A review of impact dampers to control cross wind vibration of structures due to vortex shedding

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ABSTRACT

This paper reviews the application of chain, ball and beam impact dampers to control cross wind induced vibration of structures. These structures can vibrate with large amplitudes in the cross wind direction when the Scruton number has an insufficient value to prevent high amplitude vibrations and when the Strouhal number achieves a critical value. Thus, added damping is required to reduce the amplitude of motion to prevent possible fatigue failure of the structure in question.

Impact dampers are relatively inexpensive and, in general, do not require exact tuning as for the case of tuned mass dampers. These two factors make impact dampers attractive as add on damping for slender structures.

Important variables considered in the design of the impact dampers will be discussed and emphasis will be made on the need for testing of the largest possible experimental model of the structure, if possible, due to some of the unknowns, as for example, the coefficient of restitution of the impacting bodies required to provide damping.

Keywords: Structural vibration, Impact damping, Ball, Beam, Chain. I-INCE Classification of Subjects Number(s): 41.3 and 47

1. INTRODUCTION

Slender masts, towers, structural lattices of roof support structures and horizontal beams can be excited into large amplitude cross wind structural vibration if:

- The Strouhal number (f_s D/U) has a value of approximately 0.2; Strouhal number value depends upon shape of beam or mast; where f_s is the vortex shedding frequency, D is the diameter of the slender structure and U is the free stream velocity approaching the slender structure
- The vortex shedding frequency equals the natural frequency of the structure
- Mass damping ratio or Scruton number ($2m\,(2\,\pi\,\xi)/(\rho\,D^2)$) is low; where m is mass per unit length of structure, ξ is the damping ratio of the vibrating structure, ρ is air density and D is the diameter of the slender structure.

Added damping is required to reduce the amplitude of vibration if the three above dot point conditions exist for a structure; an effective method of implementing added damping is to use an impact damper. Impact damper provide structural damping by momentum reversal during impacts and energy dissipation due to the impacts due to the impacts themselves.

1.1 Impact Dampers

An example of a ball impact damper is shown in Figure 1 where a steady state sinusoidal force acts on the mass and creates a resonant condition. The ball moves between the two walls due to the motion of the structural mass, M, and during a cycle of vibration the ball can impact either wall, both walls, or not impact the walls at all. Optimum damping exists when two impacts per cycle of vibration occur. Research and development efforts for the design of impact dampers have been associated with

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determining the parameters that give optimum damping.

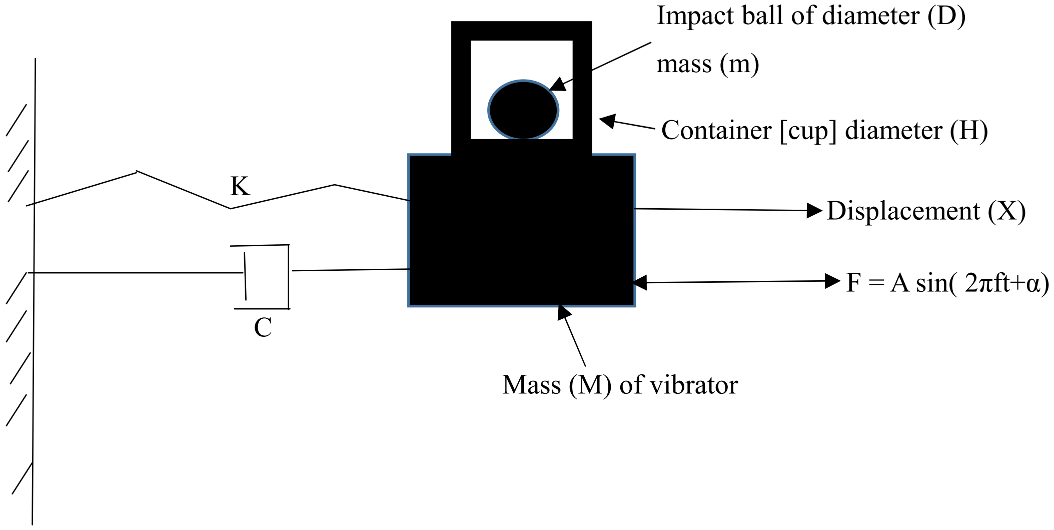

Figure 1 Schematic of a single degree of freedom vibratory system with stiffness K, mass M, damping constant C, with a sinusoidal force F with amplitude A, frequency f and phase angle α, acting on the vibratory system. The impact damper consists of a ball of mass, m, and of diameter D sitting in a cup with an inner diameter of H; the gap (clearance) is defined as d=H-D. The terms vibrator and oscillator are interchangeable.

