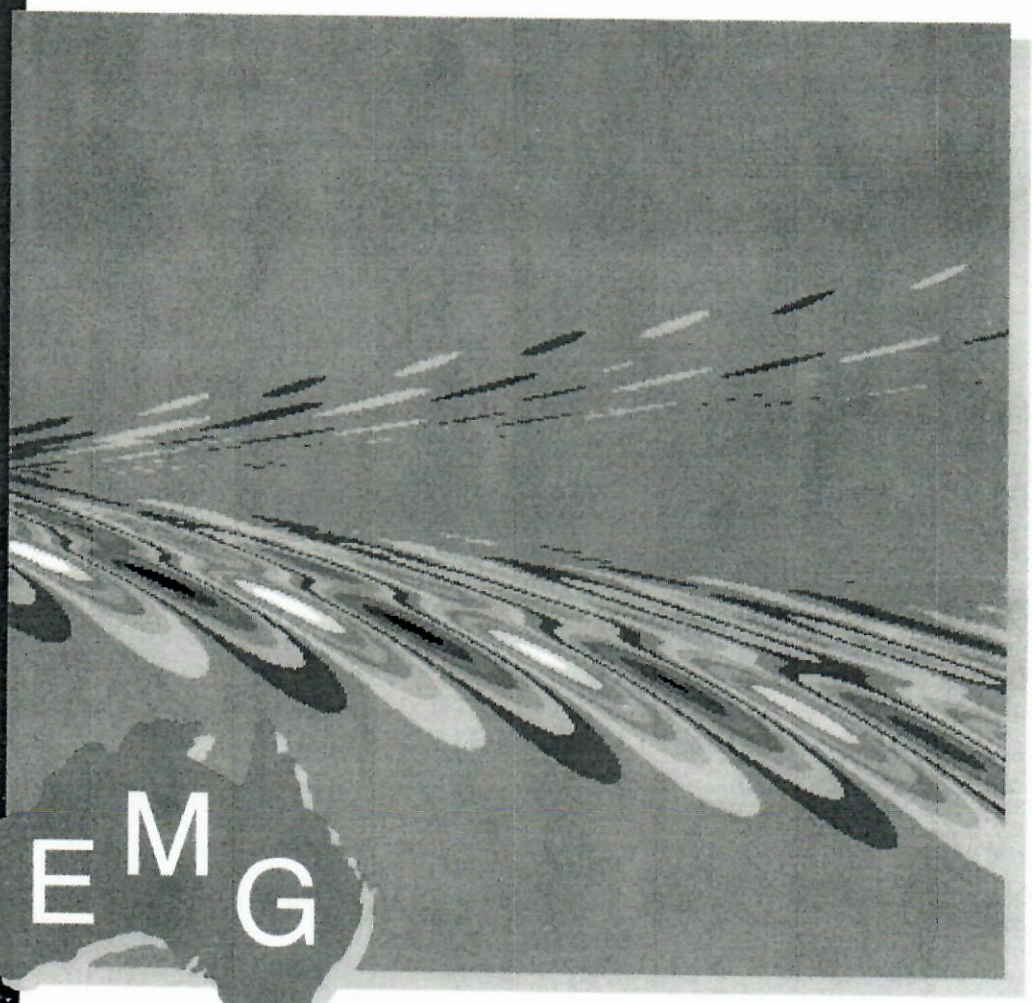
EMAC '98

3rd Biennial Engineering Mathematics and Applications Conference



13-16 July 1998
The University of Adelaide
South Australia

The Institution of Engineers, Australia

Sponsored by the Engineering Mathematics Group (A specialist group of ANZIAM) and The Institution of Engineers, Australia.

Proceedings of The Third Biennial Engineering Mathematics and Applications Conference

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Preface

This volume contains papers presented formally at the 3rd Biennial Engineering Mathematics and Applications Conference (EMAC'98) held at the University of Adelaide from the 13th to the 16th July 1998.

This conference builds on its two predecessors AEMC94, AEMC96 and is held under the auspices of the Engineering Mathematics Group (EMG), a special interest group of the Australian and New Zealand Industrial and Applied Mathematics (ANZIAM) a Division of the Australian Mathematical Society and the Institution of Engineers, Australia (IEAust).

