Contact Analysis for Obstacle Negotiation with Planetary Exploration Rovers

Sadhbh MacMahon[1], Francisco González[2], Bahareh Ghotbi[3] and József Kövecses[4]

[1,3,4]*Centre for Intelligent Machines, Department of Mechanical Engineering, McGill University,*
[sadhbh.macmahon,bahareh.ghotbi]@mail.mcgill.ca, jozsef.kovecses@mcgill.ca
[2]*Laboratorio de Ingeniería Mecánica, University of La Coruña, f.gonzalez@udc.es*

Autonomous navigation is a requirement of any planetary exploration rover exploring an environment too far from earth for efficient communication between the rover and ground control. An important feature of this autonomy is the capability of the rover to successfully negotiate obstacles that may lie in its chosen path. To accommodate this need, JPL has established a successful design by furnishing their rovers with the passive, rocker bogie suspension feature, and designers of rovers for future missions have been following a similar trend. These bogies, along with active articulation of various joints, allow the rover to assume a configuration that assists it to overcome the obstacles in its path. This is achieved due to the effect that the rover configuration will have on wheel-terrain and wheel-obstacle contact forces. Consequently, the analysis of these forces, and how they vary with rover configuration, can assist with enhancing the mobility of the rover. Typically contact is analyzed with one of a number of possible tools which ultimately model the forces that develop throughout the duration of contact. These force based models however, depend on material properties and other parameters which can be difficult to obtain, especially in the case of extra terrestrial environments. A tool proposed in this paper, which will demonstrate the trend between contact forces and system configuration, without the need to determine the material properties of the system, is a particular measurement of the kinetic energy of the system at the onset of contact. The kinetic energy in question, referred to as the “effective kinetic energy of impact", involves measurement of kinetic energy that is associated with motion of the system in directions that will be constrained by the impact or contact surfaces. These directions, which are typically normal to the contact surfaces, constitute the subspace of constrained motion (SCM). Effective kinetic energy is then the kinetic energy of a system that is associated with the SCM at the instant that contact is made. [1]. In this paper, the initial step of obstacle negotiation involving an impact with the obstacle is considered, and the relationship between impact force and effective kinetic energy as configuration is varied, is explored.

One way to express this effective kinetic energy is explained as follows. Let us consider that the motion of a system can be described with an $n\times 1$ array of generalized velocities $\mathbf{v}$, and the directions constrained by the impact are interpreted as $\mathbf{A}\mathbf{v}=\mathbf{u}_c$, with $\mathbf{A}$ an $m\times n$ matrix. The set of generalized velocities $\mathbf{v}$ can be decomposed into components associated with the SCM and its orthogonal complement, the subspace of admissible motion (SAM), as

$$\mathbf{v}=\mathbf{v}_c+\mathbf{v}_a=\mathbf{P}_c\mathbf{v}+\mathbf{P}_a\mathbf{v} \tag{1}$$

where $\mathbf{P}_c$ and $\mathbf{P}_a$ are projection matrices onto the SCM and the SAM, respectively. This decomposition allows for obtaining the kinetic energy associated with the SCM as

$$T_c=\frac{1}{2}\mathbf{v}_c^{\mathrm{T}}\mathbf{M}\mathbf{v}_c \tag{2}$$

where $\mathbf{M}$ is the $n\times n$ system mass matrix. The expression of the projection matrix $\mathbf{P}_c$ is given by [2]

$$\mathbf{P_c}=\mathbf{M}^{-1}\mathbf{A}^{\mathrm{T}}\left(\mathbf{A}\mathbf{M}^{-1}\mathbf{A}^{\mathrm{T}}\right)^{-1}\mathbf{A} \tag{3}$$

If we assume an elastic contact, all the kinetic energy associated with the SCM will be transformed into elastic potential energy at the end of the compression phase of the impact. Therefore, the value of T_c at the moment at which the impact begins, T_c^-, can be used to characterize the maximum value of the normal force during the impact, and the intensity of contact in general. This kinetic energy can be determined for a set of impact situations, where the impacts are identical except for one parameter. This parameter is varied over a range of values, and the effective kinetic energy values are recorded and compared. A 3-D model of a rover (Fig. 1) was used to demonstrate the relationship between T_c^- and the maximum impact force. Simulations of the impact of the rover with an obstacle

