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ADJUSTMENT OF THE TRANSMISSIBILITY OF A SINGLE-DEGREE OF FREEDOM VIBRATING SYSTEM, PART I: UNIT TRANSMISSIBILITY

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ABSTRACT

The purpose of this paper is to present an efficient simple technique for the adjustment of the transmissibility of a single degree of freedom system through the optimal selection of one parameter which is the damping ratio of the vibrating system. As an application a case of constant unit transmissibility is considered with proper dynamics of the vibration amplitude ratio. Different objective function relationships are presented and the best one is assigned leading to exactly the desired unit force transmissibility and a frequency spectrum of the system vibration amplitude ratio having a settling frequency ratio as low as 0.038.

KEYWORDS: Vibration isolators design, transmissibility adjustments, constant unit transmissibility, settling frequency ratio, optimum system dynamics, performance indices.

INTRODUCTION

Force transmissibility plays an important role in structural dynamics since it excites structure vibration and noise in near-by locations. Research activities are focused on this aspect over years. Here, I will present some of the research activities regarding this aspect during the last 13 years.

Johnson, 2002 developed a structure damage feature based on transmissibility providing three levels of damage identification. He used data from an experimental 3-story building model where the transmissibility based damage feature was found. Du, 2003 used the force transmissibility through each isolator and the rational sound power of the foundation as criteria to show the effects and significance of the internal resonances on isolator performance. Luca, Chira and Rosca, 2005 examined the effect of using passive, semi-active and active isolators of the force transmissibility of a single degree of freedom vibrating system. Robertson et al., 2006 presented simulation results for using a magnetic spring arrangement for active vibration isolation of large load structures. Transmissibility less than unity was demonstrated over the entire frequency spectrum. Yadav, 2007 discussed the vibration analysis of a 3-layer sandwich beam. He evaluated the effectiveness of the beam for general mounting of a primary system using the transmissibility and the primary system response for beam core thickness from 2.5 to 10 mm.

Rustighi and Elliott, 2008 presented a general method for the computing of the force transmissibility for complex system with more than one support. They illustrated their technique using an oscillator travelling over a beam on three simple supports. Coppola and Liu, 2010 examined he characteristics of an active vibration isolator and developed its control strategy. They formulated an optimization problem to determine the optimal controller parameters by minimizing the second norm of the system displacement transmissibility. Lu et al. 2011 used properly configured nonlinear isolators to provide vibration isolation. They used the force transmissibility in forms of the RMS of the transmitted force for random excitation. Ho, Lang and Billing, 2012 have chosen nonlinear viscous damping to solve te problem of increased force transmissibility over high frequency ranges in vibration isolation systems with nonlinear stiffness under sinusoidal excitation. Wang, Elahinia and Nguyen, 2013 designed an effective algorithm to control both the force and displacement transmissibility in a quarter-car model incorporating a MR fluid mount. They showed that the mixed mode MR fluid mount was able to achieve desired dynamic stiffness profile to minimize the dual-transmissibility criterion.

Lage, Maia and Neves, 2014 proposed the reconstruction of forces, based on the direct and inverse problems of transmissibility in multi-degree of freedom systems. They used the force transmissibility to calculate reactions for a specific applied load. Mareta, Halim and Popov, 2014 proposed an active vibration control method using compliant-based actuators for controlling a wide range of vibration and noise associated applications. They claimed that the capabilities of their isolation system are beneficial for developing an effective vibration isolation system, particularly for controlling the vibration transmissibility at low frequencies. Collette and Matichard, 2015 discussed sensor fusion techniques to increase the control bandwidth. They showed the improvement expected for several case studies. They presented the effect of three types of sensors on the stability, transmissibility and compliance using several models of increasing complexity.

Analysis

A single-degree of freedom vibrating system excited by harmonic excitation is shown in Fig.1. The harmonic force is $F_o \sin\omega t$, the isolators have equivalent stiffness k and equivalent damping coefficient c. The system lumped mass is M and its dynamic motion is x.

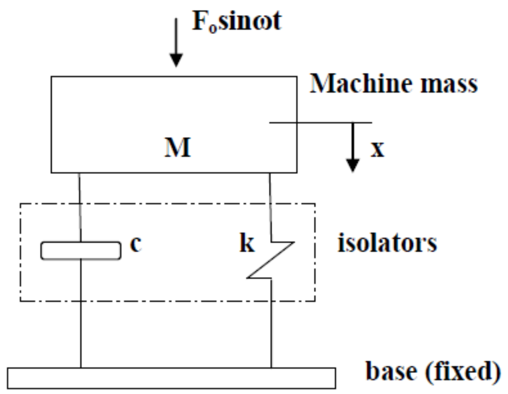

Fig.1 SDOF vibrating system excited by a harmonic force.

