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Original Research Paper

Combined viscoelastic and elastic wave dissipation mechanism at low velocity impact

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ABSTRACT

The understanding of effects occurring during low velocity normal particle impact on a hard elastic plate is important for the description of different processes occurring during pneumatic conveying, in jet mills, mixers, or fluidized bed apparatuses. In this study, a suitable semi-empiric method is proposed to calculate the coefficient of restitution. This coefficient of restitution is modelled by means of combination of two different approaches. The first approach is based on dissipation of impact energy due to bending wave excitation in the plate described only by one inelasticity parameter. The second approach is based on viscoelastic mechanism of energy dissipation, represented by an additional viscoelastic damping coefficient. Thus, these two coefficients are responsible for bending and viscoelastic energy dissipation and are calculated independently from each other. The summarized energy dissipation is used to determine both material parameters and coefficients. A good agreement between calculated and measured coefficient of restitution was observed. In this way, the interaction between steel spheres impacting on glass plates with a thickness comparable to the diameter of the sphere was calculated as an example.

1. Introduction

During production, treatment, transportation and handling, particles are exposed to numerous mechanical stressing events that often occur due to particle–particle or particle–wall impacts see e.g. Schönert [1] or Fig. 1 in Russel et al. [2]. This types of stressing take place in processing apparatuses like dryers, jet mills, conveyors, granulators, fluidized beds or mixers. In this context, impact parameters i.e., coefficient of restitution (CoR) and contact time have to be predicted exactly to find the optimum of the production and handling conditions [1–12].

The impact behaviour can be described by means of different theoretical approaches depending on the mechanisms of energy dissipation [13–25]. Usually, three mechanisms of energy dissipation are considered:

1. The first one is elastic wave excitation during contact of impacting bodies [14,15,24]. Elastic waves propagate within the bodies and vanish due to viscosity of material.
2. The second mechanism of energy dissipation during impact is plastic deformation in the contact region [16,19]. The very large contact pressure within the contact zone exceeds the yield stress and the resulting strain-rate independent microplastic contact yielding, deformation and flattening contributes essentially to this local energy dissipation [21,23].
3. The third possible source of kinetic energy loss is viscoelastic material behaviour that is modelled as parallel connected spring-dashpot [17,18,20]. All materials exhibit some viscoelastic response. In common metals such as steel or aluminium, as well as in glass, at room temperature and at small strain, the behaviour does not deviate much from elastic. However, due to the short duration of impact and high local strain within the contact point, even a small viscoelastic response can be significant [17,18]. Those various sources of energy dissipation often overlap and affect each other [16,20,24]. Therefore, it seems to be difficult to calculate the resulting impact parameters such as CoR and contact time.

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Nomenclature

A	dissipation constant, s	T	characteristic time, s
d	sphere diameter, mm	t	time, s
c	propagation velocity of elastic waves, m/s	v	velocity, m/s
E	modulus of elasticity, GPa	α	bending constant, s/kg
CoR	coefficient of restitution, –	δ	viscoelastic damping coefficient, –
F	force, N	λ	inelasticity parameter, –
G	shear modulus, MPa	ν	Poisson's ratio, –
H, h	height, thickness, m	ρ	density, kg/m^3
k_{Hz}	Hertzian elastic stiffness constant, MPa s1/2	σ	dimensionless displacement, –
L	length, m	τ	dimensionless time, –
m	mass, kg		
R	radius of surface curvature prior contact flattening, m		
s	contact displacement, m		

In terms of a defined mechanism of energy dissipation, the impact parameters can be easily determined with acceptable accuracy by means of a corresponding theoretical approach. However, for practical applications, it is reasonable to consider not only a single dissipation mechanism but also two or more sources of energy loss acting simultaneously. For cases where brittle fracture, adhesion, moisture etc. have to be considered different appropriate models may be applied [21,23,25].

In the present study, we show that a realistic combination of two mechanisms of energy dissipation (bending waves and viscoelastic response), may be applied to simulate the impact behaviour of steel spheres. The contact time, impact and rebound velocity of a steel sphere (soldered with a very thin flexible conductive wire) impacting on a glass plate (coated with a thin conductive gold layer) are measured by means of contact current between sphere and plate. A combination of energy dissipation due to elastic wave vibration and viscoelastic deformation of the sphere and the plate is applied for the calculation of the impact parameters. In this way, the wall impact behaviour can be described.

