RE-EXAMINATION OF NIST ACOUSTIC EMISSION ABSOLUTE SENSOR CALIBRATION: Part II - Finite element modeling of acoustic emission signal from glass capillary fracture*#

M. A. HAMSTAD
National Institute of Standards and Technology, Materials Reliability Division (653), 325 Broadway, Boulder, CO 80305-3328 and Mechanical and Materials Engineering Department, School of Engineering and Computer Science, University of Denver, Denver, CO 80208

Abstract

A validated axisymmetric finite-element code was used to model the out-of-plane displacement acoustic emission (AE) signal at 100 mm from a glass capillary fracture on the surface of a large steel block under the control of National Institute of Standards and Technology (NIST). This situation corresponds to the absolute sensor calibration approach described in the test method ASTM E1106-07. A number of source parameters relating to the fracture of the glass capillary source were studied: (i) value of the rise-time of the force release, (ii) temporal shape of the force release, (iii) spatial size and spatial distribution of the normal stress on the block surface, and (iv) the magnitude of the force. The results of the dynamic finite-element model (FEM) were compared to the signal from the capacitance sensor used in the AE sensor calibration at NIST. The FEM results indicate that the magnitude of the signal is a linear function of the force released, and that all other source parameters change the magnitude of the Rayleigh wave that dominates the displacement signal. During calibration, only the force at fracture is measured. It is not clear at present how the other parameters can be measured. Based on the results in this study, recommendations are made relative to the content of ASTM E1106-07.

Keywords: Absolute AE sensor calibration; ASTM E1106-07; finite-element modeling; glass-capillary fracture; NIST steel block; Rayleigh wave

1. Introduction

In late 2009, the large steel cylinder (900 mm diameter by 430 mm long under the control of the National Institute of Standards and Technology (NIST)) referred to in the test method ASTM E1106-07 [1] for absolute calibration of acoustic emission (AE) sensors was moved from NIST-Gaithersburg to NIST-Boulder. Figure 1 shows a photograph of the steel cylinder. As a result of this move, a study was initiated by use of finite element modeling to examine both the surface loading from the glass capillary (used in the calibration procedure described in E1106 [1]) and the subsequent wave generated by the fracture of the glass capillary. Part I of this paper [2] provided the results from the static loading just prior to the capillary fracture. Those results provided key input to the research reported here.

The research presented here examined with dynamic finite-element modeling a number of variables to determine their influence on the wave generated by the fracture of the glass capillary. In particular, the variables examined were the source rise-time (of the force released by the fracture) and its temporal shape, the spatial size and the spatial distribution of the normal surface

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loading at the fracture load and the magnitude of the force at fracture. In addition, the finite element approach allowed a study of the “overshoot” (defined at an appropriate point later in this paper) that is observed in the experimental out-of-plane signal recorded by the reference capacitance sensor located 100 mm from the glass capillary source. This distance corresponds to the propagation distance to both the capacitance sensor and the sensor being calibrated.

Fig. 1 Cylindrical block of steel has a diameter of 900 mm and a length of 430 mm with a highly polished top surface.

Information on the Finite Element Modeling

A validated axisymmetric finite-element code was used for the current research [3]. The results shown in this paper are the out-of-plane displacement signals versus time (where zero time corresponds to the start of the operation of the source) obtained on the top surface of the steel cylinder at a propagation distance of 100 mm (radial direction) from the capillary fracture. The code uses a uniform cell size (or element size) in both the axial and radial directions. Due to past experience with finite element modeling (FEM) when a Rayleigh wave was present [4], double-precision calculations were made in order to avoid errors due to numerical round-off. The axisymmetric code was used rather than a 3-D code, because much smaller cell sizes could be used while making use of reasonable computing facilities. For most of the FEM runs, the size of the steel block was reduced in order to decrease the size of the domain of the calculation. This decrease in size was limited such that reflections from the block boundaries did not occur until some time after the completion of the full arrival and departure of the Rayleigh wave at the 100 mm propagation distance. The AE source was always located at the center of the top surface of the steel block. Unless specifically stated, the normal surface stress released (to generate the signal) was uniformly distributed over the first 80% of the source radius and linearly decreased to zero over the final 20%. In addition, the total force (that generated the normal stress) for all results shown was 10 N. The bulk velocities used in the FEM code were 5850 m/s and 3188 m/s, respectively, for the longitudinal and shear velocities. These velocities were obtained from the
ultrasonic characterization of the block at NIST Gaithersburg. The density used in the code was 7.8 Mg/m³.

