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Development of A Four Arms Viscoelasic Damper And Its Application To A Heavy Floor Vibration Due To Walking Excitation

Dr. Adnan D. Mohammed*

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Abstract

High levels of unwanted vibrations are normally occur in light, and (or) long span floor systems due to human activities such as walking or jumping. It causes annoyance and discomfort to the occupants. Hence, rectification measures would be required to minimize floor vibrational displacement amplitudes. This work is concerned with the development of a new innovative passive viscoelastic four arms damper. The mission of this damper is to reduce floor vibration. The damper is tuned to the fundamental frequency of a vibrating concrete floor of 4.4 Hz. A transient, finite element numerical analyses are performed on the coupled floor-four arms damper system and on the uncoupled systems to monitor and to compare the transient responses due to walking excitation. Similar analysis is done on the floor when the latter is coupled to a single arm viscoelasic damper having the same mass ratio. The single arm damper has been recently developed in a small laboratory scale by the author of this work. A reduction factor of 1.7 in the floor vibrational amplitude is obtained when the single arm damper is attached to the floor while a 1.8 reduction factor is observed when the new damper is attached. The reduction factors obtained are considered to be excellent results for ***heavy*** concrete floors applications.

Keywords: Floor vibrations, viscoelastic damper, four-arm damper, heavy concrete floors.

تطوير مخمدة رباعية الاذرع من النوع اللزج المرن وتطبيقاتها على اهتزازات الارضيات الكونكريتية الثقيلة المثارة بالمشي

الخلاصة

ان المعدلات العالية لسعات الاهتزازات تحصل عادة في الارضيات الخفيفة و (او) الارضيات ذات الابعاد الكبيرة نتيجة لفعاليات البشر مثل المشي او القفز. هذه الاهتزازات تسبب الازعاج وعدم الراحة لشاغلي هذه الارضيات. لذلك السبب فان اساليب المعالجة تصبح مطلوبة لغرض تقليل سعات الازاحات الاهتزازية. ان البحث الحالي يعنى بتطوير مخمدة اهتزاز مبتكرة رباعية الاذرع من النوع اللزج المرن . ان الغاية من استخدام هذه المخمدة هي لتقليل اهتزاز الارضية. لقد تم توليف قيمة التردد الطبيعي للمخمدة المبتكرة لتساوي التردد الطبيعي الاول لارضية كونكريتية ثقيلة والبالغ 4.4 هرتز. لقد تم استخدام طريقة العناصر المحددة لاجراء تحليلات عددية عابرة على النظام المرتبط المؤلف من الارضية والمخمدة رباعية الاذرع وكذلك على الانظمة غير المرتبطة لمراقبة ومقارنة الاستجابات الاهتزازية العابرة للارضية نتيجة الاثارة بالمشي. لقد تم اجراء نفس التحليلات على الارضية عندما تكون الاخيرة مرتبطة بمخمدة مكافئة احادية الذراع ومن النوع اللزج المرن وتمتلك نفس نسبة الكتلة للمخمدة رباعية الاذرع. لقد تم تطوير المخمدة احادية الذراع بقياس مختبري صغير من قبل باحث هذا العمل في عهد قريب. من البحث الحالي تم الحصول على نسبة تخفيض في سعة اهتزاز الارضية مقدارها 1.7 عند ربط المخمدة احادية الذراع بينما تم الحصول على نسبة تخفيض مقدارها 1.8 عند ربط

***Electromechanical Engineering Department, University of Technology/ Baghdad**

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

المخمدة الجديدة. ان نسب التخفيض التي تم الحصول عليها يمكن اعتبارها نتيجة ممتـــازة فـــي تطبيقات الارضيات الثقيلة.

List of Symbols and abbreviations

Symbol	Descriptions
TMD	Tuned Mass Damper
m_1	Mass of primary system (Kg)
m_2	Mass of secondary system (Kg)
Y	Geometric parameter
E_1	Young's modulus of the top plate (N/m^2)
E_3	Young's modulus of the bottom plate (N/m^2)
A_1	Cross sectional area of the top plate (m^2)
A_3	Cross sectional area of the bottom plate (m^2)
d	Distance between the centroids of the cross sectional areas of top and bottom plates
I_1	Area moment of inertia of top plate (m^4)
I_3	Area moment of inertia of bottom plate (m^4)
g	Shear parameter
f	Frequency (Hz)
f_n	Natural frequency
f_d	Damped natural frequency (Hz)
K	Stiffness (N/m)
$(EI)_{eff}$	Effective flexural rigidity ($N.m^2$)
$(EI)_{total}$	Total flexural rigidity of the composite system ($N.m^2$)
L	Length (m)
G_i	Fourier coefficient
m_{end}	End mass (Kg)
F(t)	Applied force (N)
ρ	Density (Kg/m^3)
μ	Mass ratio
η	Overall loss factor of the composite beam
β	Dissipation loss factor of viscoelastic material

Introduction

The first study of the application of the Tuned Mass Damper (TMD) for the control of floor vibrations was performed by Lenzen (1966) who used an absorber mass of about 2% of the floor mass. Allen and Swallow (1975) used TMD in the form of a steel box loaded with concrete blocks. Allen and Pernica (1984) designed a special simple tuned mass damper consisting of wooden planks with weights on top for the reduction of annoying vibrations due to walking. Setareh and Hanson (1992*a*, 1992*b*) used TMD to control the floor vibrations due to dancing in an auditorium floor. Webster and Vaicajtis (1992) used TMDs to control the annoying vibrations of a long-span cantilevered composite floor system due to human movements. Bell (1994) used a TMD to control annoying vibrations of a museum floor due to walking. Shope and Murray (1995) and Rottmann (1996) used TMD to control walking vibrations in office floors. All previously mentioned studies use viscous damping mechanisms as the media for vibrational energy dissipation. Saidi *et al.* (2007, 2008) have developed a viscoelastic TMD using the principle of constrained damping developed by Mead and Markus (1975). Saidi *et al* converted the conventional viscous damping mechanism into a viscoelastic one and examined the effectiveness of the developed TMD when attached to a laboratory size simply supported steel beam. Good agreement is found between the analytical, numerical and experimental solutions. The present study is a continuing research to that of Saidi *et al*. It is a numerical study on the effectiveness of a new four arms viscoelastic damper in suppressing the unwanted vibration of a heavy concrete floor. The floor is excited by a walking person of 94 kg. The walking is simulated as a time variant function following the model of Murray *et al* (1997).

