1984, Fichter confirmed the conclusion that the exact solution could not be obtained through a numerical method of kinematic forward solution [52]. At present, the methods of positive solution mainly include elimination method [53], Newton Raphson method [54], interval analysis method [55], numerical calculation method, neural network method [56], and quaternion coordinate method [57].

The elimination method is a closed solution of Stewart's positive solution. The elimination methods include resultant elimination method, Wu method, vector elimination method and grabner basis method [58]. The elimination method has fast convergence, but it needs to be screened to get an effective solution. The solution of the elimination method is still unstable and may produce missing solutions [59].

Newton Raphson method is a kind of numerical iteration method, which is based on the inverse kinematics solution. After the initial value is given, the iterative calculation reaches the accuracy threshold and gradually approaches the attitude of the moving platform. Its mathematical model is simple, versatile and accurate, but it is highly dependent on the initial value. If the initial value is selected improperly, the result will not converge or the convergence value is incorrect [60]. Shijing Li [61] used Newton Raphson method and continuation method to construct homotopy equation, selected iterative initial values, and improved many shortcomings of traditional methods in efficiency and computational stability. Zhang Hui improved the iteration efficiency by improving the Jacobian matrix. Wenwei Dai [62] compared the vibration isolation kinematics of the 6-SPS platform with the Lie group lie algebra method and the Newton Raphson method, and confirmed that the lie algebra method does not need to estimate the six coordinate position and attitude, and has strong accuracy and real-time performance. The effect of using the lie algebra positive solution method in the vibration isolation simulation is about 90%.

Using genetic algorithm, neural network and other methods to optimize the solution can obtain the unique solution more accurately, but the algorithm is time-consuming and needs high-quality hardware support, which is insufficient in implementation. Lile He, et al. [63] proposed a method of using GA+BP hybrid algorithm to solve the forward position solution of the six degree of freedom parallel platform. The neural network can solve the iterative initial value of Newton Raphson method to obtain a more accurate solution.

Due to the high nonlinearity and coupling, Stewart platform forward solution method can not get analytical solution, which has always been a difficulty in the research of parallel robot. The solution to the forward solution problem not only needs algorithm, but also needs to be selected in combination with mechanism configuration, size, sensor accuracy layout, etc. At present, it is constantly improving and optimizing in the direction of simplicity, accuracy and efficiency.

4.2. Stewart Dynamic Model

Stewart dynamics is the key to analyze the actuator force and control effect of vibration isolation platform. Dynamics is also divided into positive solution and inverse solution. The positive solution is to solve the equation of motion through the six bar driving force; the inverse solution is to solve the driving force according to the motion. At present, the main Stewart dynamic methods are divided into impedance method, admittance method, Newton Euler method, Lagrange method, Kane method, virtual work principle, elastic comprehensive connection method, Hamilton canonical equation Boltzmann Hamel equation and Roberson Wittenburg method.

The commonly used method is Newton Euler. Newton Euler method is based on the method of rigid body dynamics, which represents the motion state of the platform and outrigger with a certain point, and establishes the mechanical equation in the space coordinate system in the form of vector. Although the derivation process is intuitive and simple, there are many formulas, which are cumbersome, and involve a lot of reaction forces and moments. Therefore, compared with other methods, its modeling process is simple and easy to solve, but there are many vector calculations.

The admittance method is to calculate the frequency response function of each outrigger structure, establish the boundary conditions through force balance and displacement, and then solve each structure simultaneously to obtain the Stewart dynamic model. The admittance method based on the frequency response function can reflect the natural frequency and other dynamic characteristics, but when the platform structure is complex and there are many single elements to be analyzed, the calculation is large and difficult to operate.

Lagrange method [64] is a kinematic equation based on the viewpoint of energy. The key is to select appropriate generalized coordinates and calculate the kinetic energy of the system to avoid binding calculation, but the calculation of partial derivatives is also more complex. Chen Li published for the first time in China about the establishment of a complete parallel mechanism dynamic model based on Lagrange method, making a certain breakthrough in the series control algorithm to the parallel robot.

The principle of the virtual work method is to establish the Stewart platform dynamic equation with the virtual work principle. Through the generalized force, the force generated by the joint force and other interactions is omitted, and there is no energy equation, so the complex derivation is avoided. The commonly used fictional method is Kane method [65]. Kane's process of establishing the dynamic model is simple and the direct results are very concise. The main idea is to calculate the generalized active force and generalized inertial force in the multi rigid body system, avoiding the calculation of binding force and partial derivative of kinetic energy to generalized coordinates.

