International Journal of Innovation and Applied Studies
ISSN 2028-9324 Vol. 8 No. 4 Oct. 2014, pp. 1669-1678

http://www.ijias.issr-journals.org/

Dynamics of a Nonlinear Automatic Door Closing Torsional Mechanism

Galal A. Hassaan

Department of Mechanical Design & Production,
Faculty of Engineering, Cairo University,
Giza, Egypt

Galalhassaan@ymail.com

ABSTRACT: Door closing mechanisms are used in all building venues using air conditioning systems to reduce thermal losses. One of the closing mechanisms is the torsional type. The visco-elastic characteristics of the closing mechanism may exhibit certain sort of nonlinearities from its linear characteristics. The dynamics of the door with nonlinear characteristic with positive and negative deviation from the linear characteristics of the door closing mechanism are studied. The system dynamics are defined by a nonlinear ordinary second-order differential equation which is solved using Runge-Kutta 4 technique through the MATLAB environment. Two types of nonlinearity are considered depending on the deviation from the linear characteristics of the closing mechanism. One type reveals dynamic behaviour similar to that of overdamped linear dynamic system while the other type reveals dynamic behaviour similar to that of underdamped linear dynamic system. The second type has large effect on the door dynamics where the maximum deviation in the door dynamic response may exceed 700 % from the linear characteristics of the door.

KEYWORDS: Automatic door closing mechanism, Nonlinear mechanism characteristics, Door dynamics.

1 INTRODUCTION

Door closing mechanisms are required when building doors are required not to be open in its default condition. Application of this is air-conditioned building where energy saving is a requirement. This covers conference rooms, classrooms, administration buildings, airports travel terminals, banks, and other many applications. In such applications, the door has to close automatically in a minimum time to minimize heat transfer from outside to inside the building and vice versa. Others may require the door to close slowly not to heart the other users. A mechanical recoiling mechanism is used for this purpose consisting of a parallel spring and damper connected to the door at its joints. Two styles are available: the translational type and the torsional type. Only the second type is considered in this work where torsional spring and torsional dampers are used.

Clabaugh (2004) set an important guidelines for designing, constructing and renovating instructional spaces in educational classrooms. Regarding the classroom doors he stated that the doors should be equipped with hardware for slow and quiet closure [1]. Al-Bassiouny (2005) investigated the effect of quadratic and cubic nonlinearities in elastomeric material dampers to quiet torsional vibrations of internal combustion engines shafts. His study covered the effects of damping, nonlinear terms and excitation magnitude on the system dynamics [2]. Tjahjowidodo, Al-Bender and Brussel (2006) offered a model for torsional compliance of harmonic drives. The characteristics of the system compliance were highly nonlinear as shown experimentally [3]. Meirelles, Zampieri and Mendes (2007) studied the crankshaft torsional vibration in internal combustion engines. They considered a rubber and a viscous damper assembled to the crankshaft front-end [4]. Filipowicz (2007) studied experimentally the characteristics of a torsionally flexible metal coupling. He showed that it has linear characteristics during loading and unloading with different torsional stiffness [5]. Lee and Hsieh (2009) designed a motor-gear transmission system based on analysis and design theory for motion of a gear train for the automatic opening and closing of a car door [6]. Bayly et. al. (2010) set a classroom design guide including door design requirements. They pointed out the door dimensions and direction of opening and to have visual identification, opening force and hardware confirming to ADA standards [7]. Homik (2010) described methods of diagnosing, maintenance and regeneration of torsional vibration dampers used in ship building. He illustrated the types of failures occurring in viscous and spring torsional vibration dampers [8]. Homik (2011) presented means fo damping the torsional vibrations and methods for selection of viscous torsional vibration dampers for a given type of engine [9]. Filipovic et. al. (2012) presented a possible approach to define the parameters of torsional vibrating systems of internal combustion engines needed for a preliminary selection of the basic parameters of viscous type torsional vibration dampers such as the elastic damper, the balance weight damper and the dual mass flywheel [10]. Carpino et. al. (2012) presented the design of a compact torsional spring to be used in a compliant system for series elastic actuators. They considered the designed spring having linear characteristics with error up to 6 % [11]. Mahdi (2013) developed a software system to lock doors using electromagnetic door lock for security purposes [12]. Yang et.al. (2013) used a torsional spring in a spring-loaded antibacklash gear transmission to improve the transmission precision. They investigated th dynamic characteristics of the system with study of the effect of the torsional spring stiffness using damping rational preload on the dynamic transmission error [13]. Soni and Roy (2013) described the design , calibration and characterization of a thrust stand capable of nano-Newton resolution. They employed a passive eddy-current non-contact and vacuum compatible damper [14]. Joshi, Hung and Vengallatore (2014) presented an overview of recent advances in damping from viewpoint of device design. They connected and organized techniques for the rational and effective control of linear damping in miniaturized mechanical resonators [15].