Theory

The theoretical model of this work depends mainly on that recently published by the author [10] and [11]. The basis of the tuned mass damper (TMD) is the attachment of an auxiliary single degree of freedom system to the primary vibrating system (the floor that needs to be controlled). The attached system should has a natural frequency equals to the fundamental frequency of the vibrating floor under consideration. The resulting system is a two degree of freedom one. A typical example demonstrating the effectiveness of the TMD is shown in figure (1). The frequency separation between the natural frequencies of the coupled system, (f_1 and f_2), depends on the mass ratio. The latter is defined as,

$$m = \frac{m_2}{m_1} \qquad \ldots\ldots (1)$$

Where m_1 and m_2 are the masses of the primary system and the TMD respectively.

Design of viscoelastic damper

Figure (2) shows an arrangement of a constrained-layer damping treatment. This consists of a sandwich of two outer elastic layers with a viscoelastic material (commercial rubber) as the core. When the base structure undergoes bending vibration, the viscoelastic material is forced to deform in shear because of the upper stiff layer. The constrained-layer damping is more effective than the free-layer design since more energy is consumed and dissipated into heat in the work done by the shearing mode within the viscoelastic layer. The symmetric configuration in which the base and the constraining layers have the same thickness and stiffness is by far the most effective design since it maximizes the shear deformation in the core layer. In this composite sandwich beam, shown in figure (2), the viscoelastic material experiences considerable shear strain as it bends, dissipating energy and attenuating vibration response (Mace 1994). There are many factors which affect the damping performance of viscoelastic materials including temperature, thickness and bonding. The damper developed in this paper is for interior use so the variation in the temperature is not very significant. The two main variable factors to be taken into the account for the design of the damper are the viscoelastic material type and thickness. Mead (1982) developed a detailed analytical method to estimate the overall dissipation loss factor of the composite system (η) based on the dissipation loss factor of the viscoelastic material (rubber), (β), thickness of rubber, geometric parameters and Young moduli of the top and bottom plates. The analytical model considers that the core resists the shear. Transverse direct strains in both core and face plates are neglected and no slip occurs at the interfaces of the core and face plates. Boundary conditions have no significant effect on the loss factor and the following method can be applied to any composite beam configuration such as simply supported beam, cantilever etc. The overall loss factor of the composite system can be estimated by using the following Equation [9]:

$$h = \frac{bY}{2+Y+2(1+Y)^{1/2}(1+b^2)^{1/2}} \quad .(2)$$

Where Y is a geometric parameter which can be calculated as;

$$Y = \frac{(E_1A_1)(E_3A_3)d^2}{(E_1A_1+E_3A_3)(E_1I_1'+E_3I_3')} \qquad (3)$$

Where E_1 and E_3 are the Young moduli of the top and bottom constraining face plates respectively, I'_1 and I'_3 are the moment of inertia of top and bottom constraining plates about their neutral axes respectively and d is the distance between the centroids of the cross sectional areas of top and bottom plates. The stiffness or the total flexural rigidity $(EI)_{total}$ of the composite viscoelastic system can be calculated as follows [9];

$$\frac{(EI)_{total}}{E_1I_1'+E_3I_3'} = 1 + \frac{gY(1+g(1+b^2))}{1+2g+g^2(1+b^2)} \quad \ldots(4)$$

Where g represents the shear parameter which can be written as;

$$g = \frac{1}{\sqrt{(1+Y)(1+b^2)}} \quad \ldots\ldots(5)$$

If the viscoelastic configuration, shown in figure (2), is modeled as a cantilever beam with an end mass (m_{end}) at its free end. The resulting system is a viscoelasic tuned mass damper with a fundamental natural frequency that can be written in the basic form as;

$$f_d = \frac{1}{2p}\sqrt{\frac{k}{m}} \qquad \text{.....(6)}$$

where k and m are the effective stiffness and mass of cantilever beam respectively. The effective stiffness of a cantilever beam can be calculated according to basic deformation principle as;

$$k = \left(\frac{3\ EI}{l^{3}}\right)_{eff} \qquad \text{......(7)}$$

where E, I and l are the Young's modulus, moment of inertia and length of composite viscoelastic cantilever beam respectively. The effective mass of composite beam can be calculated as;

$$m = \frac{33}{140}\, rAl\ + m_{end} \qquad (8)$$

where ρ, A and l are density, cross-sectional area and length of composite cantilever beam respectively. The length of viscoelastic beam and mass can be calculated from Equations 7 & 8 respectively, since the mass from Equation 1 and natural frequency from Equation 6 must be maintained to comply with optimum damper parameters. The viscoelastic damper is designed with 1% mass ratio. Note that the natural frequency and the mass of the primary system are input known variables. A computer program is developed for the purpose of design of 1% optimum viscoelastic cantilever damper using equations 1-8

Walking Excitation

Several investigations have attempted to characterize the human induced excitation of different activities such as walking, jumping, and jogging. Walking is one of the common types of excitation that occur in structural floors. It can be represented by a continuous, time-dependent periodic forcing function at a pacing frequency range of 1.6-2.4 Hz. It can be written, according to Murray *et al* [15], in the Fourier series form:

$$F(t) = G_0 + G_1 Sin\, 2pft + \sum_{i=2}^{n} G_i Sin(2p\, i\, ft - f_i) \qquad \text{....(9)}$$

Where G_0 represents the weight of the walking person and . is the phase angle. f is the pacing frequency and i is the order of the harmonics. This means that the frequency of the harmonics of the periodic signal occurs at f, $2f$, $3f$, ...nf.

