WHY AND HOW TO INCREASE THE STRUCTURAL DAMPING OF STRUCTURES

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1. ABSTRACT

- *This paper presents practical examples of damper systems .As advances in material technology and structural efficiency find reflection in structures that are lighter, more slender, and more daring architecturally, design teams must focus on controlling vibrations to ensure safe, comfortable conditions .*
- *All structures have internal damping and in many cases it might be of interest to increase the structural damping.*

A damper system may be required for many different purposes :

- **To reduce or cancel** excessive vibration generated by the vortex shedding (turbulences – Van Karman vortex…)
- **To increase** the lifespan of the structure with respect to fatigue
- **To reduce** along wind forces on structures by reducing the Cd dynamical factor (huge costs saving on structures and foundations especially for slender structures)
- **To increase** the level of comfort for inhabitants of high-rise buildings (increasing the damping would result in reduction of the level of acceleration; acceleration resulting of vortex shedding as above)
- **To increase** the level of comfort on bridges or footbridges, in buildings when the natural frequencies are in the range to be excited by pedestrians (increasing the damping would result in reduction of the level of acceleration; acceleration resulting from the action of people walking)
- **To reduce** the action of earthquakes in seismic area
- **To increase** the life span (over 3 to 4 times) of the lights on top of poles (especially in open air area)

2. WHY TO USE DAMPERS

2.1 Wind induced vibration-vortex shedding

Figure 1 : Karman Vortex Street

Alternatively, due to vortex leaving the Structure given areas in pressure or under pressure are generated and consequently alternative forces are acting on the structure.

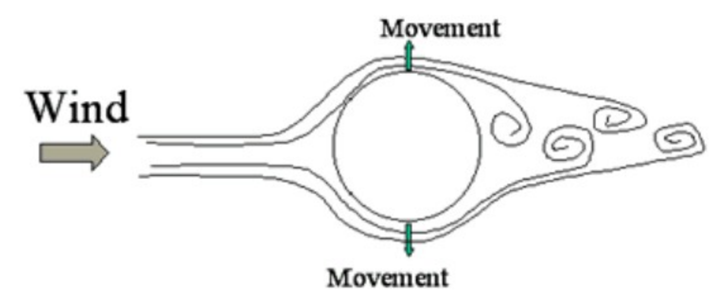


Figure 3 : cross wind vibration

When the structure is exposed to wind vortex are created downstream. The vortex Are created at regular intervals;
if the frequency of the vortex is in phase with one of the Structures natural frequency,
the structure would start to vibrate.

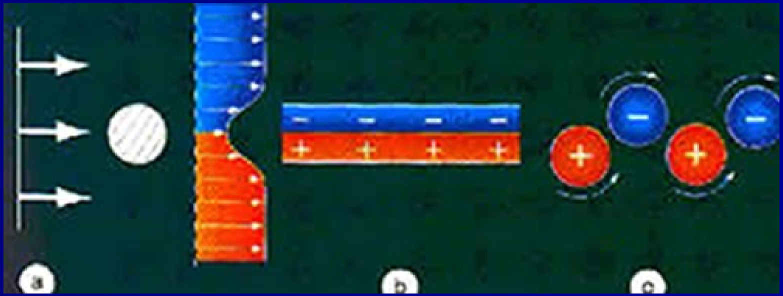


Figure 2 : formation of the pressure area

Alternatively, due to vortex leaving the structure given areas in pressure or under pressure are generated and consequently alternative forces are acting on the structure.

2. WHY TO USE DAMPERS

The structure is subject to alternative forces in the crosswind direction and would vibrate in that direction.
The wind speed for which the frequency of the vortex is in phase with one of the structures natural frequencies is called: critical wind speed. If one of the **critical wind speed** is within the wind speed range in the considered area then structure vibration can be expected.
If the critical wind speed is low such as 10 to 13 m/s, which is rather a low wind speed occurring every day (depending on the area) a high number of vibration cycles can be expected. The structural resistance with respect to fatigue has to be investigated. If the critical wind speed is high then the risk is no longer **fatigue** but **huge vibration** amplitudes with extremely important loads (wind loads are a function of wind velocity at the power 2).
Not only slender structures such as stacks, columns, masts and towers are affected by this phenomena. Other structures such as bridges or footbridges are often affected.

CASE OF THE BRIDGE BEAM

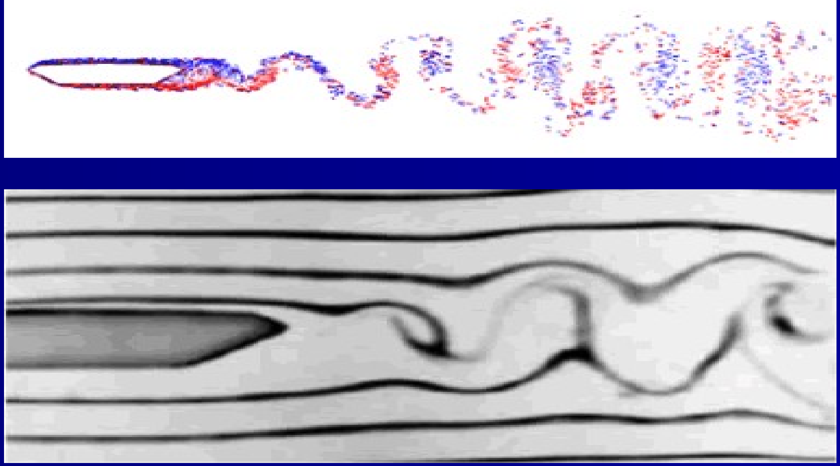


Figure 4 : Vortex behind a bridge deck

These two examples show the vortex behind a bridge deck. These vortexes are going to create vertical and/or torsional vibration in the deck.
The vibration of the deck could have different consequences such as fatigue problems in the structure, unacceptable amplitude of vibrations with a risk of failure (see TOCOMA bridge), sensation of un-comfort for pedestrians with risk of panic,

2. WHY TO USE DAMPERS

2.2 First effect of wind vibration : fatigue of structure

Fatigue of a structure is dependent mainly on the number of vibration cycles and on the amplitude of vibration. For wind loading the number of vibration cycles can be huge when the critical wind speed is low.

