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Technical note

Direct visualization and model validation of microsphere impact and surface capture

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Abstract

Digital high-speed photographic images of microsphere impact with a flat surface were made over a range of incident microsphere velocities. The incident and rebound velocities determined from successive images were used to validate a recently published model for low-speed impact. This model is shown to predict the experimental values of the normal coefficient of restitution and the surface-capture velocity to within 95% confidence.

Keywords: Microparticle; Impact; Capture velocity

In the experiments, 40-μm diameter Ag-coated glass microspheres were dispersed from different heights above a flat silica surface 'target' under standard atmospheric conditions. A digital high-speed camera (Fastcam ultraAPX IMAGER, Fotron, ThorLABSinc) was used to record the microsphere incidence, rebound and surface capture at a frame rate of 6000 frames/s. Sequences of the obtained image were processed to obtain the exact microsphere coordinates in time, and, hence, the incident and rebound (if any) velocities of the microsphere normal to the target.

An example case of experimental results and their comparison with the recently published impact model of Kim and Dunn (2007) are shown in Fig. 1. In this figure, the normal coefficient of restitution, e_n, defined as the ratio of rebound-to-incident normal velocities, is plotted versus the incident normal velocity. It is seen that e_n monotonically decreases to zero as the incident normal velocity of the microsphere decreases to the surface capture velocity, v_c. For this case, the capture velocity was 0.08 m/s. The maximum incident velocity was 0.44 m/s. These velocities are well below the yield velocity for the materials.

The EA model, presented by Kim and Dunn (2007), considers an elastic impact with adhesion. The microspheres kinetic energy is related to the static elastic and adhesion forces and their dynamic dissipative forces. Because the range of velocities considered are well below the yield velocity of the materials, the dissipation forces due to plastic deformation can be neglected. The model expression for the normal coefficient of restitution is

$$e_n = \sqrt{1 - \psi_A(1 + C_A v_n) - \psi_H C_H}, \tag{1}$$

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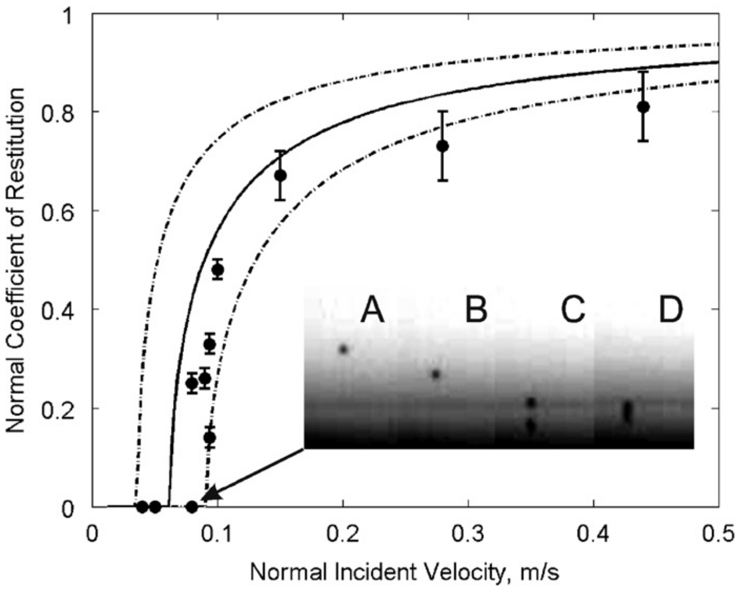

Fig. 1. Normal coefficient of restitution versus normal incident velocity of data (solid circles) and EA model predictions (solid line). The dash-dotted lines are the 95% confidence limits of the model. Frames A–D sequentially show the event of microsphere capture by the surface.