This conference has again succeeded in attracting participants from across the globe, hence fostering international cooperation and the interaction of users of Engineering Mathematics in Government, Industry and Education.

The timing of this conference has made it possible to organise a mini-symposia celebrating the centenary of the publication of a famous paper on ship hydrodynamics by J. H. Michell, who was a Professor of Mathematics at the University of Melbourne.

The editors would like to acknowledge the generous support of the following sponsors:-
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The editors also gratefully acknowledge the members of the technical program committee for their efforts in reviewing the large body of material submitted for presentation at this conference. Finally we would like to express our thanks to the members of the Executive Committee for their guidance and also acknowledge the organisational support of Plevin & Associates.

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The final versions of all papers presented at this conference were refereed by at least one member of this committee.

At the time of editing the proceedings we are looking forward to meeting all of the authors in Adelaide and are anticipating an event that will stimulate research activities in all areas of engineering mathematics.

Ernie Tuck and Jill Stott, June 1998.

Numerical Analysis of Hollow Piezoceramic Cylindrical Vibrators Under Non-Stationary Conditions

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1 Introduction

The solution of many complex problems in science and engineering requires a unification of physical theories that have been considered separately for decades. One classical example of such a unification is thermoelasticity, which describes thermal and elastic fields as a unified entity. There is an emerging trend towards the coupling of different physical fields in mathematical models. This trend will persist in the next century due to the continuing quest for technological advances and for more precise description of natural phenomena and processes.

This paper deals with two-dimensional models of coupled dynamic electroelasticity as well as with a more general model taking into account magnetic and thermal effects. Research activity in this field has increased dramatically over recent years due to new applications of piezoelectrics in biophysics, electronics and smart structure technology [1, 2].

Another application of the models considered in this paper is the influence of piezoeffect on the behaviour of biological tissues. There is experimental evidence confirming that many biological tissues undergo electric polarisation when subjected to mechanical stress. This ability is often considered as a feedback mechanism that controls cell activity.

Due to their fast response to vibrations or other external stimuli, piezoelectrics are widely used (in particular, as sensors and/or activators) in such advanced technological areas as aerospace and oceanographic research. Surface-bonded piezoelectrics or piezoelectrics embedded in composite structures are also becoming common in structural control. In all these cases vibrations of piezoelectric elements influence the performance of the whole device. Therefore, predicting and improving vibrational characteristics of such devices constitutes an important engineering task. Displacement control of piezoelectrics is also important in many other applications such as non-destructive investigation in geophysics, design of medical ultrasonic equipment, low-tolerance positioning devices, stereo-viewing and image storage devices.

These and many other piezoelectric applications require an accurate quantification of the dynamics in response to various driving forces, taking into account inter-influence of elastic and electric fields. Since in the general case the influence of thermal and magnetic fields on the dynamic behaviour of piezoelectrics may not be negligible, we start from a general model of thermo-magneto-electro-elasticity.

2 Mathematical Model

We consider a piezoelectric body Ω, bounded by $\partial\Omega$, in an electromagnetic field and subjected to external loading (say, mass forces $\mathbf{F} = (F_1, F_2, F_3)$ and surface loading $\mathbf{p}$). Our model couples Maxwell's equations of electromagnetism and elastic-stress equations of motion in a way first proposed by Mindlin (see references in [3]). We have

$$\begin{cases} \operatorname{curl} \mathbf{H} = \mathbf{J} + \partial\mathbf{D}/\partial t, & \operatorname{div} \mathbf{D} = \rho_0, \\ \operatorname{curl} \mathbf{E} = -\partial\mathbf{B}/\partial t, & \operatorname{div} \mathbf{B} = 0, \end{cases} \tag{1}$$

where $\mathbf{E}$ and $\mathbf{H}$ are vectors of electric and magnetic fields respectively, $\mathbf{B}$ is the vector of magnetic induction, $\mathbf{D}$ is the vector of electric bias, $\mathbf{J}$ is the current density and ρ_0 is the spatial charge density. We supplement system (1) by the material relationships

$$\mathbf{D} = \epsilon_0\mathbf{E} + \mathbf{P}, \quad \mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}), \tag{2}$$