There is no way of reducing in most of the cases the number of vibration cycles because it depends on external causes such as wind, walking pedestrians, etc. So the only way to reduce the fatigue stresses is by reducing the response of the structure.

If you consider a structure such as a cylindrical stack, the max amplitude Yc at the top is a reverse function of the Scruton number (Sc)

$$Sc = 2 * m * \delta / (Q * d^2)$$

m : reduced or modal mass /meter

δ : Logarithmic decrement of damping

Q= density of air

D : outer structure diameter

So by increasing the logarithmic damping δ, we proportionally reduce the structures max amplitude Yc.

A structure can be modelled by individual masses mi vibrating with the frequency fi and the amplitude yi

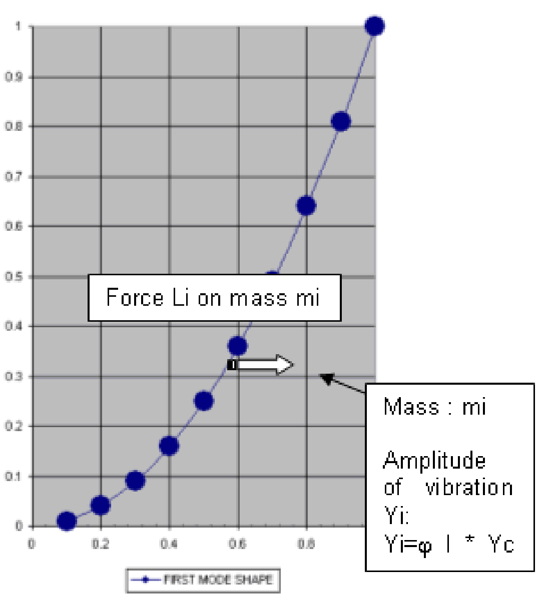


Figure 4 : Vortex behind a bridge deck

2. WHY TO USE DAMPERS

The structures mass is supposed to be concentrated at given location (mass mi) at elevation zi
The inertial loads would be $Li = mi * acc\ i$
mi :individual mass mi
acc i= acceleration of the mass mi

fi : the structure frequency
$acc\ i= Yi * (2 * \pi * fi)^2$
$Yi=Yc\ max * \varphi i$
φi mode shape of the given mode at elevation zi

The bending moment at stack base is:
$\Sigma Li * zi = Yc\ max * \Sigma\ k*mi*(\varphi I)^2$

So again by reducing the amplitude Yc we also reduce the inertial force generated by the vibration

The same principle van be adjusted for any structure and for any frequency

2.3 Increasing the level of comfort for inhabitants of buildings or pedestrians on bridges.

Using the same formula :
$acc\ i= Yi * (2 * \pi * fi)^2$
shows that by increasing the damping to reduce the amplitude of vibration would result in reducing the structures acceleration. This is of interest to increase the comfort of high-rise building occupants or of pedestrians on bridges, footbridges,…… The sensation of comfort increases when the acceleration decreases.

2.4 Along wind reduction

Some of the most recent codes have introduced the possibility of reducing the along wind by reducing the dynamic coefficient. In previous wind codes such as the French Neige et Vent 1969, the dynamic coefficient β was only a function of the type of structure (steel, reinforced concrete, pre stress concrete)…. In Eurocode 1 - part 2.4 wind actions on structures annexe B (wind response in wind direction) the logarithmic decrement of damping δ is introduced in the Rx coefficient (equation B.10).

On some given cases the reduction of load in the wind direction could be as great as 30% and even more resulting in huge saving in structural and foundation costs.

3. GENERAL PRINCIPLE OF DAMPERS

3.1 Simplified model of a structure

In order to be able to design a damper system, it is necessary to use a simplified model of the structure. A slender structure vibrating with the first mode could be modelled by a vertical beam with no mass except one, mass M at the top and having the same stiffness than the original structure. The unique mass M is called the reduced mass or modal mass.

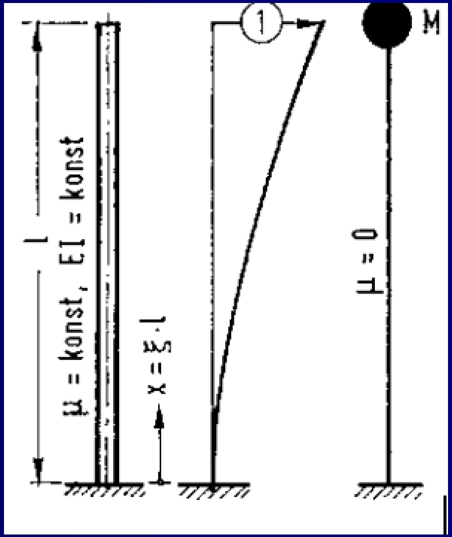
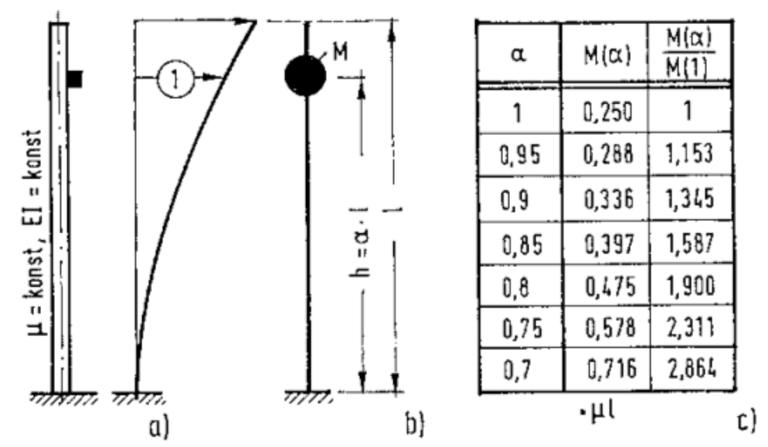


Figure 6 : example of a slender structure

For a structure of constant stiffness the reduced mass is about 25% of the total mass if the reduced mass is placed at the very top.



