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Evaluation of percent critical damping of process towers

It is suggested that for wind and seismic analysis of tall process towers, percent critical damping should be assessed by considering several contributing factors judiciously for a more economic design. These factors are analyzed here

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DAMPING MECHANISMS in components like materials used, insulation, soil-foundation, appendages and phenomena like liquid sloshing, and aerodynamics contribute to the dynamic response of process towers. Using a tower-foundation example, each of these damping rnechanisms is quantified and overall system damping is obtained by summing the individual logarithmic decrements.

Types of damping. The damping forces frequently encountered in practical engineering vibration problems are of four types[1]:

- 'Viscous' damping, when the damping force is proportional to the velocity.
- 'Coloumb' damping, when the damping force is independent of the velocity and depends on the normal pressure.
- 'Aerodynarnic' damping, assumed to be proportional to the square or some higher power of the velocity
- 'Hysteretic' or 'Material' damping, independent of the velocity but dependent on the amplitude of motion.

For evaluating the total damping of the tower foundation structural system, the contribution of all the four types of damping forces are taken into account. The various types of damping forces acting on the system are shown in Fig. 1 and Table 1.

Material damping.

From formula. The damping of the tower is calculated from the formula as given by Sachs[2]

$$\delta_m = EJ\sigma_{\max}{}^{n-2}(\alpha / \beta)$$

where δ_m is the material logarithmic decrement, E, the modulus of elasticity of tower material, *J*, the material constant, *n*, the material constant (2.15 for mild steel), $\sigma_{\max}$ the cyclic stress (between 0.5 and 1.5 times the fatigue strength), and α, β, the constants dependent on the stress distribution in the structure and *n*.

In the above equation the units for *E* and $\sigma_{\max}$ are in psi and psf, respectively as given in 'Shock and Vibration Handbook' by C. M. Harris and C. E. Crede.

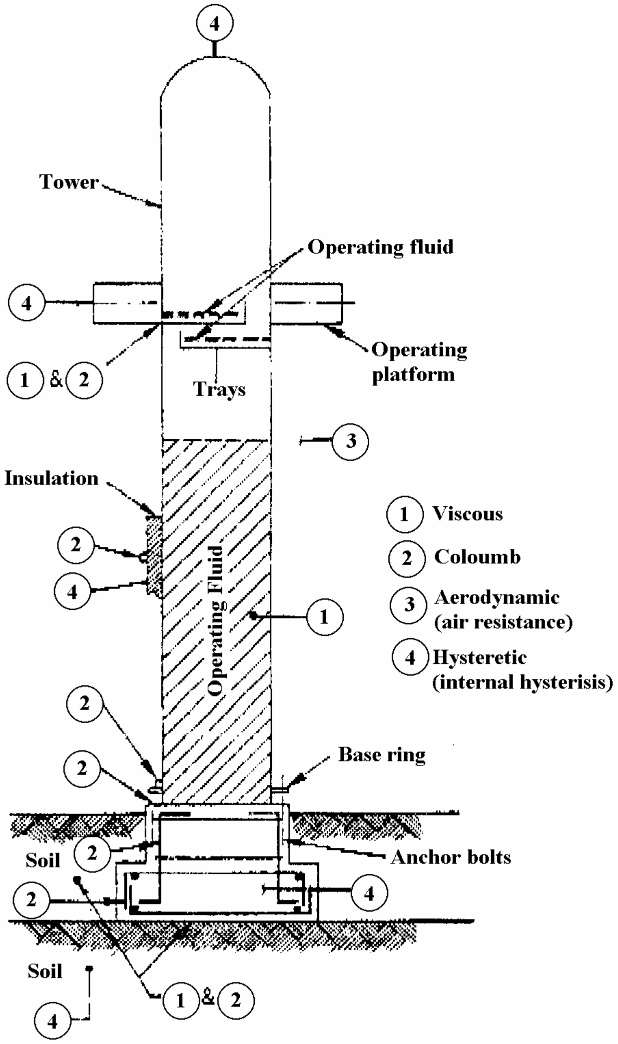

Fig. 1 - Damping Forces acting on tower foundation system.

Example. Determine δ_m, for a tower having diameter 1800 mm, shell thickness 52 mm, material carbon steel.
D/t = 1800/52 = 34.6, say, 30.

From Fig. 2 (Sachs[2]) for clamped free cylinder,
D/t = 30 and *n* = 2.15, β/α = 1.1,α/β = 1/1.1 = 0.909.