The differential equation of the vibrating mass M is:

$$Mx'' + cx' + kx = F_o \sin\omega t \quad (1)$$

The steady-state vibration response using Eq.1 is:

$$x = X\sin(\omega t - \varphi) \quad (2)$$

where X is the peak amplitude of the mass vibration and φ is the phase angle between the exciting force and mass displacement.

The peak amplitude ratio X/Xo as function of the frequency ratio (r=ω/ωn) and damping ratio of the system ζ is given by Rao, 2011 as:

$$X/X_o = 1 / \sqrt{(1 - r^2)^2 + (2\zeta r)^2} \quad (3)$$

The force transmissibility of the system, TR is given by Thomson, 1997 and Meirovitch, 2001 as:

$$TR = \sqrt{1 + (2\zeta r)^2} / \sqrt{(1 - r^2)^2 + (2\zeta r)^2} \quad (4)$$

Optimal Dynamic System Performance

The objective of this study is to provide force transmissibility TR very close to a unit value. This dynamically means that the transmitted force to the base of Fig.1 is equal to the amplitude of the exciting force F_o independent of the exciting frequency ratio. To achieve this objective, we define as error function e as the difference between the force transmissibility TR at any frequency ratio and the unit value. That is:

$$e = TR - 1 \quad (5)$$

Now, we define an objective function f which depends mainly on the error function e of Eq.5 as follows:

A. Integral of Square Error (ISE)

In the integral of square error, the objective function f_{ISE} is defined as (Hussain et al., 2014 and Soni and Bhatt, 2013):

$$f_{ISE} = \int e^2 dr \quad (6)$$

The objective function of Eq.6 is minimized using the MATLAB command 'fminunc' with one unknown system parameter which is the damping ratio (Venkataraman, 2009) . The results are as follows:

- Damping ratio: 21.1
- Mean transmissibility for a frequency range $0 \leq r \leq 4$: 0.9979
- Standard deviation of TR from mean: 0
- Maximum amplitude ratio: 1
- Settling frequency ratio: 0.475

  The amplitude ratio settles within 0.05 band from zero value.
- The optimal force transmissibility: Fig.2.
- The optimal amplitude ratio: Fig.3.

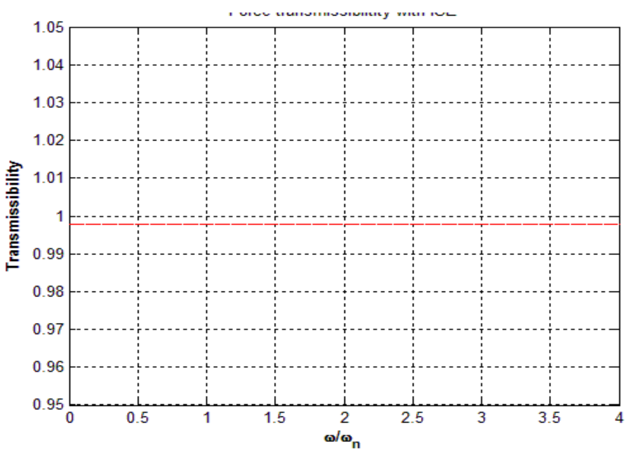

Fig.2 Optimal force transmissibility with ISE function.

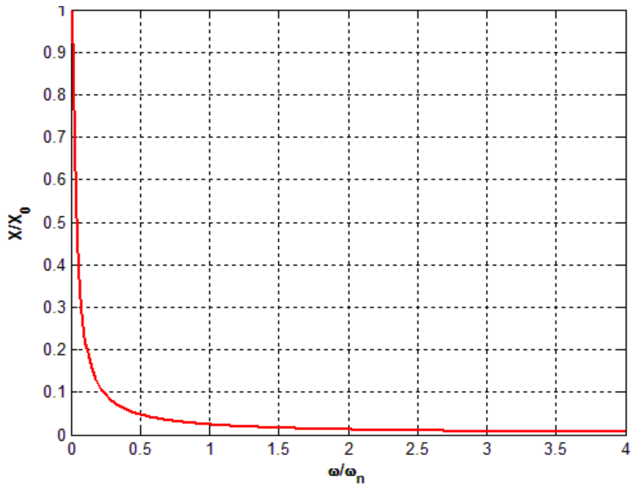

Fig.3 Optimal amplitude ratio with ISE function.

