High-rise Structure Vibration Control with Gyroscopes

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Abstract. The traditional damper is inconvenient for high-rise structure. The rotor of gimbal gyroscope has two rotational degrees of freedom, and the gyroscope produce moment to resist two orthogonal displacements when the rotor rotates with high speed, so the structure deformation under external force can be reduced. A method for installing some gimbal gyroscopes on the high-rise structure to reduce the structural horizontal and torsional vibration is presented. The movement mechanism of the gimbal gyroscope is introduced, and the dynamic equation for the multi-dimensional control system with gyroscope dampers is established. A steel tower with gyroscope dampers is analyzed to verify the control performance under fluctuating wind loadings and earthquake action. The results show that the dynamic response of high-rise structure can be reduced effectively by the gyroscope dampers with appropriate parameters.

Introduction

High-rise structure is a kind of slender structure with larger height and smaller cross section, and the transverse load plays a major part in dynamic action. Because the beautiful shape, the high-rise structure is widely used in telecommunications, electricity and chemical industry, etc [1]. Compared with ordinary structure, the horizontal stiffness of high-rise structure is small. It is sensitive to wind load and earthquake action and it is easy to trigger large static and dynamic response. As a result, the dynamic behavior and dynamic control of the high-rise structure get more and more attention [2, 3].The devices which apply to dynamic control of high-rise structure include: viscous dampers, tuned mass damper, tuned liquid damper and tuned spring damper, etc. [3-7]. The mechanism of damping device is explicit. With optimized analysis, normal production and installation, effective damping can be obtained by using the device. The vibration of high-rise structure takes the first vibration mode as the principal thing, the optimal control location is usually at the top, but the location is partial soft and internal space is limited, which lead to the more requirements of quality and volume and the condition of the tuned damper in the practical application. Aiming at these problems, the research and development of the new type of the damping device are necessary, which effectively reduce the dynamic response of high-rise structure by other means.

Gyroscope is a kind of device which is based on the conservation of angular momentum theory and designed to sense and maintain direction. Gyroscope is mainly composed of gyro rotor, frame and accessories, when the axis of the gyro rotor rotates at high speed, will produce inertia and resistance, pointing in the direction of fixed the gyro rotor axis of rotation, the nature is called fixed axis. Zheng-Hao Wang once used single-degree-of-freedom gyro method for structure stochastic control based on conservation of gyro axis [8], but this method is brief and can't realize multidirectional vibration reduction. This paper which based on this theory advances a kind of gimbal gyroscope damper, and it can control horizontal vibration of the structure. Subject to wind load and earthquake action, the inner rotor of the damper can rotate with high speed, fixed axis gyro can provide reverse torque which reduces the horizontal deformation of the structure, and the overall damper has the function of dissipating external kinetic energy so as to ensure the safety of structure.

This paper expounds mechanics principle of the gimbal gyroscope (two degrees of freedom gyro), the dynamics equation of the multidimensional vibration control is established, and the damping effect on high-rise structure of the gimbal gyroscope damper is studied. Results show that the reasonable arrangement of gimbal gyroscope damper can effectively control the horizontal and torsional vibration of the structure which subject to wind load and earthquake action.

Gimbal Gyroscope Damper

Gimbal gyroscope damper includes outer framework which can rotate around one certain horizontal axis, inner frame which can rotate around the horizontal axis that Orthogonal with the above-mentioned horizontal axis, gyro rotor which rotate with the electric power and dynamo which offer electric power [9, 10]. The gyro device in the damper is AFG, which namely has inner and outer frameworks that make the rotor axis two rotational degrees of freedom to ensure the gyro device rotate at a certain angular velocity subjected to the effect of dynamic action, generating the moment which resists the displacement of two orthogonal horizontal direction, trying to keep features of spin axis relative invariable inertia space azimuth, which can inhibit that the structure generate large horizontal displacement or deflection. The structure of the damper gimbal gyroscope is shown in Fig.1.

