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The initiation of rotational motion of a lying object caused by wind gusts

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ABSTRACT

In this paper, the initiation of motion of an object lying on a horizontal floor due to the aerodynamic force produced by a time-dependent wind is considered. It is assumed in this paper that when the aerodynamic force is large enough, the body starts to rotate around the most rearward supporting contact point, or pivoting point. This motion is analyzed by studying the dynamics of the rotation of the body around a pivoting point fixed to the floor, and placed in a gravity field under time-dependent aerodynamic loads produced by a non-steady incoming flow. This rotation initiation phase, which is relevant in the case of a time-varying gusty flow, is an intermediate phase between the two stages generally considered, namely, the initial static equilibrium without motion, and the final flight. In this intermediate phase, which is studied here, the rotational dynamics of the body should be taken into account and the gust characteristics as well, in order to determine whether once initiated the motion it leads to either a frustrated motion or to a successful one. A non-linear mathematical model has been developed, and a linear approximation is deduced, which allows us to obtain the condition for a successful flight. This condition shows two limits, valid for either long or short duration gusts, respectively. Some experiments have been performed in a gust wind tunnel, and results show a satisfactory agreement. To take into account the intrinsic random character of the phenomena in practical situations, expressions for the probability of exceeding the condition for successful flight under short duration gusts are obtained, assuming common probability density functions for the random parameters involved.

1. Introduction

The flight of objects carried by the wind, in different configurations, has received a strong interest by the scientific community since old times. In this regard, three related problems can be outlined: eolian erosion, flying debris, and ballast pick-up by high speed trains.

One of the most ancient problems of Wind Engineering is the eolian erosion, where the wind close to the ground is able to put into motion, drag and eventually, put into flight, soil particles and small stones in a number of ways (saltation, suspension, etc.) (Bagnold, 1941).

A more recent specific interest has appeared concerning the flight of bodies of much larger size: the debris generated by the destructive effect of strong wind storms, in order to predict the damage that these bodies can produce when they impact the built environment or pedestrians.

An even more recent interest and the main purpose of this paper is the flight of ballast produced by the high speed trains, when they overpass some critical speed. The impacts of these flying stones both on the low parts of the train and on the infrastructure (if the stones are projected outside of the track) produce considerable damages that are to be avoided e.g. by limiting the permitted operational speed. The study of the initiation of the motion of the ballast as a result of the successful initiation of rotation is the main aim of this paper, whose results could be applied also to the other two problems.

Concerning the first problem, wind erosion, a large number of papers has been devoted to determine criteria to predict the start of this phenomenon. The criteria are based on the surpassing of a given critical speed or critical shear stress at the ground surface. To that purpose it can be used, for instance, the Shields number, Θ, defined as

$$\Theta = \frac{\rho_a U_*^2}{g(\rho_p - \rho_a) d_p}$$

where U_* is the friction velocity, g is the acceleration of gravity, ρ_p and ρ_a are the density of the solid particle and the air, respectively, and d_p the diameter of the particle (Bagnold, 1941). It has been found that its critical value for soil particles is $\Theta \approx 0.1$. These criteria are based on the condition of static equilibrium of the body under a steady flow.

