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Computational Acoustics: PNL (1/4) Presentation 3**3D modeling for acoustic waves and vibrations in solid structures with frictional cracks****Vladislav Aleshin***LEMACE, Institute of Electronics, Microelectronics and Nanotechnology, Villeneuve d'Ascq, Nord, 59652, FRANCE; aleshinv@mail.ru***Anton Pylypenko***Institute of Electronics, Microelectronics and Nanotechnology, Villeneuve d'Ascq, Hauts-de-France FRANCE; antonpylypenko1995@gmail.com***Kevin Truyaert, Steven Delrue and Koen Van Den Abeele***KU Leuven Campus Kortrijk, Kortrijk, West Flanders, BELGIUM; kevin.truyaert@kuleuven.be, steven.delrue@kuleuven.be, koen.vandenabeele@kuleuven.be*

We present a numerical modeling tool for engineering applications related to materials and systems having internal frictional contacts in their structure. The technique is based on a semi-analytical method for simulating contact mechanical problems, called the Method of Memory Diagrams (MMD) [1,3], which is able to calculate hysteretic frictional contact responses. The MMD is applicable when an axisymmetric contact system is excited by an arbitrarily changing shift in 3D [2] and can be extended to the contact of globally plane surfaces with isotropic roughness. The method uses some assumptions and does not provide the full functionality of purely numerical contact modeling, but is much more efficient computationally. This quantitative gain in performance makes the MMD applicable to the case of acoustic or random excitation signals containing a large number of oscillations. The integration of the MMD contact model in a finite element environment [4] (COMSOL) allows to simulate acoustic wave propagation and vibration in structures or materials containing hidden frictional interfaces (cracks, delaminations, loose joints, etc). We discuss proof-of-concept results in a simple 3D geometry containing to a surface-breaking crack insonified by an oblique compression wave simultaneously exciting normal and tangential interactions.

1. INTRODUCTION

Description of dynamic excitations of frictional defects in solids is a challenging problem. The main difficulty is that a crack or a delamination corresponds, from a mathematical point of view, to an additional internal boundary at which appropriate boundary conditions in terms of loads (N, T_x, T_y) and/or displacements (a, b_x, b_y) should be defined (see Fig. 1 (a)). At the same time, mechanics of friction does not suggest any simple solutions for these boundary conditions. Indeed, depending on the excitation, crack faces can locally slide or be stuck. In the former case, the Coulomb friction law - the standard approximation for the frictional interaction - provides a link between the normal and tangential loads. In the latter situation, the tangential displacement does not change which follows from the very definition of stick. In addition, contact faces can not penetrate into each other resulting in a constraint for the normal displacement. Moreover, the contact state (stick, sliding or contact loss) at a given point is not known *a priori* and changes following an elastic reaction of the entire structure. Hence, the description of elastic waves in materials with cracks is usually done via an implicit procedure in which the contact state and the related boundary conditions are determined in an iterative way^[5].

In a series of papers^[1-4] by the authors, an alternative approach was developed that accounts for roughness of internal contact faces while traditionally they are considered smooth. It is shown that despite the additional complexity introduced due to the random microgeometry, calculations can be organized in an explicit manner providing unknown loads for known displacements. The reason is that asperities can recede under load both in the normal and tangential directions. Normal loading of rough surfaces is then described by the load-displacement dependence $N = N(a)$, a smooth monotonous curve defined for all a . In the paper^[3] it is suggested to use an approximation $N = Ca^2$ for positive a (compression) and $N = 0$ for negative a (contact loss). The tangential reaction in a system with friction is hysteretic but can also be calculated explicitly which is explained below.

