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On the mechatronic servo bandwidth of a stewart platform for active vibration isolating in a super antenna

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ABSTRACT

As being independent of the magnitude of reference input signal, the conventional concept of servo bandwidth stemming from electronics fails to reflect the ability of the multiple degree-of-freedom (DOF) mechatronic system to perform vibration control. Considering the magnitude and frequency of reference input signal, a novel definition of mechatronic servo bandwidth of the Stewart platform-based active vibration isolator for a super antenna is proposed firstly. Then its mechatronic servo bandwidth is theoretically evaluated according to electrical and mechanical performances by using an optimization method. Experiments were conducted on the Stewart platform prototype, and the results validate the definition of and solution to the mechatronic servo bandwidth. From the application point of view, the mechatronic servo bandwidth can be employed to measure the manipulating rapidity of a multiple DOF mechatronic system and the range of vibrations that an isolator is able to overcome.

1. Introduction

The five-hundred-meter aperture spherical radio telescope (FAST) has attracted global interests since its inception, which is being built in the unique karst limestone formation in China [1,2]. From the engineering point of view, one of the prominent innovations of FAST lies in the cable supporting subsystem for the feed, which integrates mechanical, electronic and optical technologies, will effectively reduce the weight and cost of the supporting structure [3] (See Fig. 1). However, the amplitude of wind induced vibration of the cabin structure may be as large as half of one meter, much greater than its astronomical specifications. To enhance the reliability of this mechatronic design, an active vibration isolator will be utilized to achieve the desirable positioning and orientating precision for the feed [4]. On the other hand, the requirements for vibration isolation in engineering fields can be divided into two levels: vibration isolation at a component level and structural vibration suppression at a system level [5]. In this research, the vibration source has both translational components (along *X*-, *Y*-, *Z*-axes) and rotational components including roll, pitch and yaw angles. The six degrees-of-freedom (DOF) Stewart platform mechanism is thus an appropriate candidate as this multiple DOF vibration isolator. Under this condition, even though the wind induced vibrations of the cabin exist, the millimeter-level positioning precision of the feed mounted on the mobile platform of Stewart platform in good design can be achieved [3]. It is of great importance to design a Stewart platform with higher servo bandwidth than the vibration of the cabin.

The vibration control application of Stewart platform in this super antenna system differs from those for motion generation or CNC machining. The previous associated work by other researchers included what follows. Geng and Haynes developed a six-DOF active vibration isolation system based on a Stewart platform mechanism used for precision control of a wide range of space-based structures as well as earth-based systems [5]. The short stroke Terfenol-D actuator design and robust adaptive filter algorithm for active vibration control were employed. Their real-time experiments achieved 30dB attenuation of vibration with small amplitude. Hanieh investigated the application of the Stewart platform with flexible joints in the active vibration isolation and damping of the sensitive equipments [6]. Each leg of her Stewart platform consisted of a voice coil actuator, a force sensor and two flexible joints. In the field of large amplitude vibration control, Cheng and Ren et al. studied the vibration control of the Stewart platform on flexibly supported structures [7,8]. The characteristic of this application lied in that the upper and lower platforms are dynamically coupled. A proportional and derivative control law based on the position prediction was used in the system. Their work was further developed by Lu and Zhu later [9], the field model experiments manifested the effectiveness of the Stewart platform in isolating the vibration and improving the positioning and orientating accuracy.

More recently, Tang et al. [2] studied the self-excited vibration and natural frequency, and then the dynamical coupling [12,13] of

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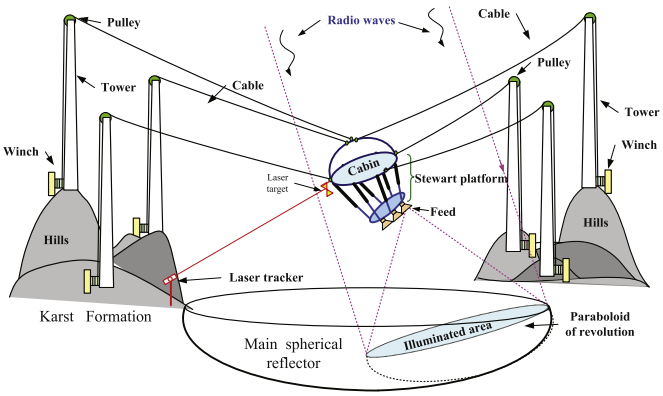

Fig. 1. Application of Stewart platform in FAST super antenna.

the feed support system in FAST application. Ding et al. [10] studied the application of actuation redundancy in a general Stewart platform to regulate the preloads on its active joints for the purpose of backlash prevention. Shao et al. [11] presented the inertia matching issue to realize good potentials of the Stewart platform. However, these work has not yet directly dealt with servo bandwidth of Stewart platform in motion control of all types.

