Time-domain Analysis of Resonant Acoustic Nonlinearity Arising from Cracks in Multilayer Ceramic Capacitors

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Abstract. Acoustic nonlinearity of cracked and uncracked multilayer ceramic capacitors (MLCCs) was characterized through time-domain analysis of resonant waveforms following tone-burst excitation. A phase-sensitive receiver was employed to measure the phase, relative to a reference sinusoid, of decaying oscillations of a resonant mode near 1 MHz that was excited through ferroelectric coupling within the barium-titanate-based ceramic of the MLCC. Amplitude dependence of the resonant frequency during decay of the oscillations was characterized through measurements of changes in the resonant phase versus time. Waveforms were analyzed by fitting the recorded RF amplitude versus time to a decaying exponential and inserting the parameters of this fit into a second function to fit the time-dependent phase, with amplitude dependence of the resonant frequency incorporated in the second function. The measurements and analyses were performed on unmounted type-1210 MLCCs before and after quenching in ice water from elevated temperatures. This thermal treatment generated surface-breaking cracks in a fraction of the specimens. Measurements of a nonlinear parameter $B$ of the capacitors before quenching were used to set a range corresponding to plus and minus three standard deviations ($\pm3\sigma$) relative to the mean of a Gaussian fit to the distribution of this parameter. 93% of the values of $B$ determined for heat-treated MLCCs with cracks were outside of this $\pm3\sigma$ range of the as-received MLCCs, while only 10% of the values of $B$ for heat-treated MLCCs without visible cracks were outside this range. These results indicate that time-domain nonlinear measurements with tone-burst excitation are a promising approach for rapid nondestructive detection of cracks that have no significant initial effect on the electrical characteristics of an MLCC but can evolve into conductive pathways during service and lead to electrical-device failure. They also illustrate the potential of this approach for nonlinear acoustic detection of structural flaws in other materials.

Introduction

The failure of multilayer ceramic capacitors (MLCCs) is often a limiting factor in the reliability of electronic devices in which these capacitors are incorporated[1]. Despite substantial advances in manufacturing techniques, the ceramic material in MLCCs remains vulnerable to cracking under stress during manufacture, soldering, and service[2]. Such cracks can eventually evolve into conducting pathways, leading to drainage of power sources or total device failure. Therefore, nondestructive methods are needed for detecting the presence of cracks in MLCCs before their deployment in devices. This need is especially critical for applications in which the effects of device failure can be catastrophic or replacement is impossible, costly, and/or dangerous, such as implantable medical devices and spacecraft.

Established methods for industrial screening of MLCCs before and after mounting in devices include automated visual inspection, X-ray inspection, acoustic microscopy, and measurements of electrical leakage current. As summarized by Erdahl and Ume[3], these methods can fail to detect subsurface cracks that have not yet evolved into...
conducting pathways. In particular, none of these methods has adequate sensitivity to the presence of nonconducting cracks near the corners beneath the endcaps, where stresses are likely to be greatest[3].

A number of alternate approaches for detecting cracks in MLCCs have been previously explored[2, 3, 4, 5, 6, 7, 8], and the relative advantages, disadvantages, and limitations of some of these approaches have been discussed by Erdahl and Ume[3] (through 2004) and Teverovsky[2] (through 2008). Over the past several years, our research in this area has employed resonant ultrasound spectroscopy (RUS) and electromechanical resonance[6, 7, 8]. In two previous studies[7, 8], we explored the sensitivity of nonlinear acoustic measurements to the presence of cracks. An advantage of this approach over linear acoustic spectroscopy is that nonlinear measurements are based on relative shifts in resonant frequency or harmonic amplitude as a function of excitation amplitude[9] and, therefore, are insensitive to variations in frequencies that arise from dimensional variations of the MLCCs.

The study reported here is an extension of a previous study[8] that focused on the dependence of resonant frequencies on the amplitude of resonant tone-burst excitation of type-1210 MLCCs with and without visible cracks that were generated by thermal quenching from elevated temperatures. In that previous work, resonant frequencies were found to shift approximately linearly with excitation amplitude, and the magnitudes of these shifts were found to be strongly correlated with the presence of visible cracks. For the particular set of capacitors studied, an acceptance criterion based on the 95% probability interval of a Gaussian fit of a parameter characterizing the amplitude dependence of frequencies of as-received MLCCs was found to lead to 89% of quenched MLCCs with visible cracks being rejected. The current report is focused on extracting values of nonlinear amplitude dependence of MLCC frequencies from an analysis of the time dependence of the phase during ringdown. This analysis employs waveforms that were acquired in parallel with the frequency measurements presented in our earlier report[8]. The primary motivation for pursuing this alternative approach is that it is expected to eventually enable more rapid characterization of acoustic nonlinearity, because it does not require acquisition of data at multiple excitation levels.