2. Theoretical approach

2.1. Hertzian approach for perfect elastic impact

The theory of Hertz [13] is traditionally applied to study the impact behaviour of spherical elastic bodies. Hertz assumed that the period of impact (contact time) t_{el} is larger than propagation time of elastic waves within the region of contact t_K thus, $t_{el} \gg t_K$.

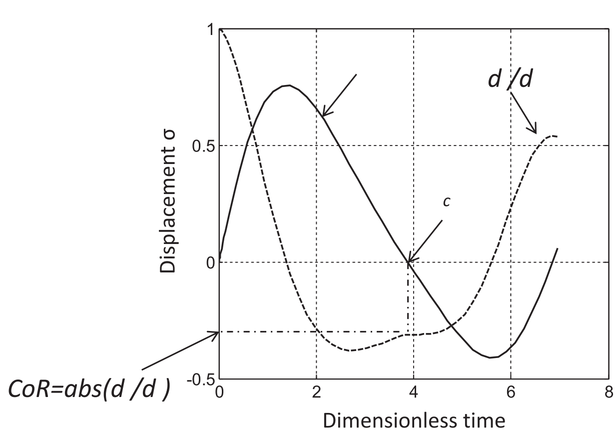

Fig. 1. The CoR is the absolute value of $d\sigma/d\tau$ (dimensionless velocity) at the contact time $\sigma(\tau_c) = 0$.

During contact deformation an apparently static equilibrium state between contacting spheres is reached. As result, this equilibrium state corresponds to apparently static conditions. In terms of this model, the contact time, the pressure and the contact deformation can be exactly evaluated using known static relations.

The quasi-static impact force between two spheres, in terms of the Hertz model [13], equals

$$F = k_{\mathrm{Hz}} \cdot s^{3/2} \tag{1}$$

with

$$k_{\mathrm{Hz}} = \frac{2}{3} E_{1,2} R_{1,2}^{1/2} \tag{2}$$

where s is the displacement between the centres of spheres and $E_{1,2}$ the effective modulus of elasticity according to Tomas [21] with the average material stiffness as series of elastic elements 1 and 2 (which is equivalent to the sum of element compliances

$$E_{1,2} = 2\left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)^{-1} \tag{3}$$

Consider, that E^* is often written without the factor 2. But $E^* = \frac{E}{1-\nu^2}$ should be equivalent to the "plaine-strain modulus" [27] for particles 1 and 2 having the same material stiffness.

In Eqs. (2) and (3), E_1 and E_2 are the moduli of elasticity, ν_1 and ν_2 are the Poisson's ratios of the impacting bodies and $R_{1,2}$ is the effective radius of surface curvature

$$R_{1,2} = \left(\frac{R_1 R_2}{R_1 + R_2}\right) \tag{4}$$

which results from the radius of surface curvature of the contact areas of the impacting bodies R_1, R_2 (before any contact flattening). The resulting maximum elastic displacement (at $ds/dt = 0$) follows to

$$s_{el,\max} = \left(\frac{225}{64}\frac{m_{1,2}^2 \upsilon_{1,2}^4}{E_{1,2}^2 R_{1,2}}\right)^{1/5} \tag{5}$$

with $m_{1,2}$ the effective mass $m_{1,2} = \left(\frac{m_1 m_2}{m_1 + m_2}\right)$ and $\upsilon_{1,2}$ the impact (incoming) velocity.

The contact time $t_{el,\mathrm{Hz}}$ can be determined from Eq. (5) as [13]

$$t_{el,\mathrm{Hz}} = 2.945 \frac{s_{el,\max}}{\upsilon_{1,2}} \tag{6}$$

In terms of Hertz approach, the coefficient of restitution (CoR) remains constant and equal to one. The contact time t_{el} can be exactly calculated based on Hertz model. However, for plates with finite thickness H, the contact times t_{el} becomes comparable to the