Three texts treat the concept of mechanical impact, the first by Goldsmith (1) deals with the theory of impact between two materials and the second by Babitsky (2) treats theory and applications of impacts, one of which is damping of mechanical vibrations. Ibrahim (3) has written a major review on impact dynamics and contains 1100 references on all topics relating to impacts and impact damping. Impact damping usage is associated with reduction of machine tool vibration and reduction of structural vibration and many papers have been written on both these topics. As an example, the concept of using impact damping for structures was advanced in the 1950s by Grubin (4) and Warburton (5); originally the term acceleration damper was employed rather than the term impact damper. Reed (6) gave an experimental and theoretical analysis of chain vibration dampers and provided two practical experimental cases where chain impact damping was employed to reduce wind induced vibration. The major difference between Reed's work and other analytical and experimental studies is that Reed used a constant amplitude sinusoidal displacement for the masts undergoing vibration, whereas the other studies use constant amplitude sinusoidal force to vibrate the structure. Koss and Melbourne (7) gave examples of the use of impact chain dampers in reducing cross- wind response of several structures.

Masri (8) derived equations for the stability boundaries for 2 impact per cycle damping by employing a dimensionless factor $\mu d/(A/K)$ where μ is the mass ratio of m/M. For the case of mass ratios much less than unity and the coefficient of restitution (e) equal to just less than 0.8, the term $\mu X_{max}/(A/K)$ is 0.087. As $X_{max}/(A/K)$ is a magnification factor, the vibration amplitude will decreased considerably by the impact damper. Also, Masri (8) showed that a high value of e is much better for impact damping than that a low value of e. Masri (9) compared an analytical solution of the impact damping process to analog solutions with good results being obtained but results that were different than in past studies. Popplewell, Bapat and McLachlan (10) showed that " impact motions are shown to be very sensitive to small fluctuations in the clearance between masses and the stiffness and loading of the oscillator near it's linear or collisionless resonant frequency". They also demonstrate that the rigid impact mass is an effective damper at this frequency or slightly above this frequency. Bapat, Sankar (11) developed charts for "optimum gaps and corresponding displacement amplitude reduction" and these charts are very useful for the practicing engineer for designing impact damper parameters. Poplewell and Liao (12) developed a simple design procedure with explicit formulas for developing ball impact dampers for different cases of original structural damping, and coefficient of restitution of the impact ball and its container. Specifically equations [10] and [19] of (12) are very useful for the design of a ball impact damper system.

2. VARIABLES OF IMPORTANCE FOR DESIGN OF AN IMPACT DAMPER

Many variables are taken into consideration for the design of an impact vibration damper for a given structure; these variables include the amount of space required to locate an absorber on the structure and direction of motion of the structure e.g. vertical or horizontal. Listed in Table 1 are recommended impact damper designs for the direction of cross wind motion, and dimensionless ratios that have to be determined for the design is given in Table 2.

Table 1 – Impact damper type based upon cross wind vibration direction. The term g is for the gravitational constant 9.81 ms^{-2} and θ is the angle the mast makes with the vertical axis

Structure	Direction of vibration motion	Impact damper type 1	Impact damper type 2
Hollow mast with room inside for damper	horizontal	Impact chain	Impact ball
Hollow mast with room inside for damper	vertical	Impact beam attached to mast	1 g impact damper
Diagonal beam	Simultaneous horizontal and vertical motions	Chain lying along beam with acceleration > $g\sin(\theta)$	Horizontal moving impact ball in cup