α	M(α)	$\frac{M(\alpha)}{M(1)}$
1	0,250	1
0,95	0,288	1,153
0,9	0,336	1,345
0,85	0,397	1,587
0,8	0,475	1,900
0,75	0,578	2,311
0,7	0,716	2,864

· μl

Figure 7 :

*if the reduced mass is not at the very top but at an elevation α * H, then the required reduced mass to simulate the structures behaviour is increased. For a reduced mass at 70% of the total height, the reduced mass is increased by a factor 2.70*

3. GENERAL PRINCIPLE OF DAMPERS

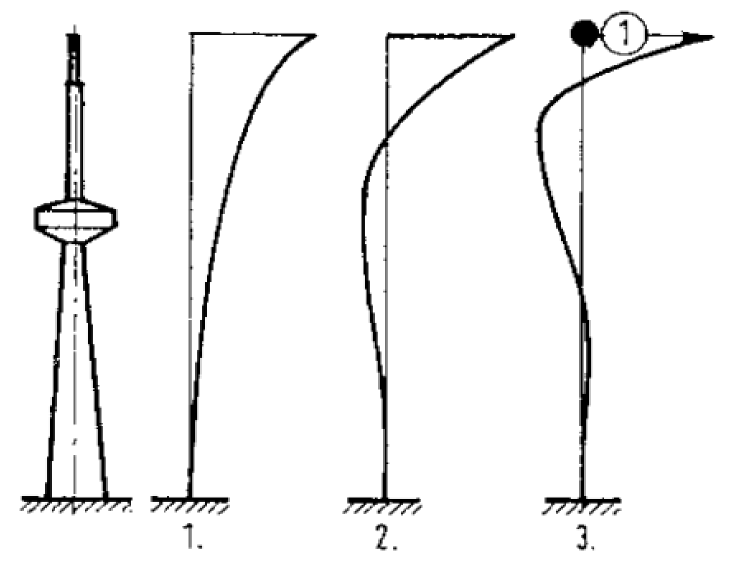


Figure 8 : *Radio tower: mode shape for the first three modes*

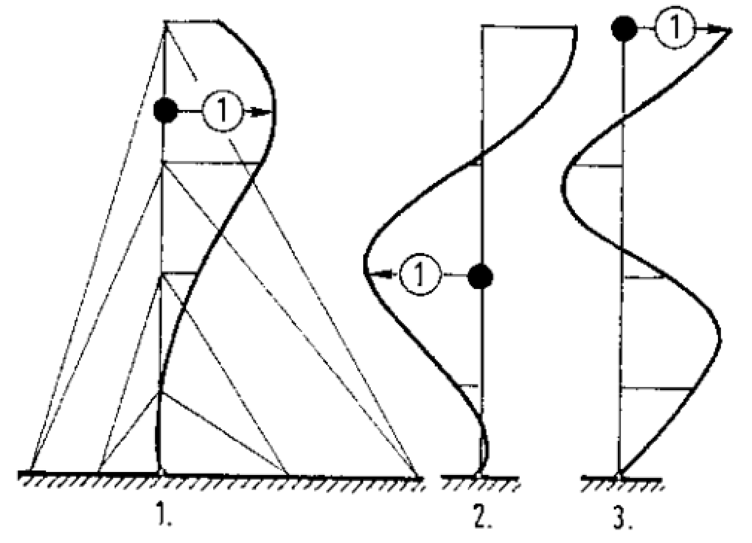


Figure 9 : *Guyed mast: mode shape for the first three modes*

3. GENERAL PRINCIPLE OF DAMPERS

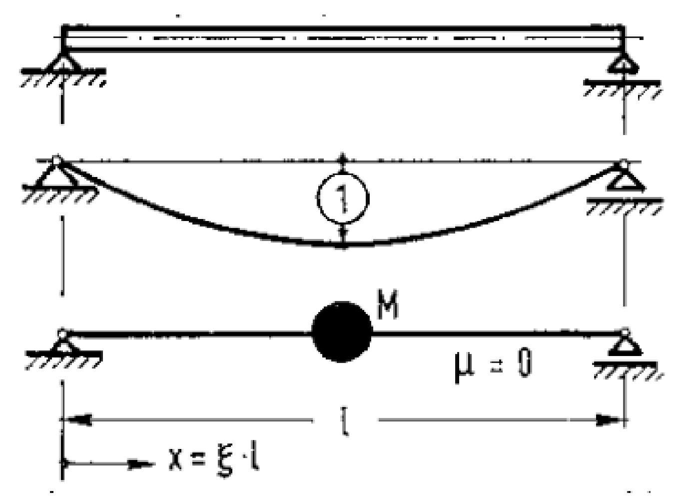


Figure 10a : *bridge deck: first mode shape*

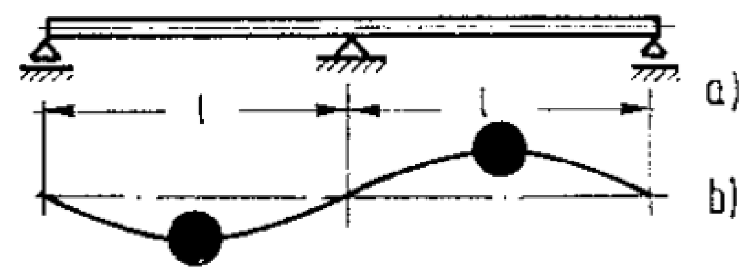


Figure 10b : *bridge deck: second mode shape*

Note: Depending of the structures mode shape more than one mass has to be taken into consideration to model the structural behaviour.