2 ANALYSIS

The automatic door is a door hinged with the wall with a number of revolute joint allowing only one rotational motion θ as shown in Fig.1 (plan view). The revolute joint is at O and a closing mechanism consisting of a torsional damper and a torsional damper is attached to the door at the centreline of the revolute joint.

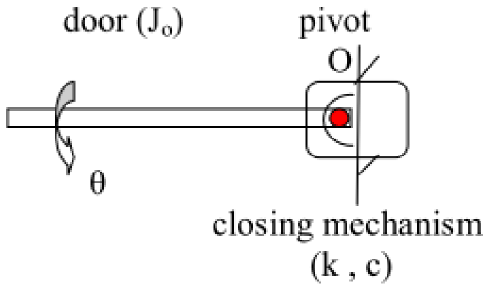

Fig. 1.   Automatic door closing mechanism.

The dynamic system of Fig.1 has the parameters:

- Door mass moment of inertia about the joint centerline, J_o.
- Closing mechanism torsional stiffness, k.
- Closing mechanism torsional damping coefficient, c.

The differential equation of the dynamic system in Fig.1 in terms of the dynamic motion θ is:

$$\mathbf{J_o\theta'' + c\theta' + k\theta = 0} \quad (1)$$

The damping and elastic torque of the closing mechanism against the door motion are assumed nonlinear. The variation of the damping torque with door angular velocity θ' and the spring torque with the angular motion of the door θ is shown in Figures 2 and 3 for 3 levels of nonlinearity and negative and positive deviations respectively.