where $\mathbf{P}$ is the electrical polarisation vector, $\mathbf{M}$ is the magnetisation vector and ϵ_0, μ_0 are, respectively, electric and magnetic permittivity of a vacuum. ¿From the energy balance equation (see Section 4), we derive the equation of motion for piezoelectrics:

$$\sigma_{ji,j} + F_i = \rho\partial^2 u_i/\partial t^2, \quad \sigma_{ji} = \sigma_{ij}, \; i = 1, 2, 3, \tag{3}$$

where ρ is the density of material, $\mathbf{u} = (u_1, u_2, u_3)$ is the displacement vector and σ_{ij} is the stress tensor. In equation (3) (and further in this paper) we

use the standard notation of tensor analysis where a comma indicates covariant spatial derivative of corresponding tensors.

We assume the entropy balance

$$T\partial S/\partial t = -q_{i,i} + Q, \tag{4}$$

where T is the temperature of the piezoelectric body, S is the entropy per unit volume, $\mathbf{q} = (q_1, q_2, q_3)$ is the heat influx through the body surface and Q is the energy due to heat generation inside of the body. Equation (4) can be linearised under additional assumptions connected with the definition of the heat flux. We will not discuss possible definitions here, noting that the standard (however, not always acceptable) simplification is based on the Fourier law and the assumption $|\Theta/T_0| \ll 1$.

The connection between (1)—(4) is expressed by constitutive relationships which can be determined by approximating the enthalpy function H as a function of the internal mechanical and electromagnetic energy. Additional assumptions on H lead to the possibility of different closures of the mathematical model (1)—(4). In this paper we use the following relationships

$$\begin{cases} \sigma_{ij} = c_{ijkl}\varepsilon_{kl} - \gamma_{ij}\Theta - e_{kij}E_k, \\ S = \gamma_{ij}\varepsilon_{ij} + c_\epsilon\Theta/T_0 + g_iE_i, \\ D_i = e_{ikl}\varepsilon_{kl} + g_i\Theta + \epsilon_{ik}E_k, \end{cases} \tag{5}$$

where T_0 is the temperature in the absence of strains, stresses and electro-magnetic fields, $\Theta = T - T_0$, k_{ij} is the tensor of thermal conductivity, γ_{ij} is the tensor of thermal expansion, c_ϵ is the heat capacity and g_i are electro-thermal coupling coefficients. We assume that H depends only on strains, electric field and temperature (or on strains and polarisation) and neglects the dependence of H on the heat flux, magnetic field and the gradient of polarisation. As a result, material constants from (5) can be formally determined through second derivatives of function $H \equiv H(\varepsilon_{ij}, E_i, T)$ calculated at $(0, 0, T_0)$:

$$\begin{cases} c_{ijkl} = \dfrac{\partial^2 H}{\partial\varepsilon_{ij}\partial\varepsilon_{kl}}, \quad \epsilon_{ij} = \dfrac{\partial^2 H}{\partial E_{ij}\partial E_{kl}}, \\ c_\epsilon/T_0 = -\dfrac{\partial^2 H}{\partial T^2}, \quad e_{ijk} = -\dfrac{\partial^2 H}{\partial\varepsilon_{jk}\partial E_i}, \\ \gamma_{ij} = -\dfrac{\partial^2 H}{\partial\varepsilon_{jk}\partial T}, \quad g_i = -\dfrac{\partial^2 H}{\partial E_i\partial T}. \end{cases} \tag{6}$$

As usual, the relation for the strain tensor, ε_{ij}, is given by the Cauchy formula

$$\varepsilon_{ij} = 1/2(\partial u_i/\partial x_j + \partial u_j/\partial x_i). \tag{7}$$

Finally, system (1)—(5) is supplemented by initial conditions and boundary conditions on the surface boundary $\partial\Omega$.

In such a general setting we have to deal with 61 material constants. We simplify this model by considering adiabatic processes in piezoelectrics and assuming, as for non-magnetised dielectrics, that

$$\mathbf{J} = 0, \quad \mathbf{M} = 0, \quad \rho_0 = 0. \tag{8}$$

Then the polarisation vector can be defined as

$$\mathbf{P} = \mathbf{D} - \epsilon_0\mathbf{E}. \tag{9}$$

We also use the fact that the quasi-electrostatic approximation of the electromagnetic field,

$$\mathrm{curl}\mathbf{E} = 0, \quad \mathbf{B} = 0, \quad \mathbf{E} = -\mathrm{grad}\varphi, \tag{10}$$

is usually adequate for the study of piezoelectric phenomena. Under such an assumption the Maxwell equations (1) are reduced to the Gauss equation, $\mathrm{div}\mathbf{D} = 0$, which is coupled to the equation of motion (3) by constitutive relationships (5).