3. GENERAL PRINCIPLE OF DAMPERS

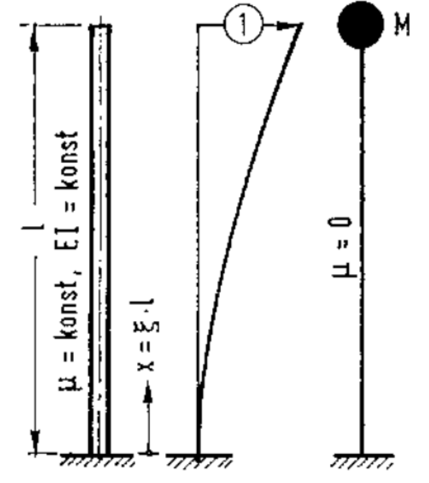
3.2 General consideration

So all structures could be simplified by considering one or more “reduced mass” for one given frequency mode. The general principle of the damper is that the damper has to counterbalance the energy of the reduced mass vibrating at the frequency f and with the amplitude y. The energy produced by these vibrations has to be dissipated by the damping elements of the damper.

3.3 Practical Tuned Mass Damper system

In a Tuned Mass Damper a moving mass representing a fraction μ of the reduced mass (5 to 15% in most cases) is fitted to the structure, tuned to the structures frequency and a damping element is fitted between the structure and the moving mass. Damper devices could be very light: 5 to 15 % of reduced mass which represent less than 1 to 3 % of the total structure weight.

In order to explain the principle lets go back again to a very simple structure such as a stack or column.



The stack could be modelled as a vertical beam with no mass on the total height but with the same stiffness and inertial properties as the real stack. For the first mode of vibration, only one mass is placed at top: M1= modal mass or reduced mass.

The simplified model with this unique mass M1 behaves for the first mode exactly as the real stack. The stack stiffness and inertial properties could be modelled by a spring of stiffness K1 and the structural damping by C1

3. GENERAL PRINCIPLE OF DAMPERS

The damper consists of a mass M2, of a spring K2 and of a damping C2

The value of M2 and K2 are chosen so that the moving part of the damper system can be tuned properly to the structure frequency.

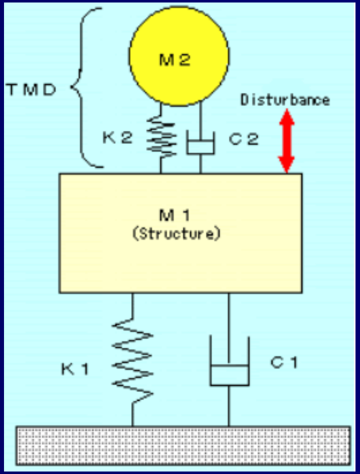


Figure 11 : *mechanical principle principle of Tuned Mass Damper*

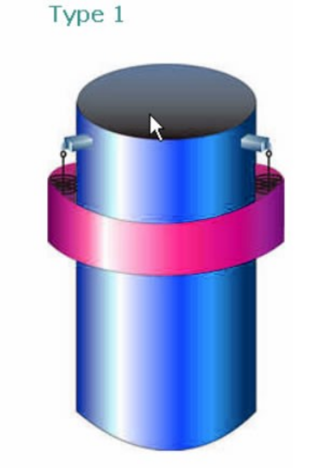


Figure 12 : *general practical design of a Tuned Mass Damper (TMD) on a circular structure*

Above the mass M2 of the damper is represented in red and the structure in blue. The mass is suspended by 3 cables on three locations 120° apart.. The length of the cable being such that the free movement of the mass M2 to be tuned with the structure frequency.

Between the structure and the moving mass the damping elements are inserted. This damping element could be of many different kinds such as dashpot, set of cables, viscous damper,….

The choice of the damping element to be made taking into consideration the environmental conditions, the frequency, the acceleration and also the number of vibration cycles.

3. GENERAL PRINCIPLE OF DAMPERS

Figure 13 : *stack with a TMD – damping elements made of cables*

3. GENERAL PRINCIPLE OF DAMPERS

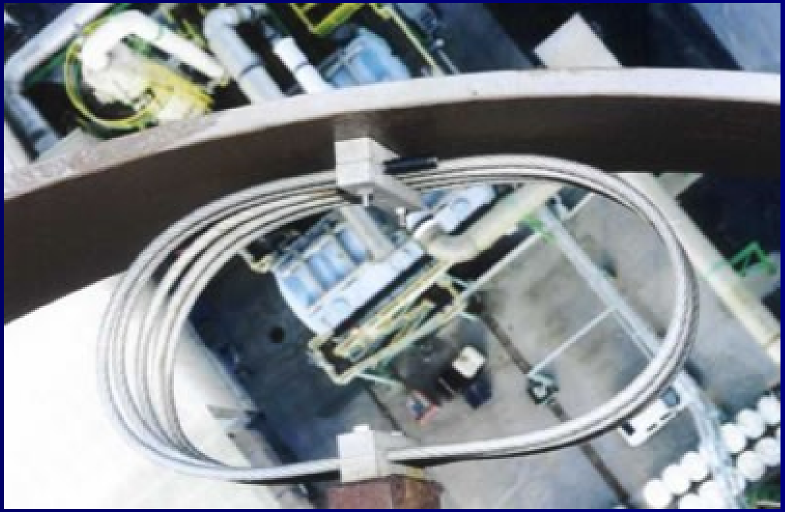


Figure 14 : *detail of the cable-damping element*

Figure 15 : daspot damping system

3. GENERAL PRINCIPLE OF DAMPERS

3.4 Liquid damper system

The principles of a liquid damper are different than those of a TMD but the general philosophy is the same.

The liquid damper has no moving parts, so no abrasion, no mechanical wearing would occurs resulting in no maintenance. They are also recommended when the number of cycles is high and where other types of damper system would require frequent maintenance.

