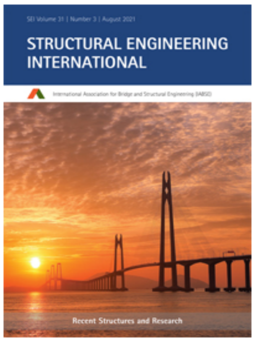

Taylor & Francis
Taylor & Francis Group

Structural Engineering International

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tsei20

The Effectiveness of the Gyroscopic Effect for Controlling Structural Vibrations

Oscar Curadelli Dr & Marta Amani Dr

The Effectiveness of the Gyroscopic Effect for Controlling Structural Vibrations

Oscar Curadelli, Dr; **Marta Amani,** Dr, Laboratory of Experimental Dynamic, National University of Cuyo, CONICET, Mendoza, Argentina. Contact: oscar.curadelli@ingenieria.uncuyo.edu.ar.
DOI: 10.1080/10168664.2021.1930331

Abstract

It is well known that seismic and wind induced vibration is an important issue in structural performance. To mitigate the problem of structural vibrations, many methodologies have been proposed and implemented. In this work, the performance and effectiveness of a pseudo-passive vibration control system based on the gyroscopic moment to control lateral vibrations in beam-like structures is studied numerically and experimentally. A series of experimental tests that include free and forced vibrations are conducted on a slender structure provided with a gyroscopic system. Results show a high effectiveness in controlling the tip displacement of a prototype structure by the gyroscopic system. Complementarily, a simple numerical model capable of predicting the structural response of the system is presented. A marked improvement in structural vibration control over the traditional tuned mass damper is also verified.

Keywords: Structural vibration control; gyroscopic effect; slender structures; experimental model; gyro stabilization

Introduction

For enhanced wind and seismic performance of slender structures such as high-rise buildings, slender towers, etc., the use of vibration control systems based on energy dissipation[1,2] is well known and recognized, especially those using tuned mass dampers (TMDs) in different versions: active (AMD), passive (TMD) and hybrid (ATMD), which is a combination of both.[3]

An alternative vibration attenuation system, which has not been widely used, particularly in civil applications, is that based on the gyroscopic moment.

Scientific literature shows that the space industry and the branch of mechanical engineering concerned with the study of the dynamics and stability characteristics of rotating machinery, called rotor dynamics, were the area pioneers in the development of gyroscopic effect theory.

Thus, in rotor dynamics, among the most recent studies related to the modelling of flexible rotors that include the gyroscopic effect can be highlighted those performed in Refs. [4, 5, 6, 7]. On nonlinear vibration analysis, the studies in Refs. [8, 9] can be cited. Ref. [10] presented an important experimental study on the gyroscopic effect of a rotating rotor and wind heading angle on floating wind turbine responses. A recent work published deals with the application of methods based on perturbation theory to solve the problem on the dependence of the eigenfrequencies of a real rotor with friction.[11]

In the space industry, actuators for the attitude control and vibration suppression of space flexible manipulators based on the gyroscopic moment are used widely. Here, it is important to highlight two relevant works, in one of which (Ref. [12]) the efficiency and accuracy in terms of the torque amplification properties of control moment gyroscopes (CMGs) used as a momentum control actuator was highlighted and a detailed analysis of the equations of motion was described. In the other (Ref. [13]), a complete and general derivation of the equations for the dynamics of structures with CMGs along with an analysis of the scale effects on their performance were detailed. Refs. [14, 15, 16] presented the respective control strategies applicable to CMG systems for the attitude control of satellites. Refs. [17, 18] employed CMGs as reactionless actuators for space robots. Ref. [19] adopted variable-speed control moment gyros (VS-CMGs) as actuators for the vibration suppression of space flexible manipulators. In addition, later, Ref. [20] suggested using CMGs to achieve attitude manoeuvres and vibration reduction of a flexible spacecraft. The resultant system is the so-called gyroelastic body. Ref. [21, 22] developed a micro-vibration isolation system for single-gimbal control moment gyros. Ref. [23] proposed active vibration isolation using H_∞-optimal control for the unbalanced induced vibrations of a rotating shaft.

A recent paper Ref. [24] addressed the dynamics of flexible multibody systems with variable-speed CMGs using a generic global matrix formulation.[24] Ref. [25] studied some cases where the free response of non-conservative systems exhibits a transient divergent time history. Moreover, the forced response of these systems was addressed, highlighting how, and in which cases, an unexpected amplification of the forced response may occur.

In terrestrial applications, the gyroscopic moment is being used as a stabilizer in platforms as shown in Refs. [26, 27] and mostly in the shipbuilding industry. Originally, the gyroscopic effect of spinning wheels used to control a ship's rolling motion was proposed in the early twentieth century.[28] Initially, the use of these devices was rejected due to the large size of flywheels and the inability to maintain performance within a wide range of amplitudes and frequencies of waves. Further developments and improvements addressed those drawbacks.[29–31] Nowadays, new materials and designs, electrical drivers and computer control systems have again raised interest. Recently and importantly, the yacht industry has developed gyrostabilizers to counteract rolling motion.[32] Based on wave modulation theory, a new mode of operation using two flywheels spinning in opposing directions while being forced to nutate in opposition at constant rates has been proposed.[33] The ride control levels reached in pitch

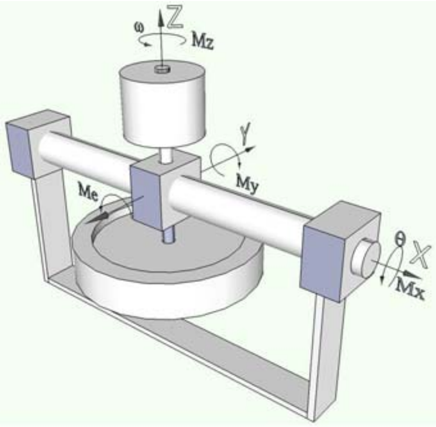

Fig. 1: Single gimbal sketch

and roll of small and medium size vessels were consistent with contemporary external systems. A recent work presented a review paper covering developments in various ship roll motion control systems together with different mathematical models and control methods that have been implemented and validated with full-scale experiments.[34]

In civil industry, the use of the gyroscopic moment has been limited and restricted to those structures that

Fig. 3: Experimental implementation of single gimbal

display bending modes (beam-like structures) because their gyroscopic moment is generated when the structure undergoes a bending deformation. The earliest studies cited in the literature were performed at the beginning of the nineties.[35, 36] To control wind-induced vibrations, Refs. [37, 38] performed experimental tests

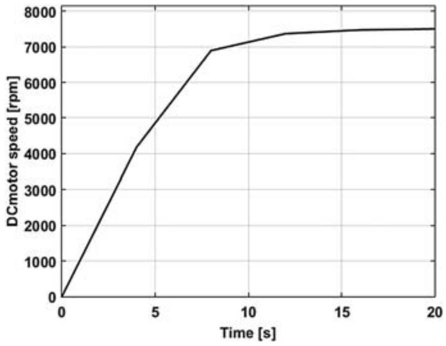

Fig. 4: Acceleration ramp of the gyroscope–motor assembly

on a tower of height 60 m. Refs. [39, 40] conducted a full-scale test on a 108 m tower-like structure. Ref. [41] provided the same tower with a new control system (constant and variable gain control) that improved its structural behaviour under weak and strong winds reducing accelerations by more than half.

