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Acoustic evaluation of the impact of moist spherical granules and glass beads

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ABSTRACT

The impact behavior of spherical dominant elastic-plastic γ-Al_2O_3 granules, elastic-plastic zeolite 4A granules and elastic glass beads has been investigated using free fall tests. The elastic sonic waves generated at impact within the plate have been recorded by an acoustic sensor and have been used to determine the normal coefficient of restitution (CoR).

Moreover, the influences of impact velocity, moisture content, surface roughness of the plate and the ratio of particle diameter to plate thickness have been investigated. Due to various influences, the impact behavior of the granules is characterized as to be in the elastic-plastic range. However, the materials exhibit almost constant values of the CoR within the investigated range of impact velocities. Furthermore, with increasing moisture content and surface roughness, the coefficient of restitution slightly decreases. The influence of elastic waves has been evaluated with the model of Zener.

1. Introduction

An impact is an interaction between colliding bodies within a short time period. Impacts are characterized by a change in the state of motion, the impulse and the energy of the colliding bodies. Since only inner forces are transmitted at impact, the total impulse and the total energy are conserved. The laws of impact have been presented by Christiaan Huygens (1629–1695) [1].

Natural impacts occur for instance, in astronomy during aggregation and agglomeration of gas, dust and particles in protoplanetary disks as well as in interstellar clouds. Furthermore, natural impacts occur in physical geography, during ice and debris avalanches and during weather phenomenon like tornados and dust devils. In industrial processes, impacts may occur during processing, transportation, storage and handling of granular materials. Especially at impact crushing, during milling, in fluidized beds and at pneumatic conveying, impacts occur between the granules and between the granules and the walls of the apparatuses.

The coefficient of restitution (CoR) e is a physical parameter representing the ratio of the impulse of the rebound phase ($t_C \le t \le t_R$) to the impulse of the compression phase ($0 \le t \le t_C$), shown in Fig. 1

$$e = \frac{\int_{t_C}^{t_R} F \, dt}{\int_{0}^{t_C} F \, dt}, \quad (1)$$

with the acting force F. The CoR is used for the physical description and simulation of impacts, where the parameter characterizes energy dissipation and damping, respectively. For instance, the CoR is an essential parameter for the numerical simulation of particle systems by the discrete element method [2].

Additionally, the CoR may be represented as an energetic CoR by the relation of the energies. In this case, the CoR results from the square root of the ratio of the kinetic energy of the rebound phase $E_{kin,R}$ (elastic strain energy released during restitution) to the kinetic energy of the impact phase $E_{kin,A}$ (internal energy of deformation absorbed during compression)

$$e = \sqrt{\frac{E_{kin,R}}{E_{kin,A}}} = \sqrt{\frac{E_{kin,A}\text{-}E_{diss}}{E_{kin,A}}} = \sqrt{1\text{-}\frac{E_{diss}}{E_{kin,A}}}. \quad (2)$$

E_{diss} is the portion of the kinetic energy of impact that is dissipated during the collision event. Provided that a merely translatory motion

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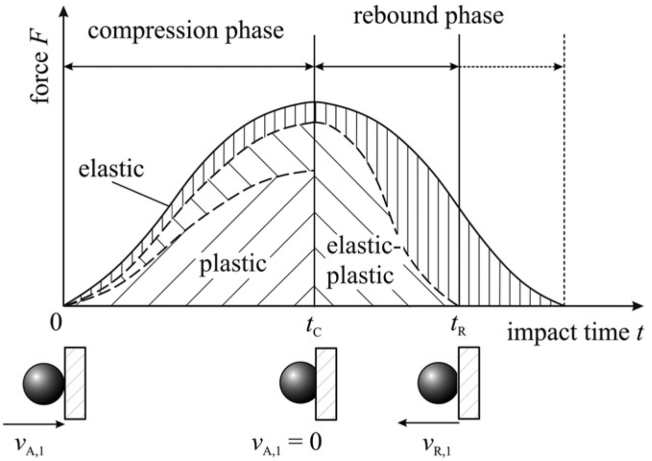

Fig. 1. Characteristic force-displacement diagram for the elastic, elastic-plastic and plastic impact.

appears, the CoR can be specified as the ratio of the relative velocities of the colliding bodies 1 and 2 before and after impact (Δv_A, Δv_R)

$$e = \sqrt{\frac{E_{kin,R}}{E_{kin,A}}} = \sqrt{\frac{{}^1\!/_2 \cdot m \cdot \Delta v_R^2}{{}^1\!/_2 \cdot m \cdot \Delta v_A^2}} = \frac{|\vec{v}_{R,1} - \vec{v}_{R,2}|}{|\vec{v}_{A,2} + \vec{v}_{A,1}|}. \tag{3}$$