By taking $G_1 = 0.4G_0$, $G_2 = G_3 = 0.1G0$, $\phi = \phi = \pi 2$ and excluding higher order terms [15], equation (9) may now be written as,

$$F(t) = G_0 + G_1 Sin\ 2pft + G_2 Sin\,(4pft - \frac{p}{2}) + G_3\, Sin\,(6p\ \ ft - \frac{p}{2}) \qquad \text{....(10)}$$

Equation 9 is solved for a person weight of 94 Kg and pacing frequency of 2.2 Hz (period of 0.45Sec.). The frequency of pacing is selected to match the fundamental bending frequency of the excited floor. Therefore the walking excitation will force the floor to vibrate at resonance in the second harmonic. The form of the time history of the walking excitation signal is shown in figure (3).

Four Arms Viscoelasic Damper

The 1% viscoelastic vibration damper discussed in a previous section (above) is split into four smaller, identical dampers with mass ratio of 0.25%. Each arm is designed such that its fundamental frequency in bending matches that the fundamental frequency of the floor (primary vibrating system). The aim is to examine the effectiveness of the damper compared to that of the single arm damper and to establish a new geometry for the design purposes of viscoelasic dampers. Figure (4) and figure (5) show the single arm and the four arms dampers configurations respectively.

Numerical analysis

To illustrate the effectiveness of the proposed tuned mass viscoelasic damper, a reinforced concrete beam is used for modeling the vibrating floor (primary system). The 9.5 m long, heavy concrete beam is simply supported at its ends and simulates a proportion of a typical long span floor construction. It has the cross section shown in figure (6). The properties of the beam are: effective mass = 3091 kg, natural frequency, f_n = 4.4 Hz and it has a damping ratio,. = 1.75%. The data (above) used in the modeling of the vibrating floor is taken from a real laboratory structure located at the Civil Engineering Department, University of Melbourne, Australia. The reason for using this data is that it will be used in a future paper that concern with experimental investigations. The properties of the single arm and four arms dampers are shown in tables 1 and 2 respectively

In order to make sure that the fundamental frequencies of the concrete floor (primary system) and the viscoelastic damper (secondary system) are matching to each other, an FE (Ansys11) harmonic analysis is performed on each system with an arbitrary values for the amplitude harmonic excitation and dissipation loss factor. The aim is to produce modal pictures for these systems. The harmonic response amplitude for the floor and the damper are shown in figures (7) and (8) respectively. The figures confirm the design value of 4.4 Hz for the matched fundamental natural frequencies.

The newly developed four arm damper is equivalent to a four oscillators system attached at the mid point of the floor by a steel bracket. The mass of the bracket is small compared to the heavy floor therefore has no effect on the vibration characteristics of the floor. The attachment configurations of the single arm and the four arms dampers are shown in figures (9) and (10) respectively. A finite element transient analysis is performed on the coupled system using Ansys11 finite element package. The floor is excited by the periodic force (walking) of the form shown in figure (3) above. Results of the transient bending response of the floor are monitored for the cases:

1. Empty concrete floor (no damper attached)
2. The 0.25% mass ratio, four arms damper attached to the concrete floor
3. The 1% mass ratio single arm damper attached to the concrete floor.

The final results of the transient response for the three analyzed cases are shown in figure (11), (12), (13) and (14). Figure (11) displays the time history of the transient response amplitude of the concrete floor due to walking excitation for the case when the floor is empty and that when the floor is equipped with 1% mass ratio single arm viscoelastic damper. A considerable reduction in the amplitude is noted with a reduction factor of a bout 1.7. Figure (12) shows the effectiveness of the newly developed 0.25% mass ratio, four arms viscoelastic damper, in suppressing the concrete floor transient response due to walking excitation. A relatively better performance can be observed especially at the lower peaks. An overall reduction factor of about 1.8 is obtained. Figure (13) demonstrates a comparison on the effectiveness of the single arm damper and the newly developed, equivalent, four arms viscoelastic damper in reducing the unwanted floor vibration due to human activity (walking). The figure shows the relative enhancement in the effectiveness of the new damper. Figure (14) displays a summary of the results obtained in this numerical study. From the results shown in the figures above it can be concluded that the newly developed damper is highly effective, in the frequency range of interest, as the single arm one. Note that the retrofitted floor is quite heavy and therefore one may considers that the reduction factor of 1.7 and 1.8 are excellent results. The reduction factor obviously increases as the treated system becomes lighter [10, 11].

Concluding remarks

The numerical study of this paper has presented the development of a new geometry of a tuned mass viscoelastic damper. The new damper is composed of four arms each of which represents a separate viscoelastic elastic damper with the same value of natural frequency as that of the treated floor. The total mass ratio of the new damper is equivalent to that of a single arm. The effectiveness of the new damper when attached to a 9.5 m long simply supported, heavy concrete beam is almost similar to that of the single arm that has the same mass ratio. The new system is equivalent to four oscillators system attached at one point on the floor. The effectiveness of the damper were judged by the reduction factors of 1.7 and 1.8 in the transient response amplitude of the retrofitted floor. This is considered as an excellent result for heavy floor vibration control applications.

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Table (1) Properties of the single arm damper

Length (L)	510 mm
Width (b)	100 mm
Thickness of the top steel layer	6.25 mm
Thickness of the bottom steel layer	6.25 mm
Thickness of rubber	38 mm
Dissipation loss factor of rubber (b)	0.2
End mass of the damper	28.7 Kg
Natural frequency	4.4 Hz

Table (2) Properties of each arm of the four arms damper

Length (L)	510 mm
Width (b)	100 mm
Thickness of the top steel layer	1.25 mm
Thickness of the bottom steel layer	1.25 mm
Thickness of rubber	38 mm
Dissipation loss factor of rubber (b)	0.2
End mass of the damper	7.4418 Kg
Natural Frequency	4.4 Hz