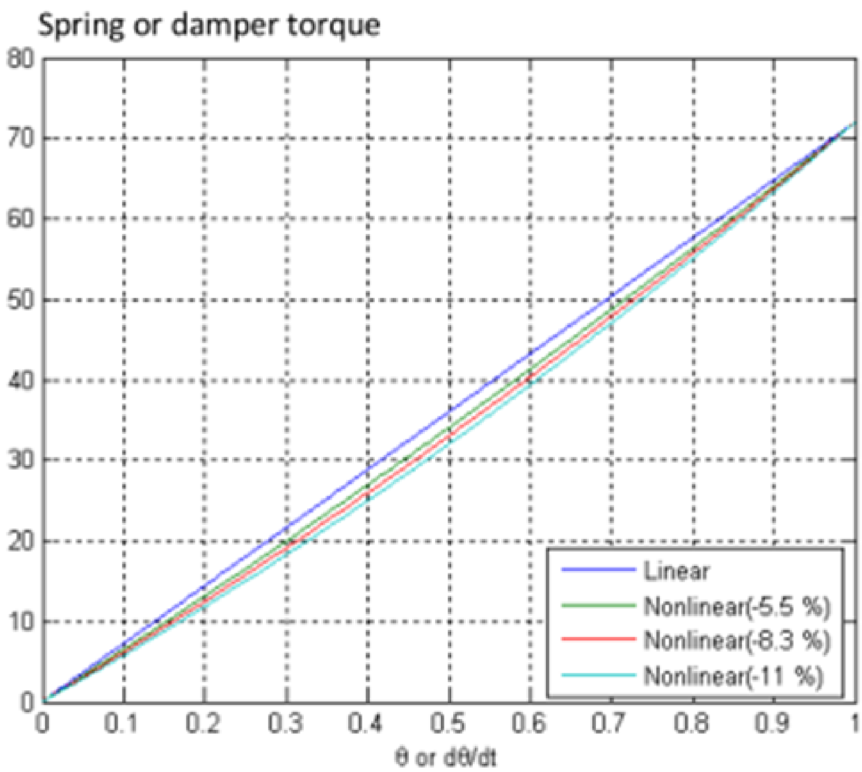

Fig.2 Closing mechanism characteristics (negative deviation)

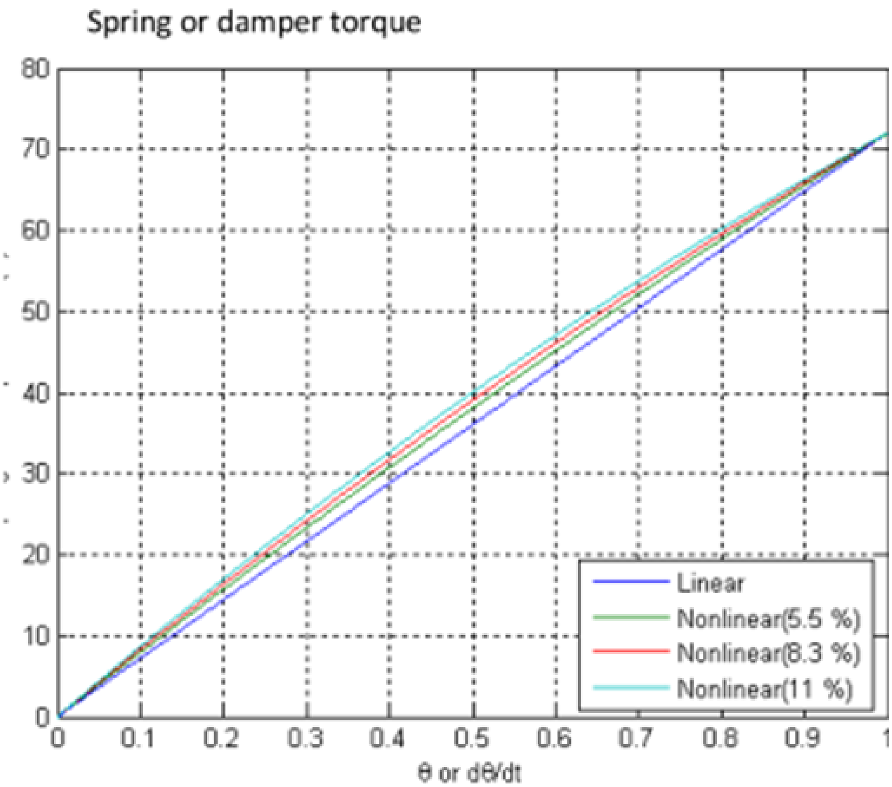

Fig.3 Closing mechanism characteristics (positive deviation)

The six nonlinearity levels correspond to the maximum deviation of the linear characteristics of the torsional closing elements as follows:

Level 1: - 5.5 % (maximum deviation).

Level 2: - 8.3 % (maximum deviation).

Level 3: - 11.0 % (maximum deviation).

Level 4: 5.5 % (maximum deviation).

Level 5: 8.3 % (maximum deviation).

Level 6: 11.0 % (maximum deviation).

The static torque applied to the closing mechanism, T is related to the mechanism deflection and/or velocity, q through the fitted second-order polynomial model:

$$T = a_0q^2 + a_1q + a_2 \quad (2)$$

The parameters of the nonlinear model of Eq.2 depend on the deviation level from linear characteristics. They are given in Table 1.