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Nomenclature

A_{Fp}	plan form area
C_1, C_2	integration constants
c_m	coefficient of aerodynamic moment with regard to point A
$c_{m\alpha}$	slope of the curve of variation of aerodynamic moment coefficient vs. angle of attack
d_{cmA}	distance between the centre of mass and the pivoting point A
$f(t)$	dimensionless variation of wind speed
$f_i(x_i)$	probability density function
g	acceleration of gravity
I	moment of inertia with regard to point A
K_0	Tachikawa number referred to the mean velocity U_0
k_I	inertia ratio
k_{VA}	flatness ratio of the stone
M_{fa}	moment of applied forces
M_p	stone mass
M_r	moment of the ground reaction force with regard to point A
R	characteristic stone dimension, e.g. radius of the sphere circumscribing the stone
R_{gA}	inertia radius corresponding to the inertia moment with regard to point A
T	dimensionless time
t	time
t_c	characteristic time
t_{cn}	characteristic time of the gust, period of the wave
t_{crg}	characteristic time of the stone rotation motion due to gravity
$U(t)$	wind speed
U_0	mean wind speed
U_T	train speed
Vol	volume of the stone
X	gust parameter
α	angle of attack
β	angle between the stone chord and the horizontal plane (Fig. 1)
δ_{CL}	angle between the stone chord and the zero moment line (Fig. 1)
δ_{Lcm}	angle between the zero moment line and the centre of mass line (Fig. 1)
ε	dimensionless amplitude of the sinusoidal wind variation
Ω	dimensionless angular frequency
θ	stretched angular position of the zero moment line
θ_{0lim}	limit value of θ_0 for stable evolution
ρ_a, ρ_p	density of air, of stone, respectively
θ_{cm}	angle between the centre of mass line and the horizontal plane
θ_h	homogeneous solution
θ_L	angle between the zero moment line and the horizontal plane (Fig. 1)
θ_{Llim}	limit value of θ_L for stable evolutions
θ_{Lm}	mean value of θ_L (Fig. 2)
θ_s	amplitude of the particular solution

Subscript

0	initial value (unless otherwise defined)
$_{limL}$	long gust limit
$_{limS}$	short gust limit
$_r$	reference value
$_{exc}$	exceeding
$_{nexc}$	non exceeding

One of the erosion mechanisms of relevance here is the saltation process, which has received a large attention over the years. The research performed in this field includes, among others, wind tunnel testing (Ciccone et al., 1990; Rice et al., 1995), 2D numerical simulation (Werner and Haff, 1998) and studying it as a simulation of the cascade collision and ejection of ions (Ta and Dong, 2007), and the sand-bed impact (Willets and Rice, 1985, 1986; Mitha et al., 1986; Rice et al., 1995, 1996; Werner and Haff, 1998). The cascade collision can help to explain the maintenance of saltation, but not the starting process, which is the aim of this paper.

This particular point is considered by Kurose et al. (2001), who studied experimentally the starting of the motion of individual spherical bodies, which are released by a magnetic system, and the resulting rolling and take-off motion recorded. The flow in the wind tunnel was uniform and steady. However, their results are not directly useful here, as the spherical shape is not a general situation, in fact is a singular one, as it is shown below. Further, we are interested in the behaviour under a time-dependent flow, which is the more general case, taking into account the influence of the dynamics of the stone on the process of starting of rotation.

Kind (1986) gives experimental results, obtained at reduced scale experiments in wind tunnel, concerning the wind speed at which gravel or crushed stone scour or blow off flat roof tops, specifically the wind speed at which sustained gravel scour begins, considering the effect of the roof parapet height. Although these results can not be used here to compare with the theoretical model, due to the lack of similarity of the bulk flows, his considerations on the effect of the Reynolds number are worthy in relation with our experimental set-up. Kind suggests that the Reynolds number has an influence on the flow/stone interaction process in particles with diameters less than 1 mm, and has no influence if the diameter is longer than 2 mm. This conclusion supports the experimental results considered in the current paper.

Concerning the second problem (flying debris), in the main references (Tachikawa, 1983, 1988; Wills et al., 2002; Holmes, 2004, 2006; Holmes et al., 2006; Lin et al., 2006; Baker, 2007; Richards et al., 2008) the body is considered already in flight and the aim of these studies is the determination of the trajectory and the energy at impact, without considering the study of the initiation of the motion. On the other hand, in an interesting work Vischer and Kopp (2007) study the trajectories of roof sheathing panels under high winds, but unfortunately their configuration is quite different from the one studied here, where the body is lying on the floor. The initiation of the motion considered by Vischer and Kopp is also very different from the rotation around the pivoting point relevant to a body lying on the floor.

Concerning the third problem (flying ballast), there is not much work published yet, although the great interest that exists due to its relevant applications in the increasing of the maximum operative train speed would hopefully change this situation in the future. Particularly, the initiation of flight of ballast due to the pass of a high speed train has been studied by Kwon and Park (2006) by performing experiments in wind tunnel and on the field. The results obtained are analyzed following a statistical approach. Therefore, there are no descriptions of specific