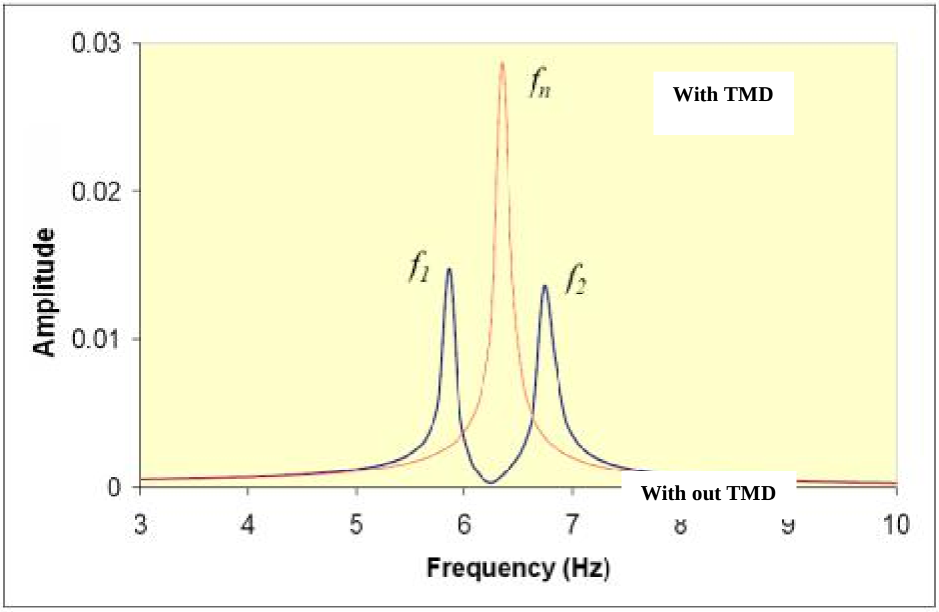

Figure (1): An example showing the effects of attaching a TMD to a primary system [10]

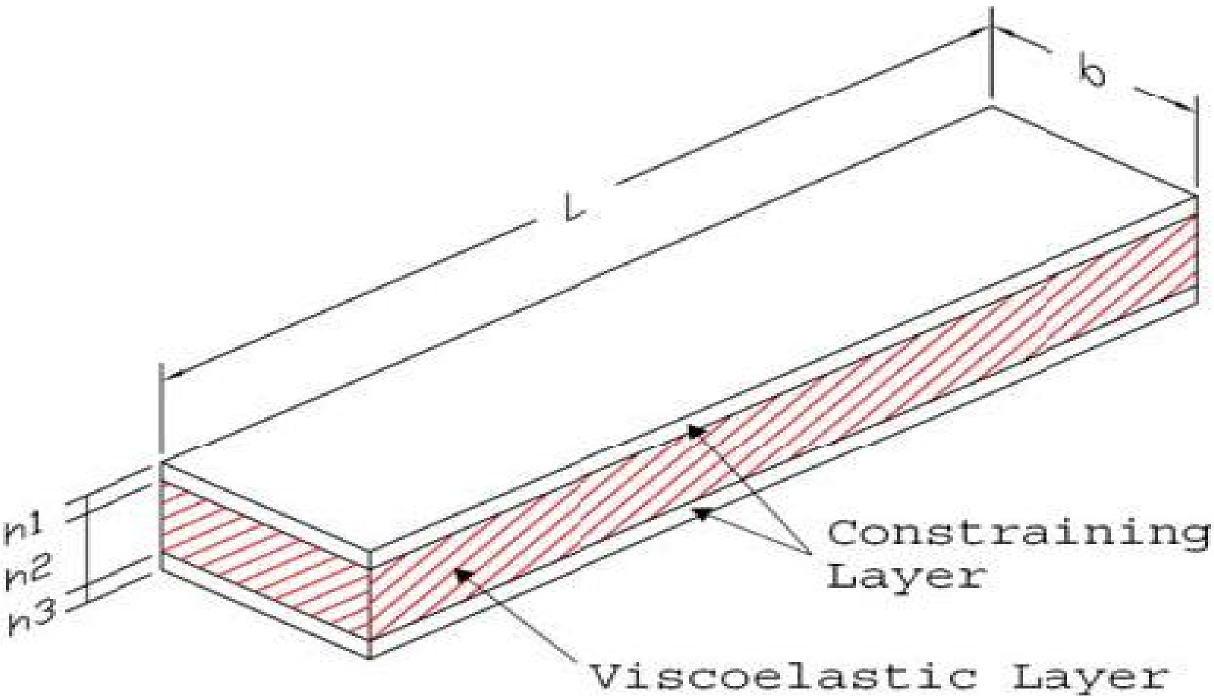

Figure (2): Constrained layers configuration [10]