Specimens

The 41 samples in this study are MLCCs manufactured by Vishay Intertechnology1, with model number VJ1210Y474KXAA1T. The specifications of these MLCCs include X7R performance (Electronic Industries Alliance standard), type 1210 geometry (metric type 3225), 0.47 µF capacitance, and 50 V maximum operating voltage. Figure 1 shows a photograph of one of the ceramic faces and metal endcaps of one of these MLCCs. The detailed geometry and nominal material compositions have been described by Johnson et al.[8]. Based on measurements performed on seven representative MLCCs, the overall dimensions were determined to be 1.40 mm ± 0.02 mm, 3.04 mm ± 0.01 mm, and 2.46 mm ± 0.01 mm, where the indicated uncertainties are standard deviations of the measurements. The core of these MLCCs contains 70 electrodes with a thickness of 2.0 µm ± 0.2 µm interleaved with layers of doped polycrystalline BaTiO3. The average periodicity of the interleaved layers is 16.38 µm ± 0.05 µm.

FIGURE 1. Photograph of an MLCC specimen, showing the largest ceramic face and metal endcaps.

1Identification of this commercial product is provided for technical completeness and does not reflect an endorsement by NIST.
After initial acoustic measurements, the MLCCs were subjected to a thermal treatment that induced crack generation in a fraction of the samples. The samples, in sets of ten, were heated in a box furnace to 189.0 °C ± 0.1 °C, as determined by a thermocouple in contact with a stainless-steel tray containing the samples. After stabilization at this temperature, the set of MLCCs was removed from the furnace and immediately dropped into ice water. A microscopic vicinal illumination technique similar to that described by Burns et al.[12] was used to identify near-surface cracks induced by the thermal treatment.

**Experimental Methods**

Ferroelectric transduction[5, 8] was employed to excite and detect resonant modes in the MLCCs. As shown in Fig. 2, DC bias voltages supplied by a battery or a voltage source were applied to the MLCC through a resistor, which limited the current through the capacitor in the event of a crack or other structural flaw evolving into a short in the MLCC during acoustic measurements. A RITEC RAM-5000 SNAP system was used to provide radio-frequency (RF) tone bursts at ≈ 1 MHz with a duration of 0.2 ms. This output was passed through an active diplexer to isolate the receiver during the driving tone burst, through a 100 nF capacitor to isolate the gated amplifier and receiver from the DC bias voltage, and, then, to the MLCC. Electrical connection to the MLCC electrodes was implemented with steel sewing pins lightly pressed by elastic bands against the centers of the endcaps. Loaded DC voltages were 32.3 V ± 0.1 V across the as-received MLCCs and 30.0 V to 32.4 V across the heat-treated MLCCs. The greater variation in DC bias for some of the heat-treated MLCCs is associated with depletion of battery voltages that occurred when low-resistance pathways developed in some MLCCs during acoustic measurements. Variations in DC voltages affect the strength of resonant excitation. However, as described below, the analysis of acoustic nonlinearity is normalized to the time-dependent amplitude of the measured RF input to the receiver. Therefore, the extracted nonlinear parameters are not affected by variations in the DC voltages across the MLCCs.

![Diagram](image)

**FIGURE 2.** Block diagram of the electronic system.

Two RF drive levels were employed in this study. The analysis of time-dependent changes in frequency is focused on signals acquired with a peak-to-peak RF driving voltage of 21.83 V ± 0.07 V across the MLCCs. As described below, frequencies were also measured with a relatively low drive level of 0.57 V ± 0.05 V, and these values were employed in fitting of the time-dependent phase during ringdown.

Resonant RF signals from the MLCC during free decay (“ringdown”) after tone-burst excitation were passed to the receiver of the RITEC system and then to phase-detector modules within this instrument to extract the time-dependent in-phase and out-of-phase components of the signal, relative to the reference driving sinusoid that was gated to generate the tone burst. These components were digitized and passed to a computer.