Table 2 Mechanical dimensionless groups for Impact damper design

	Group	Formula	Variable	Variable	Variable
1a	Frequency ratio (r_c) Chain impact damper	fmast/fchain	fmast-mast frequency	fchain=$1.2(g/L)^{0.5}$ L is chain length	
1b	Frequency ratio (r_b) Impact ball damper	(forcing frequency)/foscillator	Forcing frequency	foscillator=$(K/M)^{0.5}$	
2	Mass ratio	μ=m/M	m –impact mass	M- oscillator mass	
3	Coefficient of restitution	e = Va/Vb	Va= relative speed after collision	Vb= relative speed before collision	
4a	Gap ratio impact Chain impact damper	d/X_0	gap=H-D=d	X_0=Amplitude of mast motion	
4b	Clearance ratio Impact ball damper	$d/(F_0/K)$	F_0=amplitude of sinusoidal force	K=stiffness	
5a	Damping effect- Chain impact damper	Equivalent damping ratio			
5b	Damping effect- Impact ball damper	Reduction in amplitude of vibration			

The choice the authors would make for a hollow vertical mast with a horizontal cross wind response is an impact chain damper as the price of chain is relatively inexpensive in comparison to a solid iron or steel ball for a given weight and is much easier to install than an impact ball damper. An example of a hanging chain damper is given in Figure 2.

Listed in Table 2 are mechanical dimensionless ratios that have to be evaluated for a given damper design. Impact ball and impact chain dampers use similar dimensionless groups that sound the same but have different variables. Also, formulas are used in reference (12) to evaluate dimensionless groups but graphs are used in Reference 6 to evaluate dimensionless groups.

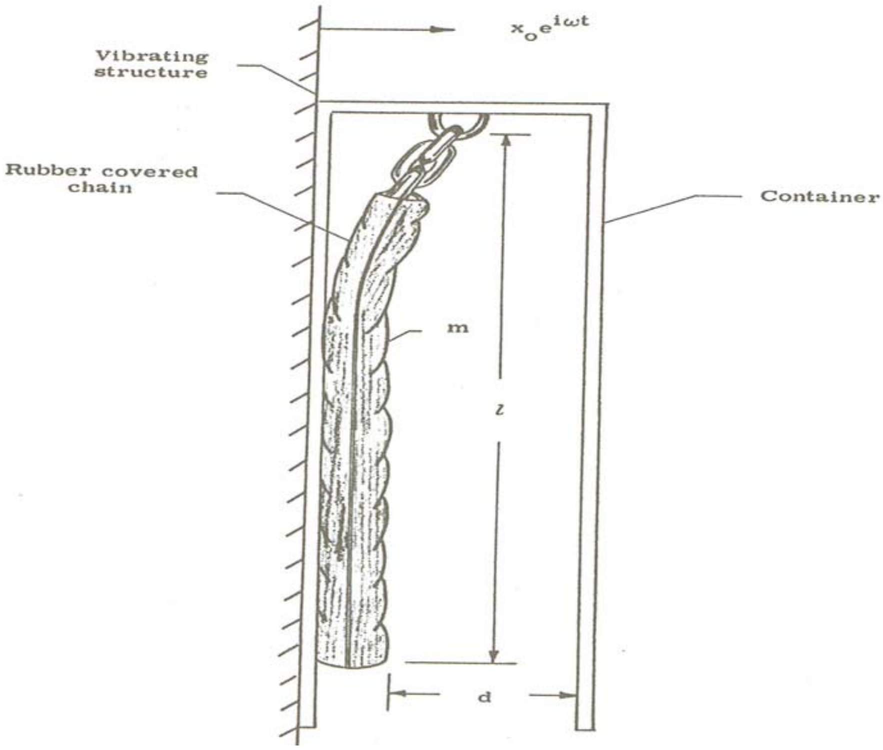

Figure 2. Hanging chain damper inside container (usually a circular hollow section). Taken from Reed (6). X_0 is the amplitude of container motion at angular frequency ω.

3. BALL AND CHAIN IMPACT DAMPER COMPARISONS

The data and formulae given in Table 3 allows for calculation of vibration damping that is achievable by using either a ball impact damper or a chain impact damper. The clearance and gap ratio formulae given in Table 3 will provide the damping effect values (Reduction ratio or equivalent ξ) given in Table 3. Ball in cup damper is the same as an impact ball damper mentioned above. Inspection of the formulae in Table 3 for clearance ratio (ball impact damper) and gap ratio (chain impact damper) demonstrates that they are determined by different sets of basic variable, although both types of dampers give impact damping. The reduction ratio, damping achieved for the ball impact damper, is given in terms of mass ratios and coefficient of restitution , whereas the equivalent viscous damping result for the chain impact damper depends upon the gap ratio, given in Table 3, and the mass ratio. The coefficient of restitution does not come into the formula as the chain impact data is based upon experimental results that have an implied coefficient of restitution.