As a related research of servo bandwidth, Pietsch and Krefft et al. [15] developed an autonomous control approach which enables the full exploitation of the dynamic potential of a parallel manipulator. Their research focused mainly on the response rapidity of the parallel robot rather than servo bandwidth. When dealing with the response rapidity of a system developed for either control or circuit purpose [16,17], the concept of servo bandwidth is used in most cases. Though it is a performance index in frequency domain, the connections of servo bandwidth relating to time domain index such as rising time or settling time can be established accurately for a second-order system [17]. Even for a higher-order system, the approximate relations are also available currently. But under the condition that a multiple DOF mechatronic system gets involved, the direct application of servo bandwidth displays two shortcomings as follows: (1) The concept of servo bandwidth is independent of the amplitude of input signal. Assume that a system has a servo bandwidth of ω_0, which suggests that the system is able to track the sinusoidal reference signal $r(t) = A\sin(\omega t + \theta)$, $0 < \omega \le \omega_0$ for any value of A in a rational range. However, this concept makes little sense for a mechatronic system, because it will bring about different mechanical effect such as driving forces or torques and constraint forces in the joints to track signals with the same frequency but different magnitudes. Therefore, a specified mechatronic system has the possibility to track either a lower frequency signal with greater magnitude or a higher frequency signal with smaller magnitude. So, applying the conventional concept of servo bandwidth directly will produce ambiguity on concept and description. (2) Whether the multiple DOF system has the identical servo bandwidth in its all DOFs is also out of the question, i.e. a scalar value of servo bandwidth is not sufficiently able to describe the multiple DOF performance of a system. Consequently, in order to describe the response rapidity of multiple DOF mechatronic systems, to build up a reasonable servo bandwidth definition and method of evaluating it is of both theoretical and applied importance.

The rest of this paper is organized as follows. The definition of mechatronic servo bandwidth for the Stewart platform is made in Section 2. The inverse kinematic and dynamical formulations based method of computing the mechatronic servo bandwidth is presented in Section 3. The case study of evaluating mechatronic servo bandwidth of the Stewart platform is conducted in Section 4. Eventually, some concise conclusions are drawn in Section 5.

2. Definition of the mechatronic servo bandwidth

The frequency response method plays an important role in the fields of information, signal processing and control [18], besides its advantage of establishing the model with experimental method and analyzing with figures; its remarkable physical sense is another motivation [17,19]. According to the viewpoint of frequency response, the dynamical process of a control system is the transmissions of the signals in its each element in turns. And each signal is regarded as the combination of a variety of sinusoidal signals with different frequencies. In the process of transmitting, the magnitudes and phase angles of the sinusoidal signals vary strictly subject to transfer functions and bring about motions with many kinds of forms. For a linear ordinary single-input–single-output (SISO) control system, its frequency characteristic function can be denoted with

$$G(j\omega) = \frac{Y(j\omega)}{U(j\omega)} \tag{1}$$

where ω represents the angular frequency of the input and steady output signals. $Y(j\omega)$ and $U(j\omega)$ are the Fourier image functions of the input and output of the plant, respectively. $G(j\omega)$ is a complex number for an arbitrary ω. In terms of the definition of bandwidth in frequency response method [17,19], the bandwidth ω_B should satisfy the following equation

$$|G(j\omega_B)| = 0.707|G(j0)| \tag{2}$$

For a particular servo control system, Eq. (2) implies that if the reference input of the servo system is assumed as a sinusoidal signal, then the servo bandwidth specifies the ability of the system to track the sinusoidal input signal. When the frequency of the input signal meets $\omega > \omega_B$, it is recognized that the frequency has been beyond the frequency range of the sinusoidal signals the servo system being able to track.

Since Stewart platform is a six DOF mechanism actuated by six electric cylinders, it is in nature a multiple-input–multiple-output (MIMO) servo system. That is to say the mobile platform can track a six-DOF reference signal consisting of three translations and three rotations (3T3R) in Cartesian frame system. The concept of frequency response analysis is further extended into the six-DOF mechatronic filed here, so that the six-dimensional angular frequency vector $\boldsymbol{\omega}$ and magnitude $\boldsymbol{A}$ including sinusoidal input signals of the Stewart platform in six DOFs can be denoted by the following equations, respectively

$$\boldsymbol{\omega} = (\omega_1, \omega_2, \ldots, \omega_6)^{\mathrm{T}} = (\omega_x, \omega_y, \omega_z, \omega_\alpha, \omega_\beta, \omega_\gamma)^{\mathrm{T}} \tag{3}$$

$$\boldsymbol{A} = \left(A_1, A_2 ,,\ldots, A_6\right)^{\mathrm{T}} = \left(A_x, A_y, A_z, A_\alpha, A_\beta, A_\gamma\right)^{\mathrm{T}} \tag{4}$$

where subscripts $x, y, z, \alpha, \beta, \gamma$ indicate the six DOFs of the Stewart platform including three translations and three rotations, respectively. For the single DOF reference input signal $r_i(t) = A_i\sin(\omega_i t)$ in ith DOF, the steady response of the mechatronic system is,

$$y_i(t) = T(\omega_i, A_i)A_i\sin(\omega_i t + \theta_i) \tag{5}$$

where $T(\omega_i, A_i)$ is the magnitude gain function, θ_i is the phase function indicating the phase variation of the output versus sinusoidal input signal. The subscript $i = 1, 2, \ldots, 6$, similarly hereinafter unless otherwise specified.

Definition 1. The separate (single DOF) mechatronic servo bandwidth vector of the Stewart platform is