



Material Damping

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MATERIAL DAMPING

CONTENTS

	Page
1. NOTATION	1
2. INTRODUCTION	3
3. THERMOELASTIC DAMPING	5
4. DISLOCATION DAMPING	7
5. MAGNETOMECHANICAL DAMPING	8
6. DAMPING OF MATERIALS WITH HETEROGENEOUS STRUCTURE	10
7. DAMPING RELATED TO PHASE CHANGE	10
8. HIGH DAMPING METALS (HIDAMETS)	11
9. COMPOSITES	14
10. COMPARISON OF DAMPING IN DIFFERENT MATERIALS	16
11. REFERENCES	19

MATERIAL DAMPING

1. NOTATION

		Units
c_p	specific heat (per unit mass) at constant stress	J/kgK
E	Young's modulus	Pa
E_L	Young's modulus in direction of fibres	Pa
E_T	Young's modulus in direction perpendicular to fibres	Pa
f	frequency	Hz
G_{LT}	shear modulus	Pa
h	thickness of beam	m
k_t	transverse thermal conductivity (in the direction of the beam thickness)	W/mK
Q	quality factor	
T_0	absolute temperature at equilibrium	K
V_f	volume fraction of fibre	
W	maximum elastic strain energy stored per unit volume	Pa
α	linear coefficient of thermal expansion	K ⁻¹
β	Hidamet parameter ($\beta = \psi_{0.1} \times \sigma_{ts}$)	
Δ_{rs}	relaxation strength	
ΔW	mechanical energy lost per cycle	Pa
δ	logarithmic decrement	
ε	strain	
ζ	equivalent viscous damping ratio	
η	loss factor	
η_{max}	maximum value of loss factor for thermoelastic damping	
ν	Poisson's ratio	
ν_{LT}	Poisson's ratio (load applied in the direction of the fibres)	
ρ	density of beam material	kg/m ³

σ	stress	Pa
σ_{ts}	tensile strength	Pa
σ_y	yield stress	Pa
τ	relaxation time	s
ϕ	phase difference between stress and strain	
ψ	specific damping capacity	
ψ_L	specific damping capacity for loading in longitudinal direction	
ψ_T	specific damping capacity for loading in transverse direction	
ψ_{LT}	specific damping capacity for in-plane shear loading	
$\psi_{0.1}$	specific damping index	
ω	frequency	rad/s
ω_1 and ω_2	are frequencies at half power (3 dB) points	rad/s
ω_n	undamped natural frequency of beam	rad/s

Abbreviations

ASTM	American Society for Testing and Materials
HIDAMET	high damping metallic material
LSS	large space structures
MEMS	microelectromechanical systems
MMD	Metallic Materials Data
MMPDS	Metallic Material Properties Development and Standardization
SDC	specific damping capacity
SDI	specific damping index