In the present paper, an experimental and numerical study on the vibration control effectiveness of a pseudo-passive system based on the gyroscopic effect is presented. Specifically, the study focuses on the effectiveness of

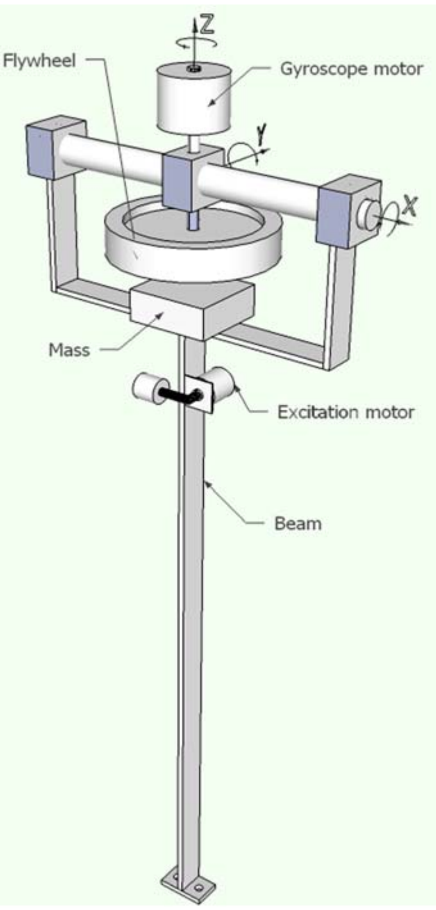

Fig. 2: Outline of experimental model

Fig. 5: Experimental set-up

Seismic record	Earthquake	Station	Record component	Date	PGA (g)
1	Helena Montana-01, USA	Carroll College	180	31 October 1935	0.161
2	Kern County, USA	Taft Lincoln School, 21	21	21 July 1952	0.159
3	Northern Calif-03, USA	Ferndale City Hall, 44	44	21 December 1954	0.163
4	Hollister-01, USA	Hollister City Hall	181	9 April 1961	0.06
5	Parkfield, USA	Temblor pre-1969	205	28 June 1966	0.356

PGA, peak ground acceleration; g, gravitational acceleration.

Table 1. Characteristics of acceleration records

a gyroscope-based device to reduce the tip deflection of a cantilever beam used as an experimental prototype. Unlike previous contributions in which the precession motion was driven by a servo motor (active precession), in this case, as the precession motion is counteracted by the weight of the device itself (passive precession) and the flywheel rotation is maintained by a spinning motor, the control system is denoted as *pseudo-passive*. The study is conducted through an experimental model structure in free vibration and under resonant and seismic excitations. The results show that a control system based on the gyroscopic moment is highly effective for controlling structural vibrations induced by different types of excitation. Additionally, a mathematical model is included and verified against experimental results. To put the present authors' results into perspective, the effectiveness of the proposed control system based on the gyroscopic effect is compared numerically with that of typical TMD-based control. Under the same conditions, the former system is markedly more effective (by at least *five times*) than the latter.

Vibration Control System based on the Gyroscopic Effect

As mentioned above, one of the most important uses of the gyroscopic effect is to reduce the roll motion in ships by means of the gyroscopic moment generated by one or more (generally two) large spinning wheels supported by a single gimbal as shown in *Fig. 1*. Focusing its use on beam-like structures, this work aims to assess the effectiveness of the gyroscopic moment for reducing structural response under different types of excitation.

Indeed, consider the single gimbal shown in *Fig. 1*, which has a rotating shaft (driven by a DC electric motor) provided with a spin angular momentum, $J_z\omega$, around the Z-axis.

Then, when the support of the simple gimbal is perturbed in its plane by a rotation around the Y-axis, a particular external excitation moment, M_e, which is proportional to the rotation rate, appears on the gyroscope. This excitation moment changes the angular momentum, $J_z\omega$, such that the gyroscope develops a precession motion (rotation θ, $\dot{\theta}(t)$) around the X-axis. Thus, by the cross product of the spin angular momentum,

$J_z\omega$, around the Z-axis, and the precession rate, $\dot{\theta}(t)$, an inertia gyroscopic moment is induced, the vector of which is perpendicular to the X–Z-plane having an angle θ with respect to the horizontal. From the dynamics theory of a gyroscope supported by a single gimbal,[42] it is possible to derive the equations corresponding to both horizontal and vertical components of the gyroscopic moment in the directions of the Z- and Y-axes, respectively, as in Ref. [29]

$$M_z(t) = J_z\omega\dot{\theta}(t)\sin\theta(t) \quad (1)$$

$$M_y(t) = J_z\omega\dot{\theta}(t)\cos\theta(t) \quad (2)$$

in which J_z and ω are the mass moment of inertia and the angular speed of the flywheel around the Z-axis, the quantity $J_z\omega$ is called spin angular momentum, and $\theta(t)$ and $\dot{\theta}(t)$ are the precession angle and precession rate, respectively.

