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Energy losses during drop weight mechanical impacts with special reference to ignition of flammable atmospheres in nuclear decommissioning: theory and determination of experimental coefficients for impact analysis and prediction

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ABSTRACT

The major purpose of this study is to provide a framework for determination of energy losses resulting from mechanical impacts of the kind that could occur during nuclear decommissioning of waste material. Measurements have been made of final translational and rotational velocities for impacts between projectiles of different length and a massive barrier. This enabled determination of experimental values of the impact coefficients and energy losses. It was found that the total energy losses could be accurately accounted for by the sum of those pertaining to the normal and tangential processes, thus indicating that these include any losses due to vibration. The results obtained clearly support an Amontons–Coulomb friction model and the previously held contention that there is a limiting value for the impulse ratio at low angles of barrier inclination. Although sliding surfaces are likely to be modified during impact, it is shown that any original contamination on the contacting surfaces results in a very large decrease in impulse ratio or friction coefficient. This represents an important finding in the context of mechanical ignition testing indicating that the state of the impact surfaces and their handling need to be taken into account. The difficulties in establishing appropriate values for the impact coefficients and dealing with the effect of mechanical vibrations on the energy losses are discussed and equations derived for determining the tangential and normal energy losses from known initial velocities.

1. Introduction

Hydrogen explosion hazards have been recognised for many years in the nuclear industry, often in respect to loss of cooling incidents in power plant. They have also been a particular concern in relation to waste storage decommissioning and reprocessing operations with hydrogen produced by corrosion or radiolysis being held up in the waste sludge. Disturbance of this sludge together with possible mechanical impacts occurring during decommissioning could lead to the generation of ignition sources and deflagration. The major purpose of this study is to provide a framework for understanding and assessing the likely energy losses resulting from such mechanical impacts. Of most interest are the energy losses associated with tangential displacement between the contacting surfaces that result in a localised increase in temperature [1] sometimes sufficient to cause the ignition of a flammable atmosphere. Impacts can arise through movement of waste debris, failure of robotic arms or simply through accidentally dropped tools striking a barrier under the action of gravity. Ignition of flammable hydrogen atmospheres is readily caused by friction generated by clean metal surfaces sliding against each other where the mechanical loading and sliding velocity are sufficient to result in surface temperatures exceeding about 700 °C for the necessary induction time period [2]. If pyrophoric substances such as Magnox-containing material from spent fuel cladding are present on the contacting surfaces, ignition becomes possible under much reduced loading conditions and sliding velocity [3]. The conditions necessary for ignition to occur when drop weight or glancing impacts are involved have also been investigated [4–6], indicating that contact surface temperatures lower than 500 °C generated by impact can result in ignition when pyrophoric substances are present. To better understand the relevance of these studies it is necessary to have fuller knowledge of how energy is dissipated during such impacts, particularly those occurring during drop weight tests where the nature and source of the uncertainties is of considerable interest. It is also of importance to determine the effect of surface contamination on the manner in which energy is dispersed during impact.

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Notation

d	distance
D	distance from centre of gravity just after impact
e	kinematic coefficient of normal restitution
e_m	coefficient of moment restitution
E	kinetic energy
E_l	kinetic energy loss
E_r	retained kinetic energy
f	coefficient of Coulomb friction
F	force
g	acceleration of gravity
h	impact tip test drop height
I	mass moment of inertia before impact
J	mass moment of inertia just after impact
k	radius of gyration
l	length
M	moment impulse
m	mass
p	impulse over a subinterval of contact duration
P	impulse over entire interval of impact duration
v	velocity just before impact
V'	velocity during the contact period
V	velocity after impact
W	work done by an impulse component
α	impact angle (defined in Fig. 1)
γ	slenderness coefficient
Δ	defined by Eq. (5)
μ	ratio of tangential to normal impulse component
μ_c	critical ratio of tangential to normal impulse component
τ	time – impact duration
Γ	defined by Eq. (4)
Φ	defined by Eq. (25)
ω	angular velocity just before impact
Ω	angular velocity after impact

