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A. (1) Title of Research Project:

A DYNAMIC ANALYSIS OF PIEZOELECTRIC STRAINED ELEMENTS

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(4) Contract Number:

DAJA45-86-C-0005

(5) 4th Periodic Report

November 1987-May 1988

(7) "The Research reported in this document has been made possible through the support and sponsorship of the U.S. government through its European Research Office of the U.S. Army. ~~This report is intended only for the internal management use of the contractor and the U.S. Government.~~"

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B. (1) In the fourth part of study, following the third,¹⁻⁹ the review article¹⁰ concerned with the dynamic applications of piezoelectric crystals is checked with emphasis on its editing and styling, and the article with its 233 references is published. Then, an updated review of the open literature is prepared which deals with waves and vibrations in piezoelectric elements and especially in those elements subjected to residual stresses and strains. This survey article summarizes the advances and trends on the subject, and it will be written up for publication.¹⁰

To reproduce some or all the fundamental equations of nonlinear piezoelectricity in variational form, certain integral and differential types of variational principles are deduced from Hamilton's principle by augmenting it through the dislocation potentials and Lagrange undetermined multipliers. This work is checked, minor revisions are made, and then it is accepted for publication. The variational principles lead, as their Euler-Lagrange equations, to the fundamental equations of electroelastic solid with small piezoelectric coupling and those of piezoelectric solid subjected to initial stress. Similar variational principles are formulated for a thermopiezoelectric solid with or without initial stress. The generalized variational principles are extracted from the principle of conservation of energy by augmenting it again through Friedrichs's transformation. These principles recover those extracted from either Hamilton's principle² or the principle of virtual work^{3,6} for the case when the effect of temperature increment is abrogated. The variational principles derived are used in constructing the system of two-dimensional, approximate equations of, high frequency vibrations of thermopiezoelectric shell,¹¹ nonlinear vibrations of piezoceramic shell¹² and vibrations of thermopiezoelectric shell under a bias.¹³

By use of the methodology described in the Second and Third Interim Reports,¹⁴

the effect of material inhomogeneity and nonlinearity and that of temperature increment are studied in piezoelectric elements.^{11-13,16} First, the effect of material nonlinearity is investigated in piezoelectric shells and plates;¹⁴ this can be considered as an extension of our earlier treatment of vibrations of quartz bars.¹⁶ A finite series representation in terms of the thickness coordinate is employed for the field quantities of piezoceramic shell. The series expansions of field quantities are inserted into the appropriate variational principle formulated and the integrations are carried out across the thickness of shell. Thus, a system of two-dimensional, governing equations of piezoceramic shell coated with perfectly conducting electrodes is consistently derived in terms of the resultants of field quantities. The system of electroelastic equations accommodates the high frequency extensional, thickness-stretch and -shear and flexural motions as well as coupled nonlinear motions of piezoceramic shell of uniform thickness. Also, attention is confined to special cases, and it is shown that the resulting electroelastic equations agree with and contain certain earlier ones for the case when the effect of nonlinearity and/or the curvature effect are abrogated.^{3,7,17}

Paralleling to the derivation of the system of electroelastic equations of high frequency nonlinear vibrations of piezoceramic shell above, a system of governing equations is formulated for vibrations of piezoceramic shell accounting for coupling of mechanical, electrical and thermal fields. The differential type of variational principle formulated for thermopiezoelectricity together with the power series expansions of field quantities in the thickness coordinate is used so as to establish the system of two-dimensional equations of successively higher orders of approximation of piezoceramic shell. The system of electroelastic governing equations are properly truncated as deemed necessary in any particular motion of piezoceramic shell. Also, a theorem of

uniqueness is proved in solutions of the truncated system of electroelastic equations of thermopiezoelectric shell, and the sufficient face- and edge-conditions are enumerated for the uniqueness. This work will be presented in a forthcoming technical meeting.¹¹

As before, a system of two-dimensional electroelastic equations is derived for small dynamic fields superposed on a static linear bias of thermopiezoelectric shell.¹³ The appropriate variational principle and the linear expansions of field quantities in the thickness coordinate are used in a consistent derivation of the system of electroelastic governing equations of piezoelectric shell subjected to initial stress. The static version of the linear two-dimensional equations will be used to determine the static biasing stresses and strains under a variety of circumstances. The biasing stresses thus determined will be used in the system of electroelastic equations to compute the influence of the bias on the dynamic behavior of prestressed thermopiezoelectric shell. This work is submitted for presentation in a technical meeting.¹³

^{1*} Dökmeçi, M.C., "Recent Progress in the Dynamic Applications of Piezoelectric Crystals", Shock Vib. Dig., 20(2), pp.3-20 (1988).

