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# FINITE ELEMENT MODELING OF STUDYING ENERGY CONSUMPTION OF DEFECTS EXCITED BY SINGLE EXCITATION ULTRASONIC PULSE FREQUENCY IN SONIC INFRARED IMAGING

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## ABSTRACT

*In this paper, a three-dimensional thermo-mechanical coupled finite element model is purposed to study the effect of excitation single driving frequency, transducer size and crack length in energy consumption of object defects. A single driving frequency is introduced into the object causing interaction between the crack surface in the FEA model. By implanting thermal-structural coupling analysis in finite element mode, the frictional heating and kinetic energy are quantitatively calculated in the FEA simulations. The general relationship between the energy consumption of defects and introduced a single driving frequency is analyzed and presented in this paper.*

Keywords: Finite Element Model, Sonic Infrared Imaging, Energy Consumption

## 1. INTRODUCTION

Sonic infrared imaging is received progressive attention as a novel hybrid, thermal-based nondestructive testing technique. [1-4]. The high power intensive ultrasonic pulse is utilized to induce nonlinearity vibration between defect contact surfaces. Such mechanical vibration will cause frictional heating, thus, defects will be revealed due to irreversible temperature change and captured by the on-site infrared camera.

The nonlinearity phenomena which also referred to as 'acoustic chaos' is observed and verified it can improve the detectability in sonic infrared imaging technique. The pure driving frequency can result in a complex spectrum: besides pure driving frequency, multiples of fractions of the driving frequency also appear. The nonlinearity is associated with a strong heat signature in the defect area, but the contribution of each harmonic and subharmonic frequencies has not been studied. In this paper, we will present the study of energy consumption of the different length defects excited by different single excitation ultrasonic pulse in Sonic Infrared Imaging.

## 2. FINITE ELEMENT ANALYSIS MODEL

The FEM analysis is widely used to do thermal and structural nonlinearity analysis. The most advantage of FEM analysis is can apply arbitrary loading to the model and solve its dynamic response. Therefore, the FEM modeling is an appropriate method to study the energy consumption of the crack contact surface under different conditions in the Sonic infrared imaging technique. In the typical SIR experimental, the short high-power ultrasonic pulse is generated by the ultrasonic transducer tip and introduced into the target object. Multiple frequencies will be obtained from the object due to the complex nonlinearity interaction between the transducer tip and object.

The FEM model package analysis contains two steps to simulate the SIR experimental inspection condition: the pre-static model and the dynamic model. The static model is built to simulate the pressure coupled sample condition and the dynamic model is created to simulate the response of single excitation frequency with different crack length.

The static model is shown in Figure 1(a) which includes a plate that built and meshed in LS-DYNA as the target plate, a plate that marked as yellow serves as a rigid post to constrain one side of the plate and a is sandwich cylinder with different radius serves as experimental transducer tips that apply initiate force coupling to the plate sample. Due to the experimental limitations, it is not possible to allow a single vibration frequency to propagate through the sample, but that driving frequency can only be utilized to the transducer tip. Therefore, a thermo-mechanical coupled FEA dynamic model is created to collect and analyze data from different scenarios.

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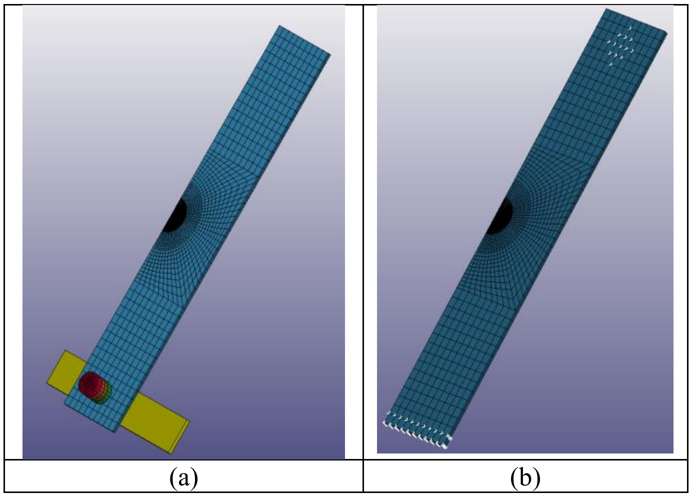


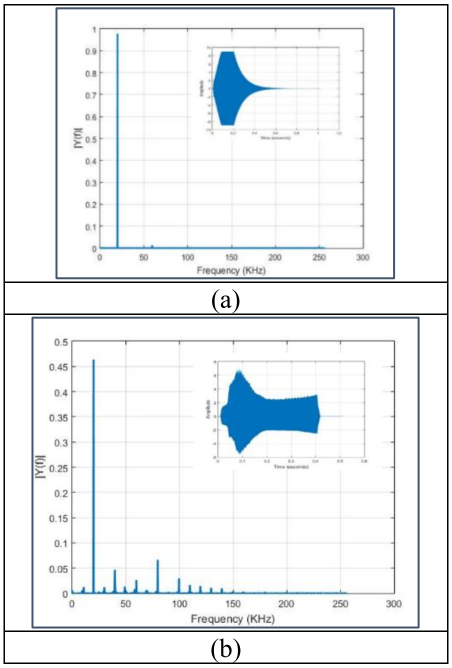
(a) (b)

**Figure 1** FEA model (a) Static FEA model (b)Dynamic FEA model

The dynamic model has a $230\,mm \times 40\,mm \times 2.4\,mm$ sample alloy plate is built and meshed in LSDYNA. The alloy material properties are simulated with density of 2.77 g/cm$^3$, Young's modulus of 69 GPa and Poisson's ratio of 0.33. The FEA model geometry detail is shown in Figure 1(b), The white marks are the positions of boundary condition: The white marks are the positions of boundary condition: bottom side of sample plate applies a six-DOF constrained boundary. For different gun tip size simulation scenario, a shape boundary condition with different size is applied at top side of the plate, it simulates the transducer area constrain condition that only allow Z-axis translational movement. Different sizes of transducer tip and crack length are simulated in the dynamic model and corresponding data are collected and analyzed.