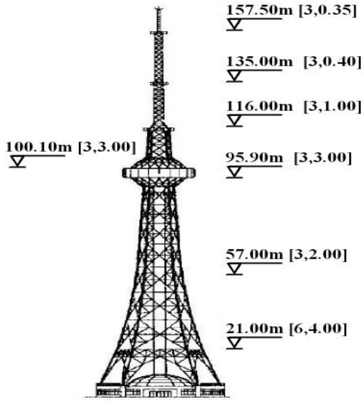

Fig. 1 Composition Diagram of Gimbal Gyroscope

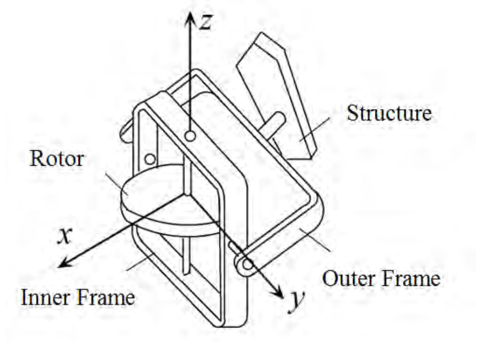

Fig. 2 Scheme of TV Tower and Location of the Gimbal Gyroscopes

AFG, mainly consists of three rigid bodies: the first one is the outer frame which has one rotational freedom, generalized coordinates around the outer gimbal axis Angle can describe the movement, the second one is the inner frame which has two rotational freedom, two generalized coordinates which circle around the axis of outer gimbal and shaft angle of inner frame can describe the movement, the third one is the rotor with three rotational freedom, three generalized coordinates circle around the rotation axis, the shaft of inner frame and the outer gimbal axis can describe the movement [11, 12].

It is known that outer ring, internal ring and rotor circle fixed coordinate system of the base x, y, and z axis of principal moments of inertia are Jx0, Jy0, Jz0, Jx1, Jy1, Jz1, JxR, JyR, JzR. When the rotor rotates with absolute high speed ω0, the gyro angular momentum constant H0= JzRω0, expresses the rotor steady-state value of absolute angular momentum. Set α and β as the corner of outer frame and internal frame, according to the moment of momentum theorem, steady-state kinetics equation under ideal constraints of gyroscope are

$$\begin{aligned}&[J_{x0}+J_{z1}+J_{zR}+(J_{x1}+J_{xR}-J_{z1}-J_{zR})\cos^2\beta]\ddot{\alpha}+(H_0\cos\beta)\dot{\beta}=M_x\\&(J_{y1}+J_{xR})\ddot{\beta}-(H_0\cos\beta)\dot{\alpha}=M_y\end{aligned} \tag{1}$$

When the outer frame and inner framework rotate in fixed rotating angular velocity, the Eq. (1) can be simplified to

$$(H_0 \cos\beta)\dot{\beta} = M_x$$
$$-(H_0 \cos\beta)\dot{\alpha} = M_y \tag{2}$$

For the structure with a certain size gimbal gyroscope, it can provide greater torque by improving the gyro rotor, inner and outer ring speed, the fixed axial torque provide force to recover the initial state of equilibrium that restrain or reduce the deformation of the structure under the action of external force. At the same time, under the condition of invariable quality, only improve gyro plane size can significantly improve the torque value, so the gyro damper is especially suitable for installation at the top of the outer space of higher and flexible structure.

Dynamic Model of Structure Which Equipped with Gyro Damper

In order to study the damping effect of the structure equipped with gyro damper, the actual structure can be equivalent to multi degree of freedom system which has multiple focus quality. It assumes that the structure has n equivalent lumped mass and arranges the gimbal gyroscope damper on multiple locations, the damper can control the motion in two horizontal directions and around the vertical axis [13].The equation of motion of structural system subject to the multi-dimensional seismic action is

$$\boldsymbol{M\ddot{U}} + \boldsymbol{C\dot{U}} + \boldsymbol{KU} = \boldsymbol{-M\ddot{U}}_g(t) + \boldsymbol{F}(t) \tag{3}$$

Among the equation, M, C and K respectively are 3n×3 n mass matrix, damping matrix and stiffness matrix of the structure. $\boldsymbol{U} = [\boldsymbol{U}_x, \boldsymbol{U}_y, \boldsymbol{U}_\theta]^T = \{u_{x1}, \cdots, u_{xn}, u_{y1}, \cdots, u_{yn}, u_{\theta 1}, \cdots, u_{\theta n}\}^T$ is the structural centroid displacement vector for the 3 dimension. $\boldsymbol{\ddot{U}}_g(t) = [\boldsymbol{\ddot{U}}_{xg}(t), \boldsymbol{\ddot{U}}_{yg}(t), \boldsymbol{\ddot{\Phi}}_{\theta g}(t)]^T$ is the structural dynamic loading or functionary acceleration input. $\boldsymbol{F}(t) = \{0, \cdots, F_x(t), 0, \cdots, F_y(t), 0, \cdots, 0\}^T$ is concentrated force which equals to moment of gymbal gyroscope, place of application is the same as to or nearby installation location of the damper.