$M_z(t)$ is a torsional moment on the structure that has no effect or can be compensated by another flywheel spinning in the opposite direction. From the point of view of vibration control, $M_y(t)$ is the more important because it is able to counteract the excitation moment, M_e, reducing the structural

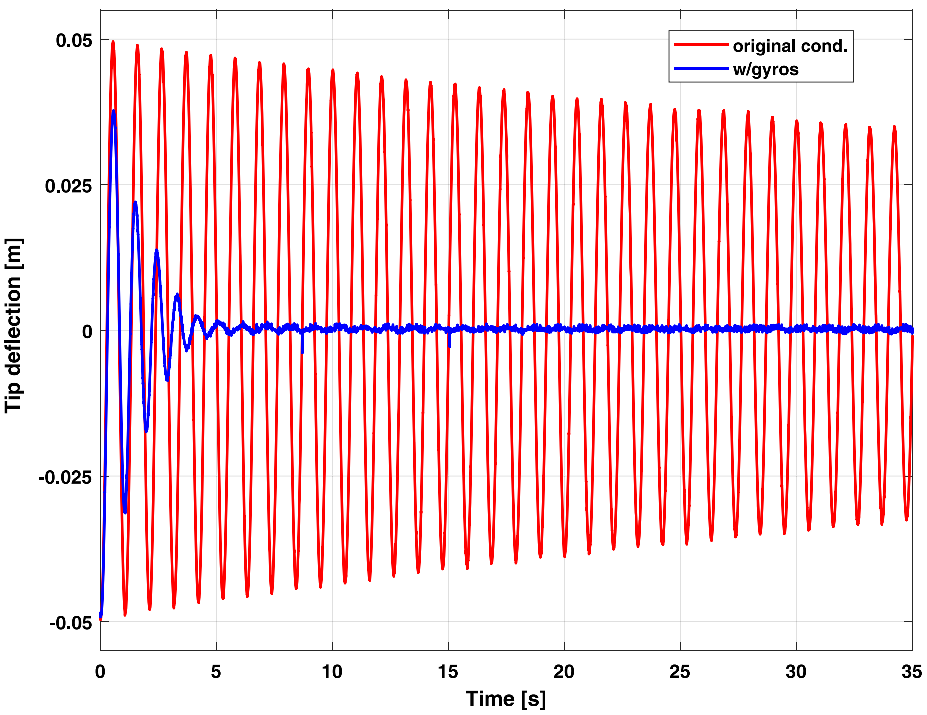

Fig. 6: Tip deflection. Free vibration test

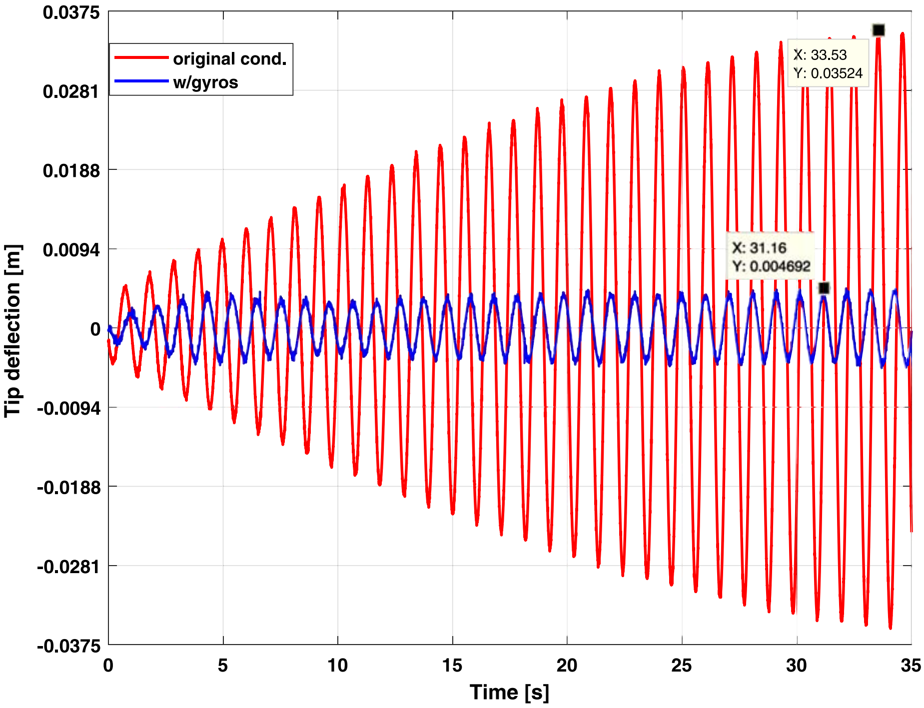

Fig. 7: Tip deflection. Resonant excitation test

response. Since this moment is proportional to the precession rate, $\dot{\theta}(t)$, it can be interpreted as a viscous damping moment.

As noted above, the components $M_z(t)$ and $M_y(t)$ of the inertia gyroscopic moment can only be developed when the gimbal assembly exhibits a certain spin angular momentum, $J_z\omega$, in the gyroscope rotating shaft, and its support experiences a rotation in its plane (around the Y-axis, see *Fig. 1*).

From this behaviour arises the possibility of using the gyroscopic effect on slender beam-like structures that undergo bending deformations.

Experimental set-up

To assess the effectiveness experimentally of the gyroscopic moment for controlling the structural response, an experimental model was built and tested in its original condition and provided with a gyroscopic device under different types of excitation. The experimental programme consisted of the following: (1) free vibration tests; and (2) forced vibration tests under resonant and real seismic excitation.

Description of the Experimental Structure

The prototype structure consisted of a slender steel cantilever beam with a length of 1.15 m, a width 0.0381 m and a thickness of 0.006,35 m (*Fig. 2*). A fundamental frequency equal to $f_1 =$ 0.95 Hz and a critical viscous damping ratio equal to 0.5% were measured prior to the beginning of the tests.

The gyroscope system consisted of an DC motor driving a steel flywheel with a mass of 0.27 kg (2.9% of the first mode mass of the structure) and rotational inertia equal to 8.25 e-4 kg-m^2, mounted on a single gimbal located at the tip of the slender cantilever beam (*Fig. 3*) (specific dimensioning of the gyroscope is outside the scope of this paper).

During tests, the rotational speed of the flywheel in the steady state (at the rated motor speed), was 7500 rpm. *Figure 4* shows the acceleration ramp of the gyroscope–motor system used in the experimental tests.

Excitation and Measuring System

Figure 5 shows the measuring setup used the experimental tests. Resonant excitation was imposed by an eccentric mass through a DC motor with brushes and permanent magnets. Real input ground motions with different characteristics, obtained from the PEER NGA Ground Motion Database,[43] were imposed through a Moog 6DOF 2000E shaking table (Table 1). Two high-speed laser displacement sensors, Micro-epsilon opto NCDT1607, were used to measure the horizontal displacement at the tip of cantilever beam and shaking table. The acceleration on the shaking table was also measured by a PCB Piezotronics accelerometer (max. acceleration 3 g, 700 mV/g). All signals were sampled at 100 sps per channel and digitalized by a PCM-DAS16D/16 data acquisition board.

It is worth mentioning that, in all cases, a linear structural behaviour was assured.