Figure 16 : model of arectangular liquid damper

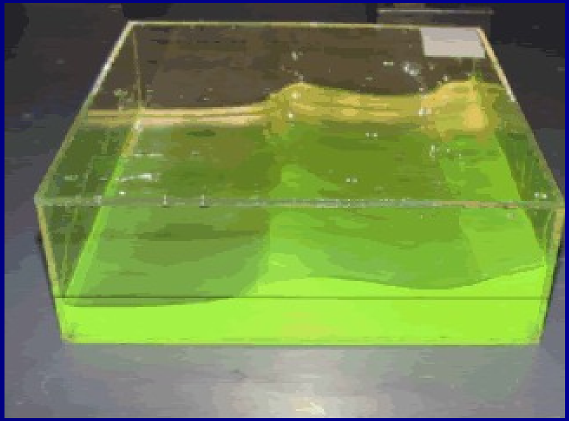


Figure 17 : *shape of a wave inside a rectangular liquid damper*

3. GENERAL PRINCIPLE OF DAMPERS

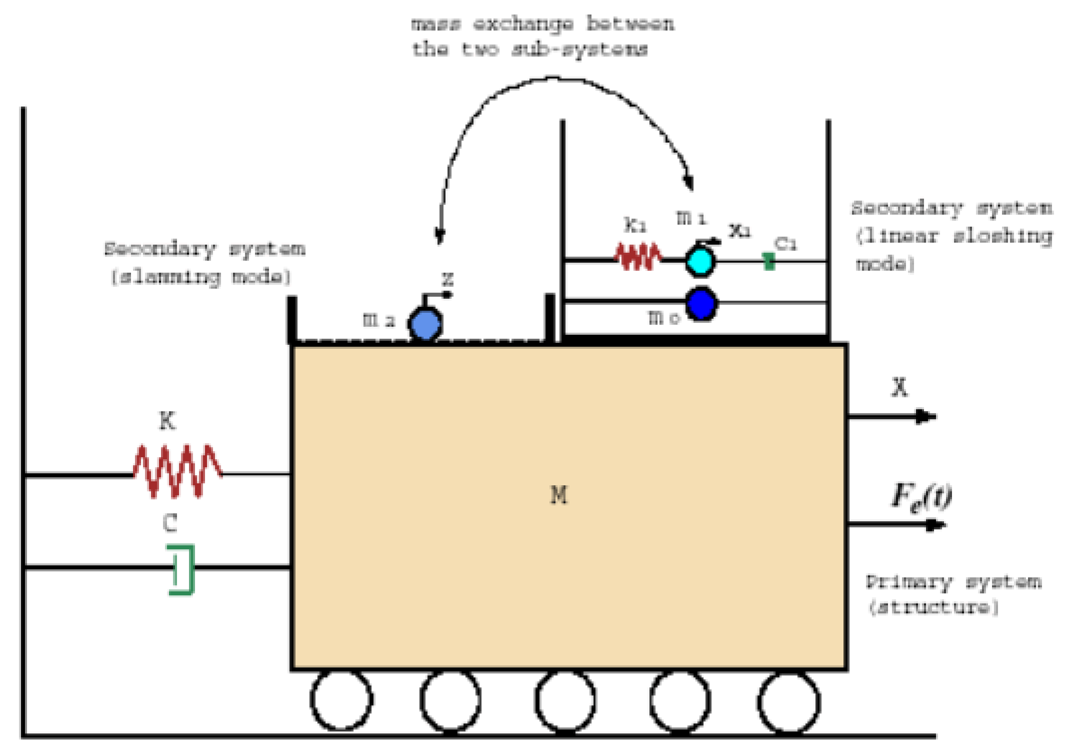


Figure 18 : mechanical principle of a rectangular liquid damper

3. GENERAL PRINCIPLE OF DAMPERS

3.5 Tuned column liquid damper

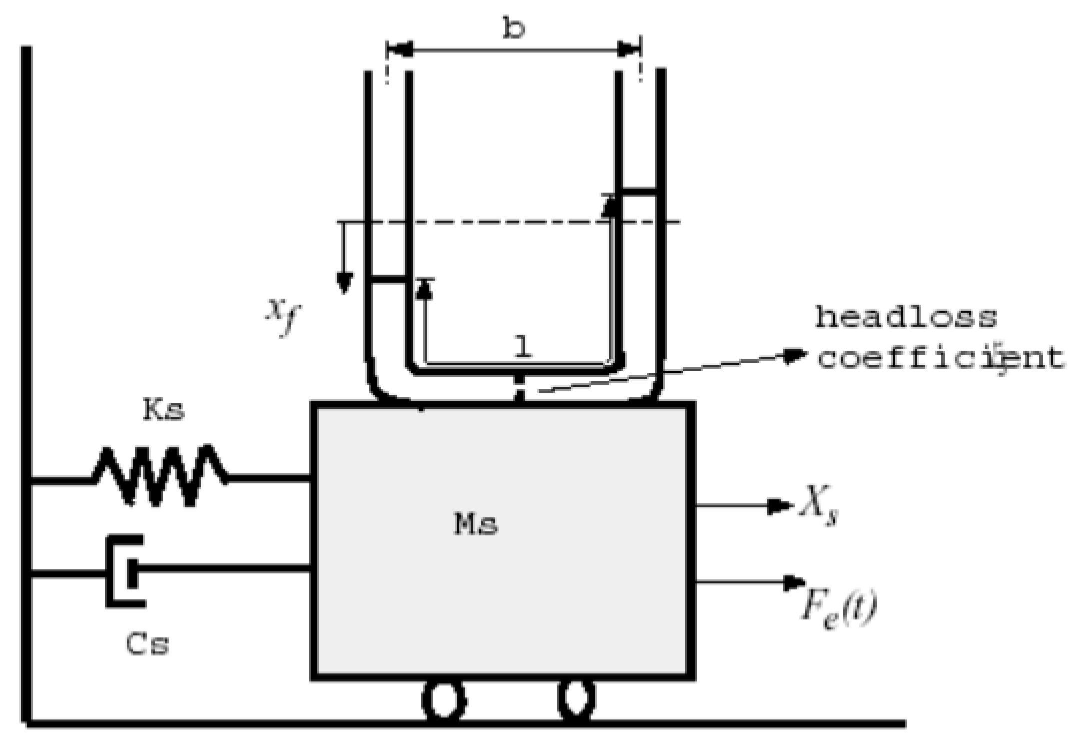


Figure 19 : Tuned Column Liquid Damper

3. GENERAL PRINCIPLE OF DAMPERS

A Tuned Liquid Column Damper (TLCD) is another type of liquid damper. This type is used mainly for small frequencies and is mainly used for very slender structures.