B. Integral of Absolute Error (IAE)

In the integral of absolute error, the objective function f_{IAE} is defined as (Hussain et al., 2014 and Soni and Bhatt, 2013):

$$f_{IAE} = \int |e| dr \quad (7)$$

The objective function of Eq.7 is minimized using the MATLAB command 'fminunc' with one unknown system parameter which is the damping ratio (Venkataraman, 2009). The results are as follows:

- Damping ratio: 120.732
- Mean transmissibility for a frequency range $0 \leq r \leq 4$: 1
- Standard deviation of TR from mean: 0
- Maximum amplitude ratio: 1
- Settling frequency ratio: 0.0825

  The amplitude ratio settles within 0.05 band from zero value.
- The optimal force transmissibility: Fig.4.
- The optimal amplitude ratio: Fig.5.

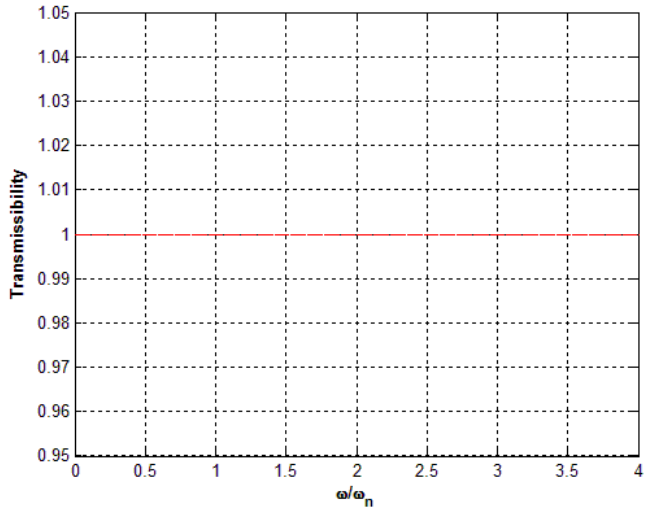

Fig.4 Optimal force transmissibility with IAE function.

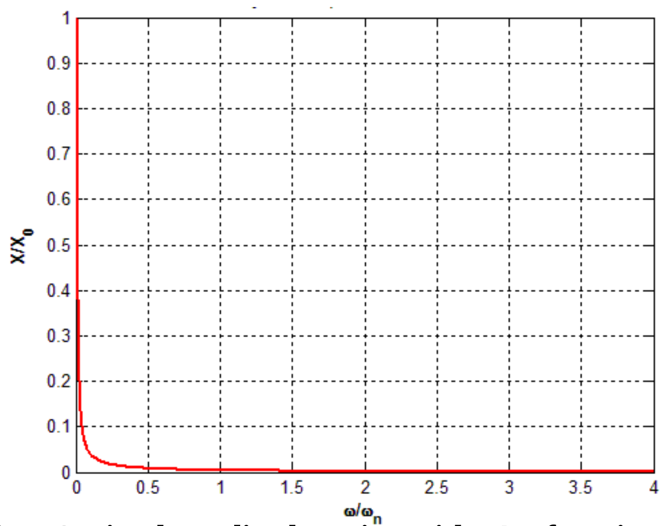

Fig.5 Optimal amplitude ration with IAE function.

C. Integral of Time Multiplied by Absolute Error (ITAE)

In the integral of time multiplied by absolute error, the objective function f_{ITAE} is defined as (Hussain et al., 2014 and Soni and Bhatt, 2013):

$$f_{ITAE} = \int r|e|dr \quad (8)$$

The objective function of Eq.8 is minimized using the MATLAB command 'fminunc' with one unknown system parameter which is the damping ratio (Venkataraman, 2009). The results are as follows:

- Damping ratio: 261.997
- Mean transmissibility for a frequency range $0 \leq r \leq 4$: 1
- Standard deviation of TR from mean: 0

- Maximum amplitude ratio: 1
- Settling frequency ratio: 0.038

  The amplitude ratio settles within 0.05 band from zero value.
- The optimal force transmissibility: Fig.6.
- The optimal amplitude ratio: Fig.7.

