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Kevin Truyaert, Koen van den Abeele, Vladislav Aleshin, Steven Delrue. Qualitative analysis of a 2D multiphysics model for vibration induced heating at closed defects. Proceedings of meetings on acoustics, 2020, pp.022007. 10.1121/2.0001183 . hal-03003427

HAL Id: hal-03003427

<https://hal.science/hal-03003427>

Submitted on 18 Nov 2020

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**2019 International Congress on Ultrasonics**

Bruges, Belgium

3-6 September 2019

Computational Acoustics: NDT: Vibrothermography for NDT, Presentation 5**Qualitative analysis of a 2D multiphysics model for vibration induced heating at closed defects****Kevin Truyaert***Department of Physics, Katholieke Universiteit Leuven - Campus Kulak Kortrijk, Kortrijk, West-Vlaanderen, 8500, BELGIUM; kevin.truyaert@kuleuven.be***Koen Van Den Abeele***KU Leuven Campus Kulak Kortrijk, Kortrijk, West-Vlaanderen, BELGIUM; koen.vandenabeele@kuleuven.be***Vladislav Aleshin***Institute of Electronics, Microelectronics and Nanotechnologies, Villeneuve d'Ascq, FRANCE; aleshin@villeneuve.fr***Steven Delrue***KU Leuven Campus Kulak Kortrijk, Kortrijk, West-Vlaanderen, BELGIUM; steven.delrue@kuleuven.be*

Vibrothermography is a promising Non-Destructive Testing (NDT) technique for the detection and characterization of closed defects. The technique uses elastic waves to excite the damaged component in order to generate frictional behavior at the internal closed defects. This results in vibrational energy dissipation through thermal diffusion. Apart from incipient damage detection, defect characterization is equally important, e.g. to anticipate the future defect growth. A proper characterization study necessitates a theoretical framework for in-depth analysis of the obtained thermal images. In the present work, we propose a 2D finite element multiphysics model for vibrothermography. The model consists of a mechanics/dynamics module to describe elastic wave propagation in samples with rough surface cracks, and accounts for nonlinear wave generation due to dynamic stimulation of the defect faces. In addition, the model is capable of calculating the energy dissipated due to frictional effects and translates it to a local generation of heat in the defect area. We will perform a qualitative analysis of the developed model by comparing the obtained numerical results with theoretical results already described in literature.

2019 INTERNATIONAL CONGRESS ON ULTRASONICS BRUGES, BELGIUM, 3-6 SEPT 2019

1. INTRODUCTION

Vibrothermography is a promising Non-Destructive Testing (NDT) technique for the detection and characterization of closed defects. The technique uses elastic waves to excite the damaged component in order to generate frictional behavior at the internal closed defects. This results in vibrational energy dissipation through thermal diffusion. Recent work has proven that the efficiency of closed defect detection by vibrothermographic NDT can be significantly enhanced by tuning the excitation frequency to the so-called in-plane Local Defect Resonance (LDR) frequency^[1]. Apart from incipient damage detection, defect characterization is equally important, e.g. to anticipate the future defect growth. A proper characterization study necessitates a theoretical framework for in-depth analysis of the obtained thermal images. In the present work, we propose a 2D finite element multiphysics model for vibrothermography. The model consists of a mechanics/dynamics module to describe elastic wave propagation in samples with rough surface cracks, and accounts for nonlinear wave generation due to dynamic stimulation of the defect faces^[2]. In addition, the model is capable of calculating the energy dissipated due to frictional effects and translates it to a local generation of heat in the defect area^[3]. We will perform a qualitative analysis of the developed model by comparing the obtained numerical results with theoretical results already described in literature.

