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Sensitivity Analysis of the 47A Signal

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The 47A Signal is the physical component of 1D-type electronic coin telephones which detects coin deposits and consequently initiates the transmission of coin-deposit information to the central office. Manufacturing problems encountered in initial production units of the Signal prompted Bell Laboratories to investigate the Signal design and operation. Rather than resort to a series of time-consuming empirical experiments to quantify the interaction of various Signal design parameters and their influence on Signal performance, we formulated a finite element model of the Signal's coin sensor. Consequently, these experiments could be performed via computer. This computer-based sensitivity analysis led to the conclusion that the coin sensor design was highly susceptible to manufacturing variables. By changing the dimensions of one of the coin sensor components, a piezoelectric ceramic, this susceptibility was eliminated. The computer-based experiment was, therefore, demonstrated to yield rapid, easily interpretable results. Moreover, resource usage was minimized when compared to a conventional laboratory approach. The results of the computer-based experiment were confirmed by production data.

I. INTRODUCTION

Proper coin telephone performance results in the transmission of coin deposit information to the central office. Simply stated, if a coin passes a series of tests at the coin telephone station set, it is determined to be valid and its denomination, also detected at the station set, constitutes the information transmitted to the central office. This validation and detection process is statistical not only because of the complex interaction of mechanical and electrical subsystems at the station, but also because of the random nature of coin deposits. The physical attributes of the coins, as well as the introduction of the customer's deposit action, lends a statistical quality to coin deposits. As a result of this random feature, coin telephone and coin telephone subsystem designs are usually proven-in via large-scale experimentation involving the deposit of tens of thousands of coins.

1D-type electronic coin telephone sets use the 47A Signal to initiate the transmission of coin deposit information to the central office. During the initial production of this Signal, manufacturing difficulties surfaced. While testing these early units for compliance with performance criteria, it was determined that an unacceptable number of Signals in fact failed to meet that criteria. Production was halted, and Bell Laboratories was faced with investigating whether a design change could remedy the situation. The cause of the manufacturing difficulties had to be determined and then a solution had to be identified. These had to be done within a short time interval and with a high degree of confidence. Therefore, an alternative to the usual time-consuming hardware experimentation was clearly required.

Sensitivity analysis or, in this case, computer-based experimentation provided that alternative. The salient features of the 47A Signal performance, and only those features, were incorporated into simplified models. First, critical design parameters were identified which were thought to bear on the difficulties noted. Second, 47A Signal performance was expressed in terms of output voltage and related to the state of mechanical stress in the Signal's piezoelectric ceramic. Third, the dependence of the stress state on critical design parameters and coin deposit variability was determined by formulating a discrete model of the Signal's coin sensor via the finite element method (FEM). Consequently, a computer-based series of experiments could be performed. These would simulate conventional hardware experiments, but would vastly reduce the time and resources required and, in addition, increase the level of confidence in the results. The approach proved to be a successful one which not only pinpointed the cause of manufacturing difficulties but also facilitated the identification of a solution.

This paper illustrates the utility of FEMs in the solution of a frequently occurring class of design problems which are ordinarily approached via empirical methods. Section II briefly describes the design and operation of the 47A Signal. The program initiated at Bell Laboratories to address the manufacturing difficulties noted is introduced in Section III. This sets the stage for the description of the modeling techniques used (Sections IV through VI) and for the discussion of the computer-based experiment (Section VII). Salient results are shown in Section VIII and production data supporting these results are cited in Section IX.