Figure 20 : Model of a TCLD on a vibrating table

3. GENERAL PRINCIPLE OF DAMPERS

3.6 Effect of damper

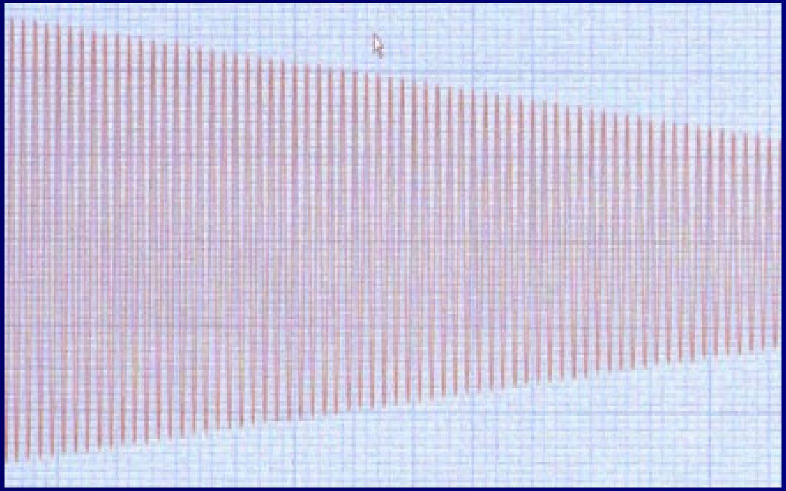


Figure 21 : *decay curve of structure with no damper*

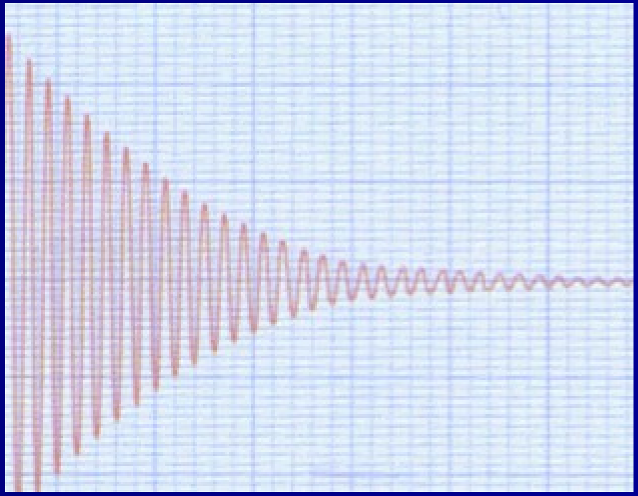


Figure 22 : decay curve of structure with a damper

3. GENERAL PRINCIPLE OF DAMPERS

3.6 Effect of damper

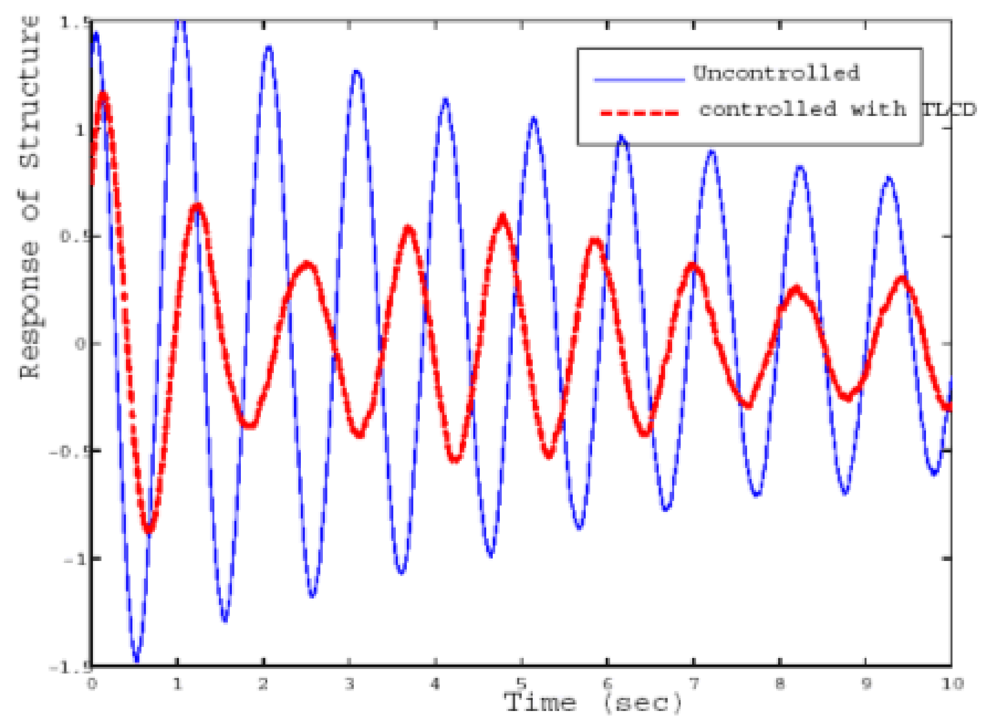


Figure 23 : comparison of the structure response with and without damper.

3. GENERAL PRINCIPLE OF DAMPERS

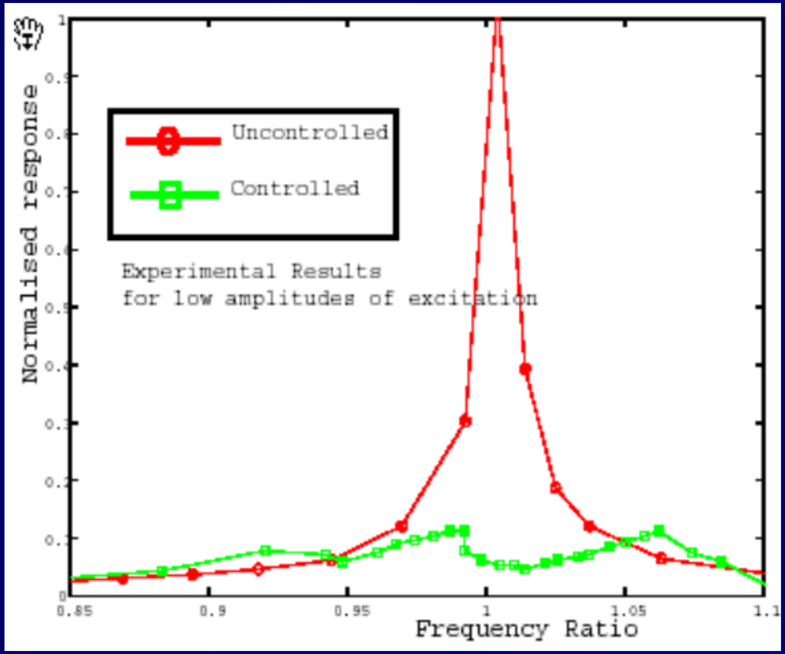


Figure 24 : reduction of the max vibration amplitude of a structure at low level of excitation