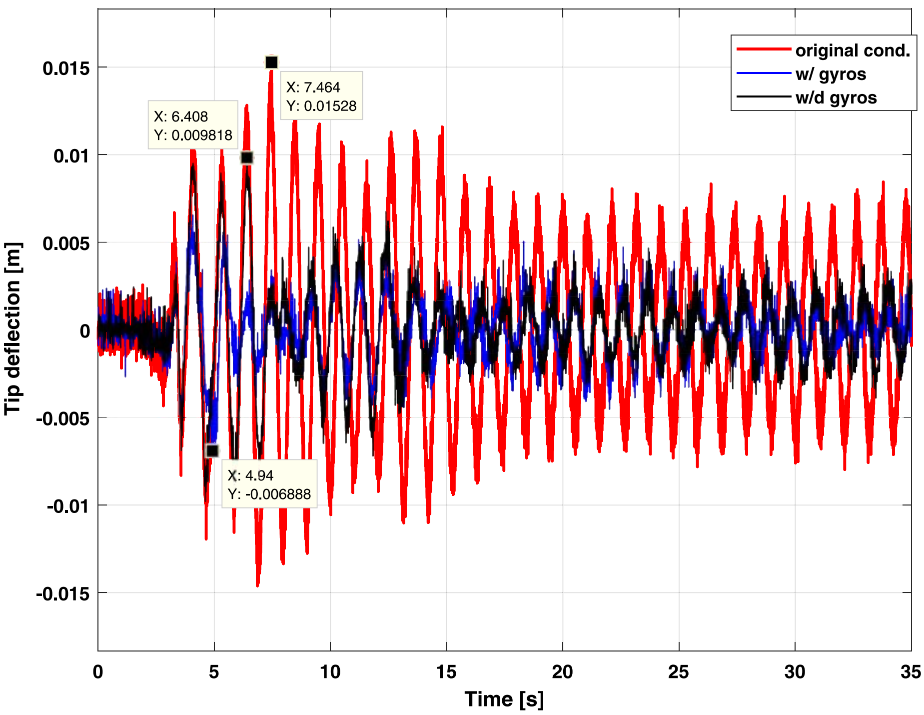

Fig. 8: Tip deflection under seismic record 1

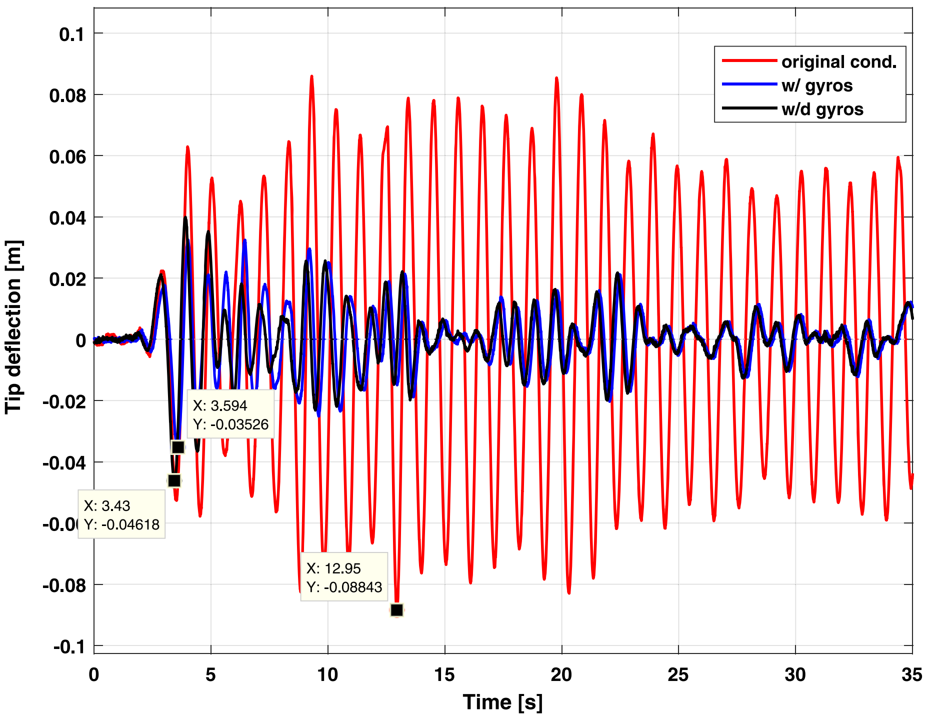

Fig. 9: Tip deflection under seismic record 2

Experimental Results

As is well known, free and resonant vibration tests are used to characterize dynamic systems; thus, in this section the structural response is summarized of each test in terms of the tip deflection of the cantilever beam in its original condition, and when provided with the gyroscopic device. Complementarily, to study the performance of the control system under random excitation, the structural response obtained under real seismic excitations is also included.

Free Vibration Tests

Figure 6 shows the tip deflection of the cantilever beam in free vibration from a prescribed initial tip deflection equal to 0.05 m.

Clearly, a steep drop in the structural response due to the gyroscopic moment effect is observed. The equivalent critical viscous damping ratio is increased from 0.5% to 10% by the inclusion of the gyroscope.

Forced Vibration Tests

Resonant Excitation

Figure 7 shows the tip deflection of cantilever beam under resonant forced vibrations imposed by an eccentric mass through a DC motor (see *Fig. 5*) from zero to nominal speed.

Figure 7 shows that, by installing the gyros device, under this type of excitation, the amplitude of structural response may be reduced to around 15%.

Seismic Excitation

To assess the influence of the start-up time on the effectiveness, in this test, the tip deflection of the cantilever beam was measured under two conditions: (a) with the flywheel spinning at the rated motor speed when the seismic event arrives at the structure (the DC motor is rotating constantly); and (b) the flywheel (or DC motor) starts rotating at the moment when the seismic event arrives at the structure (delayed gyroscope). Condition (b) is important when the control system is normally stopped and the DC motor is started by an acceleration level sensor (trigger) that detects the first vibration cycles when the excitation arrives at the structure. This is a feasible mode of operation for addressing non-permanent induced excitations, for example by people, vehicular traffic, machinery, wind or earthquakes. In this condition, the effectiveness of the system depends strongly on the acceleration rate of the excitation event and the acceleration ramp of the gyroscope–motor system.

Figures 8–12 show the tip deflection of the cantilever beam for each ground acceleration record without the control system (the original condition) (red line) and under conditions (a) (blue line) and (b) (black line) mentioned above.