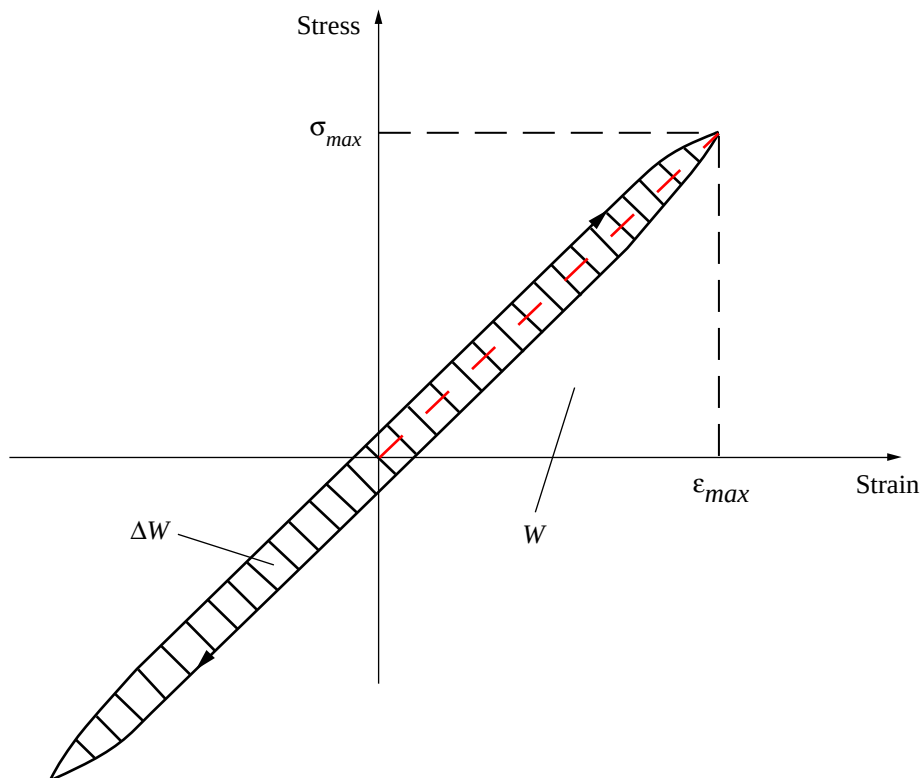
2. INTRODUCTION

The ability to dissipate vibratory energy in structures, systems of structural components, or structural materials is described by the term “damping”. The decay of the amplitude of the free vibration of a system with damping is caused by the internal and external friction as well as by the transmission of vibratory energy into the surrounding medium, *e.g.*, in the form of sound radiation (Reference 37). Similarly, the amplitude of vibration of a mechanical system at resonance, when subjected to forced vibration, decreases as the damping becomes greater. The existence of the intrinsic and external friction leads to the conversion of vibratory energy into heat.

The subject of this Item is material damping, a type of damping which is intrinsic in a component of a structure subjected to a vibratory motion. As it is a form of damping which is associated with a dissipation of mechanical strain energy within the material, it is also referred to as internal friction. Material damping is independent of external structural factors. Whilst these external factors can often be controlled by proper structural design, the material damping remains unchanged in a given situation. Material damping depends primarily on the nature and characteristics of the material used in construction. The amplitude of stress is important and, additionally, material damping may depend on environmental factors, such as temperature or a magnetic field. The way in which the material is prepared is significant and its heat treatment is an important factor which influences the material damping.

Components made from metals or alloys are often bolted or riveted together and the jointed connections usually provide much more damping than that which is intrinsic within the material. The term ‘structural damping’ is used to describe damping from the joints and from lubricated bearings, as well as from the intrinsic damping of the material. Welded structures have much less damping than jointed components, because there is no relative motion at the joints.

There are different ways of specifying damping (discussed in ESDU 09005, Reference 39). When cyclic stress is applied to a structural component of the specific material the stress-strain relationship is represented in the form of a hysteresis loop, shown schematically in Sketch 2.1.



Sketch 2.1 Stress-strain hysteresis loop

One of the measures of material damping is the specific damping capacity is ψ , which is defined as

$$\psi = \frac{\Delta W}{W}, \quad (2.1)$$

where ΔW is the mechanical energy dissipated during one cycle per unit volume of the material and $W = \sigma_{max}^2 / 2E = \frac{1}{2} E \epsilon_{max}^2$ is the maximum elastic strain energy stored per unit volume during the cycle, see Sketch 2.1. Young's modulus is denoted by E and σ_{max} represents the stress at maximum strain, ϵ_{max} .

The mechanical energy dissipated during one cycle per unit volume of material, ΔW , is represented by the area within the loop. When the stress-strain hysteresis loop is known, the damping, as well as the dynamic elastic modulus, may be estimated. The specific damping capacity (SDC), ψ , is usually expressed as a percentage. Provided that damping is sufficiently low, the specific damping capacity can be related to other damping measures as

$$\psi = 4\pi\zeta = 2\pi\eta = 2\delta = 2\pi \frac{\omega_2 - \omega_1}{\omega_n} = \frac{2\pi}{Q} = 2\pi \tan\phi, \quad (2.2)$$

where	ζ	the equivalent viscous damping ratio,
	η	the loss factor,
	δ	the logarithmic decrement,
	ω_1 and ω_2	are frequencies at the half power (3 dB) points,
	ω_n	the undamped natural frequency,
	Q	the quality factor and
	$\tan\phi$	the tangent of the loss angle.