Table 1. Parameters of the nonlinear characteristics in Eq.2

Deviation level (%)	a_0	a_1	a_2
-5.5	8	64	0
-8.3	12	60	0
-11.0	16	56	0
5.5	-8	80	0
8.3	-12	84	0
11.0	-16	88	0

To simplify the analysis it is assumed that the elastic and damping characteristics of the closing mechanism are defined by the same equation (Eq.2). Therefore, the stiffness of the closing mechanism is given from Eq.2 by:

$$k = dT/dq = 2a_0\theta + a_1 \qquad (3)$$

Where q is replaced by the door motion θ.

The damping coefficient of the closing mechanism using Eq.2 is:

$$c = dT/d\theta' = 2a_0\theta' + a_1 \qquad (4)$$

Now, combining Eqs.1, 3 and 4 provides the differential equation of the door during its dynamic motion as:

$$J_o\theta'' + 2a_0\theta'^2 + a_1\theta' + 2a_0\theta^2 + a_1\theta = 0 \qquad (5)$$

Eq.5 is a second-order nonlinear homogeneous differential equation describing the dynamic motion of the door as excited by the initial conditions.

3 DOOR DYNAMIC RESPONSE

The dynamic response of the automatic closing door of an 18 kgm^2 mass moment of inertia to an initial displacement θ (0) can be obtained by solving the door differential equation (Eq. 5). This is can be done by using any numerical technique such as Runge-Kutta 4 technique [16].

This requires transferring the second-order differential equation of Eq.5 to a set of first-order differential equations using the state variables. This constructs the state model of the system as follows [17]:

State variables:

$$x_1 = \theta$$
$$x_2 = \theta' = x_1'$$

Using the state variables and Eq.5, the state model of the dynamic system under study is:

$$x_1' = x_2$$
$$x_2' = -(2a_0/J_o)x_2^2 - (a_1/J_o)x_2 - (2a_0/J_o)x_1^2 - (a_1/J_o)x_1 \qquad (6)$$

MATLAB is used to apply the Runge-Kutta 4 technique to solve Eq.6 for the initial conditions $x_1(0)$ and $x_2(0)$ [18,19]. A MATLAB code is written to solve Eq.6 for the boundary conditions:

$[x_1(0)\ \ x_2(0)]^T = [1\ \ 0]^T$

The code output for different nonlinearity levels is given in Figures 4 and 5.