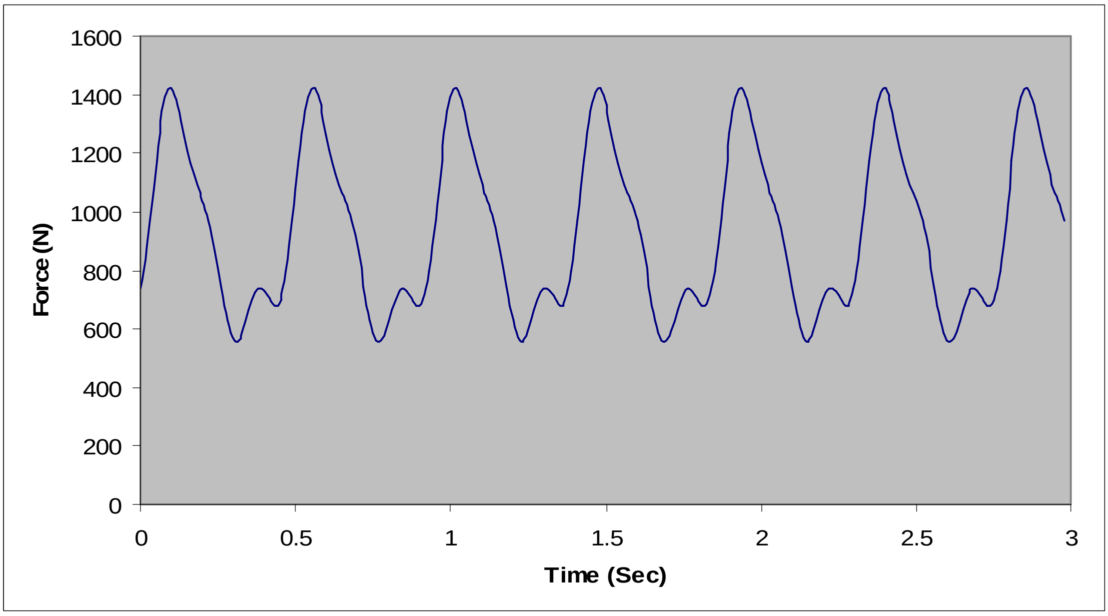

Figure (3): Time- History of Walking Excitation

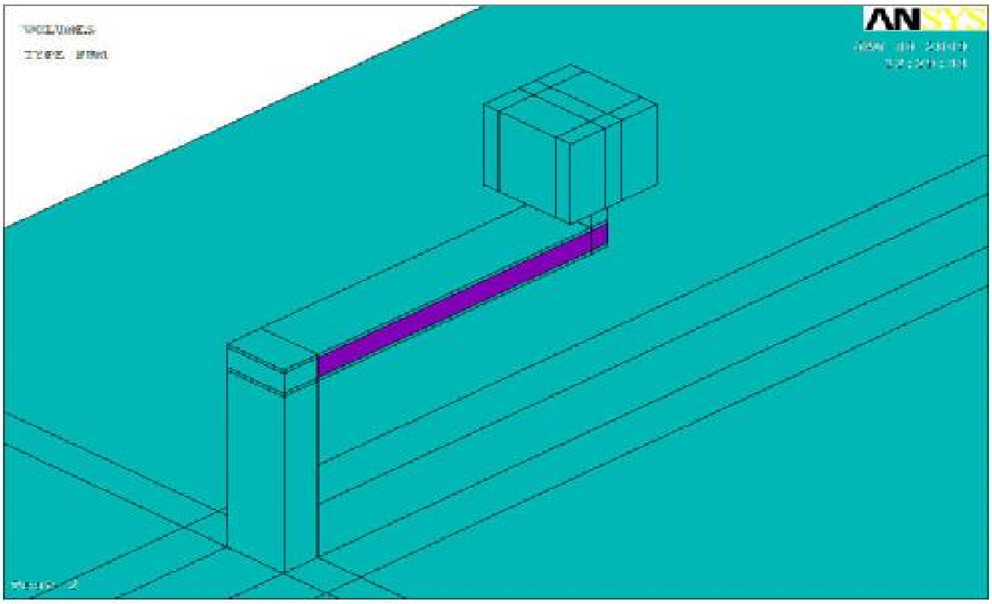

Figure (4): Single arm damper configuration

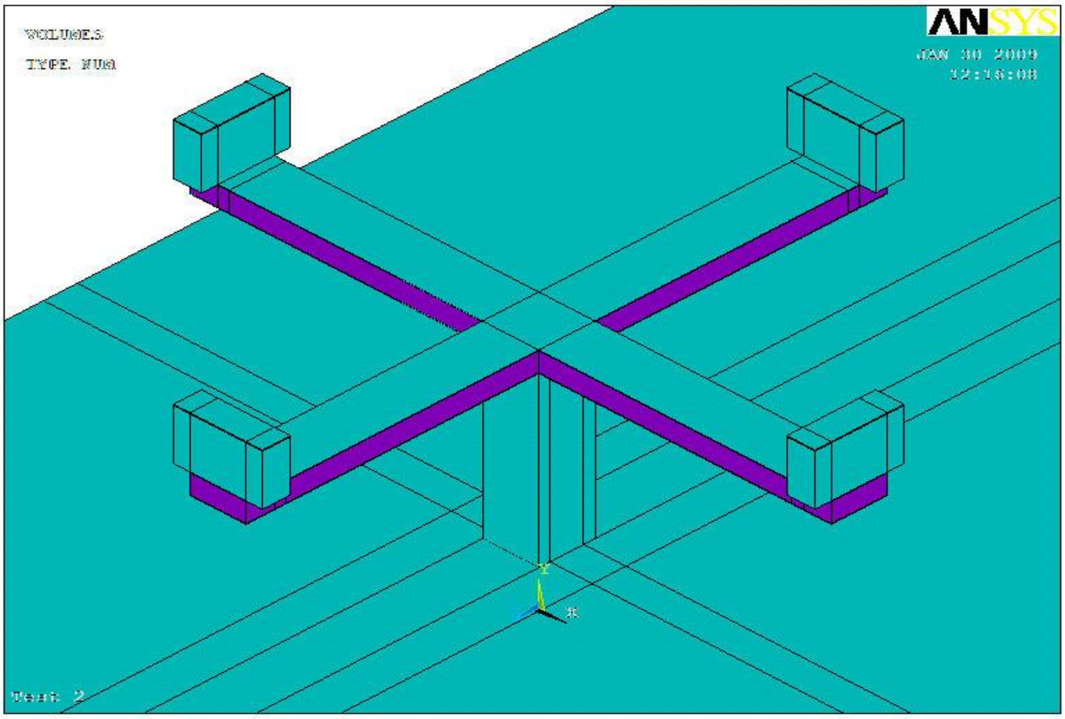

Figure (5): Four arms damper configuration

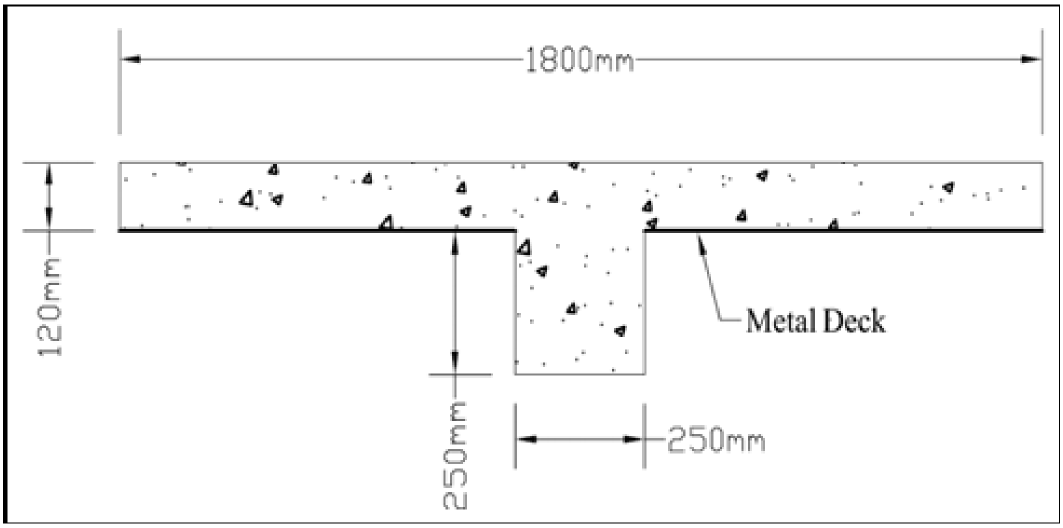