As mentioned before, the reduction of the tip deflection obtained by installing a delayed gyroscope will depend on the acceleration rate of the event, the instant of time in which the DC motor is started and

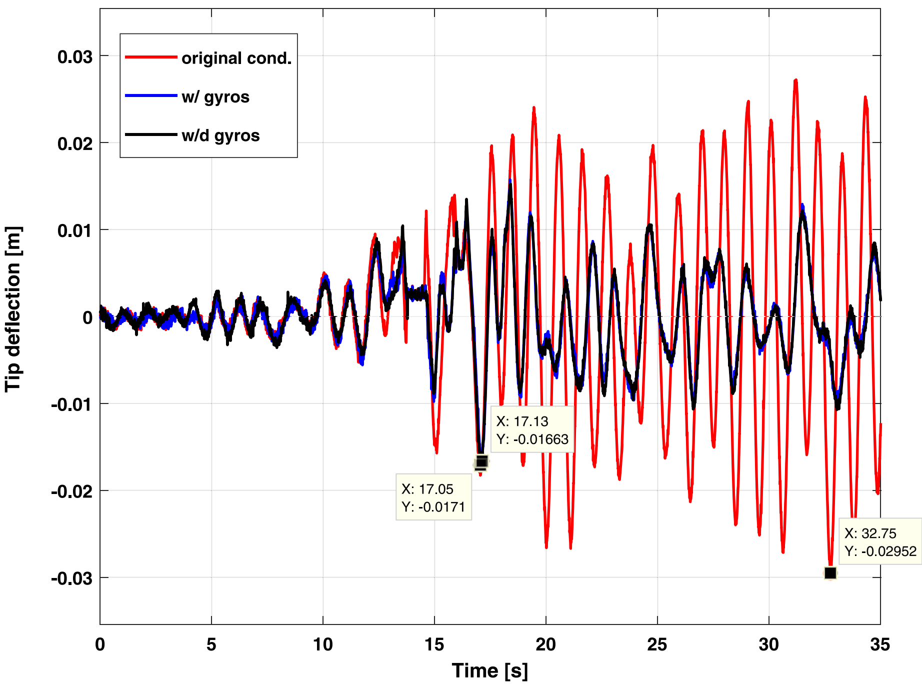

Fig. 10: Tip deflection under seismic record 3

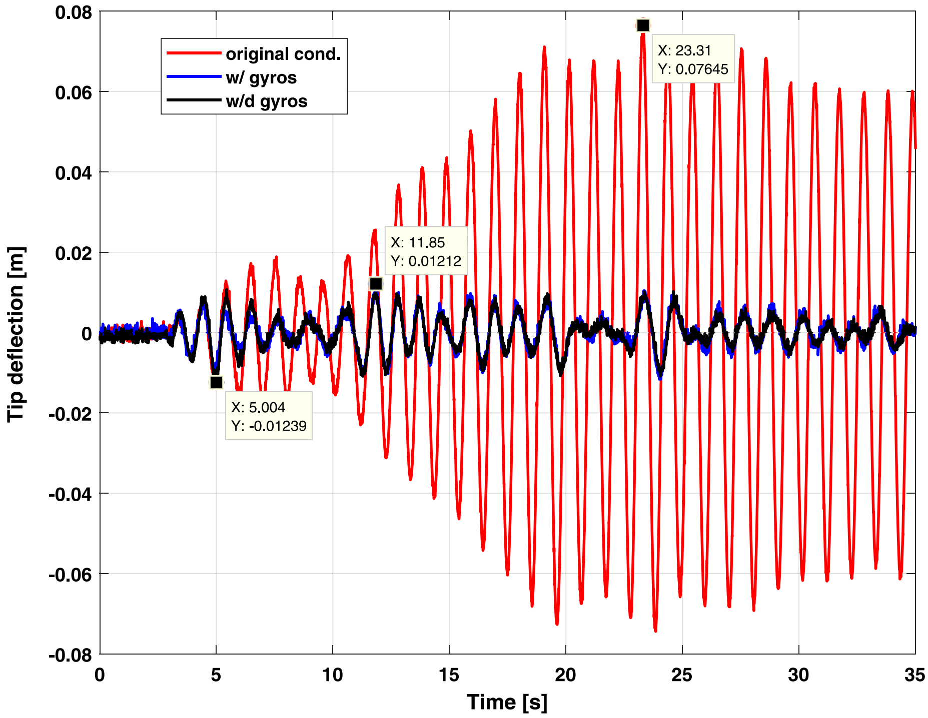

Fig. 11: Tip deflection under seismic record 4

the acceleration ramp of the gyroscope–motor system. Table 2 provides quantitative information about the reduction level that may be expected in the maximum tip deflection of the cantilever beam for both conditions mentioned above by the incorporation of the gyroscope.

From the results it is observed that the effectiveness of the gyroscopic system depends on the ratio of start-up time to peak response time (peak excitation time) as expected. In those cases, such as seismic records 1 and 5, where the ratio is 2:1, the effectiveness decreases. On the other hand, with ratios lower than 1:2 (50%) (seismic records 3 and 4), there is no loss of effectiveness for a delay in the motor start-up.

Indeed, the maximum tip deflection reduction, on average, is around 60% and 50% under the conditions (a) and (b), respectively, established in the study. It is important to highlight that significant reduction in the maximum tip deflection may be reached (around 30% for seismic record 5) even in the worst conditions, e.g. when the gyroscope has been started during the first cycles of vibration (feasible operation mode).