Fig. 2 Comparison of FEM and experimental out-of-plane displacement signals at 100 mm distance for full block. Insert shows expanded scale of bottom reflection arrivals.

**Initial FEM Result for the Full-size Steel Block**

As an overall check on the FEM-based out-of-plane displacement calculated for the propagation distance of 100 mm, a run was made by use of the full size of the steel block. This result was then compared with a typical experimental signal obtained from the capacitance sensor [5]. The FEM conditions for this run were a total source force of 10 N (corresponding to the measured value in the experiment), a source rise-time of 1 µs, a source radius of 1 mm, a time-step of 16.3 µs, and a cell-size of 0.106 mm. The temporal shape of the source rise-time was the “cosine bell” type, which for convenience will be defined by a later equation and shown in a later figure. The longer rise-time (than expected from the glass capillary fracture) allowed modeling of the whole block for a longer time period with reasonable computer resources. The comparison of the FEM signal and experimental results are shown in Fig. 2. This figure shows that the FEM signal was similar in form to the experimental signal for the key features, including arrivals of the bulk longitudinal wave, shear wave and the Rayleigh wave. Due to the long rise-time of the source in this run, the peak amplitude of the Rayleigh wave was reduced. In addition, due to the longer duration of the FEM signal, the expected reflections of the bulk longitudinal wave from the outer edge (radius of the block) and the bottom surface of the block are present in that signal. These arrivals (shown in more detail in the inset in Fig. 2) in the FEM signal are at 137 µs for the edge reflection, versus a calculated value of 136.8 µs, and for the bottom surface reflection the FEM arrival was 148 µs versus a calculated value of 148.3 µs. The calculated values were based on the actual path distances and the previously given bulk longitudinal velocity. It should be noted that
these reflections arrive well after the termination of the experimental signal from the capacitance sensor that is used and specified in the absolute sensor calibration procedure.

The FEM result prior to the reflections has a “shelf” with a constant value after the end of the Rayleigh-wave portion of the signal. This constant “shelf” was also observed in an analytical-calculation result that will be shown in a figure later in this paper. The gradual falloff of the experimental capacitance signal in the “shelf” region is characteristic of such a sensor, and it does not significantly affect the calibration due to the low frequencies involved, which are below those relevant to the AE sensor calibration.

**FEM Results from the Source Parameter Studies:**

*(a) Variation of the Temporal Shape of the Source Rise Time for a Fixed Rise Time*

Since the actual temporal shape and the rise time of the source generated by the glass capillary fracture are not known, different shapes and rise times were evaluated. Figure 3 demonstrates the FEM-based signals at the 100 mm propagation distance for three different temporal shapes of the source rise time. These three cases are shown in Fig. 4 for the normalized time dependence, $T(t)$, multiplied by the total force of 10 N and a rise time, $\tau$, of 0.3 $\mu$s. The temporal shapes, for other than the “linear” case, are the “cosine bell,” given by equation (1) and “sharp end,” which is given by equations (2) and (3). These temporal shapes have a range from smooth to abrupt starts and finishes.

$$
T(t) = \begin{cases} 
0 & \text{for } t < 0 \\
(0.5 - 0.5 \cos \left[\pi t/\tau\right]) & \text{for } 0 \leq t \leq \tau \\
1 & \text{for } t > \tau 
\end{cases}
$$

(1)

$$
T(t) = \begin{cases} 
0 & \text{for } t < 0 \\
1 - \text{erf} \left(\frac{t_2 - t_1}{\text{erf} (t_2)}\right) & \text{for } 0 \leq t \leq \tau \\
1 & \text{for } t > \tau, 
\end{cases}
$$