Figure (6): Concrete floor cross sectional area

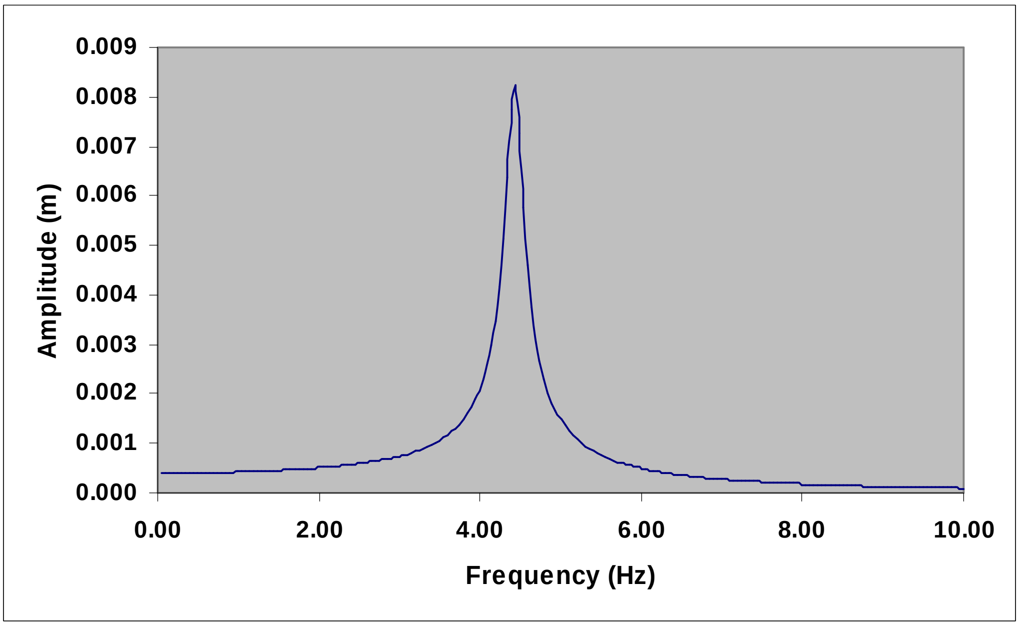

Figure (7): Fundamental frequency of floor

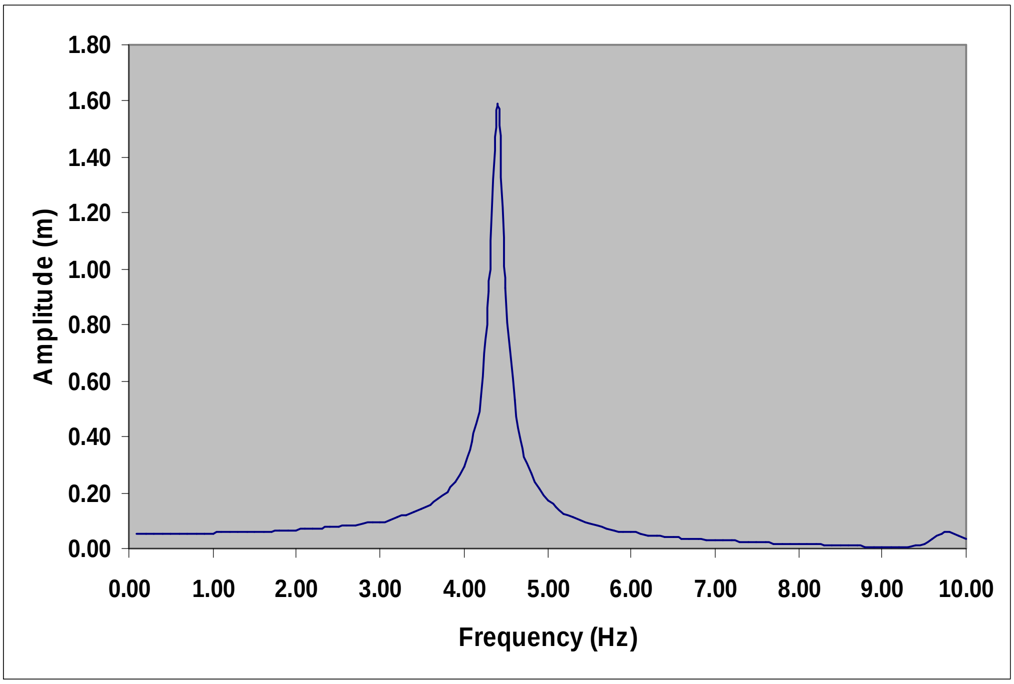

Figure (8): Fundamental frequency of damper

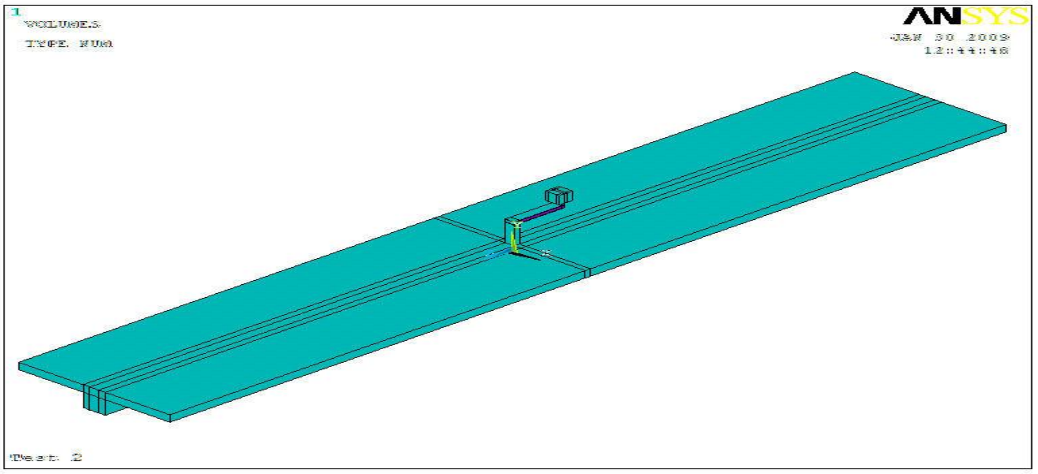