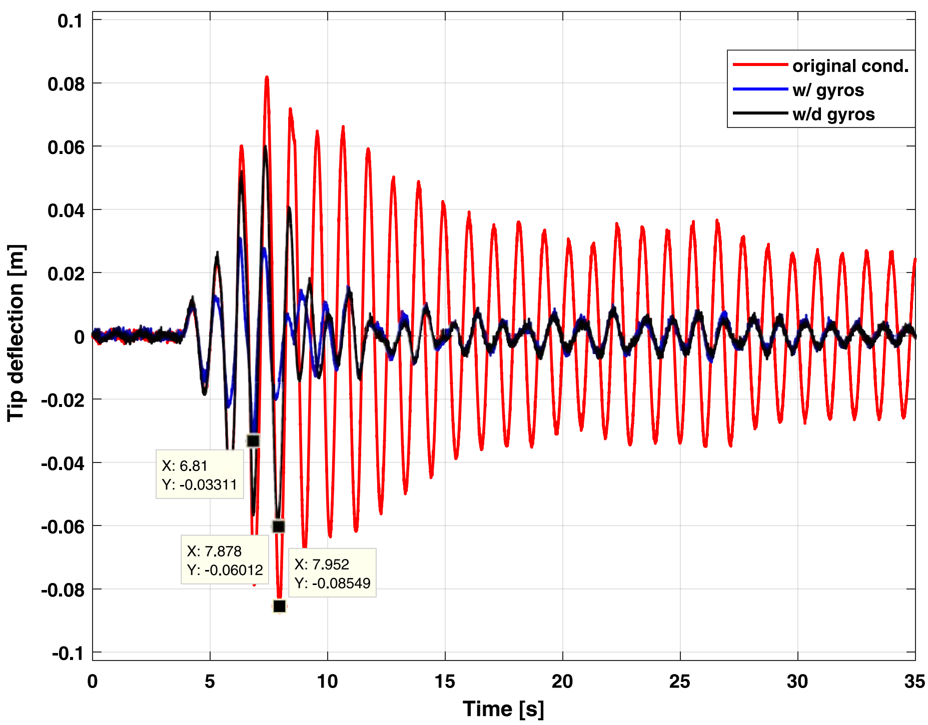

Fig. 12: Tip deflection under seismic record 5

Numerical Model

In order to design or predict the structural behaviour of a structure provided with a vibration control system based on the gyroscopic effect, a numerical model is required. This section presents a simple numerical model that includes a gyroscopic device located at the tip of a cantilever beam. The equation of motion of the original system can be written as

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F(t), \quad (3)$$

in which M, C and K are the mass, damping and stiffness matrices, respectively, $x(t)$ is the displacement vector, and $F(t)$ is the external force vector.

When the gyroscopic device is mounted at the tip of the cantilever beam (*Fig. 5*) the following gyroscopic stabilizing torque (Eq. 4 from Eq. 2) is incorporated, as external load, into the particular equation of the system of equations (Eq. 3) that corresponds to the rotational degree of freedom at the tip of cantilever beam:

$$T_g = J_z \omega \dot{\theta} \cos\theta \quad (4)$$

As noted, this torque, associated with the rotational degree of freedom at the tip of the structure, depends on the precession angle, $\theta(t)$, and the precession rate, $\dot{\theta}(t)$, of the gyroscope. Thus, the gyroscope precession dynamics are added into the system of equations, Eq. (3) through Eq. (5), as a new degree of freedom:

$$I_p\ddot{\theta} + C_p\dot{\theta} + K_p\theta = J_z\omega\dot{\theta}\cos\theta \quad (5)$$

in which I_p, C_p and K_p are the inertia, damping and restoring terms about the precession X-axis due to the location of the gyroscope centre of mass relative to the precession axis.[30] Thus, the equation that corresponds to the rotational degree of

	Tip deflection				
	Original condition	Delayed gyroscope		Gyroscope	
Seismic record	Max. value (m)	Max. value (m)	Reduction (%)	Max. value (m)	Reduction (%)
1	0.01528	0.009818	35.75	0.006888	54.92
2	0.08843	0.04618	47.78	0.03526	60.13
3	0.02952	0.0171	42.07	0.01663	43.67
4	0.0764	0.0124	83.77	0.0121	84.16
5	0.08549	0.06012	29.68	0.03311	61.27
Average			47.81		60.83

Table 2. Reduction of tip deflection

freedom at the tip of the structure (Eq. 3) is coupled to the new degree of freedom associated with the precession angle of the gyroscope. Note that all the dissipation of the energy (friction, etc.) is assumed to be through the damping coefficient, C_p.

Numerical and Experimental Results

To show the degree of accuracy in the estimate of the structural response, the measured tip deflection, and that obtained numerically, on the structure provided with the gyroscope under resonant excitation are shown in *Fig. 13*. While, in the first cycles, a small phase shift is perceived between the two signals (the start-up period of the gyroscope), good agreement is clearly observed in the remaining time.

Comparative Study

To gain a perspective on the vibration control, the maximum tip deflection of the cantilever beam provided with the gyroscopic device is compared with that obtained numerically, with the implementation of a typical translational TMD located at the tip of the structure, under the same conditions. The TMD parameters denoted as stiffness, k_{tmd}, and damping critical ratio, ξ_{tmd}, were obtained optimally through Warburton's[44] equations (*Fig. 14*). To make a valid comparison, the TMD mass was set equal to the flywheel mass (2.9% of the first mode mass of the structure).

As depicted in *Fig. 14*, a vibration control device based on the gyroscopic effect can reduce the maximum tip deflection of a cantilever beam fivefold compared with a traditional TMD device when the structure is under resonant excitation.

It is important to note that the implementation of another optimization approach or TMD type could lead to different results.

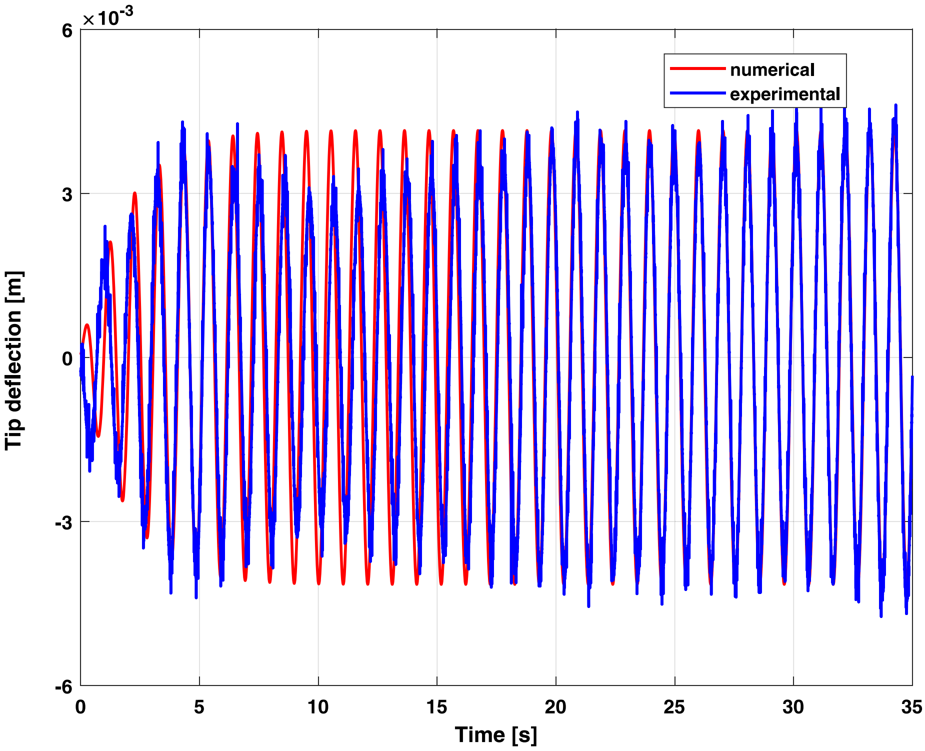

Fig. 13: Experimental and numerical tip deflection. Resonant excitation

Conclusions

With the aim of assessing the effectiveness of controlling structural vibrations in beam-like structures, a pseudo-passive device based on the gyroscopic effect was studied. The study was conducted through a prototype structure under three excitation conditions: (a) free vibration; (b) resonant excitation; and (c) realistic seismic excitation.