Two values are computed for $\sigma_{\max}{}^2$ = 20 X 10^3 lb/in^2 (1406 kgf/cm^2) and 40 x 10^3 lb/in^2 (2812 kgf/cm^2), *i.e.*, for 2880 x 10^3 lb/ft^2 and 5760 x 10^3 lb/ft^2, *E* = 30 x 10^6 lb/in^2 (2l90 x 10^3 kgf/crn^2), and *J* = 447 x 10^{-12} (from Table2).

δ_m = 30 x 10^6 (447 x 10^{-12})(2880 x 10^3)$^{2.15-2}$(0.909)
= 0.1135
C_m = material damping ratio = $\delta_m/2\pi$ = 0.1135/2π
= 1.8%.

TABLE 1—Damping forces on system

Nature of damping	Location/inter-action between	Mode of energy dissipation
Hysterectic	Soil	Stress reversals, heat generation and shock wave fronts radiating outwards in the soil
Viscous	Soil and foundation	Rocking of foundation and heat generation
Coloumb	Soil-foundation	Nonlinear slippages at interfaces and heat generation
Hysteretic	Foundation concrete	Stress reversal and heat generation
Coloumb	Foundation concrete-reinforcement	Nonlinear slippages at interfaces and heat generation
Coloumb	Foundation-anchor bolts	Nonlinear slippages at interfaces and heat generation
Coloumb	Base ring -tower shell	Nonlinear slippages at interfaces and heat generation
Viscous	Tower shell-operating fluid	Sloshing of liquid and heat generation
Coloumb	Tower-shell insulation	Nonlinear slippages at interfaces and heat generation
Coloumb	Tower shell and trays and platforms and other appendages	Nonlinear slippages at interfaces and heat generation
Viscous	Tower shell and trays and platforms and other appendages	Out of phase vibration and heat generation
Hysteretic	Tower shell	Stress reversals, strains, and heat generation
Hysteretic	Insulation	Stress reversals, strains, and heat generation
Hysteretic	Platform, trays and other appendages	Stress reversals, strains, and heat generation
Aerodyn-amic	Tower, appendages, insulation and air	Vortex formation, shock waves and heat generation

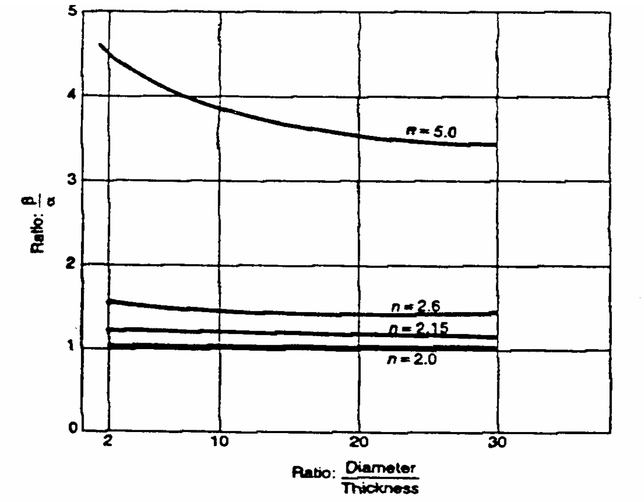

Fig. 2 - β/α for cylinders of various thickness ratios and different damping constants, *n* (clamped free cylinders).

TABLE 2—Values for *J* and *n* for various materials

Material	Mild steel	70/30 Brass	Aluminium	Glass reinforced plastic
J	$447 \text{x} 10^{-12}$	$30.5 \text{x} 10^{-12}$	$1221 \text{x} 10^{-12}$	$4.2 \text{x} 10^{-12}$
n	2.14	2.52	2.10	2.90

$$\delta_m = 30 \text{ X } 10^6 (447 \text{ x } 10^{-12}) (5760 \text{ x } 10^3)^{0.15} (0.909) = 0.1259$$

$$C_M = 0.02 = 2\%$$

From case histories. Not much field work has been done on the damping measurement of process towers. However Sachs[2] has listed some field empirical data for welded steel stacks, lined and unlined. These are as listed in Table 3.

TABLE 3 - Logarithmic decrement for unlined welded steel stacks

Height ft	Tip diameter ft-in.	Logarithmic decrement, δ	REMARKS $\delta_m = \frac{0.297}{8}$
150	4 0	0.010	= 0.037
225	11 4	0.027	$C_M = \frac{0.037}{2\pi}$
225	11 4	0.070	
200	11 0	0.040	
250	7 0	0.050	= 0.0059
296	17 6	0.030	= 0.59%
274	13 6	0.038	
253	12 9	0.032	

Zorrilla[3], has also reported an average value of logarithmic decrement of 0.0322 for welded unlined circular stacks and recommends a value of 0.03.

$$C_M = 0.03/2\pi = 0.478\%$$

Material damping as adopted. For towers additional decrement can be allowed for allowed for bolted joints, attachments, piping, etc. However, to be on the conservative side, the average of 1.8 percent and 0.478 percent based on lower stress level and for unlined complete welded stack respectively, is considered:

$$(1.8 + 0.478)/2 = 1.14\%$$

Insulation damping. Freese[4] has given the field test results to establish the effect of insulation on the logarithmic decrement of tall towers:

➔ Before the insulation (tower empty)

$\delta = 0.0463$

$C_1 = 0.0463/2\pi = 0.737\%$

➔ After the insulation (tower empty)

$\delta = 0.0848$

$C_2 = 0.0848/2\pi = 1.35\%$

In this case the addition of insulation almost doubled the percent damping of the tower.