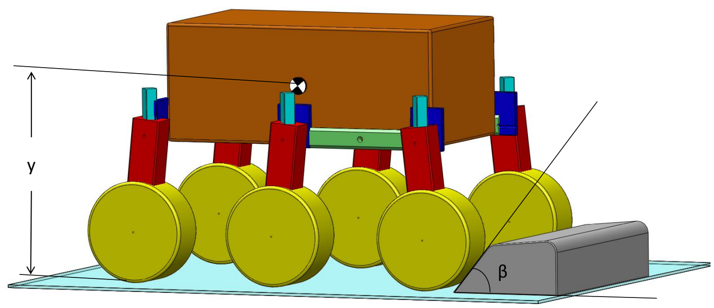

Fig. 1: A 3-D model of a rover undergoing an impact with an obstacle

were carried out for different impact angles β and heights of the centre of mass (COM) of the vehicle with respect to the ground y. The effective kinetic energy was evaluated at the instant just before contact was established, and the maximum impact force was determined using the non linear spring-damper model proposed by Hunt and Crossley [3]

$$f_n = -k\delta^{3/2}\left[1 + \frac{3\left(1-e_{eff}\right)}{2}\frac{\dot{\delta}}{v_i}\right] \tag{4}$$

where f_n is the normal force at the contact interface, k is the contact stiffness, δ is the indentation of contacting bodies, e_{eff} is the coefficient of restitution, and v_i is the initial penetration velocity.

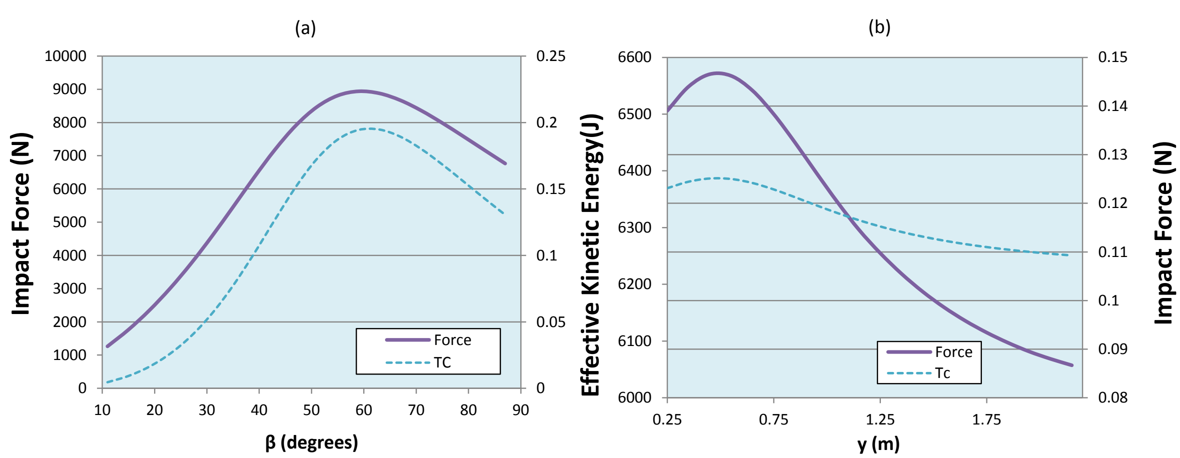

Fig. 2: Maximum impact force and effective energy T_c^- for impact simulations with a coefficient of restitution of one. Impact parameters varied are: (a) impact angles β and (b) vertical displacements of the COM of the rover y.

Results in Fig. 2 show that the effect of modifying the impact configuration on the impact force f_n can be captured using T_c^-. This supports the validity of the effective energy as an indicator in the estimation of the intensity of impact. An advantage to effective energy analysis is that it can be carried out without the need for detailed information about the constitution of the bodies involved in the impact.

References

[1] F. González, J. Kövecses, J.M Font-Llagunas. Load Assessment and Analysis of Impact in Multibody Systems. Multibody System Dynamics, online first, 2015
D.O.I.: 10.1007/s11044-015-9485-4

[2] J. Kövecses. Dynamics of mechanical systems and the generalized free-body diagram – part I: General formulation. ASME Journal of Applied Mechanics, Vol. 75, paper 061012, 2008.

[3] K. H. Hunt, F. R. E. Crossley. Coefficient of restitution interpreted as damping in vibroimpact. Journal of Applied Mechanics, Vol. 42, No. 2, pp. 440–445, 1975.