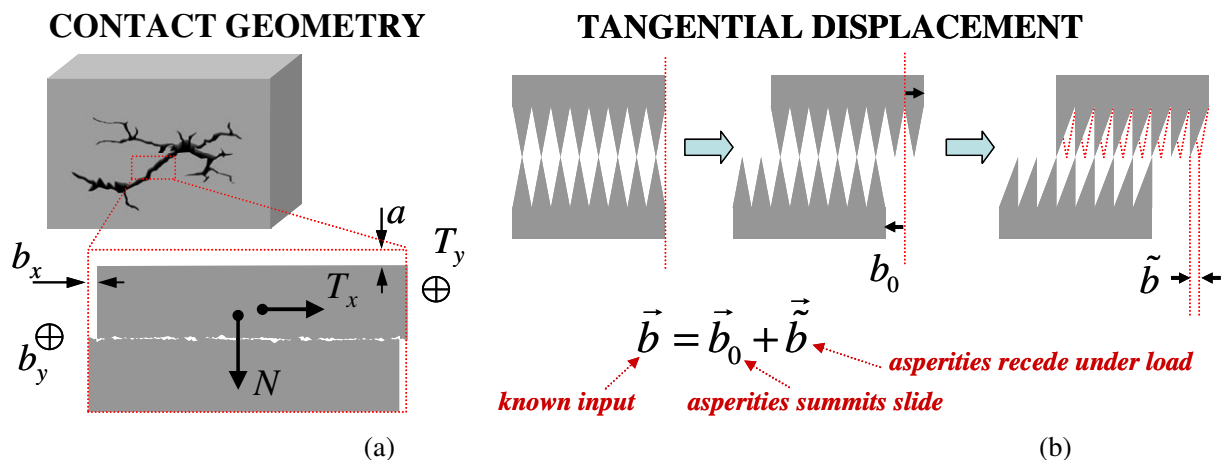


Figure 1: (a) Geometry of the contact problem with loads and displacements; (b) tangential displacement comprising two components.

2. CONTACT MODEL

When precompressed rough surfaces are subject to weak tangential load, partial slip occurs when some contact points slide and some do not. In that situation, asperities experience tangential deformations that grow as loading increase, and the stick zones shrink. When the tangential load reaches the Coulomb threshold μN , the stick zone disappears and the last two stuck asperities start sliding. The corresponding tangential displacement consists of two components (Fig. 1 (b)) appearing since asperities summits slide and since asperities recede under load:

$$\vec{b} = \vec{b}_0 + \vec{\tilde{b}}. \quad (1)$$

This repartition allows one using a procedure (Fig. 2) for calculation of the sought-for tangential load \vec{T} . The simplest case is the contact loss state in which all loads equal zero. Further, in the case of total sliding, the Coulomb threshold is achieved, therefore the absolute value of the tangential load is known, $|\vec{T}| = \mu N(a)$, but its orientation is still to be found. To do so, we rewrite the repartition (1) in a previous moment of time, $\vec{b}_p = \vec{b}_{0p} + \vec{\tilde{b}}_p$, and introduce a unit vector of the proper deformation, $\vec{l} = \vec{\tilde{b}} / |\vec{\tilde{b}}|$. This vector should be collinear to the tangential load, $\vec{l} \uparrow \uparrow \vec{T}$, since the proper deformation is induced by this load. At the same time, according to the Coulomb friction law, the tangential force is collinear to the slip direction, $\vec{T} \uparrow \uparrow \Delta \vec{b}_0$. The above conditions determine \vec{l} as a unit vector in the direction $\vec{l} \uparrow \uparrow \vec{b} - \vec{b}_{0p}$ where the both vectors \vec{b} and \vec{b}_{0p} are known. Finally, in the partial slip state, \vec{T} is obtained via the Method of Memory Diagrams (MMD) previously elaborated for this case^[1,2].

The MMD can be seen as an extension of the Hertz-Mindlin solution^[6] for the contact of two spheres subject to an oblique load, in which contact geometry is not necessarily spherical, but, for instance, represents contact of rough surfaces. The MMD allows one to fully automate the calculation of tangential hysteretic responses for partial slip when the contact system is excited by an oblique shift changing in time in an arbitrary way.