(2)

where

$$t_1 = t a^{1/2}$$

$$t_2 = \tau a^{1/2}$$

and

$$a = - \ln \left(0.5\right) / (3\tau/8)^2.$$

The other FEM conditions for the results in Fig. 3 were a source radius of 0.5 mm, cell size of 30 $\mu$m, and a time step of 4.5 ns. The time scale in Fig. 3 was expanded to “focus” on the region of the shear and Rayleigh wave arrivals where the amplitudes are significant. In this region, the most important features of the signal appear. The figure demonstrates the changes in the peak amplitude of the Rayleigh wave as the temporal shape of the source changes. Figure 3 also demonstrates the positive “overshoot” prior to the steady-state “shelf.” Finite-element results (not shown) demonstrated that the magnitude of the “shelf” depended only on the total force release of the source, and the amplitude of the complete FEM signal depended linearly on the value of the total force over the range from 10 N to 20 N that is applicable in the calibration process.

*(b) Variation of the Source Rise Time for a Fixed Temporal Shape*

Figure 5 demonstrates, for the “focus” region of the shear and Rayleigh waves, that the peak magnitude of the Rayleigh wave decreases as the rise time increases from 0.2 $\mu$s to 0.4 $\mu$s. The net result is a 12% decrease in the Rayleigh wave peak amplitude for the longer rise time com-
pared to that for the shortest rise time. The FEM parameters for these runs were a source radius of 0.5 mm, cell size of 30 µm, a “sharp-end” rise-time temporal shape and a time step of 4.5 ns.

Fig. 3 Changes in shear/Rayleigh wave region as the temporal aspect of the source rise-time changes.

Fig. 4 Temporal shapes of rise time shown for a 0.3 µs rise-time and 10 N force.

Fig. 5 Increasing the source rise-time (for the three values shown) decreases the peak amplitude of the Rayleigh wave.

Fig. 6 Two different source radii (values shown) show large differences in the Rayleigh wave peak amplitude.

(c) Variation of the Source Spatial Size
The radius of the source region upon which the normal stress was applied was examined for a 1-mm and a 0.14-mm radius. These values were chosen based on some of the results reported in part I [2]. Part I showed that the loading (from the glass capillary) on the top surface of the block results in a normal stress that is approximately elliptical in shape, with major and minor axis values of about 2 mm by 0.28 mm, respectively, at a total load of 10 N. Figure 6 demonstrates in the
“focus” region a large drop of 39% in the Rayleigh peak amplitude when the source radius increased from 0.14 mm to 1 mm. It should be pointed out that the result for the large radius did not show an “overshoot.” The FEM parameters for these runs were a rise time of 0.35 µs, cell size of 12.5 µm, a “cosine bell” rise-time temporal shape and a time step of 1.9 ns.

Fig. 7 Reference experimental signal from capacitance sensor with “overshoot” and “shelf.”

Fig. 8 Analytical result for non-dimensional out-of-plane displacement versus non-dimensional time for various non-dimensional rise times [6].

(d) Examination of the Positive “Overshoot”
Figure 7 shows for the “focus” region the Rayleigh wave, the “overshoot” and the drooping of the “shelf” for the experimental capacitance sensor signal [5]. As shown in Fig. 8, an analytical result [6] for three different finite rise times does not show an “overshoot”. (Note that the polarity of the source function is opposite in this figure versus the other results in this paper.) These analytical results are relevant to the current work, because the results are for finite rise times. To
examine as realistically as possible the “overshoot” by use of the FEM axisymmetric code, the normal stress loading as determined in part I [2] was averaged over 26 circular “rings,” each 0.046 mm wide. By this means, the elliptically shaped region of normal stress loading was approximated in a way that could be used with the axisymmetric code. Figure 9 shows the loading approximation as a function of radius from the center of the surface loading on the steel block. This input spatial loading distribution was used for a “cosine bell” temporal loading with a 0.3-μs rise time and a series of ever smaller cell sizes until the resultant out-of-plane displacement signal at the 100 mm propagation distance converged with no “overshoot.” The FEM conditions for the converged result were a cell size of 12.5 μm and a time step of 1.9 ns. It was found that these displacement results could be resampled to a time step of 25 ns without changing the resulting signal. This fact led to a conclusion that the small cell size and time step of the original converged run was required only for the immediate region of the source. Figure 10 shows the 25 ns time-step result (note this time step supports a Nyquist frequency of nearly 20 MHz) as well as the result after a 6 MHz low-pass Butterworth infinite-response filter of order six was applied to the 25 ns time-step data. This filter resulted in no “overshoot” and did not change the Rayleigh wave peak amplitude. It did result in the small time delay shown in Fig. 10.