Slight intrinsic nonlinearity of the gain of the receiver and relative gain imbalances of the two phase-detector channels of the RITEC instrument were determined through measurements with a series of levels of continuous sinusoidal RF voltages as input to the receiver. Calibration functions derived from these measurements were used to compensate acquired waveforms. Compensation for electronic DC offsets in the phase-detector voltages was implemented by acquiring and averaging the baseline voltages acquired before each tone burst.

The relative time-dependent phase φ(t), which is equal to the arctangent of the ratio of the out-of-phase and in-phase signal components, was calculated at each recorded time point. Apart from any time-dependent phase noise
or drift associated with electronics, temperature, or external perturbations, the instantaneous time derivative of $\phi(t)$ during ringdown is given by [11]

$$\frac{d\phi}{dt} = 2\pi [f_{res}(t) - f_{ref}],$$

(1)

where $f_{res}(t)$ is the resonant acoustic frequency of the sample in free decay, and $f_{ref}$ is the frequency of the reference sinusoid that is gated to generate the driving tone burst.

As described elsewhere [8], the average resonant frequency during each ringdown was estimated during repeated measurements of each MLCC, and the drive frequency $f_{ref}$ for the subsequent tone burst was adjusted in real time to match this estimate. This procedure facilitated tracking of relatively slow changes in $f_{res}(t)$ that were found to occur after the DC bias voltage was introduced. These changes are tentatively assumed to arise from time-dependent alignment of ferroelectric domains.

**Finite-element Calculations**

Peterson *et al.* [10] performed finite-element calculations of the resonant frequencies and displacement patterns obtained from a model with external geometry, internal structure, elastic constants, and material densities that approximate those of the capacitors employed in this study. One result from those calculations is presented here. The calculated displacement pattern for the dominant mode that is excited with the ferroelectric transduction method described above is shown in Fig. 3. This mode is estimated from the calculation to have a frequency of 0.977 MHz, which is within 1% of the average measured resonant frequency (0.99 MHz) of as-received MLCCs in this study.

![Finite-element calculation of the displacement pattern of a vibrational mode of an MLCC excited with a resonant frequency calculated to be at 0.977 MHz. Red outlines indicate the undeformed shape of the MLCC.](image)

**FIGURE 3.** Finite-element calculation of the displacement pattern of a vibrational mode of an MLCC excited with a resonant frequency calculated to be at 0.977 MHz. Red outlines indicate the undeformed shape of the MLCC.

The displacement pattern shown in Fig. 3 involves predominantly extensional displacements along the intermediate dimension (horizontally in Fig. 3 (b)) and corresponding Poisson contraction in the other perpendicular directions. Consistent with the approximate symmetry of the internal electrodes and corresponding symmetry of the driving excitation, the symmetry elements of the deformation pattern include all of the symmetry elements of the undeformed capacitor. In group-theoretical notation, the symmetry of this mode corresponds to the $A_{1g}$ irreducible representation of the orthorhombic point group $D_{2h}$ (in the Schoenflies notation)[10]. This mode has the third lowest resonant frequency of the $A_{1g}$ modes.

**Measurements and Analysis**

Fig. 4 shows an example of measurements of the time-dependent in-phase component $PhDet1$ and out-of-phase component $PhDet2$ of the signal from an MLCC, after amplification within the RF receiver module of the RITEC.
instrument. The timescale in this figure is referenced to the beginning of the 0.2 ms tone burst. Fig. 5 shows the corresponding time-dependent magnitude $A(t)$ of the RF signal at the input to the receiver, given by

$$A(t) = \frac{(\text{PhDet1})^2 + \text{PhDet2}^2)^{1/2}}{\text{receiver gain}}. \tag{2}$$

where the receiver gain is specified by the user.

During resonant ringdown, RF voltages across an MLCC are generated within the DC-biased ferroelectric of the interleaved core through piezoelectric coupling to the vibrational strain. Therefore, the RF amplitude $A(t)$ is proportional to the instantaneous vibrational amplitude of the resonant mode during ringdown for a given MLCC. Variations in the geometry of the interleaved core and the ferroelectric domain structure may affect piezoelectric coupling efficiency. However, in this study, this efficiency is assumed to be the same for all of the samples. The RF amplitude is, therefore, taken to be a consistent relative measure of vibrational amplitude.

