ELECTRO-MECHANICAL RESPONSE SIMULATION OF ELECTROSTATIC VOLTMETERS USING MSC/NASTRAN

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ABSTRACT

This paper describes the application of the MSC/NASTRAN to simulate the electro-mechanical behavior of in situ electrostatic voltmeters. These "tuning fork" style transducers are used to continuously monitor photoconductor voltage during xerographic copier and printer operation. Voltmeter theory of operation is discussed, and finite element model development is detailed showing a 6% correlation of natural frequency with empirical results. From an existence proof, model boundary conditions were adjusted to show correct voltmeter dynamic response. Based on this empirical behavior, structural design modifications were made to the model until similar dynamic response was analytically achieved. These modifications were then applied to the hardware and correct performance was empirically verified. Conclusions and recommendations on future work are also cited.

1. INTRODUCTION

A main requirement for successful xerographic process control is the continuous monitoring of electrostatic charge on the photoconductor. This investigation was conducted in order to correct a problem with a new electrostatic voltmeter (ESV) design which displayed erratic behavior when used with existing controller hardware. Since changes in the controller design was not an option, a change in the mechanical design of the ESV was the only recourse. The "tuning fork" style transducer, which electro-mechanical operation is similar in theory to the crystals once used in watches and other precision time related devices, was simulated using MSC/NASTRAN. From an existence proof showing correct behavior was possible with a boundary condition adjustment, a well correlated model was first used to simulate this behavior. Since manufacturing tolerances would not allow a mounting change, modifications to the geometry were made to produce similar corrected behavior. The end result of this activity enabled a more reliable ESV as well as help achieve a 2 to 1 cost savings.

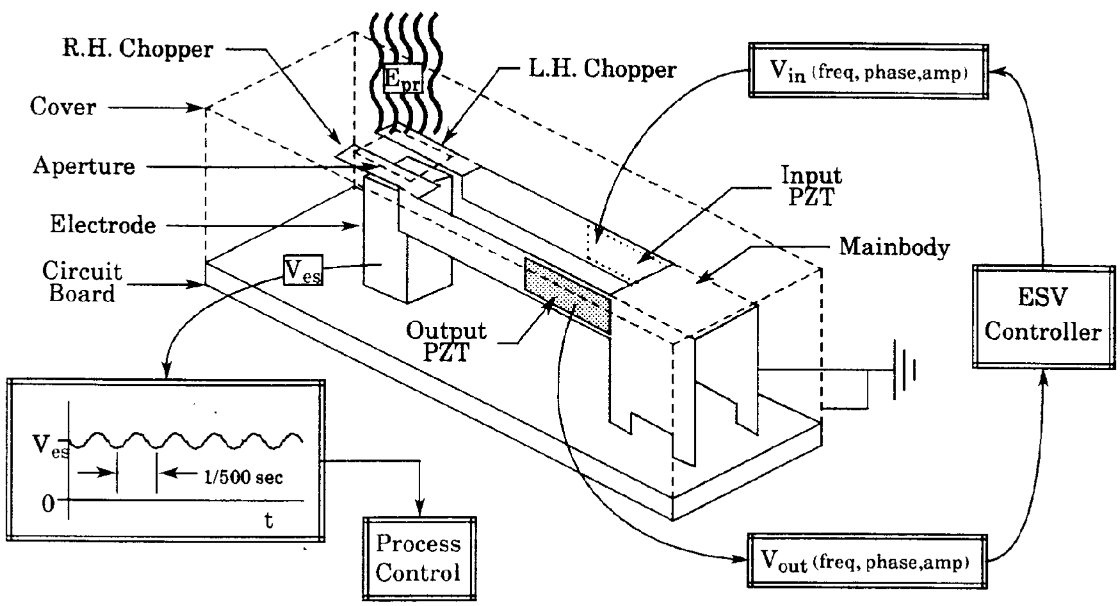

Figure 1. Schematic of the baseline electrostatic voltmeter design and operation.
(not to scale)

2. THEORY OF OPERATION

The electrostatic field of the charged photoconductor, E_{pr}, is modulated by mechanically varying the entrance aperture between the pickup electrode and the photoconductor. This modulates the capacitance between surfaces thus creating a signal which is representative of the photoconductor charge voltage, V_{es}. The mechanical variation of the entrance aperture is accomplished by oscillating the tuning fork with "chopper" plates in close proximity to the aperture as depicted in figure 1.