Sachs[2] also has given the value of logarithmic decrement for the lined welded steel stacks, Table 4.

For welded lined steel stacks, Zorilla[3] has recommended a value of 0.05 for logarithmic decrement. So

$$C = 0.05/2\pi = 0.00796 = 0.796\%$$

Comparison of Table 3 and 4 indicates that the effect of lining is to increase the damping to the order of 0.3 percent. From values of damping percent calculated

TABLE 4-Logarithmic decrement for welded lined steel stacks

Height ft	Tip diameter ft-in	Logarithmic decrement, δ	REMARKS
225	11 4	0.04	$\delta_m = \frac{0.4}{7}$
225	11 4	0.07	
200	11 0	0.06	= 0.057
250	16 6	0.06	$C = \frac{0.057}{2\pi}$
300	14 6	0.03	
		0.09	
		0.05	= 0.907%

based on Zorrilla's reported values of logarithmic decrements, it is also observed that the effect of lining, is to increase the damping to the order of 0.3 percent.

Accordingly, for insulation a conservative value of 0.1 percent can be safely considered since in the case of towers the insulation density is much less than that of stack lining material.

Therefore, vessel insulation percent damping, = C_1 = 0.1 percent.

Soil foundation damping. The contribution of foundation damping is quite large towards total damping of the system. According to Richart, *et al*[5], soil foundation damping is of two types, internal damping and radiation damping.

The phenomenon of internal damping occurs in dry cohesionless soil where the energy is lost in developing friction between soil particles during stress reversals. Radiation damping occurs when the kinetic energy imposed on the soil in the form of vibrations, is sent out in waves and travels long distances through the soil.

Out of the four types of damping discussed earlier, three occur in the foundation soil interaction. Viscous damping occurs when one side of the foundation starts to lift and the other starts to depress under the action of horizontal forces due to wind or earthquake. The contact area under the foundation can be imagined as a piston, trying to slide through a cylinder of soil, with air or water rushing in to fill the void left by the foundation or being squeezed out on the opposite side.

As the sides of the foundation slide on the surrounding soil, dry Coloumb friction damping force develops at these interfaces. At the same time the soil below the foundation undergoes the stress variation resulting in hysteretic damping. The energy is transformed into heat and wave energy and thus lost.

All these effects contribute to the loss of energy, thereby reducing the vibration amplitude of successive cycles, *i.e.*, logarithmic decrement.

Barkan[6] stated that, “since the coefficient of damping is inversely proportional to the amplitude of vibrations at resonances, it follows that in the case under consideration the value of the coefficient of damping for a backfilled foundation will be approximately 3.5 times larger than that for an exposed foundation.” A considerable effect of backfilling on the value of damping was also observed in investigations of foundations placed on grey sands. For example, damping increased from 19 to 32 percent when a foundation was backfilled to the height of 1 m.

The foundation soil interaction has major effect on the damping of the structure [5-7]. For sands, Barkan[6] gives a value of damping up to 19 percent, Richart and Whitman[5] give up to 3 percent. Newmark and Rosenblueth[7] state that the percent damping is a function of the shear wave velocity and give values from 2 to 10 percent.

Whitman and Richart[5], gave an empirical equation for internal damping of soil as follows:

$$D \cong \delta/2\pi = 4.5\, \gamma_{xz}^{0.2}\, \sigma_o^{-0.5}$$

where γ_{xz} is the shearing strain (1×10^{-6} to 1×10^{-4}), σ_o, the confining pressure, psf (500 to 3000), and D, the soil damping ratio. For $\gamma_{xz} = 1 \times 10^{-1}$

$$D = 4.5\,(1 \times 10^{-4})^{0.2}(3000)^{-0.5}$$
$$= 0.0131 = 1.31\%$$

To be on conservative side, least of the above values is considered to arrive at the average value of the percent critical soil damping. Therefore,

$$C_{SF} = (3 + 2 + 1.31)/3 = 2.1\%, \text{ say } 2\%$$

Damping from appendages. Another source of damping which is very difficult to evaluate is that due to the out of phase vibration of attachments like trays, platforms, ladders, piping, etc. Because of large differences in the mass and stiffness of these elements, such components tend to vibrate in an uncoupled mode from that of the overall tower. Damping forces are induced at the various interfaces (bolted joints, etc.) and also hysteretic damping occurs within the various appendages. Since it is very difficult to assess this damping, a very low percent of 0.1 percent can be considered. Therefore, percent critical damping, C_A = 0.1 percent.