At elastic impact, the CoR has a value of $e = 1$, at elastic-plastic impact $0 < e < 1$ and at plastic impact $e = 0$. During impact of a body (particle) against a rigid, stationary surface or plate (see Fig. 1), Eq. (3) reduces to

$$e = \frac{|\vec{v}_{R,1}|}{|\vec{v}_{A,1}|}. \tag{4}$$

In case of a freely falling body against a rigid, stationary surface, the CoR approximately corresponds to the square root of the ratio of the rebound height h_R to the initial height of fall h_A

$$e = \frac{|\vec{v}_{R,1}|}{|\vec{v}_{A,1}|} \approx \sqrt{\frac{2gh_R}{2gh_A}} = \sqrt{\frac{h_R}{h_A}}. \tag{5}$$

By dividing the impact and rebound velocities into normal and tangential components, the normal and oblique impact can be characterized, respectively, using the normal CoR

$$e_n = \frac{|\vec{v}_{n,R}|}{|\vec{v}_{n,A}|} \tag{6}$$

and the tangential CoR

$$e_t = \frac{|\vec{v}_{t,R}|}{|\vec{v}_{t,A}|}. \tag{7}$$

For the experimental investigation of the CoR of particles and particle–particle compounds, several experimental techniques can be used.

The CoR is predominantly determined using free fall tests [2–5]. In doing so, spherical particles are freely dropped on a rigid surface and the normal or oblique impact is analyzed. The procedures of impact and rebound are predominantly recorded using a high-speed camera [6]. From the recorded pictures, the impact and rebound velocities can be determined and the CoR may be calculated with Eq. (4). Other methods are the determination of the rebound height using a camera [7], where the CoR is calculated with Eq. (5), or the measurement of the time interval between two consecutive impacts of one particle by evaluation of the acoustics of the impact [8–11]. In this case, the impact and rebound velocities are determined from the time interval Δt before and after an impact respectively

$$v = \frac{g\Delta t}{2}. \tag{8}$$

With Eq. (4), the CoR is derived to

$$e = \frac{\Delta t_{n+1}}{\Delta t_n}. \tag{9}$$

During the investigation of normal impact, preferentially, the influence of the impact velocity on the CoR is studied. Higa et al. [12], Koller [13] and Tillet [7] had investigated the influence of the ratio of particle (sphere) diameter to plate thickness. Fu et al. [14] and Mangwandi et al. [15] had analyzed the influences of moisture content, binder content and binder viscosity on the impact behavior of granules.

Using free fall tests, impacts between particles and a coated plate may be investigated as well. Huang et al. [16] had dropped steel spheres of different diameters on a layer of microscopic steel particles. Kantak and Davis [17] carried out free fall tests with steel and Teflon spheres impacting on a quartz plate covered by a dry and a wet fabric, respectively. The influence of thin liquid layers with different viscosities and layer heights on the impact of γ-Al_2O_3 granules has been studied by Antonyuk et al. [18] and on the impact of glass beads by Gollwitzer et al. [19] and Müller et al. [20].

Using the free fall apparatus from Foerster et al. [21], the particle–particle impact can be studied. A spherical particle is dropped freely and a time-delayed second particle is also dropped freely subsequent to the first particle drop. Due to this experimental arrangement, the upper particle may catch up with the lower one and impact occurs.

Labous et al. [22] describes a second apparatus for the investigation of the particle–particle impact. Two particles, each in one tube, are accelerated and directly shot against each other.

With free fall tests, the oblique impact can be investigated as well [5,6,21,23,24]. A plate is arranged obliquely to the direction of fall with an adjustable angle Θ between 0° and 90°. The normal and tangential CoR, the angular velocity, the rebound angle and the Coulomb friction coefficient may be determined. During their experiments to the oblique impact, Dong and Moys [25] additionally investigated the influence of initial angular velocity of the particles.

Furthermore, the normal CoR has been investigated by pendulum experiments [26–30]. In the course of this, the impact velocity is varied as a function of the initial amplitude. With the easy arrangement of a pendulum, even the impact between two particles can be observed as done by Hrenya [29] and Donahue [31] as well as by Weir and Tallon [30]. Seifried et al. [28] as well as Weir und Tallon [30] have investigated multiple impacts using a pendulum. Moreover, a pendulum is more preferable for the measurement of low impact velocities (Hatzes et al. [27]).

A further experimental arrangement is described by Poppe et al. [32]. Using a cogwheel, microscopic spherical particles of a dust powder are dispersed, accelerated and vertically shot against a target.

The eccentric impact can be analyzed by impacting a rotatable body against a rigid target as done by Adams [33] and Brach [34] in their papers.

For the theoretical approximation of the CoR, several mechanical approaches are available that are based on different physical assumptions regarding the material behavior.

The perfect elastic impact, having a CoR of $e = 1$, has been described by Hertz [35], at which the approach for the elastic normal force F_{el} is as follows

$$F_{el} = \frac{2}{3} E^* \sqrt{R^* s^3}. \tag{10}$$