The closed loop ESV Controller receives a voltage, V_{out}, generated from piezoelectric crystal deformation (Output PZT), which is a function of frequency, phase and amplitude, and supplies a voltage to the other piezoelectric crystal (Input PZT). The input voltage, V_{in}, distorts the Input PZT thereby exciting the chopper arms. V_{in} is controlled to be 180 degrees out-of-phase to V_{out} so as to excite the fundamental asymmetric mode of vibration and cause the choppers to vibrate opposite one another and modulate the incoming field at around 500 hz. To keep ESV electronics simple and inexpensive, V_{in} is applied as a square wave.

It will be shown later that this tuning fork style crystal has symmetric and asymmetric modes which are nearly coincidental in frequency. Because of this it has been hypothesized that these modes conflict and are the cause of erratic behavior.

3. MODELING PROCEDURE

The finite element method[1] and MSC/NASTRAN[2] were used to simulate ESV behavior. Figure 2 shows the finite element model constructed of CQUAD4 shell elements representing the sheet metal mainbody and chopper arms, and CHEXA8 solid elements representing the PZT* material. The PZT

<u>Sheet Metal / NiCr Steel Alloy</u>
$E = 26.5 \times 10^6$ psi
$v = 0.29$
$Q = 5000 \rightarrow \zeta = 0.0001$
$t = 0.010$ inch

<u>Piezoelectric Crystal / Vernitron PZT5H</u>
$E_{ave} = 7.9 \times 10^6$ psi
$v = 0.31$
$Q = 65 \rightarrow \zeta = 0.0077$
$d_{21} = d_{31} = -1.07 \times 10^{-8}$ in/volt
$d_{33} = 2.33 \times 10^{-8}$ in/volt

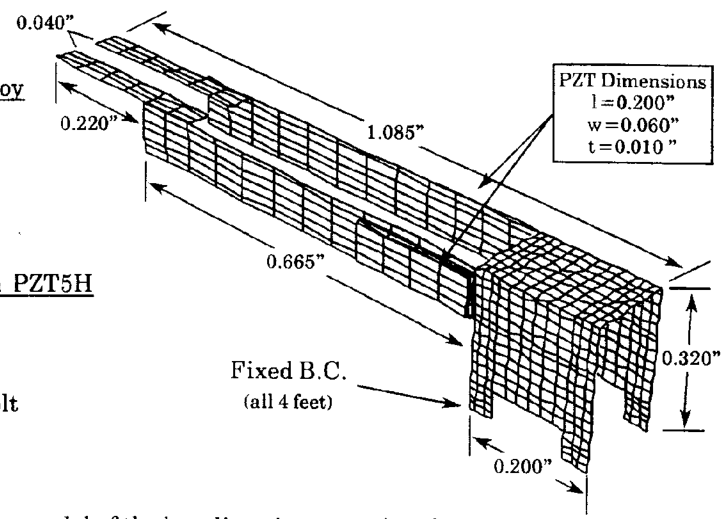

Figure 2. Finite element model of the baseline electrostatic voltmeter design.
(elements and boundary distortion is due to graphics resolution)

material was assumed to be rigidly attached to the chopper arms. In reality, the PZT is attached to the chopper arms with adhesive. Since the compliance of the adhesive was not represented, slightly higher response frequencies are expected due to less compliance. Slightly larger response amplitudes are also expected do to better energy transmission from the Input PZT to the chopper arm.

The boundary conditions were assumed fixed to ground at all four (4) feet since soldering to the circuit board is typical manufacturing practice. Consequently, the circuit board was assumed "massive" and "rigid" and was not modeled. Later it will be shown that when the front feet of the ESV model were aloud to float, the response of the PZT changed as was observed empirically in the lab.

The sheet metal is a nickel-chromium steel alloy that exhibits very low damping properties. The elastic and mass properties were supplied the material vendor and the damping constant was found in reference 3. The piezoelectric properties were found in reference 4.

The PZT electro-mechanical behavior was simulated using the thermal expansion properties of the MSC/NASTRAN analysis code. Prior to the system model being exercised, a static analysis of the PZT alone was run to verify the correct behavior of overall expansion and contraction when a simulated voltage was applied. PZT is typically anisotropic, however a complete description of the 3-D elasticity constants were unavailable with the exception of the piezoelectric charge coefficients (d_{31} and d_{33}). Therefore, the elastic coefficients were represented as isotropic materials and the charge coefficients were represented as anisotropic materials.