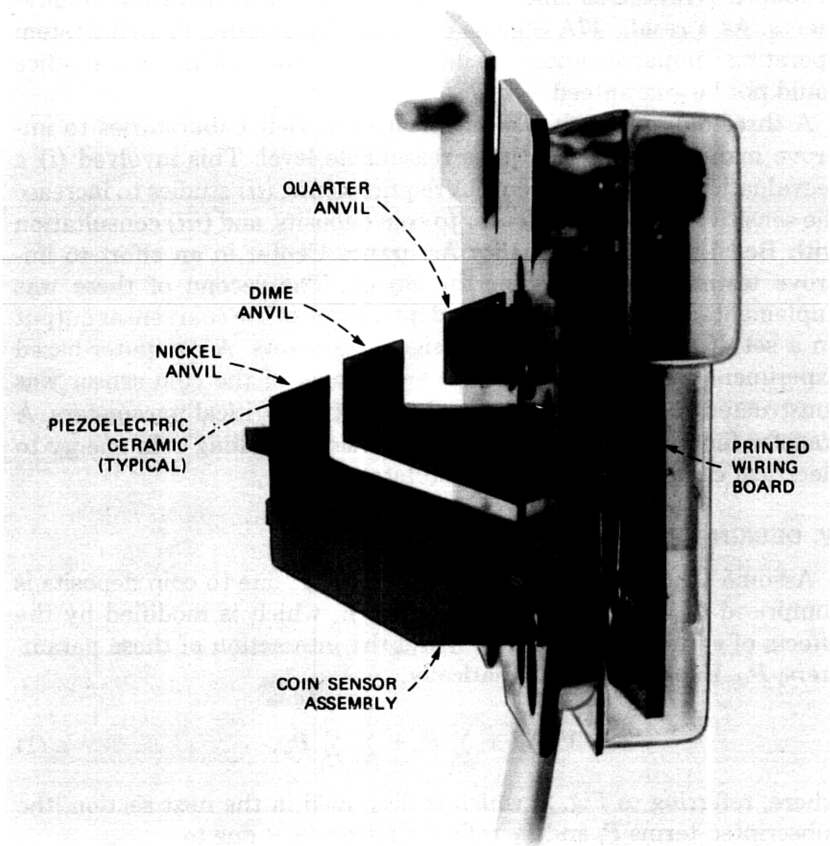

Fig. 1—47A Signal.

II. DESCRIPTION OF 47A SIGNAL OPERATION

The 47A Signal consists of a piezoelectric coin sensor assembly and a printed wiring board with its associated electronics (Fig. 1). The design and operation of the Signal is such that a valid coin deposited into a coin chute will strike either the nickel, dime, or quarter anvil of the coin sensor. This results in deformation of an embedded piezoelectric ceramic (PZT-5A, Gulton Industries), which causes a corresponding voltage to appear across the ceramic electrode surfaces. The 47A Signal circuitry transforms this time-dependent voltage into a form acceptable to coin registration logic. The central office is then notified of the denomination of the coin deposit and the call sequence is under way.

III. BELL LABORATORIES EFFORT TO IMPROVE MANUFACTURABILTY

During the fourth quarter of 1976, 28.5 percent of Western Electric-produced 47A Signals failed to meet coin-deposit registration requirements. As a result, 47A Signals could not be shipped to Bell System operating companies since coin deposit recognition at the central office could not be guaranteed.

A threefold approach was undertaken at Bell Laboratories to improve manufacturing yield to a reasonable level. This involved (*i*) a reevaluation of the Signal output requirements, (*ii*) studies to increase the sensitivity of the coin sensor to coin deposits, and (*iii*) consultation with Bell Laboratories Quality Assurance Center in an effort to improve testing procedures for the Signal. The second of these was implemented by investigating the dependency of the coin sensor output on a set of postulated critical design parameters. A computer-based experiment was designed, and an FEM model of the coin sensor was constructed to implement the variation of the critical parameters. A transfer function, to describe the conversion of falling coin energy to electrical ceramic output, was postulated.