3 The Description of Electromechanical Oscillations in Hollow Piezoelectric Cylinders

Although the technique developed in this paper is valid for bodies of different geometries, in what follows we concentrate on the study of hollow piezoceramic cylinders. There are several reasons for this. Firstly, the piezoceramic cylinder is a wide-spread active element in many currently available technical devices such as piezoelectric transformers, vibrators and emitters. Secondly, the range of applicability of cylindrical-shape piezoelectrics has substantially grown due to both classical applications and their potential applications in smart and intelligent structures, oceanographic research and electronics. On the technical side, such a situation is explained by the ability of cylindrical piezoelectric devices to absorb much greater mechanical loading, compared to planar elements. Thirdly, as an emerging area of applications in biomechanics, such cylinders can be a good model for the study of electromechanical processes in bone tissues.

Many problems mentioned above require the consideration of dynamic, rather than static, behaviour of piezoelectrics as well as taking into account the coupling between electric and mechanical fields. The model for the solution of such problems can be obtained from (1)—(10). Written in the cylindrical coordinates for the region $\bar{Q}_T = \{(r, z) : R_0 \le r \le R_1, Z_0 \le z \le Z_1\} \times \{t : 0 \le t \le T\}$ system (1)—(10) includes two equations of motion

$$\begin{cases} \rho\ddot{u}_r = \dfrac{\partial\sigma_r}{\partial r} + \dfrac{\partial\sigma_{rz}}{\partial z} + \dfrac{\sigma_r - \sigma_\theta}{r} + f_1, \\ \rho\ddot{u}_z = \dfrac{\partial\sigma_{rz}}{\partial r} + \dfrac{\partial\sigma_z}{\partial z} + \dfrac{\sigma_{rz}}{r} + f_2, \end{cases} \tag{11}$$

and the Maxwell equation for piezoelectrics (in the acoustic range of frequencies, it is the forced electroelastic equation of dielectrics called the Gauss equation):

$$\frac{1}{r}\frac{\partial(rD_r)}{\partial r} + \frac{\partial D_z}{\partial z} = f_3. \qquad (12)$$

It is well-known [3] that when electroelasticity problems are solved taking into account the coupling phenomenon, both elastic and electroelastic nonlinearities in piezoelectrics are small (in particular, such a situation holds for the range of acoustic frequencies). When appropriate, nonlinearities can be implemented through state equations. Specific forms of state equations also depend on the type of preliminary polarisation. Assuming radial preliminary polarisation from (5) and (6) we have

$$\begin{cases} \sigma_r = c_{33}\epsilon_r + c_{13}(\epsilon_\theta + \epsilon_z) - e_{33}E_r, \\ \sigma_\theta = c_{13}\epsilon_r + c_{11}\epsilon_\theta + c_{12}\epsilon_z - e_{13}E_r, \\ \sigma_z = c_{13}\epsilon_r + c_{12}\epsilon_\theta + c_{11}\epsilon_z - e_{13}E_r, \\ \sigma_{rz} = c_{44}\epsilon_{rz} - e_{15}E_z, \\ D_r = e_{33}\epsilon_r + e_{13}(\epsilon_\theta + \epsilon_z) + \epsilon_{33}E_r, \\ D_z = 2e_{15}\epsilon_{rz} + \epsilon_{11}E_z. \end{cases} \qquad (13)$$

¿From (10)

$$E_r = -\partial\varphi/\partial r, \;\; E_z = -\partial\varphi/\partial z \qquad (14)$$

and the Cauchy strain-displacement relationship (7) have the form

$$\begin{cases} \epsilon_r = \partial u_r/\partial r, \; \epsilon_\theta = u_r/r, \; \epsilon_z = \partial u_z/\partial z, \\ \epsilon_{rz} = (\partial u_r/\partial z + \partial u_z/\partial r)/2. \end{cases} \qquad (15)$$

