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Technical note

Electromagnetic control of charged particulate spray systems—Models for planning the spray-gun operations

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HIGHLIGHTS

- Derived criteria to control charged particulate sprays using electromagnetic fields.
- Such criteria can be used in physically based computer simulations for such sprays.
- Coupled multi-physics aspects of such modifications are presented.
- These aspects are critical for identifying core issues to guide future research.

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ABSTRACT

Charged particulate spray systems are common in many industrial and manufacturing processes. Using externally applied electromagnetic fields – the dynamics of these particulate sprays can be altered to achieve improved functionality and access to spray-sites that are hard to reach. With such an alteration the spray-particulate dynamics can become non-intuitive – thereby motivating a physically based modeling strategy to plan the spray-gun operations and translate this into the actual spray deposition on the target surface. In this paper we use the dynamics of charged particles to construct a set of simple geometric arguments for the identification of the mapping between the spray-gun trajectory (on its plane of traversal) and the spray-deposit location (on the plane of the target-surface). The parametric dependence of the mapping on spray-gun operation parameters (comprising nozzle velocity and trajectory) and external magnetic fields (comprising field strength and the region of applied field) is discussed. The role of such arguments in constructing appropriate computer simulation frameworks is then illustrated through an example of a discrete element simulation. Sensitivity to process parameters like particulate size and spray-gas velocity are also characterized for a given applied field.

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1. Introduction

In this work we focus on industrial and manufacturing processes that involve a stream of loosely flowing charged particulates. These include a variety of processes like electrostatic spraying (see for example [1]), electrostatic powder coating processes (see for example [2,3]), and techniques like material removal by electrostatic scrubbing (see for example [4]). Directed streams of charge particulates are also finding application in combustion processes and biological drug delivery. As the particulates (or even charged droplets in many applications) travel from their release point, their trajectory can be further modified using external electromagnetic fields of appropriate strength. This provides a potentially useful and novel way of altering these spray-processes to achieve improved functionality (for example increased uniformity in spray deposit owing to repulsive forces between like-charged particulates). It can also be used to direct particulate sprays towards a target surface that would otherwise be difficult to access directly. While the trajectory planning of a robot arm for spray-guns is a widely researched topic (for an overview of which, see [5,6], and the work on shape deposition by [7], and [8])—the use of external electromagnetic fields would require these planning strategies to be augmented appropriately. With the recent advances in available computational resources and efficient algorithms, physically based modeling and simulation provide a viable alternative to perform parametric investigations for modifying particulate spray processes using electromagnetic fields, and provide valuable insights into their engineering and development, thereby allowing for an advancement of the state-of-art in guided charged particulate sprays. In this context, we focus here on developing simple geometric criteria to map the spray-gun trajectory (on its plane of traversal), and the spray-deposit location—and

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linking such criteria to the computer aided engineering of such processes. In precise terms, the contribution of this work is to investigate the following aspects:

- the derivation of simple design criteria to guide the particles using appropriate spray-gun parameters and electromagnetic fields.
- the utility of such criteria in augmenting computer simulations of charged particulate sprays to aid process engineering and analysis.

To this end, we present a brief discussion on the dynamics of charged particles in electromagnetic fields and present some simple geometric arguments for the mapping in Sections 2 and 3. These models are implemented into a discrete element based simulation of charged sprays in Section 4 with a discussion of the coupled multi-physics aspects of such process modifications so as to identify core issues to guide future research. The focus here is on physical models and their use in computer simulation tools, and not large-scale simulations cross-validated with experimentation. This work is part of an ongoing effort to develop a general-purpose computer simulation framework using discrete element methods for charged particulate flows.

2. Modeling the particle motion

The motion of a charged particle in an electromagnetic field is governed by the classical Lorentz Force, which is given in terms of the strengths of the electric and magnetic fields ($\mathbf{E}$ and $\mathbf{B}$ respectively) as:

$$\mathbf{F}_{\text{lorentz}} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right). \tag{1}$$

It is evident that if the velocities and electric fields are decomposed in directions parallel and perpendicular to the magnetic field (e.g. $\mathbf{v} = \mathbf{v}_{\parallel} + \mathbf{v}_{\perp}$ etc.), the effective motion equations for a single particle can be decomposed as (see also [9] for detailed solutions):

$$m\frac{d\mathbf{v}_{\parallel}}{dt} = q\mathbf{E}_{\parallel}, \qquad m\frac{d\mathbf{v}_{\perp}}{dt} = q\left(\mathbf{E}_{\perp} + \mathbf{v}_{\perp} \times \mathbf{B}\right) \tag{2}$$

which is a consequence of the Lorentz force having the $\mathbf{v}\times\mathbf{B}$ term. If we consider a Cartesian coordinate system (with $\mathbf{v} = v_x\mathbf{x} + v_z\mathbf{z}$, and $\mathbf{B} = B\mathbf{y}$) and assume furthermore that $\mathbf{E} = \mathbf{0}$, the motion equations can then be written as:

$$m\frac{dv_x}{dt} = -qBv_z, \qquad m\frac{dv_z}{dt} = qBv_x. \tag{3}$$

With a given initial velocity $\mathbf{v}(0) = v_x(0)\mathbf{x} + v_z(0)\mathbf{z}$, the above can be multiplied by v_x and v_z respectively to get a form of conservation of mechanical energy as follows:

$$mv_x\frac{dv_x}{dt} + mv_z\frac{dv_z}{dt} = 0 \Rightarrow \frac{d}{dt}\frac{m}{2}\left(v_x^2 + v_z^2\right) = 0. \tag{4}$$