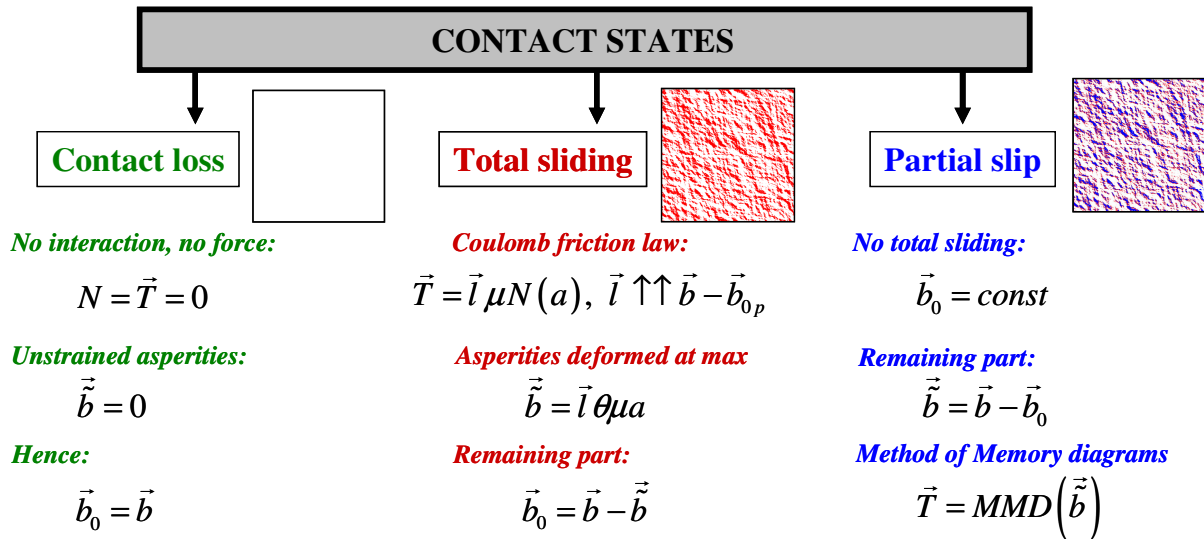


Figure 2: Three contact states and the corresponding load-displacement relationships. Square insets illustrate slip (red), stick (blue), and no-contact (white) zones for contact of rough surfaces.

3.RESULTS AND DISCUSSION

The tangential response obtained by using the contact model depicted in Fig. 2 is plotted in Fig. 3. In the considered example, the excitation signal shown in the inset is similar to a fragment of a real acoustic wave that excites all three contact regimes presented in Fig. 3 keeping the same color scheme as in Fig. 2. These results illustrate the fact that in the proposed contact model the load-displacement relationship is given in the explicit way; any displacement history produces the appropriate response directly, without having a need to interrogate neighboring volume or interface areas for getting a sort of feedback necessary for implicit procedures.