Fig. 6 shows $\phi(t)$ determined from the phase-detector data of Fig. 4:

$$\phi(t) = \arctan(\text{PhDet2}/\text{PhDet1}). \tag{3}$$

The change in the ratio of PhDet2 and PhDet1, which is obvious from inspection of Fig. 4, has led to the time dependence of $\phi(t)$.

For a nonlinear resonator with a frequency that is approximately linearly dependent on vibrational amplitude $A(t)$,

$$f_{\text{ref}}(t) = f_0 - BA(t), \tag{4}$$

where $B$ is a measure of the magnitude of the nonlinearity and $f_0$ is the frequency in the limit of infinitesimally small vibrational amplitude. In all of the measurements in this study, $A(t)$ is closely approximated by an exponential during ringdown:

$$A(t) = A_0e^{-\alpha t}, \tag{5}$$

Therefore, the time-dependent resonant frequency is predicted to be closely approximated by

$$f_{\text{ref}}(t) = f_0 - BA_0e^{-\alpha t}. \tag{6}$$

The corresponding time derivative of $\phi$ is given by inserting this expression into Eq. 1:

$$\frac{d\phi}{dt} = 2\pi(f_0 - f_{\text{ref}}) - 2\pi BA_0e^{-\alpha t}. \tag{7}$$

This equation can be integrated to provide a functional form for $\phi(t)$:

$$\phi(t) = 2\pi(f_0 - f_{\text{ref}})t + \frac{2\pi BA_0}{\alpha}e^{-\alpha t} + \phi_0, \tag{8}$$

where $\phi_0$ is a constant during a given ringdown, arising partly from a phase shift in the electronics.

The value of $f_{\text{ref}}$ is known for each acquired waveform, since it is automatically set and recorded by the software controlling the experiment. Although the low-amplitude frequency $f_0$ could be taken as an adjustable parameter in the fitting of data, this approach was not employed here. Instead, approximate values for $f_0$ were determined from measurements of resonant frequency with a relatively low tone-burst excitation level of 0.57 V peak to peak. These measurements were repeatedly performed alternately with the measurements at the higher excitation amplitude. $f_0$ was determined from the measured $\phi(t)$ under the assumption that the amplitude dependence during the ringdown at this excitation level was insignificant. In other words, the exponential term in Eq. 7 was neglected in fitting $\phi(t)$ at this excitation level. This approximation is considered valid in light of previously reported measurements of the amplitude dependence of resonant frequencies in these MLCCs[8].

To improve signal-to-noise ratios before fitting the data obtained from the MLCC samples, measurements of $\phi(t)$ from multiple waveforms were averaged after subtracting, for each waveform, the term in Eq. 8 that is linearly dependent on time. The resultant functional form of this averaged quantity $\bar{\phi}'(t)$ is a simple exponential plus a constant $\phi_0'$:

$$\bar{\phi}'(t) \equiv \frac{1}{n} \sum_{i=1}^{n} [\phi_i(t) - 2\pi(f_0 - f_{\text{ref}})t] = \frac{2\pi BA_0}{\alpha}e^{-\alpha t} + \phi_0'. \tag{9}$$
FIGURE 4. Phase detector voltages $PhDet_1(t)$ and $PhDet_2(t)$ versus time $t$ during the ringdown of an as-received MLCC after excitation with a 0.2 ms 21.8 V peak-to-peak tone burst. The zero of the time is defined to be the beginning of the toneburst.

FIGURE 5. RF amplitude $A(t)$ calculated from the data in Fig. 4 through the use of Eq. 2. The receiver gain is 10.0 ± 0.1 for this waveform.
Phase $\phi(t)$ calculated from the data in Fig. 4 through the use of Eq. 3.

The data from a series of ten waveforms were averaged for each MLCC, before and after heat treatment, over a period of 22 min beginning $\approx 10$ min after application of the DC bias. These sets of waveforms correspond to those employed in our previous report[8] that was focused on the dependence of the frequencies on excitation level. Therefore, this selection of data enables a direct comparison to be made of the results obtained here with the results obtained in the earlier study. An average $\tilde{A}(t)$ of the measured $A(t)$ from the ten waveforms was fit to a simple exponential (Eq. 5) to extract values of $A_0$ and $\alpha$ for each sample before and after heat treatment. These values were then inserted into the function on the right side of Eq. 9, and $\tilde{\phi}'(t)$ was fit to this function. Fig. 7 shows an example of $\tilde{\phi}'(t)$ obtained from an as-received MLCC, along with a least-squares fit of Eq. 9 to the data between 0.34 ms to 0.39 ms. The exclusion of points before 0.34 ms in the fit reduces potential contributions associated with incomplete electronic recovery from the tone burst, and exclusion of points after 0.39 ms reduces contributions from noise at low signal levels. This time interval was employed for all of the fits of $\tilde{A}(t)$ and $\tilde{\phi}'(t)$ in this study.