The Input PZT was excited as in actual ESV behavior. The Output PZT voltage, V_{out}, was not simulated since the control system was not being modeled. However, Output PZT structural representation is necessary to simulate correct dynamic behavior. To enable a frequency response analysis, V_{in} was assumed to be sinusoidal. This difference between sine wave excitation in the analytical model vs. square wave excitation in the hardware is not expected to effect the outcome of the analysis and will provide a clearer and more complete analytical understanding of ESV behavior.

*PZT is a trade name used by Vernitron Piezoelectric Division to describe piezoelectric material.

4. RESULTS - BASELINE DESIGN/ANALYSIS

Figure 3 shows the first two (2) calculated natural frequencies and modeshapes of the ESV. For correct ESV operation, it is desirable to excite the asymmetric mode of vibration. This causes a dynamic change in aperture size which modulates the DC electrostatic field. Exciting the symmetric mode of vibration would not cause a change in aperture size and render the ESV inoperable. An early and important outcome of this analysis was the observation of these two (2) closely spaced modes. These modes of vibration were not observed empirically but it is believed that they contribute significantly to erratic ESV behavior.

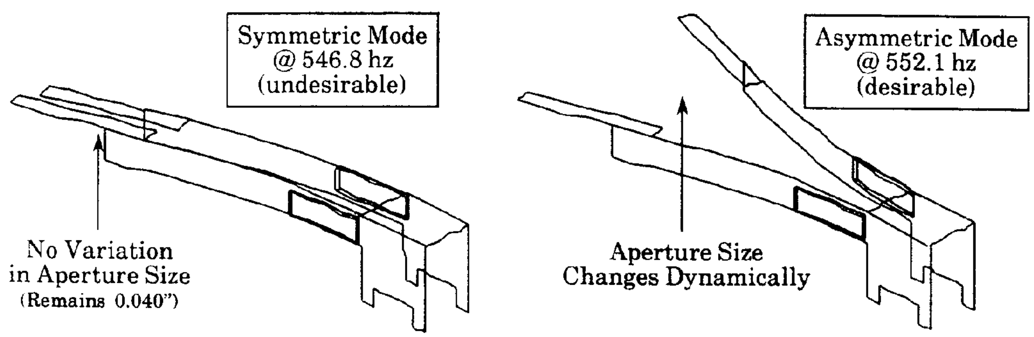

Figure 3. 1st and 2nd vibratory modes in the 0 to 1000 hz frequency range.

Empirical natural frequency results were available for ESV's with and without PZT bonded to the chopper arms. The analytical model of the ESV without PZT yielded natural frequencies of 420.7 and 423.4 hz for the symmetric and asymmetric modes of vibration, respectively, as compared to a measured value of 420 hz. This excellent correlation dropped to analytical values of 546.8 and 552.1 hz compared to an empirical value of 520 hz when the PZT was represented. The reason for this decreased correlation is attributed to not representing the elasticity of the PZT bond in the analytical model and is consistent with higher calculated natural frequencies. The difference in natural frequency correlation is not expected to effect the outcome of this study. Therefore, additional modeling of PZT bond elasticity was not undertaken.