IV. DESIGN OF THE EXPERIMENT

Assume that the ceramic output voltage, V, due to coin deposits is comprised of a population mean value, $\bar{\mu}$, which is modified by the effects of certain parameters, P_i, and the interaction of these parameters, P_{ij}. Expressed mathematically,

$$V = \bar{\mu} + \sum_{i=1}^{4} P_i + \sum_{i=1}^{4} \sum_{j=1}^{4} P_{ij}, \tag{1}$$

where, referring to Fig. 2, which is described in the next section, the subscripted terms P_i and P_{ij} reflect changes in V due to

$i = 1$, coin strike location, for which two states are permitted, center and offcenter, as depicted in Fig. 2,

$i = 2$, ceramic assembly* location, admitted anywhere in the field $0.060 \leq y \leq 0.120$, and between the nylon walls;

$i = 3$, ceramic dimensions, constrained only by the cavity size described ($i = 2$); and

$i = 4$, material properties of the ceramic environment, as represented by those portions of the sensor assembly designated in Fig. 2 as nylon and epoxy.

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* The ceramic assembly is comprised of the ceramic, its associated copper leads, and the silver conductive epoxy (Ablebond 36-2), which provides the conductive bond between them.

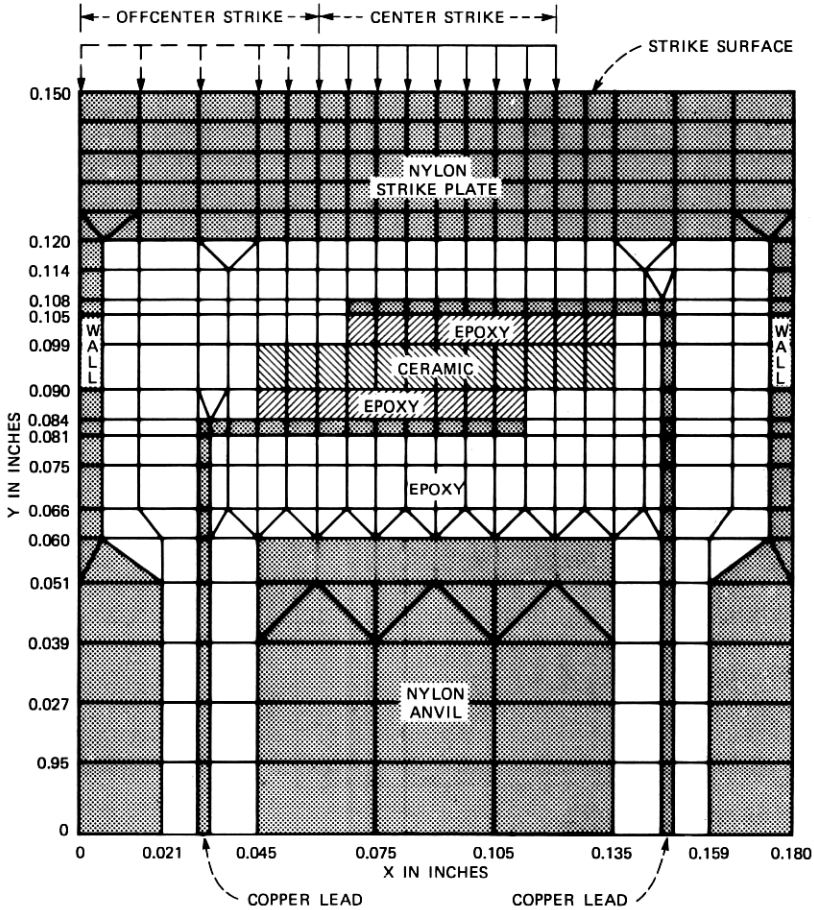

Fig. 2—Finite element representation of coin sensor.

Having the description of ceramic output voltage, as given by eq. (1), it remains to construct the FEM model of the coin sensor and to describe the voltage across the electrode surfaces of the ceramic in terms of the state of stress in the ceramic, caused by the coin deposit.