The model (11)—(15), which adequately describes the propagation of axially symmetric electroelastic waves in finite hollow piezoceramic cylinders, is supplemented by the following initial conditions

$$\begin{cases} u_r(r,z,0) = u_r^{(0)}, \; \partial u_r(r,z,0)/\partial t = u_r^{(1)}, \\ u_z(r,z,0) = u_z^{(0)}, \; \partial u_z(r,z,0)/\partial t = u_z^{(1)} \end{cases} \qquad (16)$$

with known functions $u_r^{(i)}$, $u_z^{(i)}$, $i = 1, 2$. Surface loading is defined as follows

$$\begin{cases} \sigma_r(R_i,z,t) = p_r^{(i)}, \; \sigma_z(r,Z_i,t) = p_z^{(i)}, \\ \sigma_{rz}(R_i,z,t) = p_{zt}^{(i)}, \; \sigma_{rz}(r,Z_i,t) = p_{rt}^{(i)}, \end{cases} \qquad (17)$$

where $p_r^{(i)}$, $p_z^{(i)}$, $p_{zt}^{(i)}$, $p_{rt}^{(i)}$, $i = 0, 1$ are given functions. Assuming that lateral surfaces of the cylinder are covered by infinitely thin short circuiting electrodes, and that the dielectric permittivity of the surrounding media is much less than the dielectric permittivity of ceramics, we have

$$\varphi(R_i,z,t) = 0, \; D_z(r,Z_i,t) = 0, \; i = 0, 1. \qquad (18)$$

The procedure for the reduction of more general nonhomogeneous electric boundary conditions to homogeneous conditions (18) was described in [3].

4 The Outlines of the Numerical Procedure

The solution of problem (11)–(18) is understood as the generalised solution $(u_r(r,z,t), u_z(r,z,t), \varphi(r,z,t))$ that belongs to $[W_2^1(Q_T)]^2 \times L_2(I, \overset{0}{W}{}_2^1(G))$ and satisfies some integral identities. Detailed discussion on such solutions may be found in [4] and references therein. The existence and uniqueness theory for model (11)—(18) in classes of generalised solutions was also developed earlier by the first author and his collaborators.

For the purposes of this paper we note that using the notion of generalised solutions, it is natural to derive effective numerical schemes for the solution of (11)—(18). The key point of such a derivation is the balance energy equation for the piezoelectric body. For the model (11)—(18) it has the following form:

$$\begin{aligned} \frac{d\mathcal{E}}{dt} = & \iint_\Omega r\left[\frac{\partial D_r}{\partial t}E_r + \frac{\partial D_z}{\partial t}E_z\right]d\Omega + \\ & \int_{R_0}^{R_1} r\left[\sigma_{rz}\frac{\partial u_r}{\partial t} + \sigma_z\frac{\partial u_z}{\partial t}\right]dr\Bigg|_{Z_0}^{Z_1} + \\ & \int_{Z_0}^{Z_1} r\left[\sigma_r\frac{\partial u_r}{\partial t} + \sigma_{rz}\frac{\partial u_z}{\partial t}\right]dz\Bigg|_{R_0}^{R_1} + \\ & \iint_\Omega r\left[f_1\frac{\partial u_r}{\partial t} + f_2\frac{\partial u_z}{\partial t}\right]d\Omega, \end{aligned} \qquad (19)$$

where the energy of the system, $\mathcal{E}$, is defined by its three components, kinetic energy

$$K = \frac{\rho}{2}\iint_\Omega r\left\{\left(\frac{\partial u_r}{\partial t}\right)^2 + \left(\frac{\partial u_z}{\partial t}\right)^2\right\}d\Omega, \qquad (20)$$

energy of elastic deformation

$$\begin{aligned} W = \frac{1}{2}\iint_\Omega r\,\{c_{33}\epsilon_r^2 + c_{11}(\epsilon_\theta^2 + \epsilon_z^2) + \\ 2c_{13}(\epsilon_\theta\epsilon_r + \epsilon_z\epsilon_r) + 2c_{12}\epsilon_z\epsilon_\theta + 2c_{44}\epsilon_{rz}^2\}\,d\Omega \end{aligned} \qquad (21)$$

and electric field energy

$$P = \frac{\epsilon_{33}}{2}\iint_\Omega rE_r^2 d\Omega + \frac{\epsilon_{11}}{2}\iint_\Omega rE_z^2 d\Omega. \qquad (22)$$