An impact chain damper is easier to specify in practice for several reasons as follows:

- Iron/ steel balls are only available in a small number of sizes and masses, whereas chain size is not an issue as they come in many different sizes, designs and lengths. Thus, it is easier to achieve a given mass ratio with an impact chain damper than with an impact ball damper.
- Chain damping data is based upon experimental results, whereas the ball impact damping data is based upon theoretical calculations, simulations and a small number of experiments.
- The exact value of the coefficient of restitution, e, for the ball impact damper may not be known exactly due to unknowns of the impact geometry and e is an important variable for the calculation of damping amplitude and clearance ratio as seen from Table 3 for the ball in cup impact damper.
- The base of a ball impact damper has to be horizontal so as not to bias the position of the ball whereas in a chain impact damper the chain hangs vertically and the chain container has to be just reasonably vertical.
- Cross wind response of masts in the horizontal direction can be studied in a wind tunnel setting and full scale variables such as Strouhal number, Reynolds number and vibration displacements can be identified. Thus, the variable X_0 can be specified for a chain impact damper design, whereas the required F_0 for a ball impact damper is not so easy to measure or define.

Table 3– Comparison of Ball impact damper and Chain impact damper gap ratios and damping values that are achievable. The term X_{max} is the maximum response of the structure with the impact ball damper in place, and A is the maximum response of the structure with no impact ball damper in place.

Type of impact damper	Dimensionless group	Formulae	Notes	
Ball in cup	Clearance ratio $d/(F_0/K)$	$(2\mu+\pi^2)/(4\mu+2\xi s\pi((1-e-2\mu e)/1+e)))$	Equation [19] reference (12)	$0<\xi s<<1$ $0<e<1$
Ball in cup	Reduction ratio X_{max}/A	$(\mu+1)(1-e)\xi s\pi/((2\mu(1+e)+\xi s\pi(1-e-2\mu e)))$	Equation [10] reference (12)	Term ξs is structure damping
Impact chain damper	Gap ratio d/X_0	$0.14375\ r_c^2-1.970893\ r_c+10.572143$	Data fit to lower curved line Figure 8 Reference(6)	Mass region of chain $2<r_c<8$
Impact chain damper	Equivalent damping ratio ξeq	$0.2\ \mu\ d/X_0$	Data fit to Figure 9 Reference (6)	

The procedure for defining impact ball damper parameters is best accomplished by experimental testing of the largest possible test rig of the full scale structure with the ball impact damper proposed for damping in place. Variables such as ball size and clearance values can be tested to give optimal damping values. Impact hammer testing of the structure in question can give meaningful data if the analyst pays particular attention to the early decay of the induced vibration for a given impact. Measured data from several impacts can then be averaged and the averaged result can be used as a full scale predictor of the full scale vibration in the steady state wind excitation condition.

4. HORIZONTAL STRUCTURES VIBRATING IN VERTICAL DIRECTION

4.1 Impact Damping Using Attached Impact Mass

An example of a horizontal beam vibrating vertically due to cross wind response is shown in Figure 3. To obtain impact damping of the vibrating beam a flexible beam with impact mass is attached to the original beam with the impact mass being located inside an impact housing to obtain two impacts per cycle of vibration damping. This type of impact damping requires laboratory testing and verification of the largest possible scale model. The reason(s) for model testing are:

- At the instant of time the impact mass is in contact with the impact housing a system of conservative momentum exists (no external impact force is acting on the beam) and the impact mass does not present an external force on the beam
- Based upon experimental testing of the authors a reduced damping effect occurs for a given impact mass. If the flexible beam attachment point is at or near the centre of a simply supported beam the effect is small whereas if the attachment point is at or near the free end of a cantilever beam the effect is much greater.
- Thus, for this type of horizontal beam damper a test must be carried out on the design to determine how to optimize the damping level, and to determine methods for increasing the damping e.g. increasing the impact mass, varying the gap, changing length of impact beam etc.