Furthermore, taking second derivatives of particle velocity equations in Eq. (3) we get:

$$\frac{d^2v_x}{dt^2} = -\left(\frac{qB}{m}\right)^2 v_x, \qquad \frac{d^2v_z}{dt^2} = -\left(\frac{qB}{m}\right)^2 v_z. \tag{5}$$

The solution to this system of ordinary differential equations with given initial velocity $\mathbf{v}(0)$ and energy conservation as in Eq. (4) can be given as follows:

$$v_x(t) = |\mathbf{v}(0)|\sin\left(\omega_c t + \phi_0\right) \tag{6}$$

$$v_z(t) = |\mathbf{v}(0)|\cos\left(\omega_c t + \phi_0\right) \tag{7}$$

with $\omega_c = qB/m$ and $\tan\phi_0 = v_x(0)/v_z(0)$. The frequency $\omega_c/2\pi$ is what is referred to as the cyclotron frequency. Integrating further with respect to time, the coordinates of the particle can be obtained as follows:

$$x(t) = \frac{-|\mathbf{v}(0)|}{\omega_c}\cos\left(\omega_c t + \phi_0\right) + X_0 \tag{8}$$

$$z(t) = \frac{|\mathbf{v}(0)|}{\omega_c}\sin\left(\omega_c t + \phi_0\right) + Z_0 \tag{9}$$

with X_0 and Z_0 being defined as follows:

$$X_0 = x(0) + \frac{|\mathbf{v}(0)|}{\omega_c}\cos\phi_0, \qquad Z_0 = z(0) - \frac{|\mathbf{v}(0)|}{\omega_c}\sin\phi_0. \tag{10}$$

The particle trajectory can be given as

$$(x - X_0)^2 + (z - Z_0)^2 = \left(\frac{|\mathbf{v}(0)|}{\omega_c}\right)^2 \tag{11}$$

which is a circle with its center at (X_0, Z_0), and radius of $R_c = \frac{|\mathbf{v}(0)|}{\omega_c} = \frac{m|\mathbf{v}(0)|}{qB}$. The radius R_c is what is commonly referred to as the Larmor radius. Furthermore, the existence of a non-zero electric field induces additional components of motion—a cycloidal translation along the axis of the circle due to $\mathbf{E}_{\perp}$, and pure translation due to $\mathbf{E}_{\parallel}$. There is also additional motion in form of an induced drift from the circular trajectory due to additional (non-electromagnetic) forces acting simultaneously. For the scope of this work, these additional components of the motion are not discussed here.

3. Models for spray trajectory planning

The discussion presented in Section 2, can now be applied to derive geometric criteria for bending the trajectory of a stream of charged particulates. To develop this idea, refer to Fig. 1—wherein a charged particle is bent by an angle α by allowing it to pass through a region of applied magnetic field $B\mathbf{y}$ over a region of width d (depicted in gray). Inside the region of applied magnetic field—the dynamics of this particle can now be exactly represented by the Eqs. (6)–(9), and (11). Using simple geometric arguments for the arc of this circular path (as presented in Fig. 1), it can also be shown that the angle subtended by the circular arc of the trajectory at the center is also α. Since the original and the final trajectories are tangential to the circle, the angle can be represented as:

$$\sin\alpha = \frac{d}{R_c} = \frac{dqB}{m|\mathbf{v}(0)|}. \tag{12}$$

In order for a spray based deposition, the spray is ideally kept normal to the target surface (see for example [10], and [6] for discussions on spray incidence). Therefore, in order to bend the spray jet to be able to hit the target surface normally—the angle α should match that of the normal of the target surface with the horizontal (note that it is assumed that the distance of an edge or line of the part geometry from the spray-gun plane origin is known):

$$\sin\alpha = -\hat{\mathbf{N}}_{\text{target}} \cdot \mathbf{x} = dqB/m|\mathbf{v}(0)|. \tag{13}$$

This provides a geometric design criterion, that relates the spray-velocity and the applied magnetic field parameters to the target surface orientation—if the latter is known, the appropriate spray-conditions can be decided. Furthermore, if the mapping between the target surface geometry and the spray particulate release plane is characterized using a mapping function $\mathbf{x} = \boldsymbol{\chi}(\mathbf{X})$ as represented schematically in Fig. 2, then the normal vector of a segment of the target surface can be mapped correspondingly using the classical Nanson's formula as:

$$\hat{\mathbf{N}}_x dA_x = J[\mathbf{F}]^{-T}\hat{\mathbf{N}}_X dA_X \tag{14}$$

where dA_x and dA_X are the magnitudes of area of the discretized mesh elements in the two coordinate systems as in Fig. 2, and the second order tensor $[\mathbf{F}] = \partial\mathbf{x}/\partial\mathbf{X}$ is the deformation gradient for the mapping, and $J = \det[\mathbf{F}]$.