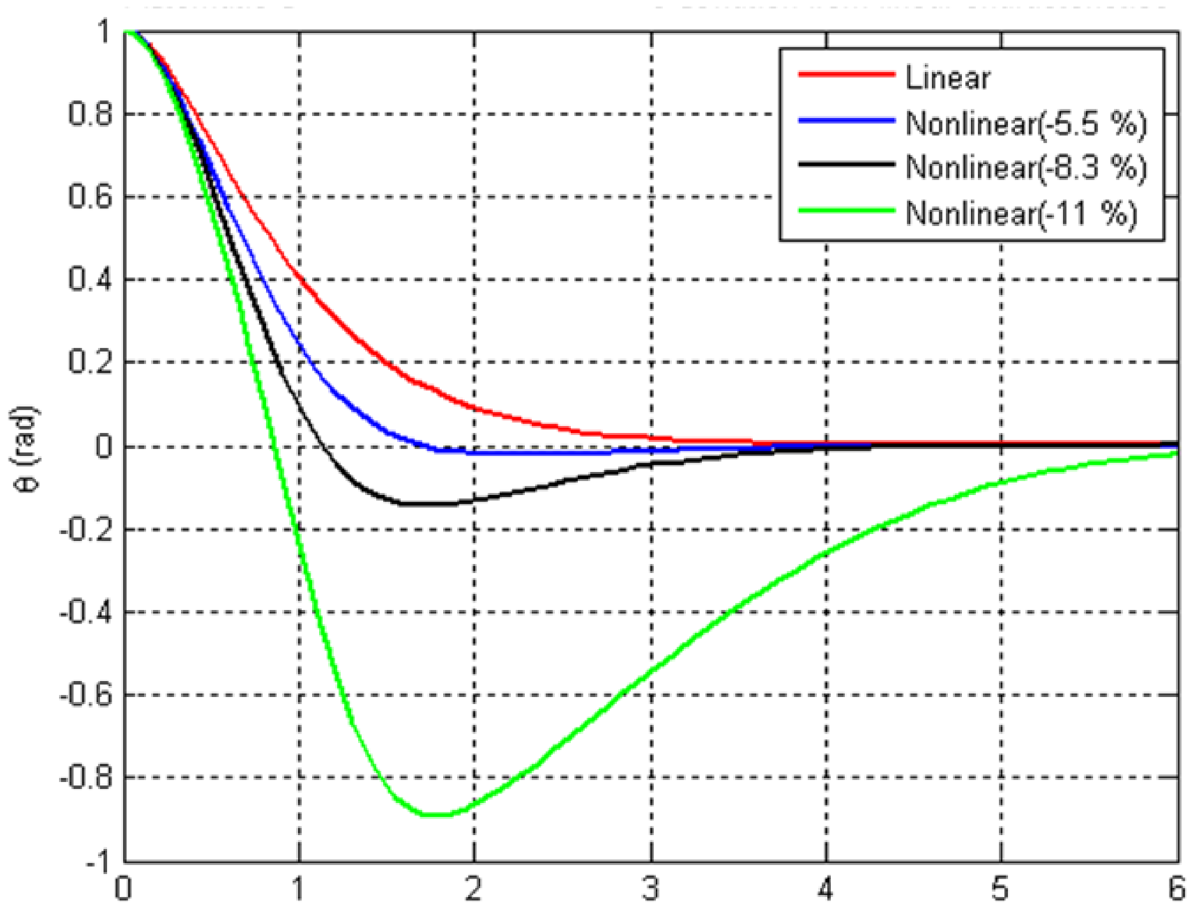

Fig.4 Door response with nonlinear negative deviation.