Due to the structure and coupling damping matrix of gyro damper coupled systems do not have orthogonality, belongs to the non-classical damping, so it can't use real modal transformation to decouple and the time history analyze the Eq.3.To solve the above problems, it can use the state space method, through the introduction of the state vector, it can turn higher order ordinary differential equation into first-order differential equation in the composition of state variables. First, define $\boldsymbol{\ddot{U}}_{ge}(t) = (\boldsymbol{I} - \frac{\boldsymbol{F}(t)}{\boldsymbol{M\ddot{U}}_g(t)})\boldsymbol{\ddot{U}}_g(t)$, which I is unit matrix. Eq.3 can be rewritten as:

$$\boldsymbol{M\ddot{U}} + \boldsymbol{C\dot{U}} + \boldsymbol{KU} = \boldsymbol{-M\ddot{U}}_{ge}(t) \tag{4}$$

Define $\boldsymbol{X} = \{\boldsymbol{U}\ \boldsymbol{\dot{U}}\}^T$, $\{\boldsymbol{Y}\} = \{\boldsymbol{U}\ \boldsymbol{\ddot{U}}\}^T$ for the system state vector, the Eq.4 can be represented as the form of the following equation of state:

$$\boldsymbol{\dot{X}} = \boldsymbol{AX} + \boldsymbol{B\ddot{U}}_{ge}\boldsymbol{(t)} \quad \boldsymbol{Y} = \boldsymbol{CX} + \boldsymbol{D\ddot{U}}_{ge}\boldsymbol{(t)} \tag{5}$$

In the type $\boldsymbol{A} = \begin{bmatrix} \boldsymbol{0} & \boldsymbol{I} \\ \boldsymbol{-M}^{-1}\boldsymbol{K} & \boldsymbol{-M}^{-1}\boldsymbol{C} \end{bmatrix}, \boldsymbol{C} = \begin{bmatrix} \boldsymbol{I} & \boldsymbol{0} \\ \boldsymbol{-M}^{-1}\boldsymbol{K} & \boldsymbol{-M}^{-1}\boldsymbol{C} \end{bmatrix}, \boldsymbol{B} = \boldsymbol{D} = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{-I} \end{bmatrix}$.In this way, according to the vector with acceleration excitation of structure, The coupling dynamic response of gyro damper and structure can be calculated by solving the system state space equations.

Calculation Example

In order to verify with multi-dimensional damping effect of high-rise structure equipped with gyro damper, this paper selects steel TV tower as the example. As shown in Fig.2, the height of the television tower total is 168m, and the body of the tower is structural space truss with regular pentagon. The body of the tower divides into three parts of antenna, tower and tower body. The seismic intensity is 7 degrees, and the site soil type is Ⅱ, near earthquake fortification. The area of Steel tower is class B landform, at the standard height of 20m, the 100 years return period corresponds to the average 10 min interval, and the maximum wind pressure is 0.55 KN/m2.

The bar and node of the TV tower are numerous, and the system is simplified with the overall truss method which consider structure node as hinged joint, the weight of each bar focuses on the two end nodes, then analysis in the space rectangular coordinate system, it can accurately reflect the mechanics characteristics of the tower. Finally the television tower is simplified to multi degree of freedom bending shear structure with multi degree of freedom which has 43 lumped mass, the first four order natural vibration period are: 1.96 s, 0.95 s, 0.38 s and 0.95s.