## 3. THEORETICAL BACKGROUND

The nonlinear phenomenon in Sonic Infrared Imaging (IR) can be described as: due to the non-linear coupling between the transducer and the target, a complex waveform is appeared in the target resulting spectrum. In addition to the original pure driving frequency, other frequency components which are multiples of fractions of the driving frequency also appear in the resulting spectrum. The nonlinear phenomenon is shown in figure 1. Figure 1(a) is the driving frequency from the ultrasonic source which is a pure 20 kHz, Figure 1(b) is the vibration spectrum of the defect area. Besides 20 kHz driving frequency, multiples of fractions of the 20 kHz appear in the spectrum. The nonlinear phenomenon can increase the detectability in SIR technology. During the excitation period, the nonlinearity bouncing between the transducer and the sample induces additional frequency components that produce nonlinear phenomenon [5,6]. Those of waves will propagate in the sample. All these frequencies including the driving frequency together cause clapping and rubbing within the crack. Thus, when we measure the vibration around the crack, multiple frequencies can be obtained.



(a)

(b)

**Figure 2** Nonlinear phenomenon (a)Source ultrasonic Vibration waveform and its Fourier transform. (b) Object's Vibration waveform and its Fourier transform

Rayleigh's theorem states that total energy is the integration of velocity squared over the excitation period in a vibration system and the total energy remains the same in the time domain and frequency domain. acoustic energy can be quantitatively calculated by apply Rayleigh's theorem shows in Equation 1. The acoustic in the crack area is related to the relative motion of the crack surface, therefore, relative velocity $v(t)$ is used to computing the energy

$$E_{\text{acoustic}} = \int_{-\infty}^{\infty} |v(t)|^2 dt = \int_{-\infty}^{\infty} |V(f)|^2 df \qquad (1)$$

where V(f) is the Fourier transform of v(t). The energy calculated in this paper is the index value, and there is no physical unit behind it.

The temperature change in SIR is due to the friction heating of the crack contact surface. Therefore, friction energy is a proper measurement to evaluate the thermal difference. The frictional energy in LS-DYNA software is calculated by Equation 2. The frictional energy is a cumulative update calculation from time n to time n+1

$$E_{frictional}^{n+1} = E_{frictional}^{n} + \left[\sum_{i=1}^{nsn} \Delta F_i^{slave} \times \Delta dist_i^{slave} + \sum_{i=1}^{nmn} \Delta F_i^{master} \times \Delta dist_i^{master}\right]^{n+\frac{1}{2}} \qquad (2)$$

Where nsn is the number of slave nodes, nmn is the number of master nodes, $\Delta F_i^{slave}$ is the interface force between the ith slave node and contact portion, $\Delta dist_i^{slave}$ is the corresponding incremental distance in computing time step, $\Delta F_i^{master}$ is the interface force between ith master node and contact portion, $\Delta dist_i^{master}$ is the corresponding incremental distance in computing time step.

## 4. RESULTS AND DISCUSSION

**TOP 3 Frequencies Contribution to Thermal Energy**

| Tip Size | *Crack Length* | | | | |
|---|---|---|---|---|---|
| | *1mm* | *3mm* | *5mm* | *10mm* | *15mm* |
| *1/4”* | 85 kHz | 90 kHz | 90 kHz | 75 kHz | 75 kHz |
| | 100kHz | 80 kHz | 80 kHz | 35 kHz | 65 kHz |
| | 50 kHz | 85 kHz | 35 kHz | 30 kHz | 60 kHz |
| *1/2”* | 85 kHz | 85 kHz | 85 kHz | 50 kHz | 55 kHz |
| | 65 kHz | 75 kHz | 65 kHz | 75 kHz | 40 kHz |
| | 90 kHz | 70 kHz | 90 kHz | 95 kHz | 75 kHz |
| *3/4”* | 75 kHz | 85 kHz | 65 kHz | 60 kHz | 50 kHz |
| | 85 kHz | 75 kHz | 75 kHz | 90 kHz | 85 kHz |
| | 55 kHz | 65 kHz | 85 kHz | 15 kHz | 70 kHz |
| *1”* | 95 kHz | 95 kHz | 50 kHz | 75 kHz | 60 kHz |
| | 65 kHz | 65 kHz | 75 kHz | 70 kHz | 70 kHz |
| | 75 kHz | 75 kHz | 65 kHz | 55 kHz | 75 kHz |

Figure 3 Top 3

**Total Thermal Energy**

| Tip Size | *Crack Length* | | | | |
|---|---|---|---|---|---|
| | *1mm* | *3mm* | *5mm* | *10mm* | *15mm* |
| *1/4”* | 0.22E+04 | 4.77E+04 | 5.12E+04 | 28.9E+04 | 5.97E+04 |
| *1/2”* | 0.73E+04 | 16.2E+04 | 16.5E+04 | 6.81E+04 | 4.60E+04 |
| *3/4”* | 0.19E+04 | 6.75E+04 | 14.0E+04 | 8.82E+04 | 7.52E+04 |
| *1”* | 0.16E+04 | 2.19E+04 | 3.47E+04 | 9.27E+04 | 7.78E+04 |

## 5. Summary

A three-dimensional thermo-mechanical coupled finite element model is purposed to study the effect of excitation single driving frequency, transducer size and different crack length in energy consumption of object defects. The results show different length and transducer tip do affect energy consumption.

## ACKNOWLEDGEMENTS

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