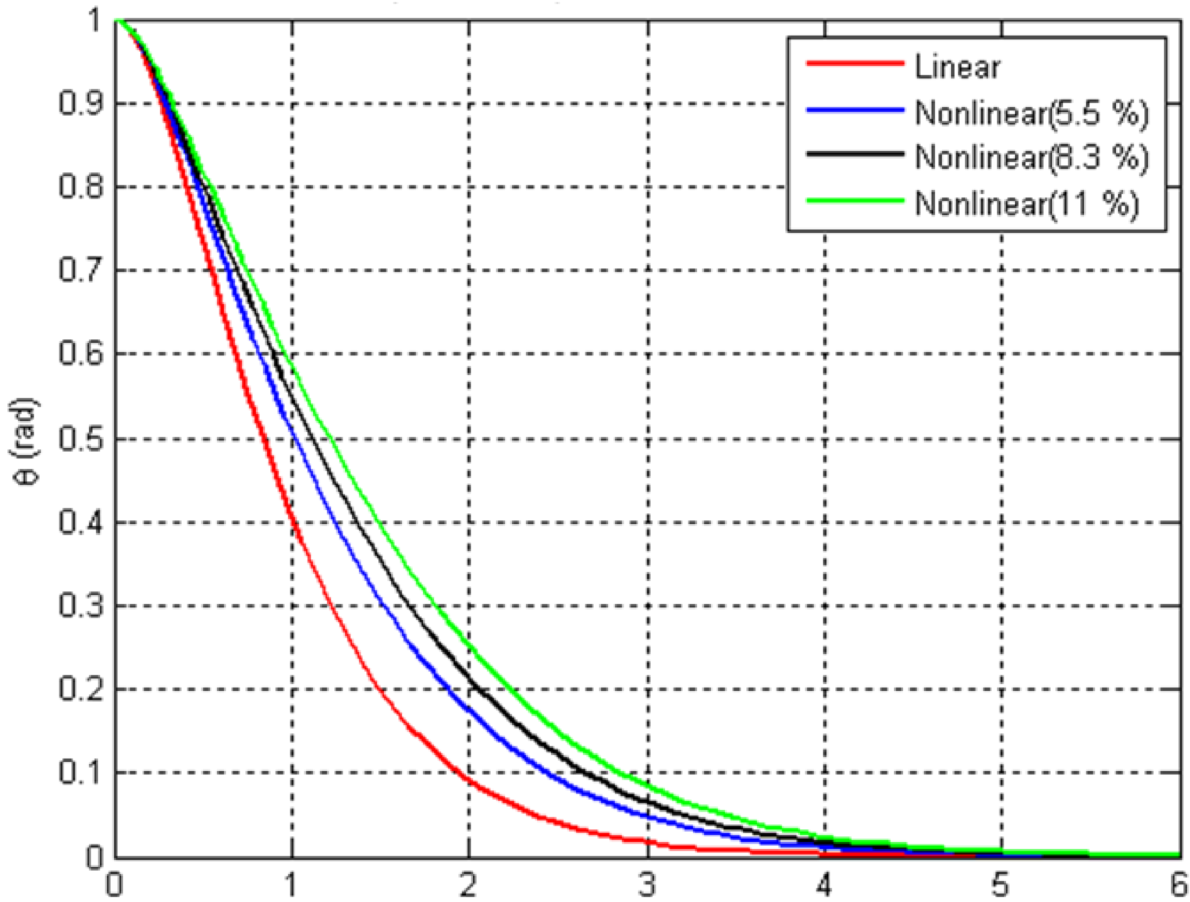

Fig.5 Door response with nonlinear positive deviation.

There is a remarkable deviation in the door response from that of a door closing mechanism with linear characteristics. This deviation is much bigger with negative deviation-nonlinear characteristics. Some of the specifications of the nonlinear door closing system based on the door time response an initial displacement motion are listed in Table 2 as extracted from Figures 4 and 5.

Table 2: Specifications of the nonlinear door closing system.

Linearity level (%)	Maximum response deviation from linear (%)	Minimum motion (rad)	Settling time (s)
0 (linear)	0	0	2.58
5.5	52.4	0	3.55
8.3	75.6	0	3.58
11.0	100	0	4.20
-5.5	-80	-0.023	2.50
-8.3	-160	-0.148	3.51
-11.0	-714	-0.840	6.00

4 Nonlinearity Effects

- For nonlinearity with positive deviation from linear characteristics, the door dynamic system behaves as an overdamped single degree of freedom system.
- For nonlinearity with negative deviation from linear characteristics, the door dynamic system behaves as an underdamped single degree of freedom system. Oscillation appears around the static equilibrium position (closing position).
- The minimum motion of the door decreases as the maximum negative deviation from linear characteristics increases.
- With maximum deviation from linear characteristics less than -8.3 %, the response deviation from linear characteristics response becomes slow and oscillating.

5 Conclusion

- An automatic door with nonlinear characteristics was studied in this work..
- Both positive and negative deviations from linear closing mechanism characteristics were considered.
- Nonlinear characteristics with positive deviation resulted in door time response similar to that of free overdamped single degree of freedom vibrating systems.
- Nonlinear characteristics with positive deviation resulted in door time response similar to that of free overdamped single degree of freedom vibrating systems.
- Nonlinear characteristics with negative deviation resulted in door time response similar to that of free underdamped single degree of freedom vibrating systems.
- Maximum door time response deviation from linear characteristics response changed from 52 to 100 % with positive deviation from linear characteristics, and from -80 to -4 % with negative deviations.
- Minimum door motion in the negative direction reached -0.84 rad for the -11.0 % maximum negative deviation.
- The speed of response was measured by the settling time corresponding to ± 2 % of the steady state response (closing position of the door).
- In general, the settling time increased with increased nonlinearity of the closing mechanism characteristics.