V. THE FEM MODEL OF THE COIN SENSOR

The FEM model of the coin sensor provides the medium for quantifying changes in the ceramic's stress state induced by the variance of the P_i and P_{ij} parameters of eq. (1). Indeed, the objective of the sensitivity analysis is the determination of changes in the ceramic's stress state, not the absolute state of stress in the ceramic. These changes can then be related to changes in voltage across the ceramic's electrode surfaces. It was decided that the two-dimensional FEM model of Fig. 2 accomplished this objective and that a state of plane stress would be suitable to describe the stress-strain relationship in the coin sensor. Furthermore, the coin sensor was assumed to behave in a linear-elastic manner; dynamic effects were not considered. The position of the input loads to the coin sensor, representing coin strikes, is shown in Fig. 2; the magnitude of the loads is assumed to be unity. This is consistent with the intent of the sensitivity analysis, since the presence of a coin chute upstream from the 47A Signal assures that all coins of a particular denomination will strike the sensor with approximately the same force.

The FEM model of the coin sensor provides the means to express coin strike information in terms of stress in the ceramic; the relationship between the ceramic's stress state and its voltage output will now be determined.

VI. THE TRANSFER FUNCTION

To simulate the generation of a voltage across the ceramic electrode surfaces such as would result from the impact of a falling coin, a suitable transfer function is needed. A simple formulation is

$$V = g_{yy} \sum_{i=1}^{N} \sigma_{yy}(x_i, y_i, z_i) \frac{(\Delta x \Delta z)_i}{A_{xz} h} + g_{yx} \sum_{i=1}^{N} \sigma_{xx}(x_i, y_i, z_i) \frac{(\Delta y \Delta z)_i}{A_{yz} h} \quad (2)$$

where, referring to Fig. 2,

g_{yy} and g_{yx} are the open circuit sensitivities of the ceramic along the y and x axes, respectively, when the ceramic is poled along the y axis (for the sensitivity analysis, g_{yy} is taken to be unity);

σ_{xx} and σ_{yy} are the normal stresses along the x and y axes;

Δx_i, Δy_i, Δz_i are the dimensions of the ith ceramic element ($\Delta z_i = 1$);

A_{xz} and A_{yz} represent the total ceramic areas parallel to the xz and yz planes, respectively;

h is the ceramic thickness;

N is the total number of ceramic elements; and

i is the running index for ceramic elements.

This formulation is derived by simplifying the piezoelectric relations[1,2] for the electrical strain induced by the state of stress in the ceramic. It should be noted that V does not represent true voltage, but only provides a vehicle for quantifying the ceramic's output so as to ascertain the effect of varying the parameters in eq. (1).

With eqs. (1) and (2) and Fig. 2, the computer-based experiment is completely described. Equation (1) provides a description of the experiment and eq. (2) describes a transfer function that yields an output voltage due to the state of stress in the ceramic. This state of stress is determined by using the finite element program PALOS[3] to calculate stresses, consistent with the two-dimensional representation of Fig. 2, which result from coin deposits.

VII. THE COMPUTER-BASED EXPERIMENT

Before the stresses computed from PALOS are used in eq. (2), it must be shown that they are sensitive to the input parameters of eq. (1) only, and not to the FEM discretization. This can be accomplished by establishing the convergence of the discretization by successively refining the FEM grid, comparing the resulting stresses, and terminating the refinement when the stresses differ by only a small, prescribed amount.

For this particular application, convergence of the voltage output function, V, of eq. (2) was demonstrated. The computer-based experiment was performed at a convergence level of 10 percent, which was economical and yet sufficient for the sensitivity analyses.

The computation of V from eq. (2) corresponding to a centered coin strike is defined to be unity when the material properties of Table I are used. All results due to parameter variations are so normalized. The influence of the parameters P_i and P_{ij} of eq. (1) on the voltage, V, will now be determined via the use of the transfer function of eq. (2).