One feature that stands out in the plots of Fig. 7 is that the magnitude of the differences between the data and the fit curve increases at longer times (after $\approx 0.41$ ms). Since the calculated $\phi$ is a function of the ratio of the phase-detector voltages, it is highly sensitive to noise and any systematic errors in these voltages. This fact is reflected in the increasing scatter of the measurements at longer times, which is much more pronounced than the scatter in the RF amplitude (Fig. 5). However, the systematic divergence of the data and fit in Fig. 7, which is not atypical of the data from other MLCCs in this study, suggests that there is a systematic error in the data or the assumptions of the analysis that has a more pronounced effect at lower signal amplitudes. The time point at which the data and the fit begin to substantially diverge is $\approx 0.41$ ms, corresponding to an RF amplitude of $\approx 0.01$ V (Fig. 5) and phase-detector voltages of 0.05 V to 0.07 V (Fig. 4). Specific possibilities for systematic errors and an estimate of the associated uncertainties in extracted values of $B$ are discussed below.

The distribution of $B$ values determined through the above procedure for all the as-received MLCCs was found through a Shapiro-Wilk test to be statistically consistent with a Gaussian distribution $(p = 0.52)$. A Gaussian fit to these data yields a maximum of the distribution at $B = 19.31 \times 10^3$/Vs and a standard deviation of $3.2 \times 10^3$/Vs. This Gaussian fit is plotted in Fig. 8 along with values of $B$ determined from MLCCs with and without visible cracks after heat treatment. No acoustic measurements were performed on four cracked MLCCs that were electrically shorted. Values of $B$ for four additional heat-treated samples are not plotted in Fig. 8 because their inclusion would expand the scale of the x-axis so much that comparisons with the Gaussian distribution for the as-received samples would not be clear.
Comparisons of the data in Figure 8 are pursued by considering the number of heat-treated samples with and without cracks that had values of $B$ well within the Gaussian distribution of the MLCCs before heat treatment, defined arbitrarily to be the range of $B$ within three standard deviations ($\pm 3\sigma$) of the Gaussian mean (the range bounded by the dashed lines in Fig. 8). The integral of the Gaussian over this range of values of $B$ is 0.997, corresponding to a 99.7% probability of as-received capacitors being in this range. All of the values of $B$ for the 41 as-received samples in this study are within this range. 25 out of 27 (93%) of the heat-treated capacitors with visible cracks were found to have values of $B$ outside the selected range, while only 1 out of 10 (10%) of the heat-treated capacitors without visible cracks was found to have a value of $B$ outside this range. These results are similar, with respect to the fraction of cracked and uncracked samples inside and outside the selected ranges, to those previously reported[8] for the dependence of frequencies on excitation level measured on the same samples.

An additional interesting feature of the data in Fig. 8 is that all of the values of $B$ of heat-treated MLCCs without visible cracks are greater than the mean of the Gaussian. This result provides statistically strong evidence for a shift in the distribution of $B$ of these heat-treated MLCCs relative to that of the as-received MLCCs. Potential causes of such a shift include quenching-induced changes in ferroelectric-domain structure and the presence of small cracks that were not optically detected.