^{2*} Dökmeçi, M.C., "Certain Integral and Differential Types of Variational Principles in Nonlinear Piezoelectricity", accepted for publication in IEEE Trans. Ultrason. Ferroelectrics Freq. Control.

^{3*} Dökmeçi, M.C., "Dynamics of Piezoceramic Shells under Initial Stress", paper presented at the 41st Ann. Freq. Cont. Symp., Philadelphia, PA., May 1987; to appear in Bull. Techn. Univ. Istanbul.

^{4*} Dökmeçi, M.C. and E.E. nanl'D., "Dynamics of Piezoelectric Rods under Initial Stresses", J. Acoust. Soc. Am., 81, pp. 573 (1987).

- 5* Dökmeci, M.C., E.E. nani'D. and N. SrgulD., "On Some Variational Principles in Contact Elasticity", Developments in Mechanics, Vol.14, pp.472-473, Purdue Univ., West Lafayette, India (1987).
- 6* Dökmeci, M.C., "The Principle of Virtual Work Applied to Nonlinear Piezoelectric Continuum and Associated Some Variational Principles", Abstr. Techn. Meet. Soc. Eng. Sci., pp.28, Univ. New York at Buffalo, N.Y. (1986).
- 7* Dökmeci, M.C., "Derivation of a Nonlinear Mathematical Model for Dynamics of Crystal Plates", paper at Sixth Int. Conf. Math. Modelling, St. Louis, Missouri, August 1987.
- 8* Dökmeci, M.C. and N. SrgulD., "Thermopiezoelectric Effects in the High Frequency Vibrations of Rods", paper at IEEE Ultrason. Symp., Denver, Colorado, October 1987.
- 9* Dökmeci, M.C., "Coupled Nonlinear Vibrations of Quartz Rectangular Bars", paper at 1st European Freq. Time Forum, Besancon, France, March 1987.
- 10* Dökmeci, M.C., "Piezoelectric Materials: Characteristics and Recent Advances and Trends in Dynamic Applications", forthcoming.
- 11* Dökmeci, M.C., "Thermopiezoelectric Equations of High Frequency Vibrations of Ceramic Shells," paper at the 115th Meet. Acoust. Soc. Am., Seattle, Washington, May 1988.
- 12* Dökmeci, M.C., "High Frequency Nonlinear Vibrations of Piezoceramic Shells", submitted for presentation.
- 13* Dökmeci, M.C. and N. SrgulD., "Dynamics of Thermopiezoelectric Prestressed Shells", submitted for presentation.
- 14* Mindlin, R.D., Lecture Notes on the Theory of Beams and Plates, Columbia University, New York (1968); see also, R.D. Mindlin and Applied Mechanics, Pergamon Press, London (1974).
- 15* Dökmeci, M.C., "Shell Theory for Vibrations of Piezoceramics Under a Bias", submitted for publication.

^{16*} Dökmeçi, M.C., "Nonlinear Electroelastic Equations of Wave Propagation and Vibrations in Quartz Bars", Proc. 40th Ann. Freq. Control Symp., pp.168-178, IEEE, New York (1986).

^{17*} Dökmeçi, M.C., "On the Higher Order Theories of Piezoelectric Crystal Surfaces", J. Math. Phys., 15, pp.2248-2252 (1974).

B. (2) In the remainder of the contract period, certain numerical solutions will be obtained by use of the lower order electroelastic equations of piezoelectric elements derived in the earlier parts of study, the papers presented at the technical meetings will be prepared for publication in periodicals and the draft final technical report will be written up.

B. (3) The author will attend and present the paper entitled "Thermopiezoelectric equations of High Frequency Vibrations of Ceramic Shells" at the 115th Meeting of the Acoustical Society of America, Seattle, Washington, May 1988, he will attend the 42nd Annual Frequency Control Symposium, Baltimore, Maryland, June 1988, and he will meet the interested people and discuss some problems on the subject at the two meetings and the universities.

(*) is used to designate the research sponsored in part by the United States Army through its European Research Office.