In Fig. 3, the effect is investigated of the material environment ($i = 4$) in direct contact with the ceramic. It is observed that, for center strikes, parameter $i = 1$, maximum output is obtained using the lowest modulus material; for offcenter strikes, the opposite is true. The cause of such behavior is due to the fact that the ceramic's output results from both compression of the ceramic and its corresponding Poisson expansion. High modulus materials in contact with the ceramic introduce tractions on the ceramic's electrode surfaces which are sufficient to reduce Poisson expansion. For center coin strikes, this Poisson contribution is significant, and restricting it results in an overall reduction of the ceramic's output. This is not the case for offcenter

Table I—Material values

Material	E_1 [Modulus (Kpsi)]	υ_1 (Poisson's Ratio)
Epoxy	500	0.30
Nylon 6/12 (30 to 35 percent glass)	1,200	0.30
Ceramic	7,110	0.30
Copper	17,000	0.33

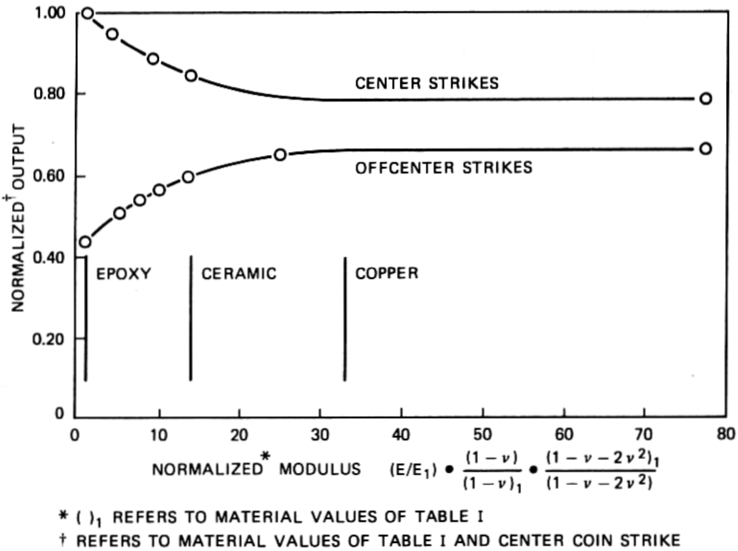

Fig. 3—Effect of environment modulus on ceramic output.

strikes, where rotations of the ceramic elements introduce displacements which contribute to the overall output. The conclusion drawn from Fig. 3 is that the use of high modulus materials in contact with the ceramic is not advisable, since the increased output realized for offcenter strikes is accompanied by decreased output for center strikes. This cannot be tolerated since coin strikes can occur anywhere on the coin strike surface depicted in Fig. 2.

In Fig. 4, parameters $i = 2$, ceramic assembly location, and $i = 3$, ceramic dimensions, are investigated in conjunction with parameter $i = 1$, coin strike location.

It is observed that the most practical method of achieving increased output is through the use of a larger ceramic. A rectangular (large) ceramic of dimensions 0.090″ × 0.140″ was chosen to replace the 0.0825″ square (small) ceramic of the original design. These dimensions represent the practical limitations imposed by the coin sensor cavity which houses the ceramic. For center strikes, the output increases range from 25 to 36 percent over that of the original design; for offcenter strikes, the increases range from 17 to 35 percent. Further, and ultimately of more significance, it is observed that the ceramic's output as originally designed is strongly dependent on the depth of the ceramic below the coin strike surface. It is postulated that the failure of some coin sensors to meet registration requirements is due to the fact that their ceramics are embedded at nonoptimum depths below the coin strike surface. This is unavoidable with current, manual