To examine the results for a frequency bandwidth closer to that expected for the experimental system, the same type of low-pass filter was applied (to the 25 ns data) with cutoffs at 3 MHz and also 2 MHz. As Fig. 11 shows, these filters caused the “overshoot” to appear and the amount of “overshoot” to be the largest for the 2 MHz low-pass data. Figure 11 includes the experimental result with an “overshoot” that appears to be similar to that from the 2 MHz low-pass result. Since the sampling rate of the experimental system is 20 MHz, it appears that there is some other hardware aspect of the experimental system that reduces the upper frequency of the bandwidth so as to induce the “overshoot.” Figure 11 also shows that the filtered Rayleigh wave peak amplitudes with the 0.3 μs rise time are close to that of the experimental result. Thus, it appears that the release of the normal stresses from the glass capillary fracture is not a step in time. This observation is supported by the result in Fig. 5, which shows that a rise time of 0.2 μs results in
an increase in the peak amplitude of the Rayleigh wave of 6.4 % compared to a rise time of 0.3 μs. It is to be expected that a step rise-time source would result in an even greater increase in the Rayleigh wave peak amplitude, and this amplitude would be much higher than the experimental and 0.3-μs FEM results. This observation is also supported by the fact that a step rise-time for a point source results in infinite amplitude of the Rayleigh wave [7]. It is important to point out that the ASTM test method E1106-07 that describes the absolute AE sensor calibration states that the calibration applies only up to a frequency of 1 MHz. Thus, the upper limitation in the frequency bandwidth of the experimental system does not change the accuracy of the test method calibration.

Fig. 11 Comparison of capacitance sensor signal and filtered FEM signal at indicated low-pass frequencies.

Comments relating to the ASTM Absolute AE Sensor Calibration Test Method

ASTM test method E1106-07 [1], as currently written, presents two approaches for absolute calibration of AE sensors. The approach using the output from a capacitance sensor that measures the out-of-plane displacement is described in detail so as to provide a result (which is required for an ASTM test method) for the calibration of a sensor. An alternate approach to the absolute sensor calibration is based on an analytical solution (see, e.g., reference [7]). The specifics of the use of this approach to provide a sensor calibration result are not described in E1106-07 [1]. This analytical solution assumes a point source and step-in-time force release. However, Part I [2] of this paper shows that the glass capillary source is not a point source. The dynamic FEM results shown here demonstrate that changes in the parameters of temporal shape of the source rise time, source rise-time value and dimensions and distribution of the region of the surface normal stress result in changes in the shear/Rayleigh wave (which dominates the wave generated). Since these parameters are unknown in the current calibration procedure and can be expected to vary from one experimental glass-capillary fracture to the next, it is not clear how the analytical solution could be rationally modified to provide a method to achieve a test result (only
the total force released is measured in the calibration). Further, it is not clear how to measure these additional parameters. In addition, as already pointed out, the amplitude of the Rayleigh wave from the analytical solution is infinite [7]. This fact results in another complication with respect to the analytical solution. Thus, it is recommended that the parts of the ASTM test method that refer to the use of an alternate approach for an AE sensor calibration by use of an analytical calculation be modified. The resulting calibration test method would be based on the use of the capacitance sensor, which would in fact have an output that includes the effects of the unknown parameters and thus provides the needed reference signal for the absolute calibration. It is important to point out in this regard that AE sensor calibrations at NIST Gaithersburg from 1982 [8] until the summer of 2009 [5] were done using the output from the capacitance sensor.

Conclusions

- Changes in the spatial distribution and spatial size of the normal-stress source from the glass capillary result in changes in the Rayleigh wave peak amplitude.
- Changes in the temporal rise time and shape also result in changes in the Rayleigh wave peak amplitude.
- Since use of a capacitance reference sensor accounts for the above spatial and temporal aspects for glass capillary fractures, it is recommended that use of an alternate calibration approach using an analytical solution, which presently cannot rationally account for the actual values of these parameters, be modified in E1106-07.

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References

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