One may notice that on the right-hand side of (19) we have sources that initiate the dynamic motion of piezoelectrics, namely loading on the body surface, mass forces and electrodynamic forces. Equation (19) can be viewed as a conservation law for the coupled electromechanical system. It has a wider applicability compared to the differential model (11)—(18). In fact, using the concept of generalised solutions, equations (11), (12) and natural boundary conditions of the problem

can be readily obtained from (19). The numerical scheme used in this paper was derived by the authors from the discrete analogue of (19) (see details in [4] and references therein). We also established conditions for a stable realisation of such a scheme. In fact, the stability conditions for our scheme are the consequence of non-negativity of the discrete energy operator which approximates integral operator $\mathcal{E}$ defined by (20)—(22). These stability conditions generalise the classical Courant-Friederichs-Lewy result, obtained for hyberbolic equations, to the 2D dynamic electroelasticity relating space-time steps to the velocity of *mixed electro-elastic waves*.

The decrease in accuracy of spatial discretisations, compared to the 1D case [3], is typical and caused by the mechanical boundary conditions (17) which are coupled to the electric field through state equations (13). We note that similar problems arise even in classical elasticity. We overcome these difficulties using the methodology described in [4]. We proved convergence of the solutions of our numerical scheme to the generalised solution of (11)—(18) with second order accuracy. In order to obtain this result, we used a special treatment of corner points [4].

5 Computational Experiments

The analysis of computations is usually a *decision making procedure* that requires some modifications in the decision taken on previous stages. In order to make such a process efficient, modifications have to be reduced to a change or correction of only certain modules that are used on the previous stages of computational experiments. As a result of this requirement we designed our program for the modelling dynamics of piezoelectrics as a collection of interacting, but relatively independent, modules. The ALTPACK package was used as the elliptic solver for our problem. The package implements the alternating-triangular method and can be applied to the solution of both linear and non-linear 2D problems. The ALTPACK applies a special procedure for ordering Chebyshev iterative parameters which allows the minimisation of the influence of round-off errors.

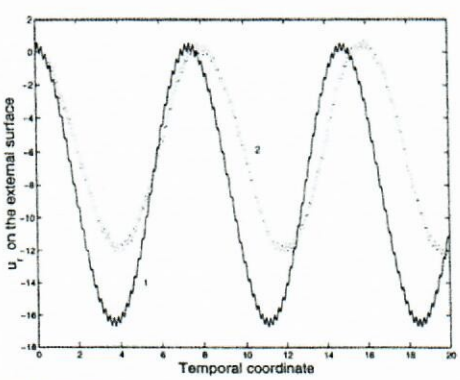

FIGURE 1. Dynamics of oscillations on the external surface of hollow PZT cylinders.

The main computational focus in this paper is the dynamics of displacements on the external cylindrical surface for radially poled cylinders. We studied the dependence of this characteristic on the ratio (a) between the cylinder thickness and its length. Figure 1 shows the dynamics of radial displacements of cylinders, made of PZT ceramic [4], when a=0.01 (curve 1) and a=1 (curve 2). Computations presented here were performed for $R_1 - R_0 = 0.09$. We conclude that when the cylinder thickness becomes comparable with its length, the magnitude of displacements significantly deviates from the results obtained with the 1D model [3]. The technique developed in this paper allows us to effectively quantify the dynamics of these displacements including the difficult and practically important case of thin piezoceramic cylinders.

6 Conclusions and Future Directions

In this paper we considered a mathematical model describing the dynamics of piezoelectrics subjected to electromagnetic and thermal fields as well as mechanical loading. Using the variational approach we constructed and justified efficient numerical procedures for the solution of a quite general problem of dynamic electroelasticity. Some numerical results on the investigation of vibrational characteristics of piezoelectric devices were presented.

In the general case, magnetoelectromechanical relations are nonlinear and may display a significant *hysteresis* and other nonlinear effects subject to appropriate forcing. The incorporation of such nonlinear effects into our model, as well as accounting for the thermal field is the subject of further development of the presented work.

7 Acknowledgements

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