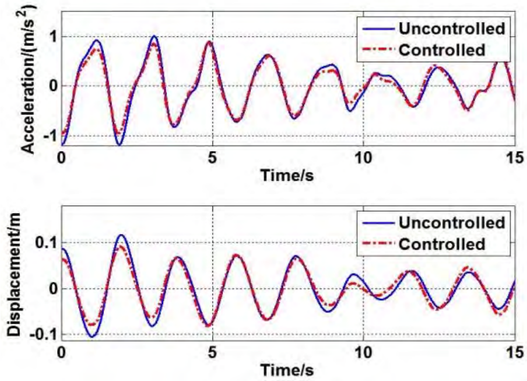

Fig. 3 Control Curves of the Tower Turret under Wind

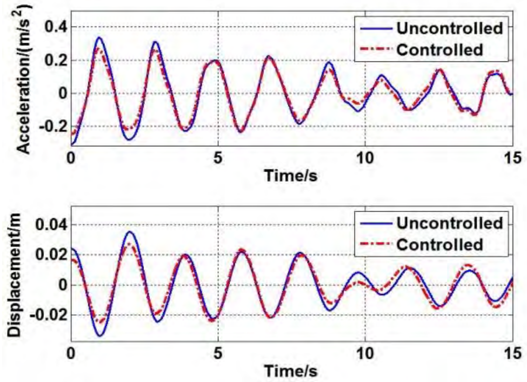

Fig. 4 Control Curves of the Tower Turret under Wind

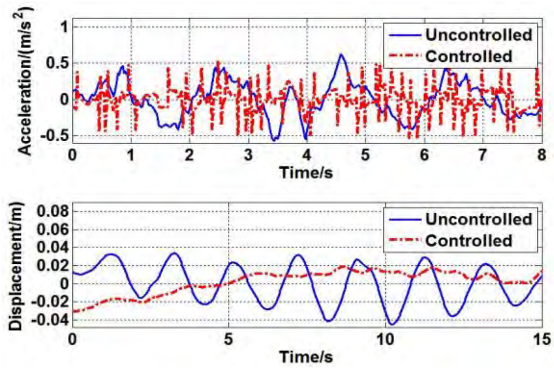

Fig. 5 Displacement Control Result of Total Tower under Wind

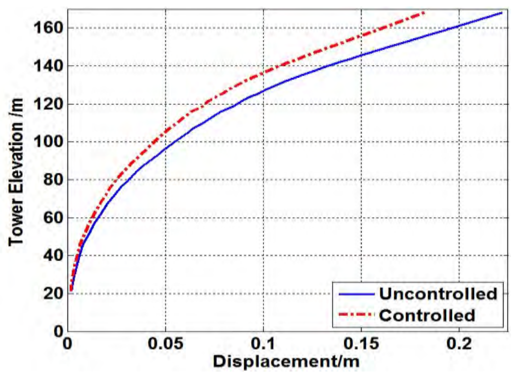

Fig. 6 Control Curves of the Tower Turret under Earthquake

Under wind load, the dynamic response of the tower is mainly caused by vibration from the wind in the transverse direction; therefore, cross wind control in both directions is studied. When simulate pulsating wind speed time history, adopt Davenport spectrum which the load code recommended, and considering the vertical correlation, harmonic superposition method is adopted to simulate the fluctuating wind speed time history, different nodes under wind load is achieved. The gyro dampers are installed in different parts of the TV tower, installation position of elevation as showed in Fig.2, in the same level, gyro damper are symmetrical uniform arranged. In Fig.2, the first item in the bracket is the number of gyro damper for a certain equivalent horizontal direction, and the second item is the diameter of the rotor of each gyro damper. The vertical thickness of gyro rotor damper can be smaller in order to save space, and the value is set as 0.1m. Assume that revolving speed using motor within each gyro rotor which move around inner frame and outer frame is respectively 1000rad/s and 0.20rad/s. Establish the coupling dynamic equation in accordance with the Eq.4, take the wind load as input, calculate the multi-dimensional dynamic response and analyze vibration damping effect before and after the installation of gyro damper tower. Considering the television tower in lateral restraint components, and gyro damper torque transmission range is limited, therefore assume that effective lever is the length of the equivalent mass of damper. Contrast diagram of the dynamic response of the tower building and tower roof is shown in Fig.3 and Fig.4, respectively, it can be seen from the results, after the installation of gyro damper, including the structure of the displacement and acceleration have been controlled in a certain degree of inhibition, gyro damper damping effect is ideal. The contrast of the tower's overall displacement before and after vibration is shown in Fig.5, and it is obvious that gyro damper can effectively control the displacement of the structure under wind vibration, especially the displacement of the top of the tower.