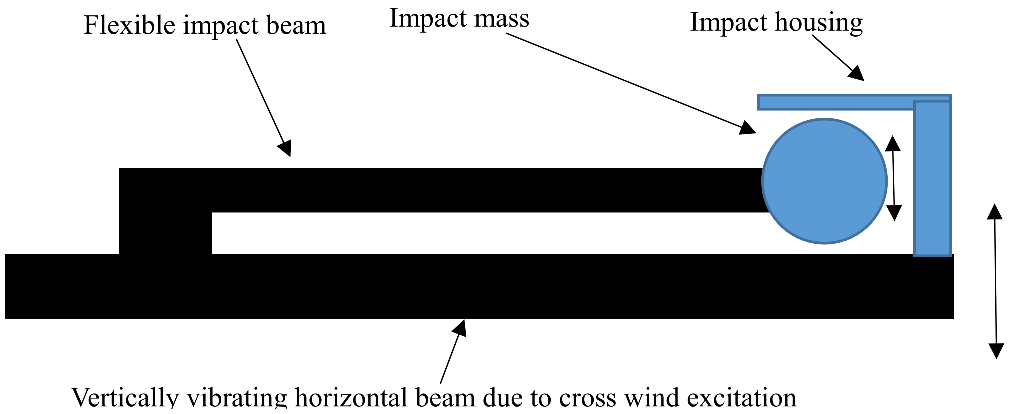

Figure 3. Example of impact damping employing attached flexible beam and impact mass; boundary conditions not specified

4.2 The 1g Impact Damper for Horizontal Beams

If the vibration amplitude is greater than 1g at positions along the beam, then either chain or ball(s) can be placed at these positions and the chain and ball will lift off and impact the beam during the course of beam vibration and provide impact damping. If the chain or ball are placed in a container attached to the beam, it is possible to affect two impacts per cycle of vibration damping. The 1 g damper is a topic open for investigation.

4.3 Example ball impact damper

Examples of chain impact damper designs are given in references (6) and (7), and an example of a ball impact damper will be given here for parameters given in Table 4. Formulae for reduction ratio and clearance ratio will be used for these calculations. The first equation to be used is that for the reduction ratio from which the mass- ratio, μ, is obtained for the case of 80 % reduction in vibration. From the mass- ratio the ball mass and diameter can be determined. Next, the force amplitude, F0, is estimated using the resonance relationship, F0 =2AKξ, and thus the clearance, or gap, can be found. The inside cup diameter, or CHS inner diameter, is obtained from the sum of the ball diameter and clearance.

Data for optimum ball impact damper parameters are given in Table 4. An 80 % reduction in vibration amplitude can be had by using a 1 % mass ratio or equivalently a 1 kg ball mass with an optimum clearance of 9.35 mm between the ball and CHS, cup. The closest off the shelf ball has a diameter of 63.5 mm which is basically a good match to the optimum value of 63.84 mm. Two closest available CHS, cup, inner diameters are listed to demonstrate the difficulty in obtaining an exact match to an optimum value.

Table 4 – Parameters for ball impact damper example

Mast parameters	Values	Optimum parameters	Values
Effective mass kg	100	Optimum Ball mass kg	1.06
Stiffness N/m	15791	Optimum Ball diameter mm	63.84
		Off the shelf closest ball diameter mm	63.5 (2.5 inches)
Virgin structural damping % critical	0.25	Optimum Clearance mm	9.35
Desired vibration reduction %	80	Optimum CHS inner diameter (id) mm	73.18
Amplitude of un-damped vibration, A, mm	10	Available CHS 1 id mm	77.9
Coefficient of restitution assumed	0.8	Available CHS 2 id mm	69.7

The authors suggest that an experimental trial(s) be conducted to determine the level of damping that can be obtained as no exact match exists between the two off the shelf CHS' and the optimum CHS that was calculated. The trial should include the 1 kg impact ball inside both available off the shelf CHS and using a 10 to 15 mm initial displacement of the structural model; as large as possible model of the structure should be constructed for these trials.

5. CONCLUSIONS

A review of impact damper types that are used in structural vibration control of cross- wind excitation has been given in this paper. Several tables have been given that list important information, equations for calculations and an example for a ball impact damper.

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