Although material damping is, in general, small for most materials there are certain metals and alloys where the damping has comparatively large values. Damping is greater when the damping process is nonlinear, as occurs with metals and their alloys under high applied cyclic stress. In these cases, the hysteresis loop, shown in Sketch 2.1, has a more pointed appearance. Metallic materials which give rise to high damping include ferromagnetic alloys, manganese-copper alloys and grey cast iron. Materials with high damping and high values of strength and elastic modulus, as well as good resistance to corrosion, are especially suitable for load carrying structures. It is also desirable that the material possesses high damping within a wide range of frequency and temperature. Such materials are widely used in engineering applications to control fatigue and vibration and, if they are metallic, the term 'Hidamet' is used to describe them. For many metallic materials, other than Hidamets, good damping can only be achieved for particular conditions, such as high temperature, as in the case, for example, of nickel-based superalloys. In general, such materials have limited engineering applications, although they can be used to damp the vibrations of hot components, such as turbine blades.

Damping of vibration has a significant role in the modelling of flexible, large space structures (LSS). Any large space structure has a high number of modes at low frequencies. LSS require active control of their dynamic response, as well as passive damping, to secure precision in space manoeuvres and the stability of the structure during these positioning operations. Passive damping is mostly achieved by material damping. Compared with other types of damping, *e.g.*, sound radiation and friction between different components of the structure, material damping maintains its importance in space structure applications, since sound radiation does not occur and friction between different structural components may be substantially reduced. Knowledge of material damping is also essential in reducing peak stresses to extend

the fatigue life of structural elements (Reference 21). Apart from applications in the aerospace industries, the subject of material damping is also important in microelectromechanical systems (MEMS), since MEMS devices, such as actuators and sensors, are required to operate with very little energy loss (Reference 34).

3. THERMOELASTIC DAMPING

Thermoelastic damping is a relaxation process in which the thermal field is coupled to the strain in the material and change of mechanical energy into heat takes place. Thermoelastic damping was first investigated theoretically by Zener with reference to beams in bending (Reference 1). As the beam bends, the fibres of the beam in tension cool and those in compression increase in temperature. Associated with the transverse gradient of temperature is a relaxation process, in which thermal currents are set up in the direction of the beam thickness and energy is dissipated. In the case of a thin homogeneous and isotropic beam with a rectangular cross-section and uniform thickness, h , the relaxation time, τ , is given by

$$\tau = \frac{h^2 \rho c_p}{\pi^2 k_t}, \quad (3.1)$$

where ρ is the density of the beam material, c_p is the specific heat at constant pressure (for metals essentially the same as at constant volume) and, k_t is the transverse thermal conductivity (in the direction of the beam thickness). The thermoelastic damping of the beam in terms of the loss factor, η , at frequency ω in rad/s is given by

$$\eta = \frac{\alpha^2 E T_0}{\rho c_p} \left(\frac{\omega \tau}{1 + \omega^2 \tau^2} \right) \quad (3.2)$$

where α is the linear coefficient of thermal expansion of the material, E is Young's modulus (isothermal modulus) of the material of the beam and T_0 is the absolute temperature at equilibrium. The loss factor

may be conveniently expressed as η/Δ_{rs} , where parameter $\Delta_{rs} = \frac{\alpha^2 E T_0}{\rho c_p}$ defines the relaxation strength.

The relaxation strength Δ_{rs} is a characteristic of the material.

The damping, in terms of the scaled loss factor, as a function of $\omega \tau$ is shown in Sketch 3.1.