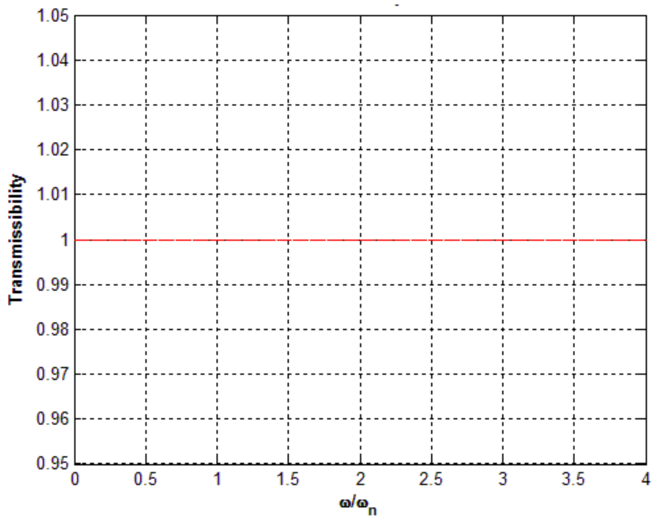

Fig.6 Optimal force transmissibility with ITAE function

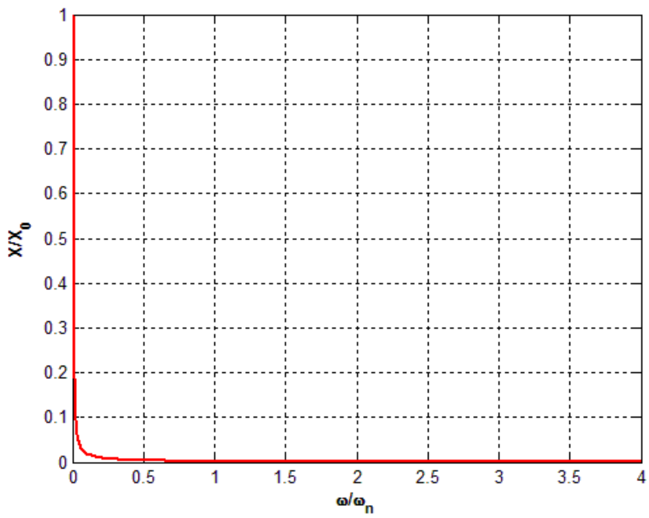

Fig.7 Optimal amplitude ration with ITAE function.

D. *Integral of Time Multiplied by Square Error (ITSE) and Integral of Square Time Multiplied by Square Error (ISTSE)*

In the integral of time multiplied by square error, the objective function f_{ITSE} is defined as (Karnavas and Dedousis, 2010):

$$f_{ITSE} = \int re^2 dr \qquad (9)$$

In the integral of square time multiplied by square error, the objective function f_{ISTSE} is defined as (Karnavas and Dedousis, 2010):

$$f_{ISTSE} = \int r^2 e^2 dr \qquad (10)$$

The objective function of Eqs.9 and 10 are minimized using the MATLAB command 'fminunc' with one unknown system parameter which is the damping ratio (Venkataraman, 2009). They give the same results as follows:

- Damping ratio: 39.5026
- Mean transmissibility for a frequency range $0 \leq r \leq 4$: 0.9994
- Standard deviation of TR from mean: 0
- Maximum amplitude ratio: 1
- Settling frequency ratio: 0.25

  The amplitude ratio settles within 0.05 band from zero value.
- The optimal force transmissibility: Fig.8.
- The optimal amplitude ratio: Fig.9.

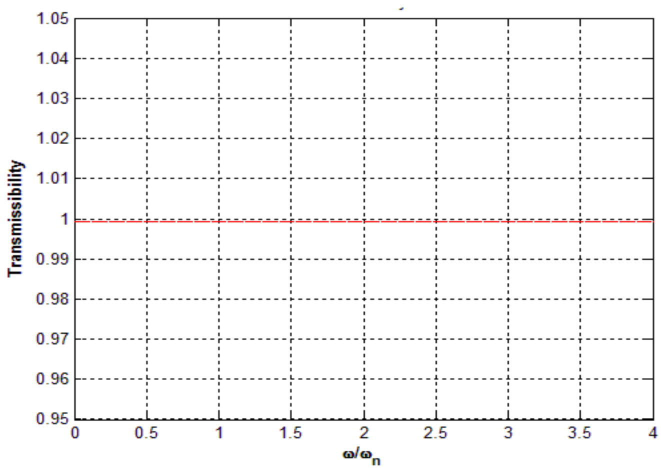

Fig.8 Optimal force transmissibility with ITSE and ISTSE functions.