The results showed that the control system based on the gyroscopic effect was highly effective in controlling structural vibrations induced by different types of excitation. The maximum tip deflection of the prototype structure was reduced to around 15% under resonant excitation and to 50% (average) under seismic excitation. Clearly, to reduce the structural response of this type of structure, gyroscopic moment-based devices may be used advantageously.

Additionally, with the purpose of designing and simulating structural behaviour, a mathematical model was developed.

By simulation, it was verified that a gyroscopic device can reduce the maximum tip deflection of the prototype structure under resonant excitation up to five times that obtained with the implementation of a typical translational TMD device.

While this work presents a conceptual study on the effectiveness of a gyroscopic device assembled on a prototype structure, comparable results are expected on similar real structures

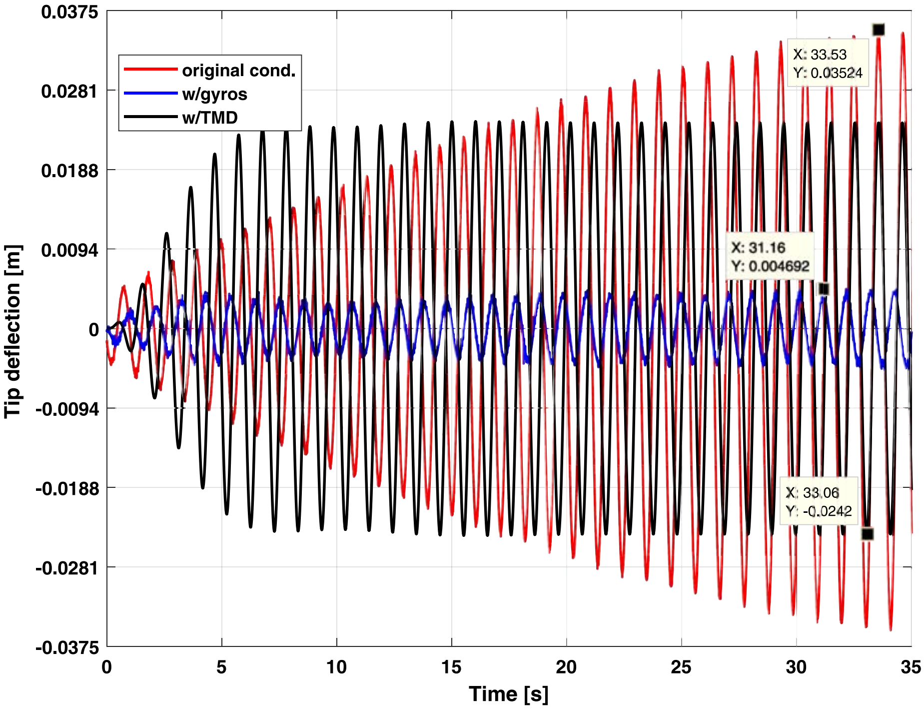

Fig. 14: Tip deflection. Structure in its original condition and provided with gyroscope and TMD

(beam-like structures with the same mass ratio between flywheel and the vibration first mode) under similar conditions of excitation. Work is currently in progress on the implementation of a gyroscopic device on a real structure.

Acknowledgements

Help received from Professor Daniel Ambrosini and Engineer Gabriel Houri during the experimental tests is gratefully acknowledged.

Funding

The authors gratefully acknowledge the financial support of the National Research Council (CONICET), Argentina, and the National University of Cuyo, Argentina [Grant Number Proyect N° 80020160200171UN].

References

[1] Soong TT, Constantinou MC. *Passive and active structural vibration control in civil engineering*. Springer-Verlag Wien; 1994. doi.org/ 10.1007/978-3-7091-3012-4.

[2] Soong TT, Dargush GF. *Passive energy dissipation systems in structural engineering*. Chichester, UK: John Wiley & Sons, 1997. https://doi.org/10.1002/stc.4300060114.

[3] Casciati F, Rodellar J, Yildirim U. Active and semi-active control of structures – theory and applications: a review of recent advances. *J Intell Mater Syst Struct*. 2012; 23: 1181–1195. https://doi: 10.1177/1045389 ×12445029.

[4] Özşahin O, Özgüven H N, Budak E. Analytical modeling of asymmetric multi-segment rotor – bearing systems with timoshenko beam model including gyroscopic moments. *Comput Struct*. 2014; 144: 119–126.

[5] Kurvinen E, Sopanen J, Mikkola A. Ball bearing model performance on various sized rotors with and without centrifugal and gyroscopic forces. *Mech Mach Theory*. 2015; 90: 240–260.

[6] Phadatare HP, Maheshwari V, Vaidya KS, Pratiher B. Large deflection model for nonlinear flexural vibration analysis of a highly flexible rotor-bearing system. *Int J Mech Sci*. 2017; 134: 532–544.

[7] Matsushita O, Tanaka M, Kanki H, Kobayashi M, Keogh P. *Gyroscopic effect on rotor vibrations. Vibrations of rotating machinery*. Mathematics for Industry, vol 16. Tokyo: Springer; 2017. https://doi.org/10.1007/978-4-431-55456-1_6.

[8] Shahgholi M, Khadem SE, Bab S. Free vibration analysis of a nonlinear slender rotating shaft with simply support conditions. *Mech Mach Theory*. 2014; 82: 128–140.

[9] Phadatare HP, Pratiher B. Nonlinear frequencies and un balanced response analysis of high speed rotor -bearing systems. 12th International Conference on Vibration Problems, ICOVP 2015. Procedia Engineering. 2016;144:801–809.

[10] Bahramiasl S, Abbaspour M, Karimirad M. Experimental study on gyroscopic effect of rotating rotor and wind heading angle on floating wind turbine responses. *Int J Environ Sci Technol*. 2018; 15: 2531–2544. https://doi.org/10.1007/s13762-017-1519-4.

[11] Brysin AN, Nikiforov AN. Approach to determining the eigenfrequencies of a gyroscopic system with friction in general form. *Mech Solids*. 2019; 54: 570–576. https://doi.org/10.3103/S0025654419040101.

[12] Schaub H, Vadali S, Junkins J. Feedback control law for variable speed control moment gyros. *J Astronaut Sci*. 1998; 46(3): 307–328.