where C_A and C_H are damping coefficients, and ψ_A and ψ_H are given by

$$\psi_A = 2C_R f_0 \left(\frac{4}{3\pi}\right)\left(\frac{5}{4K}\right)^{3/5}(r/m^2)^{1/5} v_n^{-4/5}, \tag{2}$$

and

$$\psi_H = 2(2/3)^{5/2}\frac{a_m^5}{mr^2}K/v_n. \tag{3}$$

Here, C_R accounts for the reduction of the adhesion force due to the combined microsphere–target surface roughness (Cheng, Brach, & Dunn, 2002), f_0 equals $(4.5Krw_A^2/\pi)^{1/3}$, K is the combined stiffness, r is the microsphere radius, m is the mass of the microsphere, v_n is the normal incident velocity of the particle, and a_m is the maximum contact radius given by Hertzian theory. The work of adhesion is determined as (Israelachvili, 1992)

$$w_A = 2\sqrt{\gamma_1\gamma_2}, \tag{4}$$

where γ_1 and γ_2 are the adhesion energies of the microsphere and of the surface, respectively.

As observed in the figure, there is a considerable decrease in the normal coefficient of restitution over the incident velocity range from $e_n = 0.5$ at 0.1 m/s down to $e_n = 0$ (surface capture) at 0.08 m/s. Zero values of the normal coefficient of restitution, which are indicative of surface capture, are obtained at 0.08 m/s and at the two velocity-cases below 0.08 m/s.

The frame sequence of a microsphere immediately before being captured by the surface is shown within the figure. Frames A and B show the microsphere's positions as it approaches the target surface at 2.3 and 1.5 ms, respectively, prior to surface impact. Frame C shows the microsphere's position at 0.33 ms before impact. It can be seen that the distance between the microsphere and the target surface is approximately the order of the microsphere size. The mirror image of the microsphere can be seen in the surface. Frame D shows the instant of the microsphere's contact with the target surface. For this sequence, the microsphere is captured by the surface because of adhesion.

Eq. (1) can be solved for v_n when $e_n = 0$, which is the case of surface capture. Assume for simplicity that $C_A = C_H = 0$. (A discussion of how these values are determined is presented in Kim & Dunn, 2007.) Hence, the condition for surface capture is simplified to

$$\psi_A = 1. \tag{5}$$

From this equation, the capture velocity, v_c, can be expressed as

$$v_c = \left[2C_R f_0 \left(\frac{4}{3\pi}\right) \left(\frac{5}{4K}\right)^{3/5} (r/m^2)^{1/5} \right]^{5/4}. \tag{6}$$

For the present experimental case, the following mean values of material constants were chosen: $K = 70\,\mathrm{GPa}$, $\rho_p = 1350\,\mathrm{kg/m^3}$, $\gamma_1 = 1.14$ and $\gamma_2 = 0.61$ (from Kim & Dunn, 2007, and references therein). The coefficient C_R is taken to be 0.9 which specifies the mean roughness height of 1 nm (Cheng et al., 2002), as determined previously by Dunn, Li, and Brach (1999) for that type of surface. Eq. (6) yields $v_c = 0.061\,\mathrm{m/s}$.

The maximum experimental uncertainty in v_n was $\pm 0.08\,\mathrm{m/s}$ for the incident velocity of 0.44 m/s. The corresponding maximum experimental uncertainty in e_n was ± 0.07. The maximum uncertainty in the particle radius was $\pm 2\,\mu\mathrm{m}$ ($\pm 10\%$). The typical variation for adhesion energy was $\pm 17.5\%$ and for the Hertzian stiffness was $\pm 4.3\%$ (Brach, Li, & Dunn, 2000). The variation in C_R was chosen as $\pm 5\%$ based upon surface roughness profiles (Dunn et al., 1999). The resulting uncertainties in the model prediction of e at 95% confidence was calculated using a Monte-Carlo simulation and are shown by the dash-dotted lines in the figure. As shown in the figure, the experimental and theoretical values of the normal coefficient of restitution agreed to within 95% confidence. The capture velocity predicted using Eq. (6) also agreed with the experimental capture velocity to within 95% confidence.

It is concluded that the analytical expressions given by Eqs. (1) and (6) for the normal coefficient of restitution and the capture velocity, respectively, are sufficiently accurate to model the low-speed impact of a microsphere with a surface.

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