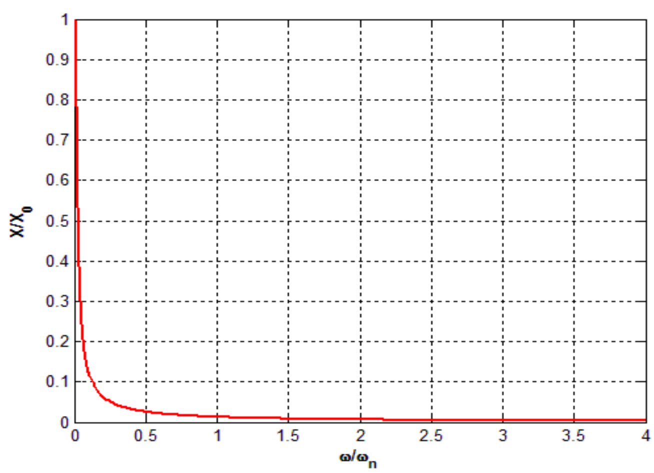

Fig.9 Optimal amplitude ration with ITSE and ISTSE functions.

Comparison of transmissibility optimal parameters

The transmissibility optimal parameters are the optimal damping ratio, transmissibility itself, maximum vibration amplitude ratio, and settling frequency ration of the vibration amplitude ratio. Those parameters depend on the objective function used in the optimization process.

A. Optimal Damping Ratio

The optimal damping ratio of the used isolators for different objective functions is shown in Fig.10.

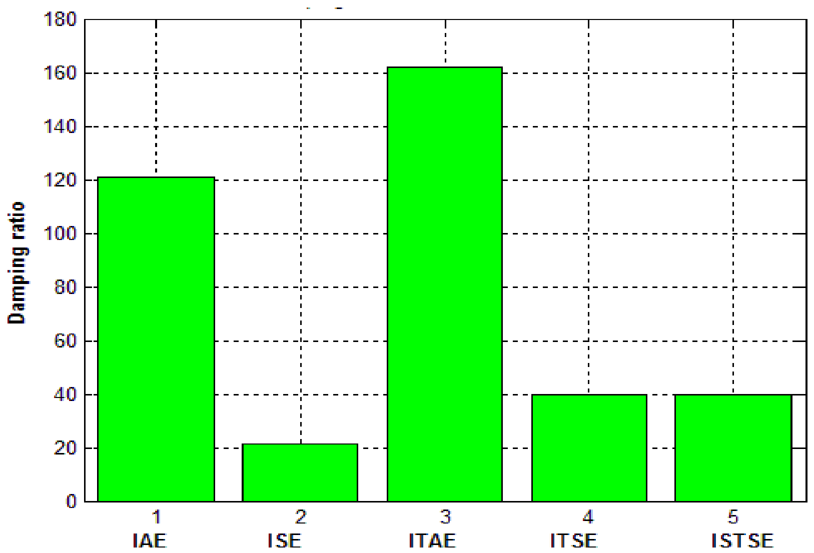

Fig.10 Optimum damping ration for different objective functions.

B. Optimal Transmissibility

The optimal transmissibility of the used isolators for different objective functions is shown in Fig.11.

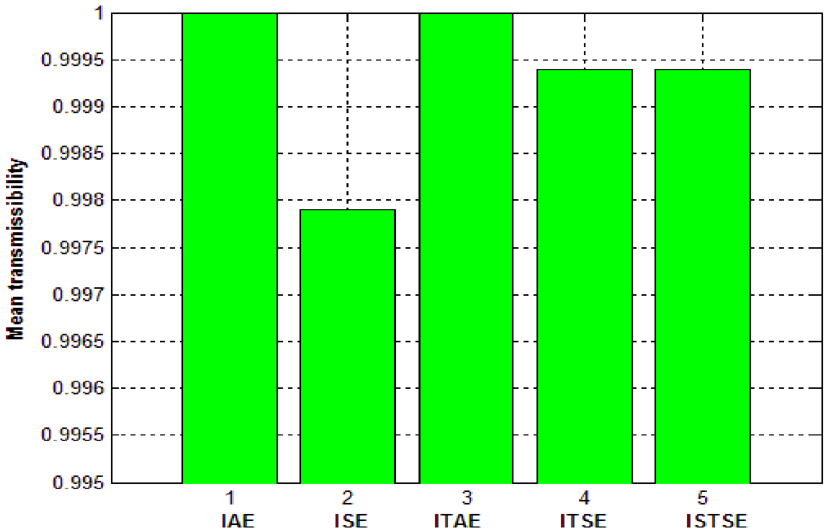

Fig.11 Optimum transmissibility for different objective functions.