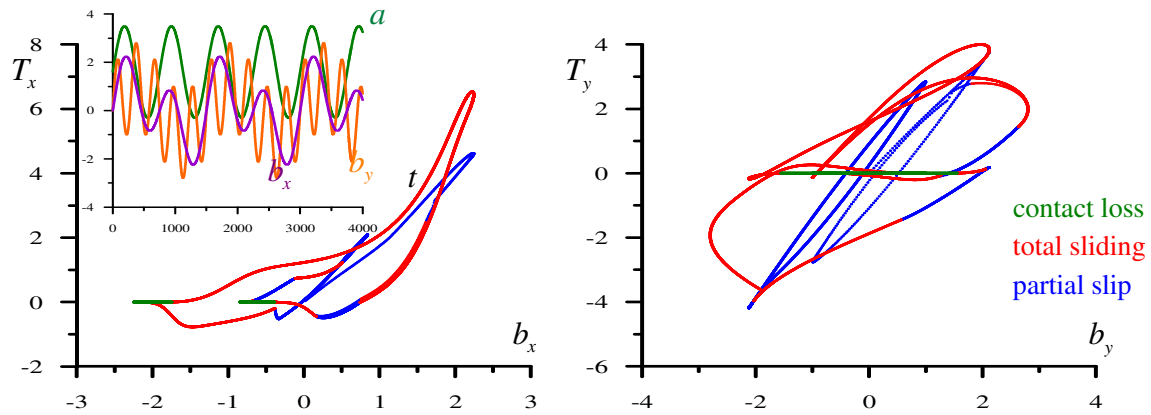
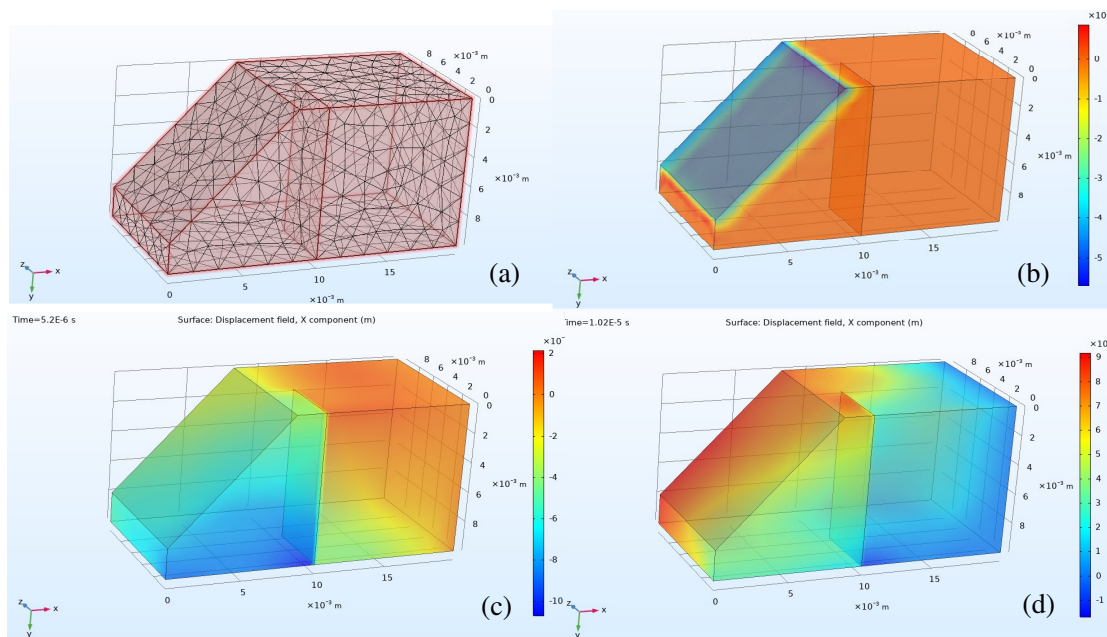


Figure 3: Tangential load-displacement curves $T_x(b_x)$ and $T_y(b_y)$ for an excitation history (three components of contact displacement) shown in the inset. The contact states - contact loss, total sliding, and partial slip are shown in green, red, and blue, respectively.

The equations of solid mechanics have been programmed in COMSOL that allows integrating external boundary conditions from MATLAB. In Fig. 4, our first numerical results for vibrations in a cracked sample in 3D are shown. The sample represents a parallelepiped with one face obliquely cut. In this case, a compressive wave generated at the cut face excites both normal and tangential displacements at the vertical crack. A long wavelength of 12 cm is comparable to the sample dimensions 20x10 cm thus representing a situation where even a coarse mesh is sufficient for representing the crack-wave interaction.



4. CONCLUSION

In this paper we propose a numerical method for describing elastic wave propagation in materials with internal frictional contacts, such as cracks, delaminations, loose joints, among others. To do this, we have used a previously developed contact model providing explicit load-displacement relationship at hidden interfaces that results from the Coulomb friction law and the account for surface roughness. The key point of the description is the Method of Memory Diagrams that allows one to automate the calculation of friction-induced

hysteretic responses in the partial slip case appearing due to the roughness. Exemplar wave propagation patterns for a simple geometry (rectangular bar with a crack) are shown to illustrate the concept. Our future efforts will be focused on experimental validation of the method with the final aim to identify damage parameters of real structures from measured response.

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