Damping from liquid sloshing.

From field tests. Freese[4] studied in field tests the effect of liquid sloshing on the logarithmic decrement of a process tower. The field test results, when the tower is empty, are

Logarithmic decrement, δ = 3.5% = 0.035

Percent critical damping = 0.035/2π = 0.557%

and when the tower is filled with operating liquid,

Logarithmic decrement, δ = 14% = 0.14

Percent critical damping = 0.14/2π = 2.2%

Hence the increase in percent critical damping due to the sloshing is 2.2 - 0.557 = 1.643 percent.

From calculations. The following procedure can be adopted to arrive at the logarithmic decrement due to liquid sloshing.

The tower could be modelled as a cantilever fixed at the foundation.

1. Analyze the cantilever without including the mass of the operating liquid and with zero damping, subjected to trapezoidal time history transient forcing functions of wind loads applied laterally at each node.
2. Obtain the dynamic amplitude and acceleration at each node, using any standard computer program.
3. Allocate mass of operating liquid at each node based on the distribution of trays and liquid level.
4. Calculate the sloshing forces at each node by multiplying liquid mass allocated at each node with the maximum acceleration as obtained in step 2.

5. Apply the above sloshing forces in the opposite direction to the direction of wind forces considered in step 2 above and obtain the dynamic amplitude.

6. Superimpose the displacements obtained in step 5 on the displacements obtained in step 2 and obtain the final displacement curve.

7. From the final displacement curve, calculate the logarithmic dec

$$\text{Percent critical damping} = \delta/2\pi$$

For a typical example, the value of percent critical damping due to liquid sloshing has been observed to be 1.5. Therefore, $C_{LS} = 1.5$ percent.

Aerodynamic damping. Generally, the aerodynamic damping is negligible. This is due to the fact that the velocity of oscillations of the tower is normally very small and the aerodynamic damping is proportional to the second (or higher) power of velocity. Therefore, aerodynamic damping may be neglected.

Total damping of tower foundation system. To arrive at the total damping of the system, one considers vibration of the tower to be predominantly in its fundamental mode. The energies dissipated by the relevant. damping mechanisms of this system are summed up and equated to the energy dissipated by a fictitious equivalent linear viscous damping mechanism which defines the total damping. As in this article the logarithmic decrements of various damping mechanisms are calculated and one is justified in adding these numerically to get the total damping.

By adopting the concept of logarithmic decrement to each damping mechanism the damping force irrespective of its law of variation is automatically linearized and converted to an equivalent viscous damping force. So, in effect only adding the several linearized viscous damping coefficients is done to get the overall damping coefficient.

The following calculation sums up the damping calculated from various logarithmic decrements for empty and operating conditions of the tower.

	Tower empty	Tower operating
Material, C_M	1.14	1.14
Insulation, C_1	0.10	0.10
Soil-foundation, C_{SF}	2.00	2.00
Appendages, C_A	0.10	0.10
Liquid sloshing, C_{LS}	—	1.50
	3.34%	4.84%

Conclusions. It is observed the percent critical damping for the tower foundation system is of the order of 3.5 and 5 percent for empty and operating conditions, respectively. Whereas the practice was to consider this value as 2 percent for both the conditions, for wind and seismic analysis as recommended in Indian Standard IS: 1893 - 1975 (Criteria of Earthquake Resistance Design of Structures) leading to conservative designs. However, in the case of seismic loading which generally covers the frequency range of 0.2 to 33 cps it is quite likely that in the case of tall towers not only the fundamental, but also a few higher modes participate in the response. The foregoing discussions are valid only for the fundamental response and require recalculation of damping coefficients corresponding to higher modes. This may be done by assuming that vibrations occur purely in these modes and repeat the procedures mentioned here. A better assessment of damping factor is bound to arise from this exercise which may be used for seismic analysis of such towers.

It is suggested that for wind and seismic analysis of tall process towers, percent critical damping should be worked out taking into account the geometry, material of construction, stress variation and foundation system and judicious values adopted to have a more economic design. (Originally presented at the Aeronautical Engineering Div., Institute of Engineers (India) Seminar on "Industrial Aerodynamics," Bangalore, Feb. 7 - 8, 1980)

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