C. Optimal Settling Frequency Ratio for the Amplitude Ratio

The optimal settling frequency ratio of the optimal amplitude ratio of the dynamic system mass for different objective functions is shown in Fig.12.

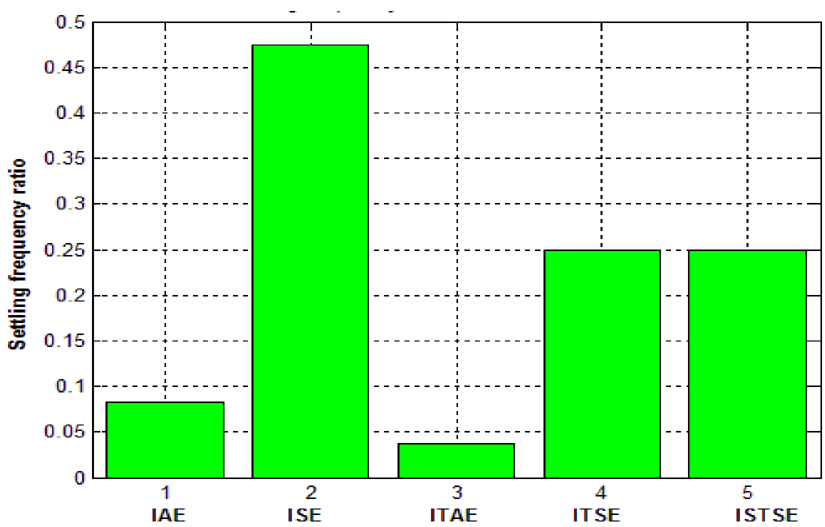

Fig.12 Optimum settling frequency ratio for different objective functions.

CONCLUSION

- The objective of this research work was to obtain the force transmissibility of a SDOF system excited by a constant amplitude harmonic force as close as possible to a unit value.
- An unconstrained optimization approach was used using the MATLAB optimization toolbox.
- Five objective functions based on the error between the force transmissibility and the desired unit value were used to assign the optimal damping ratio of the SDOF dynamic system.
- A frequency ratio range $0 \leq \omega/\omega_n \leq 4$ was used in the optimization process.
- Using the technique presented in the paper, it was possible to achieve a constant force transmissibility over the whole frequency range.
- The optimal damping ratio of the vibrating system ζ_{opt} was obtained for each objective function. It was in the range:

  $21.2 \leq \zeta_{opt} \leq 261.997$
- The optimal force transmissibility TR_{opt} obtained using the five objective function expressions was very close to a unit value. It was in the range:

  $0.9979 \leq TR_{opt} \leq 1$

- It was possible to get an exact unit force transmissibility for the whole frequency range through using the IAE and ITAE objective functions.
- The standard deviation from the mean force transmissibility over the whole frequency range was zero for all the five objective function expressions.
- The achievement of the desired unit transmissibility was accompanied by an improvement in the vibration amplitude ratio of the vibrating system. This improvement was measured by a new introduced parameter which is the settling frequency ratio.
- It was possible to go down with this parameter to only 0.038 when using the ITAE objective function.
- The importance of this result is the possibility of damping down the vibration amplitude quickly before passing the system resonance.

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DEDICATION

- I dedicate this research work to **Prof. Ibrahim Fawzi**.
- Professor Fawzi is the Emeritus Professor of Mechanical Vibrations in the Department of Mechanical Design and Production, Faculty of Engineering Cairo University, Egypt.
- He taught me a course on Mechanical Vibrations in 1971.
- He was an excellent instructor who made me love Mechanical Vibrations.
- His teaching methodology had a clear impact on my teaching experience over more than 40 years.
- Thanks dear professor.

BIOGRAPHY

Prof. Galal Ali Hassaan:

- Emeritus Professor of System Dynamics and Automatic Control.
- Has got his B.Sc. and M.Sc. from Cairo University in 1970 and 1974.
- Has got his Ph.D. in 1979 from Bradford University, UK under the supervision of Late Prof. John Parnaby.
- Now with the Faculty of Engineering, Cairo University, EGYPT.
- Research on Automatic Control, Mechanical Vibrations , Mechanism Synthesis and History of Mechanical Engineering.
- Published more than 100 research papers in international journals and conferences.
- Author of books on Experimental Systems Control, Experimental Vibrations and Evolution of Mechanical Engineering.
- Chief Justice of International Journal of Computer Techniques.
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