5. Control Method

An important application of Stewart platform is active vibration isolation. Active vibration isolation also becomes active vibration isolation. By adding active vibration isolation components, including actuators, controllers, sensors, signal acquisition devices and other equipment, the energy transmission of vibration sources to loads can be reduced. Passive vibration isolation has good stability, reliability and economy. It has obvious effect at high frequency, but it has poor inhibition ability at low frequency, and even amplifies the vibration. Active vibration isolation is mainly for low-frequency vibration isolation, and has strong adaptability to the environment, so the control mode can be changed. Therefore, Stewart vibration isolation usually adopts the active passive integration method, also known as hybrid vibration isolation. In addition to the stiffness and damping conditions of passive vibration isolation, the active control method also has a great impact on the vibration isolation effect. Stewart has many kinds of six degree of freedom vibration isolation algorithms, including feedforward control, feedback control and compound control. At present, the widely used active control methods include adaptive control, fuzzy control, robust control, optimal control, synovial control and neural network control. In recent years, compound control methods have gradually increased. The control methods of Stewart platform with different structures and different applications are the upsurge of research.

Adaptive control is a process of continuously approaching the target. Certain rules and methods are designed to continuously change the system parameters or structure according to the real-time input and output values of the system, as shown in figure 3, the input signal is processed by the controller and applied to the object to generate an output signal, which is compared with the reference signal to form an error signal. The adaptive controller adjusts the controller parameters according to the error signal and the input signal to minimize the error, this is the principle of adaptive control. Adaptive control does not need an accurate model, but can control the approximate system model through online identification or offline identification. The most commonly used algorithm is least mean square (LMS), which was first proposed by American scholar Widrow. Based on the LMS algorithm, a series of algorithms are proposed. Shanghai Jiaotong University [66] uses the adaptive algorithm of the x-least mean square controller (FX-LMS) based on finite impulse responses (FIR) to build a Stewart vibration isolation platform, achieving a 24dB vibration isolation effect on 20-100HZ [67]. Xuedong Chen and others used RLS (recursive least squares) algorithm to reduce the vibration of Stewart platform. Liu, L [68] used the adaptive control method of acceleration feedback combined with PID to overcome the amplification of low-frequency vibration displacement and suppress overturning and pitching.

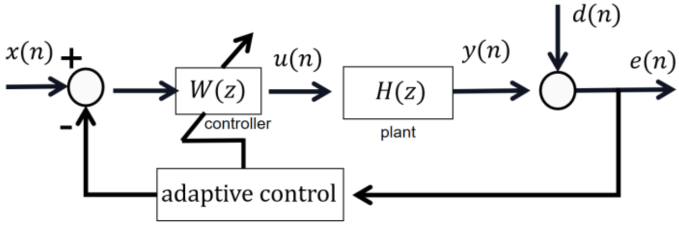


Figure 3. Simplified block diagram of adaptive control.

Fuzzy control is a computer digital control technology based on fuzzy set theory, fuzzy variables and fuzzy logic reasoning. It is an intelligent control method that imitates human fuzzy reasoning and decision-making process from the behavior. In this method, the fuzzy rules are compiled first, then the real-time signals from the sensors are fuzzed, and the fuzzy reasoning is completed according to the rules and output to the actuator. In 1996, Pattie MAEs applied fuzzy control to parallel robot [69], and I-Fang Chung [70] applied fuzzy control to Stewart platform in 1999 and proved its effectiveness and stability. Zhaojing Wu used ceiling damping fuzzy control for helicopter vibration isolation, so that the vibration isolation effect of magnetorheological Stewart platform reached 80%.

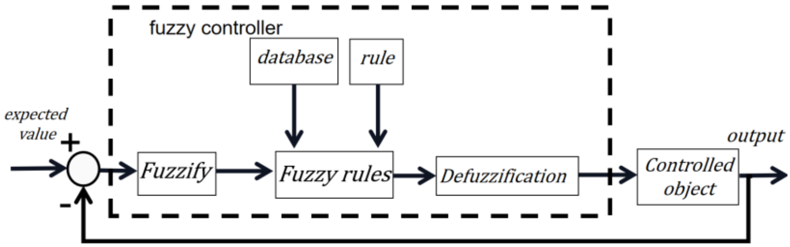


Figure 4. Simplified block diagram of fuzzy control.

The Stewart vibration isolation system model contains uncertainties such as nonlinearity and stiffness. The purpose of robust control is to design a fixed controller to make the uncertain model achieve the control quality we want. As shown in figure 4, *w* is the external input signal of the controlled object, including external disturbance, sensor noise and other signals. *u* is the controller input signal, *z* is the system output, and *y* is the system measurement signal. *G(s)* is the generalized controlled object and *K(s)* is the controller. Zanes of Canada first proposed the concept of robust control in 1981. The commonly used robust control includes H_∞ control and structural singular value theory (μAnalysis) and Kharitonov interval theory. In addition, in order to improve the real-time performance of the controller, the price is reduced. There are many researches on Stewart platform of robust control in Harbin Institute of technology in China, and Dongwei Wang [71] studied H_∞ and μ based on the comprehensive method, it is found that the formant suppression is better, and the vibration isolation interval and attenuation speed are better controlled. Ying Wu used the H_∞ [72] and μ synthesis method for the satellite vibration reduction platform, and introduced the weight matrix to improve the robust nonlinear control algorithm. Under the excitation of 0.3Hz, the vibration attenuation reached 8.8db, meeting the requirements of satellite vibration reduction. Tao Yang designed a nonlinear L2 Robust Controller, which can adjust the vibration suppression coefficient for different environments to improve the vibration isolation performance.