REFERENCES

[1] S. Clabaugh, "Classroom design manual", University of Maryland, Version 4, 2004.

[2] A. Al-Bassiouny, "Effect of nonlinearities in elastomeric material dampers on torsional oscillation control", *Applied Mathematics and Computation*, vol.162, pp.835-854, 2005.

[3] T. Tjahjowidodo, F. Al-Bender and H. Brussel, "Nonlinear modeling and identification of torsional behavior in harmonic drives", *Proceedings of ASMA*, pp.2785-2796, 2006.

[4] P. Meirelles, D. Zampieri and A. Mendes, "Mathematical model for torsional vibration analysis in internal combustion engines", *12th IFTOMM World Congress*, Besancon, France, June 18-21, 2007.

[5] K. Filipowicz, "Determining the static characteristics of a torsionally flexible metal coupling", *Acta Montanistica, Slovaca*, vol.12, no.4, pp.304-308, 2007.

[6] H. Lee and L. Hsieh, "Innovative design of an automatic car-door opening system", *Proceedings of the International Multi-Conference of Engineers and Computer Scientists*, vol. II, March 18-20, Hong Kong, 2009.

[7] N. Bayly et. al., "Emory College classroom design guide", Emory University, Georgia, USA, October 2010.

[8] W. Homik, "Diagnostics, maintenance and regeneration of torsional vibration dampers for crankshafts of ship Diesel engines", *Polish Maritime Research*, vol.17, pp.62-68, 2010.

[9] W. Homik, "Damping of torsional vibrations of ship engine crankshafts – general selection methods of viscous vibration dampers*", ibid*,, vol.18, pp.43-47, 2011.

[10] I. Filipov, D. Bibic, A. Nilasinovic and A. Pecar, "Preliminary selection of basic parameters of different torsional vibration dampers intended for use in medium-speed diesel engines", *Transactions of FAMENA* XXXVI-3, pp.79-88, 2012.

[11] G. Carpino et. al., "A novel compact torsional spring for series elastic actuators for assistive wearable robots", *ASME Journal of Mechanical Design*, vol.134, pp.1-10, 2012.

[12] S. Mahdi, "Development of anti-sheft door system for security room", *National and Applied Sciences*, vol.4, no.3, May, pp.237-242, 2013.

[13] Z. Yang et.al., "Nonlinear dynamics modeling and analysis of torsional spring-loaded antibacklash gear with time-varying meshing stiffness and friction", *Advances in Mechanical Engineering,* vol.2013, Article ID 203438, pp.1-17, 2013.

[14] J. Soni and S. Roy, "Design and characterization of a nano-Newton resolution thrust stand", *Review of Scientific Instruments*, vol.84, 095103, pp.1-8, 2013.

[15] S. Joshi, S. Hung and S. Vengallatore, "Design strategies for controlling damping in micromechanical and nanomechanical resonators", *EPJ Techniques and Instrumentation, Springer Open Journal*, pp.1-14, 2014.

[16] S. Chapra and R. Canale, "Numerical methods for engineers", McGraw-Hill Higher Education, 2010.

[17] K. Atkinson, W. Harn and D. Stewart, "Numerical solution of ordinary differential equations", *J. Wiley & Sons*, 2009.

[18] M. Brons, "Using MATLAB to solve differential equations numerically", Department of Mathematics, Technical University of Denmark, September, 1998.

[19] P. Harihara and D. Childs, "Solving problems in dynamics and vibrations using MATLAB", Department of Mechanical Engineering, Texas a and M University, May 2014.

BIOGRAPHY

Galal Ali Hassaan:

An emeritus professor in the Department of Mechanical Design and Production, Faculty of Engineering, Cairo University, EGYPT. He got his Ph.D. from Bradford University, UK in 1979. He published 10's of research papers in various International Journals. He is the author of books on Experimental Systems Control and History of Mechanical Engineering. His current research is in Mechanical Vibrations, Automatic Control and Mechanism Synthesis.