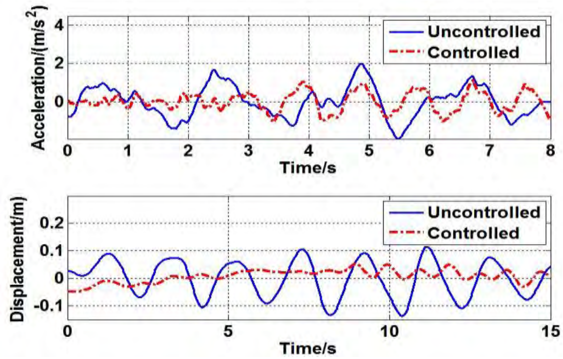

Fig. 7 Control Curves of the Tower Top under Earthquake

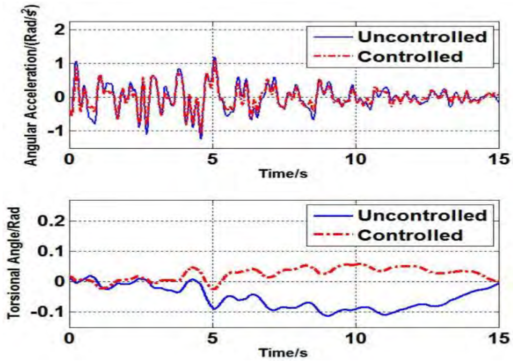

Fig. 8 Torsion Control Result of the Tower Top under Wind

Considering the site condition of the structure, take El Centro wave as the ground motion input, the acceleration amplitude is 3.417m/s2. Assume that revolving speed of each gyro rotor which move around inner frame and outer frame is respectively 1200rad/s and 0.30rad/s, calculate the multi-dimensional seismic response and the damping effect after installing the gyro damper .Under the effect of El Centro wave, the structural dynamic response time history curve if the damper is installed as shown in Fig.6 to Fig.8, it shows that : after the installation of gyro damper, including the displacement, acceleration and torsion Angle, structural response have been controlled in a certain degree of inhibition. Due to high frequency vibration component is rich, and the gyro rotor speed is higher, after installation of dampers, the acceleration of part of the location changes dramatically. Fig.9 shows the damping effect of the whole displacement of structure, the results shows that the gyro dampers can reduce the dynamic response of the tower structure under earthquake, but dampers need to be evenly dispersed decorated in order to make the whole structural deformation coordinate.

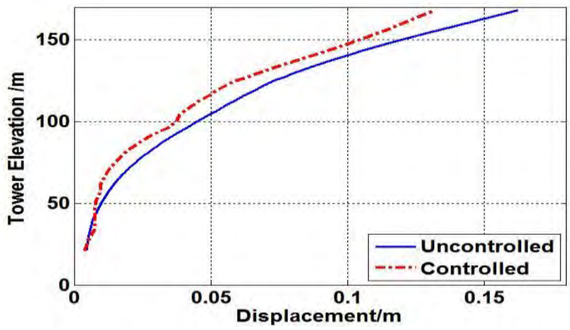

Fig. 9 Displacement Control Result of Total Tower under Earthquake

Summary

This paper studies the method to control the dynamic response of the structure using gimbal gyroscope as damper which subjected to wind load and earthquake action. Expounds the conservation of gyro axis of gimbal gyroscope, and establish the dynamics equation of the gimbal gyroscope, the mechanism of the damper which control the deformation of the structure according to its mechanical characteristics l are also described. The structure of damper is simple, it does not need large quality and stiffness, and do not take up too much internal space of structure. Establish structural multidimensional control equations of motion considering the effect of torsion. For example, a steel structure tower subject to the action of the structure in the wind load and earthquake, vibration control effect is studied. The results show that the moment provided by the gyro damper can bring inhibition effect of dynamic response, and achieve the effective vibration attenuation in horizontal direction and reverse orientation. Gyro damper damping capacity is mainly associated with the rotating speed of rotor around inside and outside the frame, it requires a high power frequency conversion motor to realize the control of the large tower structure, therefore it still needs to do some in-depth research and development related to mechanical and electrical equipment. In addition, the optimal arrangement about gyro damper optimal position and rotor speed also needs further research.

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