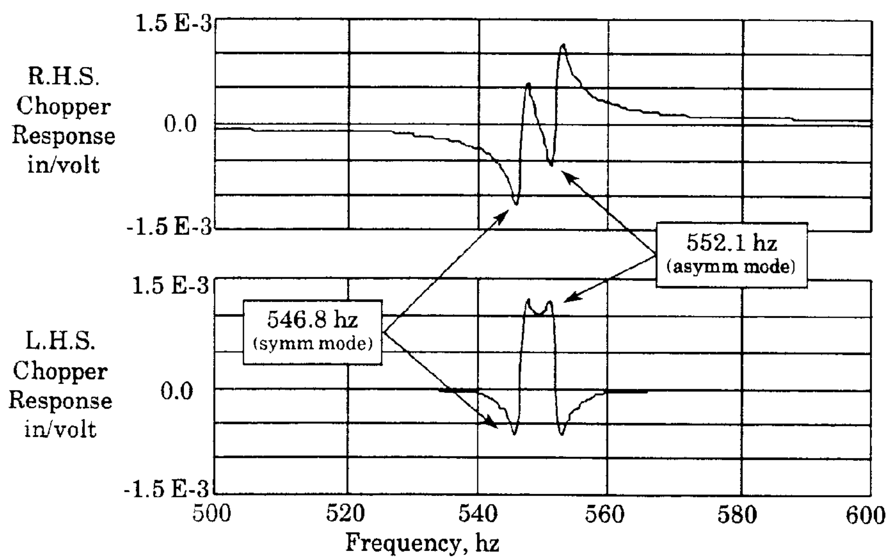

Figure 4. Right hand and left hand side chopper response in 500 to 600 hz range.

Figure 4 shows individual chopper tip displacement response per unit volt excitation of the Input PZT. As is noted in figure 4, the mode at 546.8 hz shows the displacement response of both choppers to be the same sign (ie. both + or both - for the same frequency) indicating they are moving in phase with one another. The mode at 552.1 hz shows the response of the left hand and right hand sides to be of opposite sign indicating that the aperture formed by the choppers is opening and closing dynamically. Figure 5 shows a plot of relative chopper response indicative of a change in aperture size. Note that there is only response at the 552.1 hz frequency since the choppers are moving opposite one another as shown in figure 4.

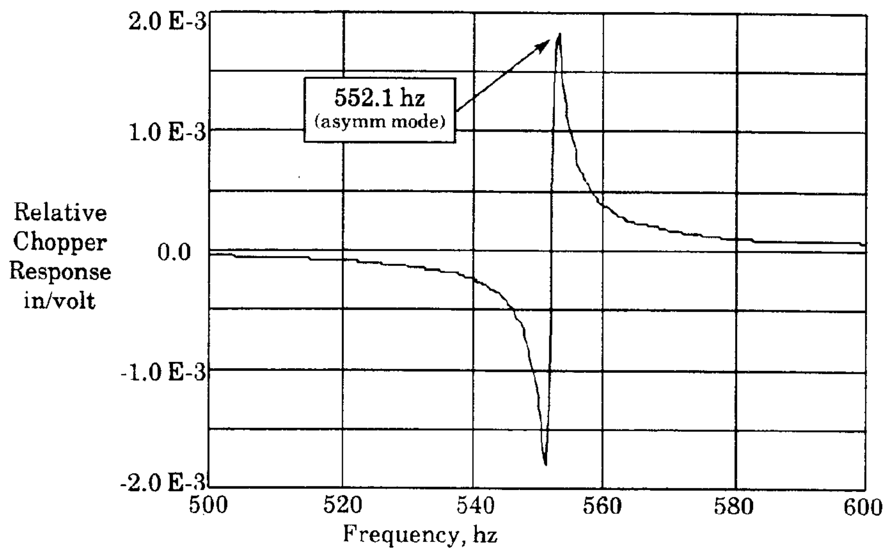

Figure 5. Relative chopper response indicative of aperture size change.

Empirical data suggests a ±0.010 inch aperture change during normal ESV operation. The results in figure 5 indicate a ±0.00175 inch displacement response per volt of PZT excitation. Assuming a V_{in} of 12 volts, a predicted aperture variation ±0.021 inch can be expected. The difference in the results is not surprising for a number of reasons. First, the PZT bond was not represented in the analytical model. From an excitation standpoint, bond elasticity would have likely acted as a filter to prevent complete exchange of excitation energy from the PZT to the chopper arm. Also, the viscoelastic properties of the bond would act to attenuate the chopper response. Secondly, the damping properties of the NiCr steel alloy were estimated and will vary depending on temperature and exact metal composition. The assumed value could be lower than in the actual ESV.

Finally, the circuit board mechanical properties were not represented along with the interface between the board and the mounting feet which were assumed to be perfectly rigid. All of these differences could easily offset the predicted results. The differences in response frequency and amplitude will not effect the outcome of the study as long as the modeling assumptions remain consistent throughout.

5. RESULTS - ERRATIC BEHAVIOR AND CORRECTION

With a representative model of the ESV in hand, design modifications and simulated changes in response where made to correct the erratic behavior observed in the lab. Laboratory observations showed that the ESV operability was corrected when the front or the rear feet of the ESV were allowed to float by not being soldered to the circuit board. This boundary condition was simulated in the model depicted in figure 2 resulting in the response shown in figure 6.