2. CONTACT DESCRIPTION

In the current model the contact physics are described through the Method of Memory Diagrams (MMD). This semi-analytical method describes the normal and tangential behavior of two axisymmetric, convex bodies in contact experiencing an arbitrarily loading procedure. The method uses a memory diagram $D(\alpha)$, a piece-wise function depending on α , a parameter linked to the indentation space, and defined on the interval $[0, a]$, where a is the maximal indentation of the contact at its current state. The corresponding normal load, N , can be calculated through a normal load-displacement relationship that is assumed to be known and is taken quadratic^[4]. The memory diagram contains all tangential properties of the current contact, remembering the hysteretic behavior of the contact. The tangential displacement and load, respectively b and T , are obtained through the integration of the memory diagram as follows:

$$b = \theta\mu \int_0^a D(\alpha) d\alpha$$

$$T = \theta\mu \int_0^a D(\alpha) \frac{dN(\alpha)}{d\alpha} d\alpha$$

where θ is a Poisson's factor dependent parameter^[4] and μ is the frictional coefficient between the surfaces. The MMD-based model can take three different states into account: contact loss, full sliding and partial slip (see figure 1). In the partial slip regime, the convex axisymmetric contact will be split up in two regions where $|T|$ is either smaller than (inner zone) or equal to μN (periphery). Hence, the contact region will both have a stick and a slip region, depending on the local normal stress. Within the partial slip regime the memory function updates itself during the loading procedure according to a set of rules, depending on the history of the contact^[4].

Contact state	If	Then	Memory diagram
Contact loss	$a(t) < 0$	$\tilde{b}(t) = 0$ $b_0(t) = b(t)$ $T(t) = N(t) = 0$	
Partial slip	$a(t) \geq 0$ $ \tilde{b}(t - \Delta t) < \theta\mu a(t)$	$b_0(t) = b_0(t - \Delta t)$ $\tilde{b}(t) = b(t) - b_0(t)$ $T(t) = MMD[\tilde{b}(t)]$	
Total sliding	$a(t) \geq 0$ $ \tilde{b}(t - \Delta t) \geq \theta\mu a(t)$	$\tilde{b}(t) = \pm\theta\mu a(t)$ $b_0(t) = b(t) - \tilde{b}(t)$ $T(t) = \pm\mu N(t)$	

Figure 1: The different states of MMD and their conditions. b_0 is the macroscopic tangential displacement and \tilde{b} is the tangential displacement part causing the deformation of the present asperities.

The instantaneous amount of energy, ΔW , dissipated due to frictional effects during the partial slip and total sliding phases can be calculated based on the parameters used in the MMD-based contact model. In case of full sliding under constant normal loading, the dissipated energy is given by: $\Delta W = 2|\Delta b|T$, where the factor 2 is a result of the MMD framework. During the partial slip phase, energy is also dissipated at the closed defect interface where locally $|T| = \mu N$. The amount of dissipated energy in this regime can be retrieved through^[3]:

$$\Delta W = 2\mu(|b| - \theta\mu\Delta a) \left(N(a) - N(q) + (q - a) \frac{dN}{da}(q) \right),$$

where q is the equivalent normal indentation required to only have the stick region as contact region. This is visualized in Figure 2.

3. NUMERICAL THERMO-MECHANICAL MODEL

The model capable of simulating a dynamically excited frictional contact and calculating the amount of instantaneous dissipated energy through friction at the contact interface has been successfully implemented in COMSOL®[5]. Through the combination of the Structural Mechanics, Heat Transfer and LiveLink for MATLAB modules, the time-dependent simulation solves simultaneously the elastic wave and thermal diffusion differential equations, both at the defect and in the bulk of the material. One time step in the algorithm goes as follows:

- Both differential equations are solved to obtain the displacements and temperature distribution at the next time step.
- Using the MMD-based contact model, the contact stresses are updated based on the obtained displacement values. At the same time, the instantaneous dissipated energy at the contact is calculated, which is then transferred into heat.
- Steps (a) and (b) are repeated for $t + \Delta t$, until the desired simulation time is reached.

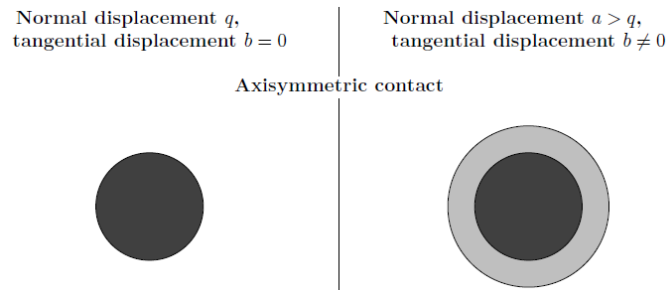


Figure 2: Representation of the contact zones to clarify the difference between the total normal indentation a of a body in contact and the equivalent indentation q , related to the stick-slip boundary.