Optimal control is to make a given system performance index reach the extreme value under a given target set and control domain. The most widely used are LQR (linear quadratic regulator), that is, linear quadratic Gaussian (LQG) optimal controller. Grewal et al. [73] designed the pneumatic Stewart Platform Based on LQG algorithm and verified the stability of the platform under unknown load. Jian Jiao, after simulating and modeling the Stewart platform, compared PID, LQR and algorithm, it was found that the acceleration effect was obvious and the algorithm was better. Xiaofang Li found by adjusting the Q and R weight matrix that the increase of Q value has a strong vibration isolation effect, but the actuator is easy to be saturated, and the increase of R value makes the actuator stable but the vibration isolation effect is poor. At the same time, the design will be an observer to obtain the outrigger displacement speed.

NC-newrocontrol (NNC) is an algorithmic mathematical model that simulates the behavior characteristics of animal neural networks and performs distributed parallel information processing. The error back propagation algorithm, referred to as BP algorithm for short, is a common neural network control method, which is widely used in solving the forward solution of Stewart platform. Liu designed a feedforward controller based on diagonal recurrent neural network to improve the robustness and position tracking ability of the system. Jia Ma designed an adaptive controller of fully adjusted RBF neural network, which has better vibration isolation effect in all directions than PD control, and almost stabilizes the initial position in the low frequency band. Bin Zi [74] realized the trajectory tracking of Stewart platform through Kalman filter and PID controller based on optimized neural network structure. This method combines the advantages of neural network self-learning and self-adaptive and PID simplicity and reliability. Table 2 summarizes the main control methods of Stewart vibration isolation platform today.

Table 2. Summary of Stewart vibration isolation algorithm.

Control method	Advantage	Shortcoming	Vibration isolation effect
PID	Simple structure and convenient adjustment	Specific mathematical model is required, and the adjustment speed is slow	0~50Hz
Fuzzy control	Simple structure, non-linear, no need for accurate model	Poor adaptability and accuracy	Combined with other controls 0~200Hz
Robust control	It does not need accurate model and has strong anti-interference ability	Poor steady-state accuracy	Low frequency vibration 2~200Hz
Optimum control	It has a wide range of applications and good nonlinearity	The determination of weighting matrix requires large amount of calculation and high accuracy of the model	Medium and high frequency 10~300hz

Neural network	Wide application, high fault tolerance, good strong coupling nonlinearity	Large amount of calculation and slow speed caused by self-learning	Combined with other controls 0~100Hz
Self-adaption control	Online identification and strong real-time performance	Large amount of calculation and poor stability	0~100Hz

6. Conclusion

This paper summarizes the applications of Stewart platform, the development of vibration isolation platform and the research results at home and abroad. It mainly summarizes Stewart kinematics solution, dynamic modeling, active vibration isolation actuator types and development, Stewart control algorithm. This paper focuses on the vibration isolation field of 6-DOF Stewart platform. The methods and development of forward and inverse kinematics are summarized; the dynamic modeling method and its advantages and disadvantages are described; the application occasions and characteristics of various actuators are summarized; the types, development, vibration isolation effects, advantages and disadvantages of active vibration isolation algorithms are summarized.

Although Stewart platform has a wide range of applications, there are many deficiencies in many aspects. Due to the large number of sensors and drivers required, the effect is often insufficient due to the size problem in some cases of small size and poor working environment. Therefore, how to integrate all mechanisms is a development focus and difficulty, and the integration of sensors and active and passive vibration isolation is a focus in the future.

The structure and size of Stewart platform have been widely discussed, but there is less research on its materials. Nowadays, there are more researches on its flexible hinges, but less on its flexible rods. Compared with rigid mechanisms, flexible mechanisms have the advantages of no lubrication, no clearance effect and no friction, and are widely used in high-precision occasions.

Stewart forward solution algorithm still has no specific analytical solution. How to improve the algorithm and combine hinge constraints, outrigger interference and other issues to obtain a more accurate and faster algorithm is also a breakthrough. In the aspect of Stewart control algorithm, how to design a controller that meets the requirements of wider frequency band, real-time parameter adjustment, online identification and strong robustness is also a research focus, especially the compound control of various algorithms to solve the problems of different gravity, temperature changes, higher frequency, mechanical rigidity and flexibility, nonlinear coupling and so on.

In terms of energy and environment, the state attaches great importance to it. It is difficult to estimate the capacity lost by vibration. If the energy storage device is added to the vibration isolation platform, the energy utilization rate will be greatly improved. How to recover energy while the Stewart platform is isolating vibration is a major innovation [75].

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