The most important thing to note in figure 6 is the large separation in frequency between the symmetric and asymmetric modes of vibration. The separation of 80 hz in contrast to less than a 6 hz

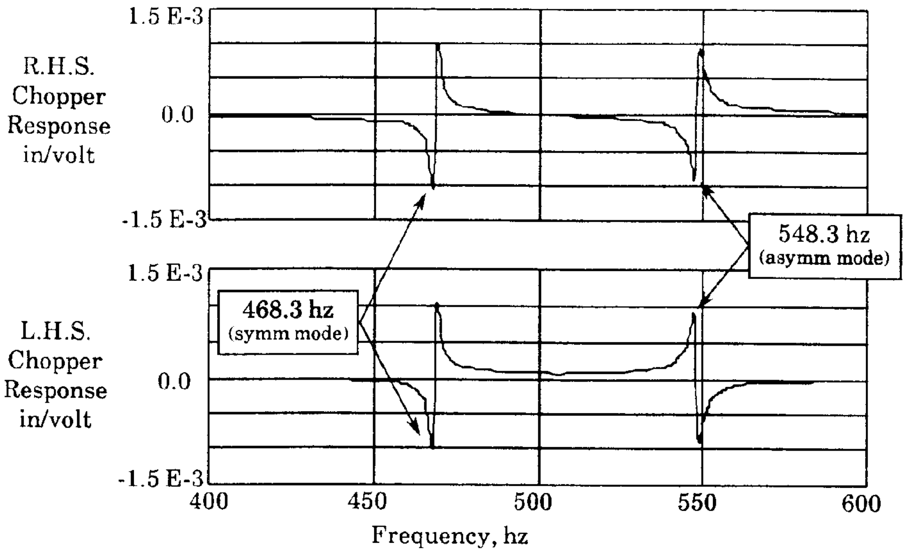

Figure 6. Response of the baseline design with "unconstrained" front feet.
(note change in frequency scale)

separation shown previously in figures 3 and 4, coupled with correct behavior, lead to the hypothesis that a "large" separation in these modes is necessary for correct ESV operation.

However, it is necessary to solder all four (4) feet of the ESV to the circuit board to maintain a critical dimension between the choppers and the cover of the ESV. The alternative was to try to modify ESV geometry to simulate the effects of the floating front feet without compromising the critical mounting dimensions. The design constraints were 1) only tooling modifications used to form the ESV structure were possible and 2) the existing ESV circuit board design could not change.

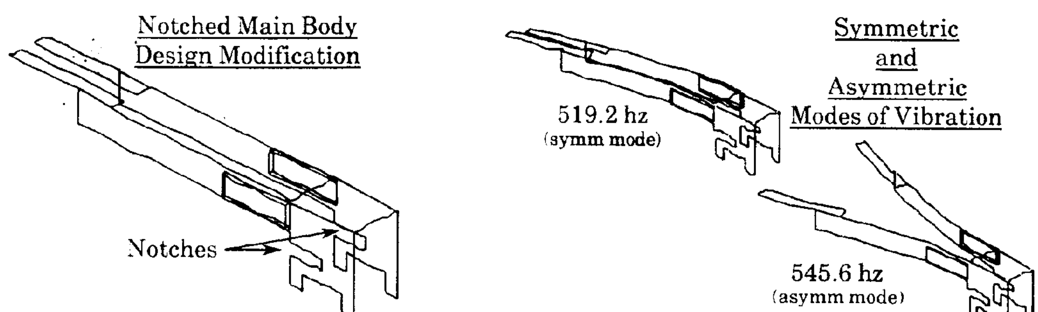

Figure 7. Schematic of the notched mainbody design, natural frequencies and modeshapes.

Since the mechanical effect of freeing up the front feet was to induce additional compliance to the front part of the ESV mainbody under the chopper arms, an alternate way to simulate the additional compliance was to remove some amount of material from under the chopper arms. This was done by adding a rectangular slot or "notch" on both sides of the ESV mainbody as shown in figure 7. The notch geometry was sized to add enough compliance to the front of the ESV to help decouple the two (2) frequencies but not too much compliance to affect critical mounting requirements. This was accomplished with several computer model iterations. The placement of these notches should be symmetric from side to side.