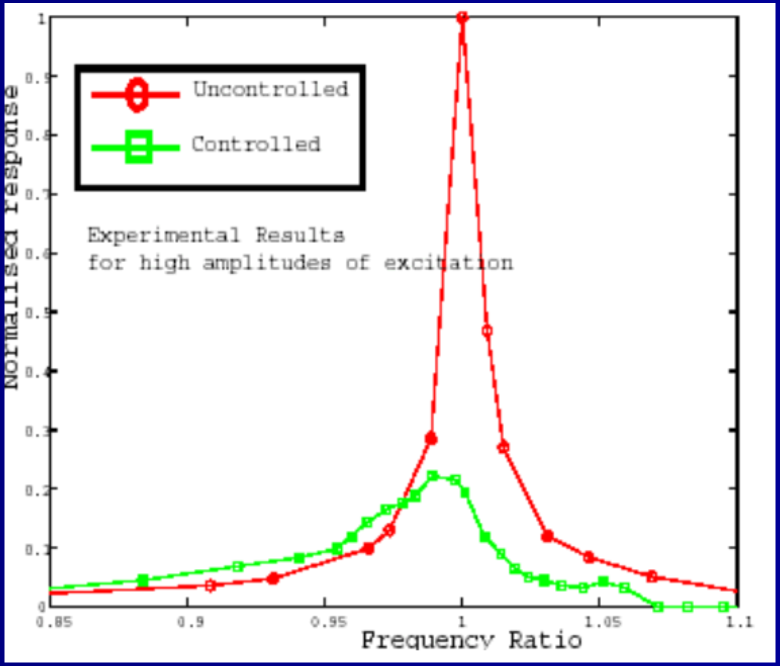


Figure 25 : *reduction of the max vibration amplitude of a structure at high level of excitation*

4. PRACTICAL EXAMPLES

4.1 Stacks, columns, masts…


Liquid damper also used as platform

Figure 26 : steel stack with a liquid damper used as a top platform

4. PRACTICAL EXAMPLES

4.1 Stacks, columns, masts…

Figure 27 : very slender structure (136 m) requiring a damper system for the second vibration mode.

4. PRACTICAL EXAMPLES

4.1 Stacks, columns, masts…

Figure 28 : *Horizontal Tuned Mass Damper enclosed in a box*

4. PRACTICAL EXAMPLES

4.2 high-rise buildings…

Figure 29 : Spinnaker 170 m high rise building

4. PRACTICAL EXAMPLES

4.2 high-rise buildings…

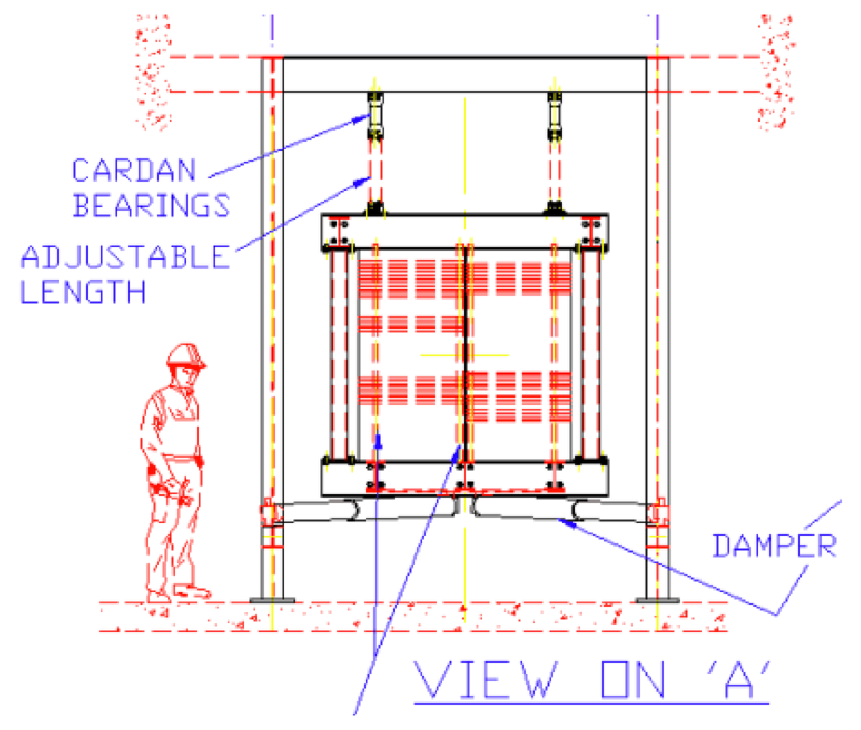


Figure 30 : principle of a Tuned Mass Damper for a high-rise building

4. PRACTICAL EXAMPLES

4.2 high-rise buildings…

Figure 31 : other high-rise building requiring a damper for inhabitant comfort

4. PRACTICAL EXAMPLES

4.3 bridges…

Figure 32 : bridge with cable support requiring a damper on the cable excited by wind.