Subscripts

a	diameter
b	massive barrier
c, d	direction of distance from centre of gravity (defined in Fig. 1)
n	coordinate normal to surface
t	coordinate tangential to surface

In order to simplify the analysis of losses occurring over the entire contact period impulse-momentum methods were used. The assumption that impacts occur instantaneously (implicit in the impulse –momentum approach) poses few problems, since information relating to the dynamics occurring during the impact period is of much less interest than determination of the final translational and angular velocities. These velocities are required to establish the energy losses. As Brach [7] points out, the simplicity of classical impact theory is that it uses coefficients of restitution or friction (impulse ratio) to represent **“**the nasty behaviour that occurs at the interface in an impact” . Although estimates of impact coefficients are often employed in predicting final velocities after an impact, appropriate experimental values are necessary for their proper evaluation and understanding. These coefficients are treated as constants in the system equations used to describe impact but there may be significant deviation from constancy in the real world owing to the influence of the material, surface condition and geometry of the impacting bodies as well as the initial velocities. To assess their usefulness in a practical context, it is thus necessary to determine experimental values and to explore their applicability over a range of impact angles and velocity.

In this paper, the relevant system equations relating to drop weight impacts are described (adopting Brach's [7] approach) and experimental results relating to impact velocities and coefficients presented. Disregarding the common assumption of point contact, Brach's more generalised concept of contact moment impulse is employed in the determination of final impact velocities and following from this the energy losses.

2. System equations for drop weight impacts

Painlevé [8,9] highlighted a paradox in a simple rigid body contact problem (a planar box or rod rotating under gravity with its lower end contacting an horizontal rough surface) where a solution did not appear possible using rational impact mechanics and Admontons-Coulomb friction Law. If the friction coefficient is sufficiently large then before the contacting body separates and lifts off, it can assume a configuration (dynamic jam), indeterminate with respect to what follows. The possibilities are that the body either rebounds from the contacting surface or it rotates and digs into it. “It is as if there is a negative normal force pulling the tip into the surface” [9]. It follows that application of the friction law and Newton's Law of restitution becomes problematic since a so-called impact without collision may be indicated whereby an impulsive jump occurs to reduce the slip velocity of the tip to zero. Zhao et al. [10] have studied the Painlevé paradox at a slender uniform 3D rod and explained how a tangential stick occurs at the contact point during the impulsive process (where $f > 4/3$). It should be noted, however, that under conditions where the mass is not uniform and concentrated near the centre of gravity the paradox can be shown to arise with low friction. Brach [7] dealt with the problem of improperly handling friction in collision problems by distinguishing the friction coefficient from the impulse ratio. In his impact model, a critical or limiting value of the impulse ratio (μ_c) exists that maximises the kinetic energy loss and which cannot be exceeded by any ascribed value of friction coefficient. This can be considered as a useful concept for many safety-case engineering applications in that μ_c is associated with the most pessimistic (i.e. largest) value of energy loss.

To characterise the amount of energy lost due to inelastic deformation during a collision, there are alternative definitions to the “kinematic” definition of the coefficient of restitution which relates the normal velocities of rebound and approach. The “kinetic” coefficient describes the ratio between the normal impulses for the restitution and compressive phases of the contact period. The “energetic” coefficient which relates the retrieved energy after impact to the initial energy has the advantage of being independent of the tangential impulse but leads to the considerable inconvenience of having to deal with non-linear equations.

For two-dimensional impact representation, Brach [7,11,12] made three assumptions in order to determine the final velocities after impact. (i) The coefficient of restitution is defined kinematically to include translational and rotational components: it represents the ratio in the normal direction of the final to initial (just before) impact velocities at the contact point or region. (ii) Ratio of the tangential to the normal impulse has a limiting value related to friction: there is a critical value μ_c, dependent on the angle of incidence, beyond which sliding ceases. (iii) Contact forces between colliding bodies may be distributed throughout a contact region rather than at a point requiring the introduction of a moment and moment impulse at the region. The moment restitution coefficient e_m indicates the presence of a moment and its corresponding impulse over the contact surfaces.

Impacts involving drop weight projectiles onto a massive barrier or anvil used in ignition studies [4] represent a special case in terms