Returning to the issue of the divergence of the data and the fitted curve in Fig. 7, two general possibilities for systematic errors are considered: (1) the values of $f_0$ that are employed in the analysis are, for some reason, incorrect, and (2) the measured phase detector voltages include contributions associated with a lack of complete recovery of the electronics following tone burst excitation. The idea that the measured $f_0$ is substantially different from the limit at infinitesimal excitation amplitude is inconsistent with the sign of the discrepancy between the data and the fit in Fig. 7, because, to bring the data closer to the fit would require $f_0$ to be decreased (i.e., in the direction of increased nonlinearity). Another possibility for inaccuracy of $f_0$ is that the acoustic excitation physically affects the nonlinearity of the MLCCs and this effect does not recover on the timescale of the measured ringdown. This possibility was explored by varying the value of $f_0$ in the calculation of $\hat{\phi}'(t)$ (Eq. 7) to see whether the data could be manipulated in this way to more closely match the fit. The conclusion of this analysis is that $f_0 - f_{ref}$ would have to be reduced by more than a factor of two to bring the data close to a fit to the revised data at intermediate times, but the time-dependence of the data would still be substantially different from an exponential at the longer times. Therefore, an acoustically-induced physical change in nonlinearity cannot fully explain the divergence of the data and fit in
Fig. 7. The other possibility that there are unidentified contributions to the phase-detector voltages was analytically explored by introducing DC offsets to these data. Although this approach was found to bring the data in much closer alignment with corresponding fits, the resultant curves for PhDet1(t) and PhDet2(t) were found not to be credible, because they do not decay to zero at long times. Finally, the possibility of residual time-dependent contributions to the phase-detector voltages was experimentally explored through measurements of PhDet1(t) and PhDet2(t) without an MLCC being connected to the gated amplifier. These measurements showed that, in this configuration, there are time-dependent voltages with magnitudes as great as 2.7 mV over the measured period of 0.34 ms to 0.50 ms, and these voltages vary as much as 1.5 mV during this period. These voltages were measured relative to the baseline before the tone burst, which, as described above, was used as a reference in the measurements on the MLCCs. Based on these preliminary tests, the discrepancies between the data and the fitted curves for $\phi(t)$ are considered likely to arise from residual time-dependent recovery of the phase detectors on the order of 1 mV to 3 mV during the ringdown. The associated systematic errors in values of $B$ reported here are estimated to be less than 5%, based on initial fitting with various offsets introduced to the phase-detector voltages.

Conclusions

Acoustic nonlinearity of MLCCs has been characterized in this report through measurements and analysis of the dependence of resonant frequencies on vibrational amplitude during ringdown following tone-burst excitation. The method of using measurements of phase during ringdown to extract nonlinear parameters from a continuous fitting function has, to our knowledge, not been previously employed. Previous time-domain analysis of acoustic nonlinearity has been performed with RF waveforms[13, 14]. However, that analysis was performed with incremental fitting or incremental Fourier transformation of RF waveforms during ringdown, rather than fitting to a continuous function.

This study provides evidence for a strong correlation of acoustic nonlinearity with the presence of visible cracks generated by stress during thermal quenching. For the particular samples studied, an acceptance criterion based on the $\pm 3\sigma$ probability interval of a Gaussian fit to the distribution of measurements on as-received MLCCs led to 93% of the MLCCs with visible cracks being rejected.
A great advantage of the presented approach over acoustic spectroscopy (which has also been found to be sensitive to the presence of cracks[6]) is that the measurements are based on relative shifts in resonant frequency as a function of vibrational amplitude and, therefore, are insensitive to variations in frequencies that arise from dimensional variations of the MLCCs. The specific use of time-domain analysis with tone-burst excitation offers the advantage of reduced measurement time, relative to measurements of resonant frequencies at multiple drive levels (although, in this initial study, data at multiple drive levels were also acquired). The specific approach of internal ferroelectric transduction employed for acoustic excitation offers the further practical advantage of not having to rely on external transducers or lasers for excitation and being easy to implement through simple electrical contact.

The results presented here illustrate that the determination of time-dependent phase is increasingly sensitive to small voltage offsets in the outputs of the phase detectors as signal levels approach the baseline during ringdown. Systematic deviations of the phase data from the predicted functional form (Eq. 9; Fig. 7) indicate the presence of significant time-dependent offsets of this type. Although these offsets are not estimated to have a substantial effect on the values of the nonlinear parameter extracted from fitting of the data earlier in the ringdown, the acquisition of more accurate measurements will require such time-dependent phase-detector offsets to be eliminated or reduced in the measurements and/or analysis.

The demonstrated method of time-domain nonlinear acoustic measurements and analysis is a promising approach for rapid nondestructive detection of cracks in MLCCs before electrical failure. Therefore, further research should be pursued to quantify levels of detection. Such research should include an exploration of correlations of nonlinear acoustic measurements with cracks below the ceramic surfaces and/or beneath the endcaps, and this is anticipated to require the implementation of destructive methods for independently detecting and characterizing subsurface cracks in MLCCs.

REFERENCES