Figure (9): Floor-Single arm damper coupled system

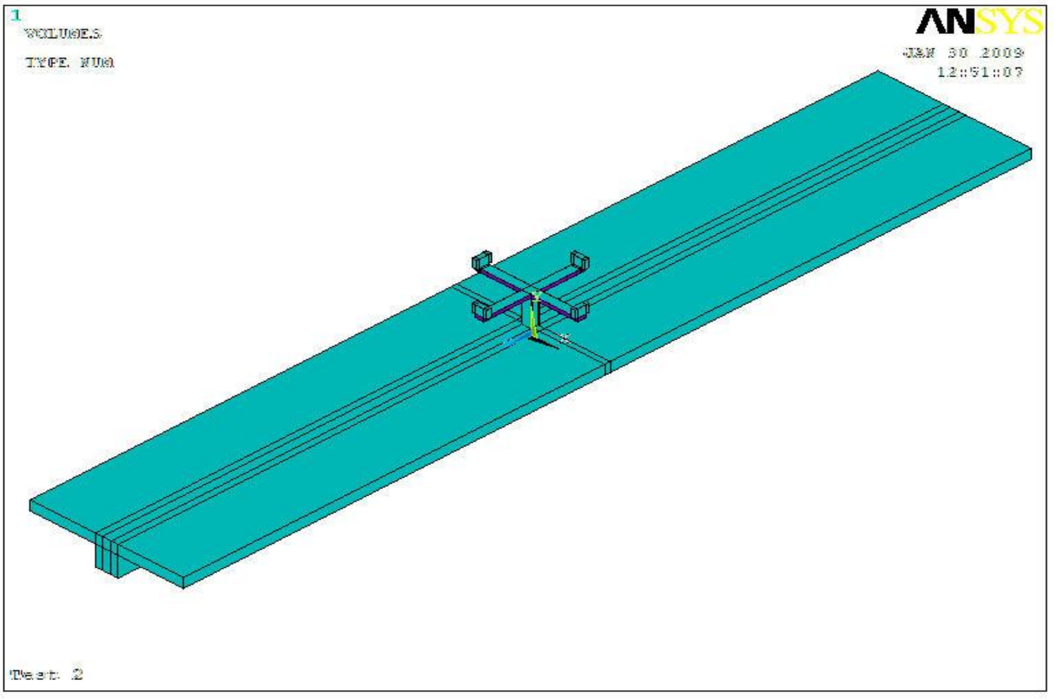

Figure (10): Floor-Four arms damper coupled system

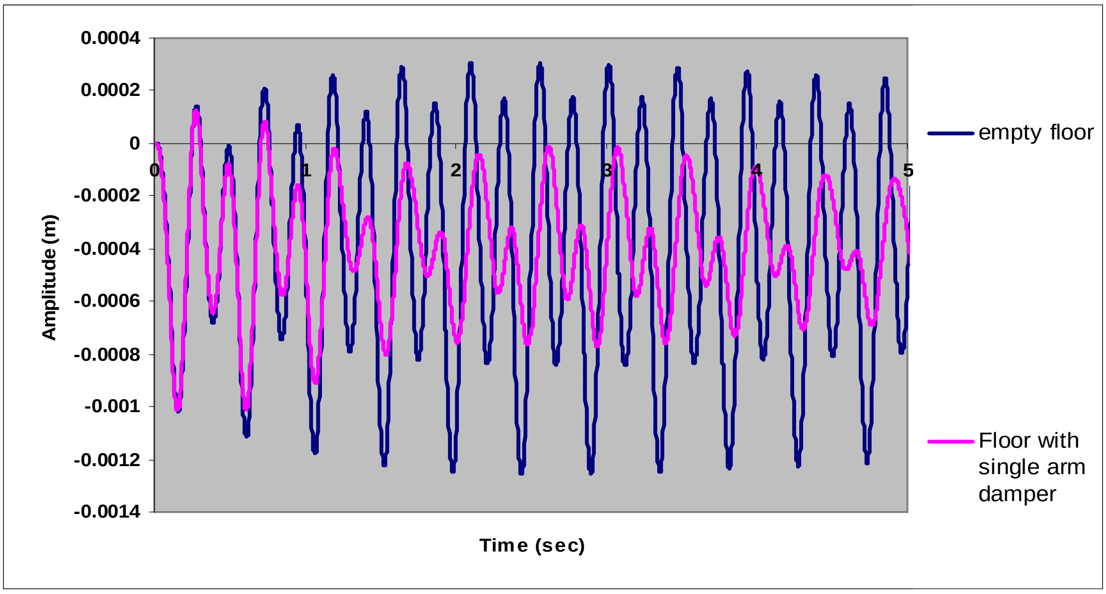

Figure (11): Transient response amplitude of the concrete floor with and without the single arm viscoelasic damper attached.