4. COMPARISON TO AN EXISTING MODEL

The consistency and stability of the presented model have been tested by considering different geometries and configurations^[5]. However, in order to assess the model's potential to accurately describe the temperature distribution around a closed defect experiencing friction through elastic waves, the outcome of the numerical model needs to be compared to either another, accepted computational model or to a basic experiment. In this paper, the obtained numerical results are compared with the results discussed by Rizi et al.^[6], who developed a similar model for crack heating through frictional losses. The main difference between both models is that the model presented here has a description of the contact that can take different contact geometries into account, including asperities. This results in the occurrence of a partial slip state, where heat can also be generated during a global stick situation as the result of the contact parameters. In Rizi et al.^[6], frictional heat is calculated based on the sliding velocity and the pressure at the contact. This means that the heat generated during partial slip phases cannot be compared as this has not been considered in the work of Rizi et al.^[6]. On the other hand, the calculation of the energy dissipated during the total sliding phase is identical. Note however that both models use different contact descriptions, possibly resulting in a different evolution of the contact loadings N and T .

A 2D simulation (the current MMD model only allows a 2D description of the contact behavior) of a vertical surface breaking crack of 20 mm in an aluminum plate of 150 mm by 150 mm at a distance of 25 mm from the left side has been performed. A displacement boundary condition has been applied on the top edge, between 75 mm and 115 mm of the left side, to excite the sample with a longitudinal sinusoidal wave with a frequency of

50 kHz. Other boundaries are chosen free. Figure 3 shows the temperature distribution within the specimen, zoomed in for all three time instances in the same region around the surface breaking crack, similar to Figures 14a and 15 in Rizi et al.^[6]. Frictional heat is generated along the crack in the same zone as was found by Rizi et al.^[6]. The heat is also dissipated through the volume of the material, as can be seen from the different time instances shown in Figure 3.

Figure 4 shows the temperature increase and contact stresses as function of time at a particular location on the crack (i.e. 15 mm from the top of the sample, in the region with the highest temperature increase as shown in figure 3). The figure depicts a temperature increase both in the full sliding state (i.e. $T = \pm\mu N$, dark grey background) and in the partial slip state (i.e. $T < \mu N$, light grey background). The timescale on which this temperature increase occurs is too small to be caused by heat dissipated away from any neighboring points on the crack surface. This shows the necessity of including partial slip into a contact model, as a contact only experiencing partial slip will also exert heat to its environment due to friction.