Also shown in figure 7 are the first two (2) natural frequencies and modeshapes of the modified design. Figure 8 shows similar response characteristics as previously observed in figure 6. The frequency separation is only about 26 hz but could be increased with further analysis. Another important outcome is that chopper amplitude is not affected by the change in geometry. The addition of these notches to ESV hardware exhibiting erratic behavior was implemented in the lab and was successful in correcting erratic behavior.

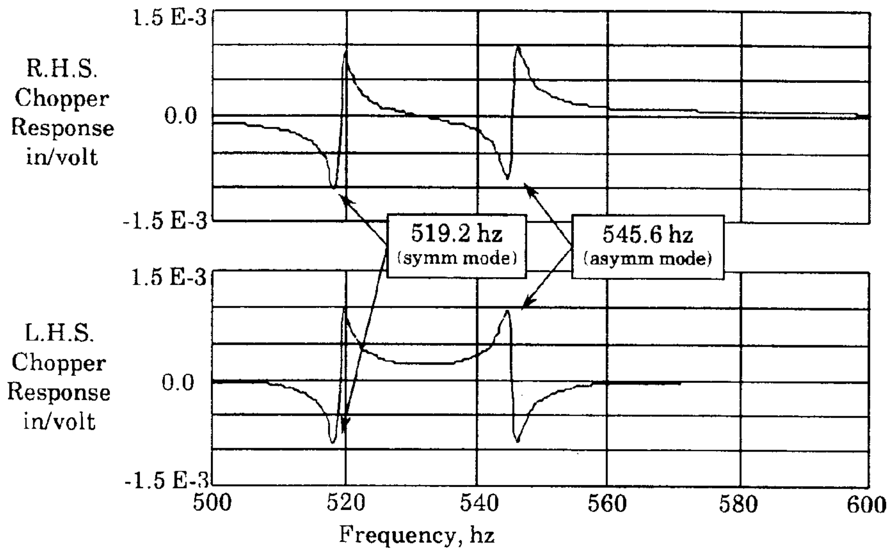

Figure 8. Response of the notched mainbody design.

6. CONCLUSIONS

The electro-mechanical behavior of electrostatic voltmeters was successfully simulated using the finite element method. Not only where correlated models developed but the ability of the finite element method to easily simulate modifications to the structural continuum led to a modified design which rectified erratic ESV behavior.

Because of the investigation into erratic behavior, it was hypothesized that closely spaced modes were an undesirable design condition which should be avoided. It was further speculated that in practice, tolerance variations could even cause the symmetric and asymmetric modes to be exactly coincidental in frequency. Thus, when the control system tries to excite the desirable asymmetric mode the undesirable symmetric mode also is excited.

7.RECOMMENDATIONS

It is recommended that tooling be modified to accommodate the notches in the ESV mainbody, since the notches had such a profound affect on rectifying the erratic ESV behavior. Additional analysis should be performed to optimize notch geometry. The additional work could show notch geometries with larger frequency spreads in symmetric and asymmetric modes of vibration. This will minimize the suspected role of manufacturing tolerances on coupling of closely spaced modes.

"Sine sweep" or other forms of frequency response testing to develop response curves similar to the ones that were analytically developed in this report would be extremely useful in future ESV development efforts. Modal tests to empirically derive and depict the modes of vibration would be even more enlightening. Along with these test methods, a non-contact transducer for response measurement would be necessary. A laser vibrometer is the transducer of choice. Unfortunately, it is also the most costly.

Modeling of the control system to gain a better understanding of the structural/controller interactions is possible and should be considered. This would significantly increase the analytical effort but would also increase the system level understanding of ESV's.

Finally, it is highly recommended that future ESV development be directed by the use of the finite element method and MSC/NASTRAN.

8. REFERENCES

1) Cook, R.D., Concepts and Applications of Finite Element Analysis, 2nd edition,John Wiley & Sons, New York, Copyright 1981.

2) MSC/NASTRAN User's Manual, Version 65, Vol.I and II, The MacNeal-Schwendler Corp., Los Angeles, Copyright 1985.

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4) "Modern Piezoelectric Ceramics," Product Catalogue, Vernitron Piezoelectric Division, 232 Forbes Road, Bedford, Ohio, 44146-5478.