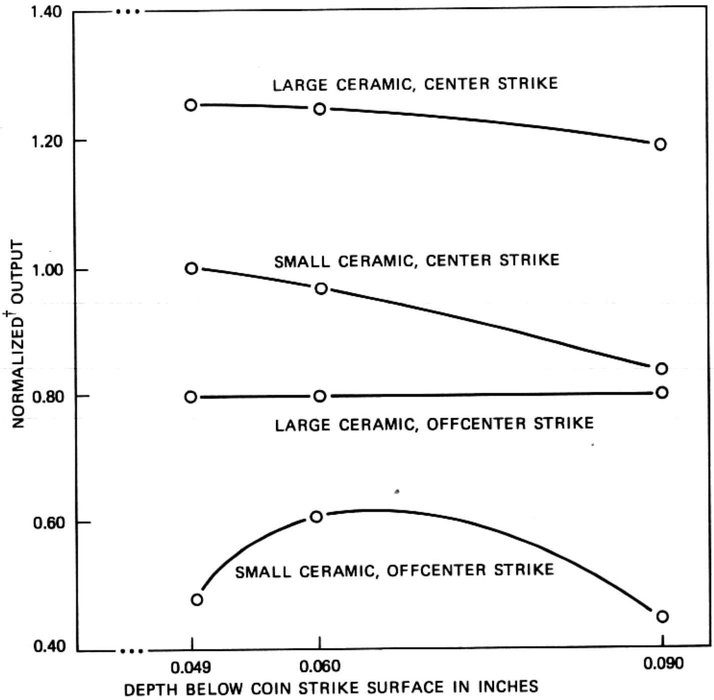

Fig. 4—Improved output capability of large ceramic.

manufacturing procedures. Especially for offcenter coin strikes, the ceramic's output in these cases is significantly reduced when compared to the output produced by optimally located ceramics. Use of the larger ceramic, however, results in negligible depth sensitivity.

VIII. RESULTS OF THE COMPUTER-BASED EXPERIMENT

The investigation of the 47A Signal coin sensor response to coin deposits was successfully implemented as a computer-based experiment through the use of FEM and the experimental design of eq. (1) in conjunction with the transfer function of eq. (2). The voltage output of the ceramic, V, was shown to be strongly modified by parameters P_1 through P_4; indeed, interaction between P_1 (coin strike location), P_2 (ceramic assembly location), and P_3 (ceramic dimensions), as well as between P_1 and P_4 (material properties), was identified. It was shown that improvement in the ceramic's output could be realized by suitable selection of the coin sensor ceramic dimensions, parameter P_3.

Of significance is the illustration that FEM-based experimentation provides an attractive alternative to hardware-oriented experimentation. The easily interpretable variances illustrated in Fig. 4 would have certainly been masked by variances induced during a hardware-oriented experiment by both coin sensor assembly tolerances and statistical errors. This masking could only have been overcome by the use of an extremely large sample of coin sensors and the actual deposits of thousands of coins, a procedure which is both time- and resource-consuming. Hardware-oriented results would have been obtained at a higher cost and at a later date and perhaps with a lower level of confidence. Insight into the physical phenomena would have been difficult to obtain via the hardware approach; it essentially comes at no cost via the computer-based experiment.

IX. PRODUCTION DATA IN SUPPORT OF RESULTS OBTAINED

Under the constraint of using the current coin sensor configuration (Fig. 1), the computer-based experiment predicts that 47A Signal manufacturing yield should be significantly improved by replacing the 0.0825″ square piezoelectric ceramic with a 0.090″ × 0.140″ rectangular one. Use of the larger ceramic should result in increased open circuit output amplitude and decreased sensitivity to mechanical assembly.

Design information was released to the Western Electric Works at Shreveport, La., on August 26, 1977, incorporating the use of the large ceramic. During September, 1977, Western Electric obtained production yield data on the first 100 large ceramic sensor units built. The data indicated an increase in yield from 80 percent (small ceramic) to 98 percent (large ceramic). This has been confirmed by 1978 and 1979 production data.

X. ACKNOWLEDGMENT

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REFERENCES

1. W. G. Cady, *Piezoelectricity*, Vol. 1, New York: Dover, 1964, p. 187.
2. Clevite Corporation, *Piezoelectric Technology Data for Designers*, 1965, p. 14.
3. G. L. Goudreau, R. E. Nickell, and R. S. Dunham, "Plane and Axisymmetric Finite Element Analysis of Locally Orthotrophic Elastic Solids and Orthotrophic Shells," University of California Report No. 67-15, August 1967.