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Dynamic coupling of fluid and structural mechanics for simulating particle motion and interaction in high speed compressible gas particle laden flow

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ABSTRACT

In this work, structural finite element analyses of particles moving and interacting within high speed compressible flow are directly coupled to computational fluid dynamics and heat transfer analyses to provide more detailed and improved simulations of particle laden flow under these operating conditions. For a given solid material model, stresses and displacements throughout the solid body are determined with the particle–particle contact following an element to element local spring force model and local fluid induced forces directly calculated from the finite volume flow solution. Plasticity and particle deformation common in such a flow regime can be incorporated in a more rigorous manner than typical discrete element models where structural conditions are not directly modeled. Using the developed techniques, simulations of normal collisions between two 1 mm radius particles with initial particle velocities of 50–150 m/s are conducted with different levels of pressure driven gas flow moving normal to the initial particle motion for elastic and elastic–plastic with strain hardening based solid material models. In this manner, the relationships between the collision velocity, the material behavior models, and the fluid flow and the particle motion and deformation can be investigated. The elastic–plastic material behavior results in post collision velocities 16–50% of their pre-collision values while the elastic-based particle collisions nearly regained their initial velocity upon rebound. The elastic–plastic material models produce contact forces less than half of those for elastic collisions, longer contact times, and greater particle deformation. Fluid flow forces affect the particle motion even at high collision speeds regardless of the solid material behavior model. With the elastic models, the collision force varied little with the strength of the gas flow driver. For the elastic–plastic models, the larger particle deformation and the resulting increasingly asymmetric loading lead to growing differences in the collision force magnitudes and directions as the gas flow strength increased. The coupled finite volume flow and finite element structural analyses provide a capability to capture the interdependencies between the interaction of the particles, the particle deformation, the fluid flow and the particle motion.

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Nomenclature

$\mathbf{B}$	shape function derivative matrix (3a)
$\mathbf{C}$	elastic stiffness matrix (11)
C^{EP}	elastic–plastic stiffness matrix (3b)
C, G, Y, S	turbulence parameters (24)
d	object spacing (25)
D	deformation rate (6)
$\mathbf{D}^e$	elastic deformation rate (14)
$\mathbf{D}^p$	plastic deformation rate (13)
E	Young's modulus (11)
f	yield function (9)
f_b	body force (1)
F_{fl}	fluid induced forces (32)
F_n	normal contact force (29)
F_t	tangential contact force (30) and (31)
h	shape function (5)
h	enthalpy (23)
h	strain hardening (11)
$\mathbf{H}$	matrix of shape functions (4)
k	spring constant (29)
$\mathbf{L}$	velocity gradient (5)
$\mathbf{n}$	normal plastic vector (10)
p	pressure (22)
r	isotropic hardening function (15)
S	shape functions (2)
$\mathbf{tr}$	surface traction (1)
u,v	displacement components (1) and (2)
V	velocity (5)
$\mathbf{vrel}$	relative velocity of particles at collision (26)
$\mathbf{W}$	spin matrix (6)

Greek letters

$\boldsymbol{\varepsilon}$	strain tensor (3a)
Γ	element surface (4)
κ,ε	turbulence parameters (24)
λ_p	plastic multiplier (11)
μ	friction coefficient (f=equivalent, s=static, d=dynamic) (31)
μ	fluid viscosity (24)
ν	Poisson's ratio (29)
ρ	density (1)
σ	stress tensor (1)
σ_e	equivalent stress (8)
σ_y	yield stress (5)
o'	deviatoric stress tensor (7)
$\overset{\triangledown}{\sigma}$	Jaumann stress rate tensor (18)
τ	stress tensor (1), (23)
Ω	element volume (4)

Subscript

e	elastic
n	associated with normal
p	plastic
$P1$, $P2$	associated with particle 1 and particle 2
t	associated with tangential
$[\dot{\ }]$	time derivative
$[\ddot{\ }]$	second time derivative

1. Introduction

Particle laden fluid flow is common in wide ranging fields from pharmaceuticals and biological applications to manufacturing and industrial processes. The ability to simulate the particle motion within the fluid flow provides significant advantages to understanding and improving the two-phase flow phenomenon. From model results, the motion of the particles can be easily visualized as the particles are carried with the flow and interact with one another and the flow path geometry. The effects of alterations in the particle size, shape, or material or in the flow conditions or flow path geometry can be virtually investigated without the creation of a physical system for testing, and more detailed data can be captured from a model than from typical physical experiments. The capability of simulating the fluid–structure interaction in the specific flow regime of interest is also important since flow/particle motion and interaction characteristics vary with the flow velocity. High speed motion of particles in a fluid, where particle volume fractions are high, and particle interaction with other particles or objects in the system is frequent, is commonly observed during the operation of ballistic systems, particulate motion in space, and many industrial processes. Often, at these speeds, particles deform either elastically or plastically upon contact, and the deformation can influence the subsequent motion of the particles and the subsequent flow conditions. Hence, modeling techniques appropriate for high particle volume fraction, high speed flows are needed that account for the effects of the particles in the flow field, the effects of particle interactions and deformation, and the effects of different solid material behavior models without extensive reliance on experimental data or gross, parameter based collision models.

A direct modeling method has been developed by the author where particles are placed directly in a computational fluid dynamics (CFD) finite volume based domain to simulate high volume fraction particle laden flows with frequent particle interaction (Florio, 2013, 2014a). Initial techniques to simulate particle motion and interaction in high speed fluid flow within a computational fluid dynamics framework were developed where the particles are treated as rigid bodies. These methods were used to study the spread of particles as they move at high speeds in free space and the interaction and exit patterns of particles leaving a flow channel. The methods were extended to include the effects of particle deformation through both the development of a collision effect model that can incorporate the effects of plasticity and the development of a method to deform the particles while maintaining the computational fluid dynamics mesh topology (Florio, 2014b). The