[13] Leve FA. Scaled control moment gyroscope dynamics effects on performance. *Acta Astronaut*. 2015;110:77–88.

[14] Abbas HS, Ali A, Hashemi SM, Werner H. LPV state-feedback control of a control moment gyroscope. *Control Eng Pract*. 2014; 24: 129–137.

[15] Keshtkar N, Keshtkar S, Moreno JA, Poznyak A, Kojima H. LMI-based sliding mode control of an underactuated control moment gyroscope system. *IFAC-Papers On Line*. 2018; 51(13): 291–296.

[16] Keshtkar S, Moreno JA, Kojima UK, Takaya K. Spherical gyroscopic moment stabilizer for attitude control of microsatellites. *Acta Astronaut*. 2018;143:9–15.

[17] Jia Y, Misra AK. Robust trajectory tracking control of a dual-arm space robot actuated by control moment gyroscopes. *Acta Astronaut*. 2017;137:287–301.

[18] Jia Y, Xu S. Decentralized adaptive sliding mode control of a space robot actuated by control moment gyroscopes. *Chin J Aeronaut*. 2016; 29(3): 688–703.

[19] Hu Q, Zhang J. Maneuver and vibration control of flexible manipulators using variable-speed control moment gyros. *Acta Astronaut*. 2015; 113: 105–119.

[20] Hu Q, Guo C, Zhang J. Singularity and steering logic for control moment gyros on flexible space structures. *Acta Astronaut*. 2017; 137: 261–273.

[21] Luo Q, Li D, Jiang J. Coupled dynamic analysis of a single gimbal control moment gyro cluster integrated with an isolation system. *J. Sound and Vibration*. 2014; 333(2): 345–363.

[22] Shi S, Li D, Luo Q. Design and dynamic analysis of micro-vibration isolator for single gimbal control moment gyro. *Procedia Eng*. 2015; 99: 551–559.

[23] Becker FB, Heindel S, Rinderknecht S. Active vibration isolation of a flexible rotor being subject to unbalance excitation and gyroscopic effect using H∞-optimal control. In: *Proceedings of the 9th IFToMM International Conference on Rotor Dynamics*, Pennacchi P, (ed), 2014 Sep 22–25; Milan. Cham: Springer; 2015. p. 1727–1739. https://doi.org/10.1007/978-3-319-06590-8_142.

[24] Feng X, Jia Y, Xu S. Dynamics of flexible multibody systems with variable-speed control moment gyroscopes. *Aerosp Sci Technol*. 2018; 79: 554–569.

[25] Giannini O. Forced response of 2-dof gyroscopic systems with stable eigenvalues. *Topics Modal Anal Testing*. 2018; 9: 15–23. https://doi.org/10.1007/978-3-319-74700-2_3.

[26] Fang J, Yin R, Lei X. An adaptive decoupling control for three-axis gyro stabilized platform based on neural networks. *Mechatronics (Oxf)*. 2015; 27: 38–46.

[27] Pan S. Robust control of gyro stabilized platform driven by ultrasonic motor. *Sens Actuators A*. 2017; 261: 280–287.

[28] Schlick O. *Gyroscopic effects of flying wheels on board ships*. London, UK: Transactions of The Institution of Naval Architects INA; 1904.

[29] Chalmers T. *The automatic stabilisation of ships*. London: Chapman and Hall, 1931.

[30] Arnold RN, Maunder L. *Gyrodynamics and its engineering applications*. New York and London: Academic Press, 1961.

[31] Burger W, Corbet AG. *Ship stabilizers*. New York: Pergamon Press Ltd; 1966.

[32] Perez T, Steinmann P. Analysis of ship roll gyrostabiliser control. In: *Proceedings of the 8th IFAC International Conference on Manoeuvring and Control of Marine Craft*, Donha DC, (ed), 2009 Sep 16–18; Guarjua. Laxenburg: IFAC; 2009. p. 310–315.

[33] Townsend NC, Murphy AJ, Shenoi RA. A new active gyrostabiliser system for ride control of marine vehicles. *Ocean Eng*. 2007; 34: 1607–1617.

[34] Perez T, Blanke M. Ship roll damping control. *Annu Rev Control*. 2012; 36: 129–147.

[35] Kitamura H, Kawamura S, Yamada M, Fujii S. Structural response control technologies of Taisei corporation. In: *Proceedings of the US National Workshop on Structural Control Research*, Housner GW, Masri SF, (eds), 1990 Oct 25–26; Los Angeles. Los Angeles: University of Southern California; 1990. p. 141–150.

[36] Kazao Y, Takahara K, Yamada M, Sakamoto S. Active vibration control of a structure using gyro stabilizers. *Proceedings of First International Conference on Motion and Vibration Control*; 1992 Sep 7–11; Yokohama. Tokyo: Japan Society of Mechanical Engineers. p. 158–163.

[37] Sakaomoto S, Yamada M, Kazao Y, Tanaka E. Test on active vibration control system using gyro stabilizer. Transactions of the Japan National Symposium on Active Structural Control; 1992. p. 145–150.

[38] Nagashima I, Yamada M, Tujita O. Development and full scale implement of passive and active response control systems to buildings. In: *Proceedings of International Workshop on Structural Control*, Housner GW, Masri SF, (eds), 1993 Aug 5–7; Honolulu. Los Angeles: University of Southern California; 1993. p. 333–345.

[39] Kazao Y, Namiki M, Yamada M, Higashiyama H, Uesu K. Active vibration control of a tower using gyroscopic moment. In: *Proceedings of the Second International Conference on Motion Vibration Control*, Yoshida K, Nonami K, (eds), 1994 Aug 30-Sep 3; Yokohama. Tokyo: Japan Society of Mechanical Engineers. p. 144–149.

[40] Yamada M, Higashiyama H, Namiki M, Kazao Y. Active vibration control system using a gyro-stabilizer. *Control Eng Pract*. 1997; 5(9): 1217–1222.

[41] Higashiyama H, Yamada M. Characteristics of active vibration control system using gyro-stabilizer. *Eng Struct*. 1998; 20(3): 176–183.

[42] Townsend NC, Shenoi RA. Modelling and analysis of a single gimbal gyroscopic energy harvester. *Nonlinear Dyn*. 2013; 72: 285–300.

[43] Pacific Earthquake Engineering Research Center (PEER) NGA Ground Motion Database. [cited February 2020]. https://ngawest2.berkeley.edu.

[44] Warburton GB. Optimum absorber parameters for various combinations of response and excitation parameters. *Earthq Eng Struct Dynam*. 1982; 10: 381–401.