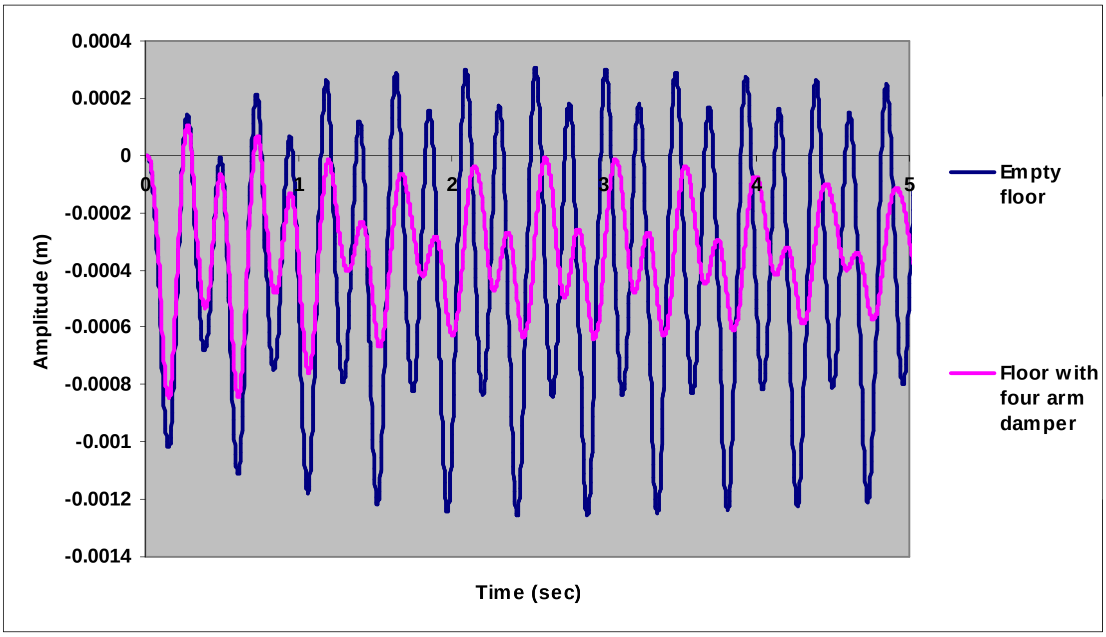

Figure (12): Transient response amplitude of the concrete floor with and without the four arms viscoelasic damper attached.

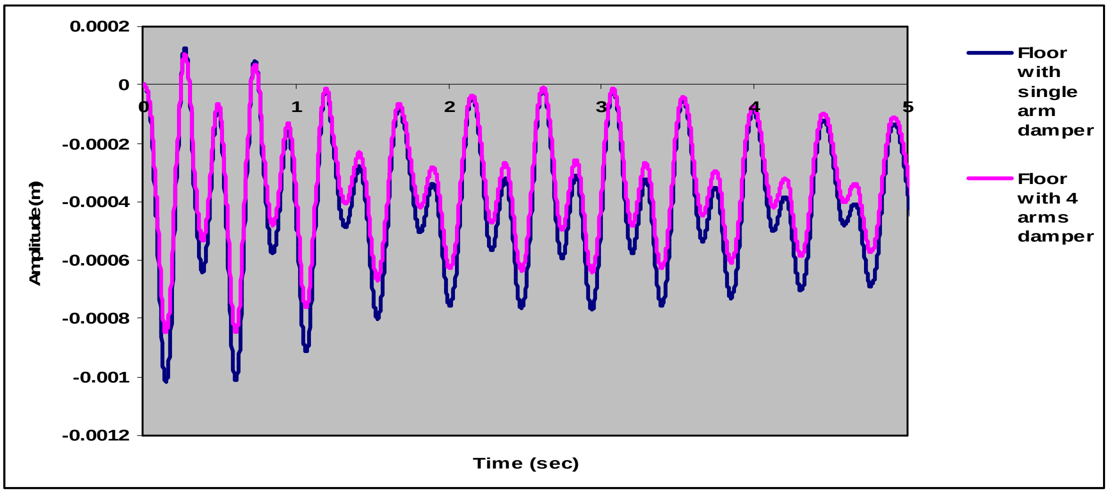

Figure (13): Comparison between transient response amplitudes of the concrete floor with the single arm or the four arms viscoelasic damper

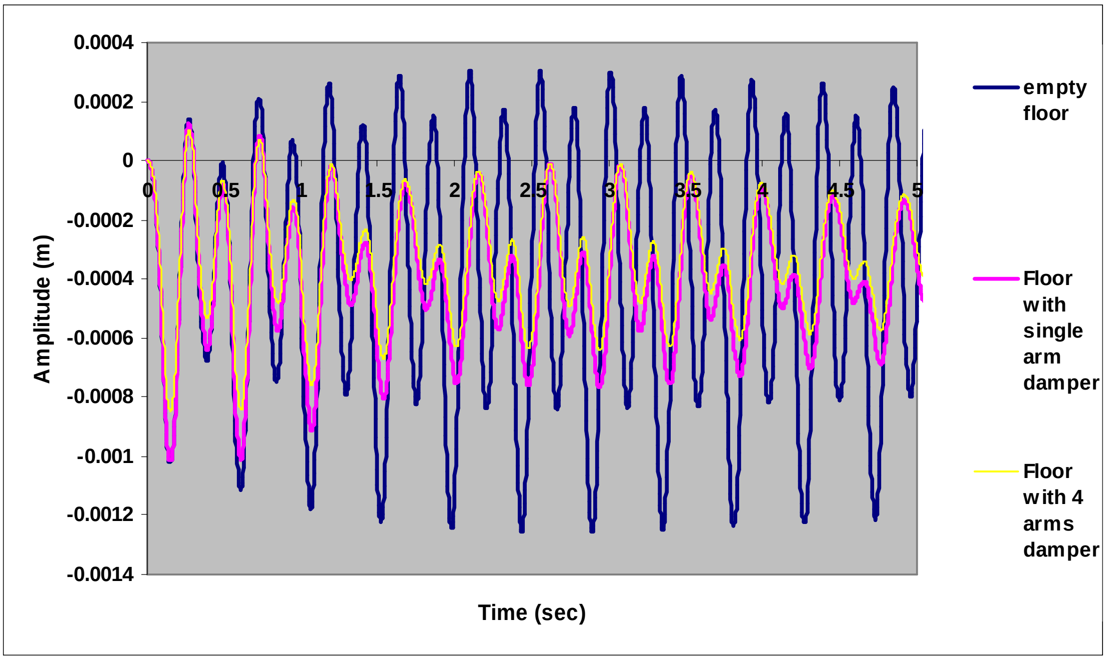

Figure (14): Comparison between the effectiveness of the single arm and the four arms viscoelastic dampers in suppressing floor vibration.