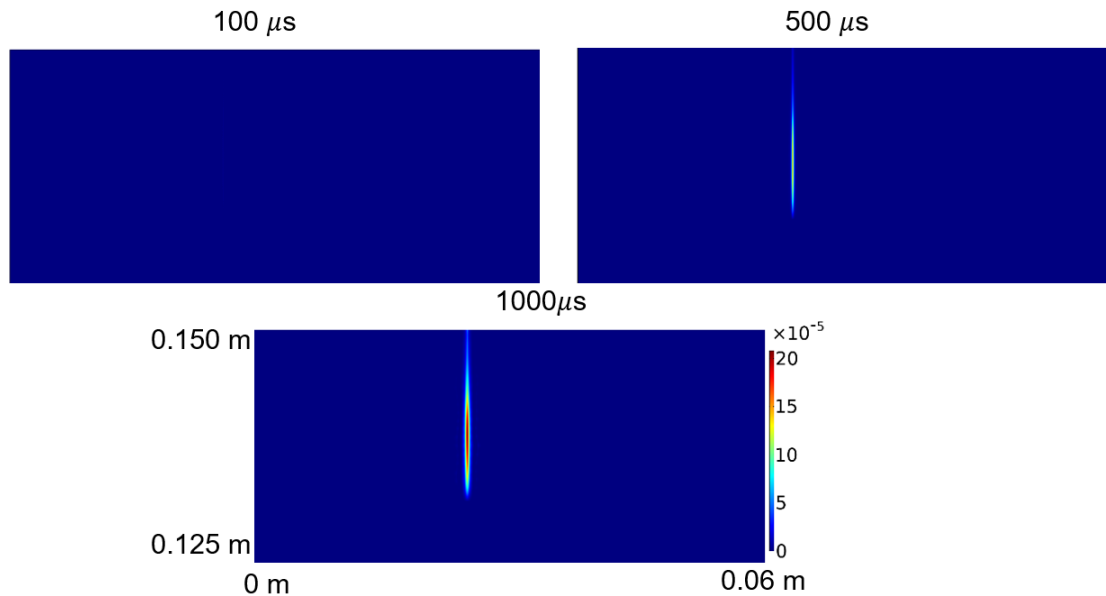


Figure 3: Temperature distribution (K) of the specimen at different stages (100 μ s, 500 μ s and 1000 μ s), zoomed in around the crack region. The temperature rise at the edge crack is due to friction.

5. CONCLUSION

After a numerical analysis of the presented model^[5], a qualitative analysis is performed by comparing the obtained results with those obtained by a different model^[6] to calculate heat dissipated through friction. Both models obtain a qualitatively interchangeable result. It has been shown that also during partial slip phases, heat can be generated. Apart from its ability to simulate nonlinear wave generation at a crack interface due to clapping and friction^[2], the proposed MMD-based model also proves its value for the field of ultrasonic vibrothermography. Both nonlinear and thermal phenomena occurring at a defect can be studied simultaneously, making the model very suitable to test different non-destructive test and evaluation methods and identify the most suitable method for the detection and/or characterization of the defect.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from Internal Funds KU Leuven (C24/15/021).

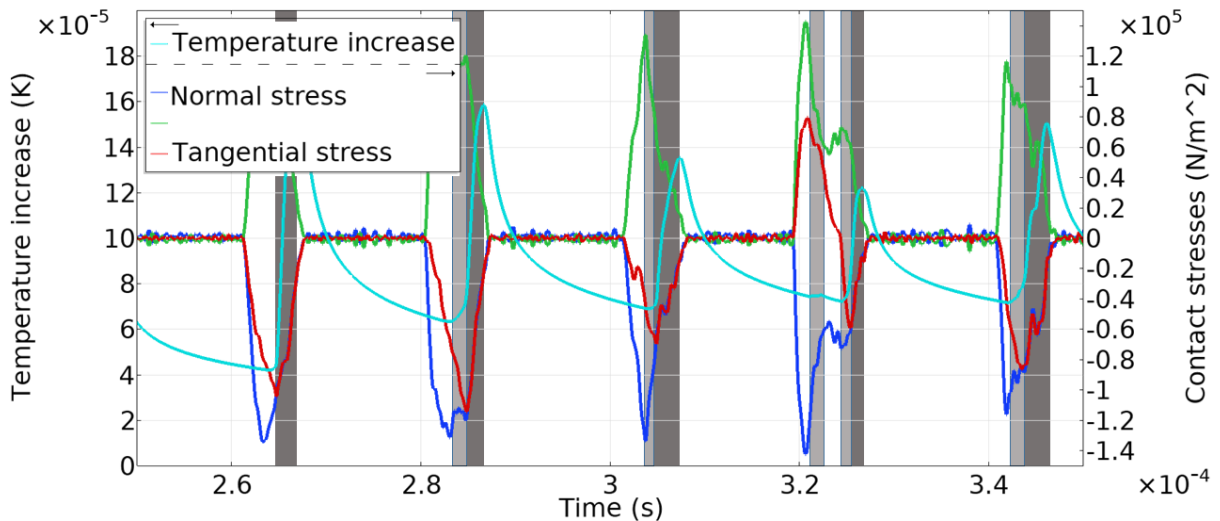


Figure 4: Temperature increase (left axis) and contact stresses (right axis) at a point along the crack during 0.25 ms to 0.35 ms after the excitation. It can be seen that temperature increases both during total sliding (dark grey background) and partial slip (light grey background).

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