4. PRACTICAL EXAMPLES

4.3 bridges…

Figure 33 : Viaduct of Millau requiring damper on the steel mast above deck to prevent vibration in some rare case of wind (perpendicular to the valley)

4. PRACTICAL EXAMPLES

4.3 bridges…

Figure 34 : detail of the steel mast damper- to be installed at the top

4. PRACTICAL EXAMPLES

4.3 bridges…

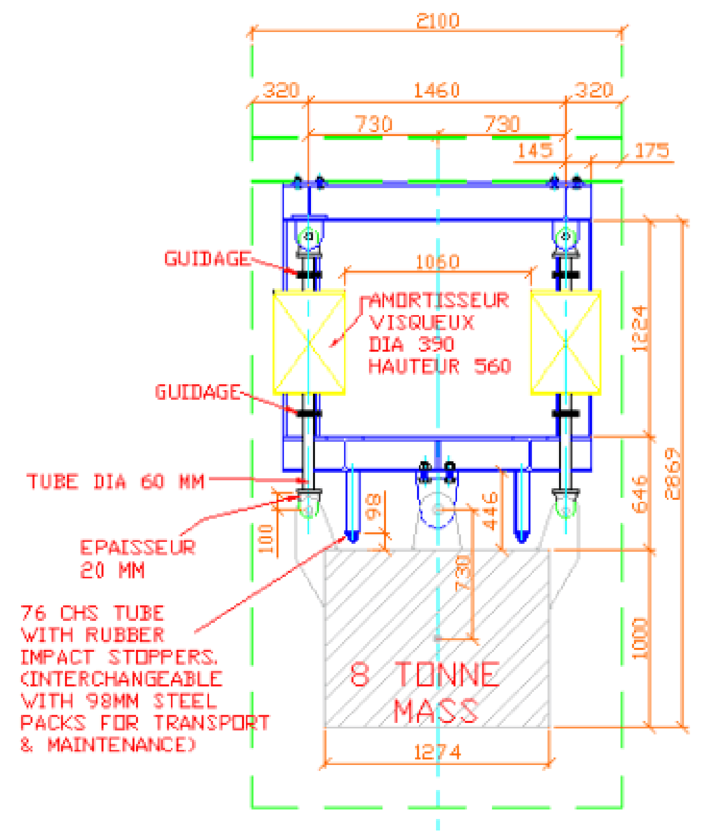


Figure 35 : detail principle of damper to be installed in a bridge pylon.

4. PRACTICAL EXAMPLES

4.3 bridges…

Figure 36 : very slender bridge supposed to vibrate verticaly as a result of pedestrians walking on it.

4. PRACTICAL EXAMPLES

4.3 bridges…

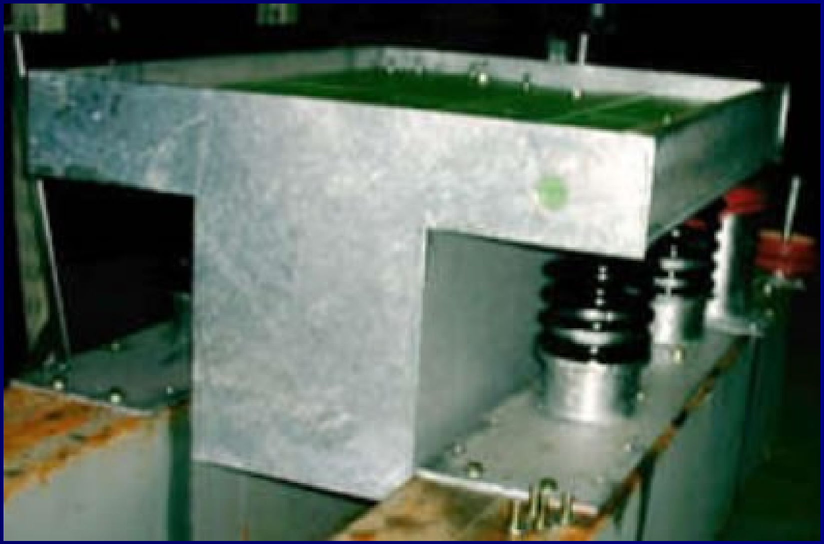


Figure 38 :
typical bridge vertical Tuned Mass Damper with a

moving mass, springs and damping elements

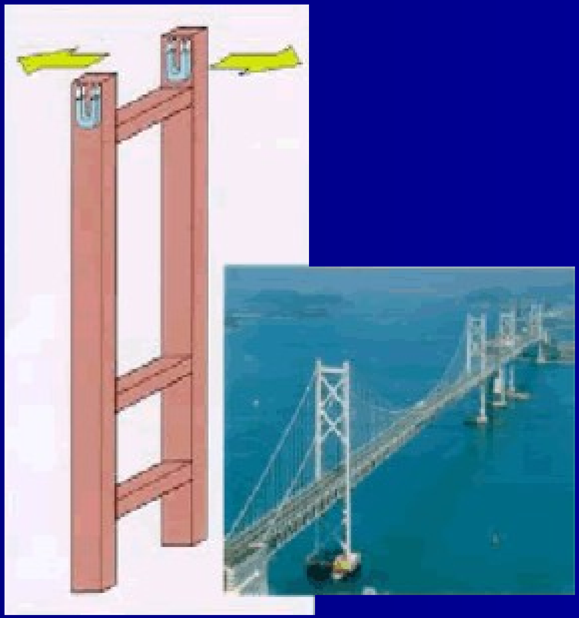


Figure 38 :
TLCD for stabilization of bridges piles.

4. PRACTICAL EXAMPLES

4.4 light poles…

Fig 39 : The light bulb fitted inside the light pole are also suffering vibration and would break as a result.

The cost of a light bulb is ridiculous compared to the price to change them.

Placing a special damper working on two frequencies as different as 2.5 Hz and 14 Hz would increase the lifespan of the light bulb by a factor 3 or 4 and reduce consequently the maintenance costs.

The damper can be fitted on existing light pole or placed inside the head if previously some arrangement has been made.

4. PRACTICAL EXAMPLES

4.4 light poles…

Figure 40 : *detail of a ample broken by fatigue*
Due to pole mast vibration excited by wind

4. PRACTICAL EXAMPLES

4.4 light poles…

Figure 41 : *detail of a light pole damper*