

Israel Society for Theoretical and Applied Mechanics

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ISTAM ANNUAL SYMPOSIUM

TECHNICAL PROGRAM, 2014

ISTAM 2014 Annual Symposium Program

Location: Room 011, Engineering Studies (Kitot Handassa) building, Tel Aviv University

09:30 – 09:50 Registration and coffee

09:50 – 10:00 Opening: Gal Debotton – Ben Gurion University

Session I, Chairman: Shmuel Osovski – Technion

10:00 – 10:20 <u>Y. Green</u>, S. Park and G Yossion - Technion, "Time Transient Effects in Heterogeneous Permselective Systems."

10:20 – 10:40 <u>R Golkov</u> and Y Shokef – Tel Aviv University, "*Elastic interaction between two active spherical dipoles.*"

10:40 – 11:00 <u>AM Boymelgreen</u>, T Miloh and G Yossifon - Technion, "On the effect of competition between dielectrophoresis and induced-charge electrophoresis on JP mobility."

11:00 – 11:20 <u>B Quinn</u>, Y Toledo and V Shrira – Tel Aviv University, "A wave action equation for water waves propagating on vertically sheared flows."

11:20 – 11:30 Coffee Break

11:30 – 11:50 <u>M Baevsky</u> and A Liberzon – Tel Aviv University, "Evolution of a turbulent patch in dilute water-polymer solutions."

11:50 – 12:10 <u>T Vrecica</u> and Y Toledo – Tel Aviv University, "Consistent nonlinear deterministic and stochastic evolution equations for deep to shallow water wave shoaling."

12:10 – 12:30 G Altshuler and <u>O Manor</u> – Technion, "Acoustic spreading of thin films of water–balancing capillary, viscous, and vibrational mechanisms."

12:30 – 13:30 Lunch Break

Session II, Chairman: Benny Bar-On – Ben Gurion University

13:30 – 13:50 <u>D Kim</u> and R. Segev – Ben Gurion University, "Various Issues Raised by the Mechanics of an Octopus's Arm."

13:50 – 14:10 <u>SB Elbaz</u> and AD Gat – Technion, "Creeping annular flow within an elastic shell."

14:10 – 14:30 <u>P Galich</u> and S Rudykh – Technion, "*Propagation of elastic waves in highly deformable composite materials.*"

14:30 – 14:50 Coffee Break

14:50 – 15:10 <u>S Rudykh</u> and MC Boyce – Technion, "Micromechanics of soft layered composites: analysis, simulations and experimental studies."

15:10 – 15:30 <u>A Tulchinsky</u> and AD Gat – Technion, "Viscous-poroelastic interaction as mechanism to create adhesion in frogs' toe pads."

15:30 – 15:50 <u>S Osovski</u> – Technion, "Modeling Ductile Fracture Toughness and Fracture Surface Roughness."

15:50 – 16:10 <u>G Shmuel</u> – Technion, "Wavelet analysis of microscale strains."

Student Award – Gal Debotton – Ben Gurion University

16:10 - 16:20 Announcement of the winner of the student award

The annual membership fee to ISTAM is 100 NIS. It includes the lunch at the symposium and can be paid during the registration.

All lectures are open to the public free of charge. The program and abstract can be downloaded from https://istam.net.technion.ac.il/

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Time Transient Effects in Heterogeneous Permselective Systems

Y Green, S Park and G Yossifon

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The passage of an electric current through a permselective medium (membranes/nanochannels) under an applied electric field is characterized by the formation of ionic concentration gradients which result in regions of depleted and enriched ionic concentration at opposite ends of the medium, i.e. concentration polarization (CP). In this work, we study the time-transient behavior of the concentration and electric potential distributions in a realistic two dimensional and three layered system (i.e. microchannel-permselective medium-microchannel device). We provide an analytical solution for the concentration under the simplifying assumptions of localelectroneutrality, ideal permselectivity and negligible convection while the electric potential is solved numerically. It is shown that time transient effects occur over the diffusive time scale until steady-state is achieved. The numerical steady state solution is compared with previous analytical results and good quantitative behavior is observed. Experiments are underway to experimentally verify these theoretical predictions.



Figure. 1: Resultant electric potential as function of time for a 1D system. The electric potential is compared with predicted solutions for t = 0 *and t* $\rightarrow \infty$ *.*

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Elastic interaction between two active spherical dipoles

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Recently published experimental results show that the rigidity of the extracellular matrix influences the cell-cell interactions. On very soft gels (500 Pa) cells tend to touch and remain in contact, while on very stiff gels (33KPa) cells contact and migrate away from each other. In this study a coarse grain model was used in which cells were represented by spherical dipoles applying contractile forces or displacements to the surrounding infinite elastic medium with linear elastic behavior in order to derive expression for the elastic interaction energy. It was shown previously that elastic interaction energy vanishes in the case of dipoles of any shape applying isotropic forces or displacements. In order to overcome this problem we defined "active" dipoles that alter the applied forces in accordance to the changes in their environment to preserve their spherical shape or alternately to preserve constant force on their surface. Our results show that in this configuration interaction energy between such dipoles is proportional to one over the distance between their centers to the 6 power and are linearly proportional to the shear modulus of the substrate. In the case of steady displacements the sign of the interaction energy is positive, in contrast to the case of steady forces when it changes to negative.

On the effect of competition between dielectrophoresis and induced-charge electrophoresis on JP mobility

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Dipolophoresis refers to the combined result of two non-linear electrokinetic effects; induced-charge electroosmosis and dielectrophoresis. In general, non-linear electrohydrodynamic flows, including induced-charge (Squires and Bazant, 2004) and alternating-current (Ramos et al, 2009) electroosmosis have received much attention amongst the micro/nanofluidic community over the past decade for their potential to produce net flow even under ac electric forcing, with applications ranging from electroosmotic pumps (Bazant and Squires, 2010) to externally controlled micromotors (Boymelgreen et al, 2014) while dielectrophoresis is a widely used separation method in biological applications. The advent of such non-linear electrokinetic flows is strongly dictated by the frequency of the applied field. However, to date, there exists no unifying theory which can exactly predict both the strength and frequency dispersion of such electrokinetic flows.

Within this work, we investigate both theoretically and experimentally the dipolophoretic mobility of metallodielectric – with one hemisphere conducting and the second insulating - Janus particles in different frequency domains; from the low frequencies (up till 10s of kHz) in which induced-charge flows are dominant to the high frequency (MHz) where the induced-charge effects decay to zero and dielectrophoresis dominates. We evaluate the effect of close proximity to the walls, which can compete with induced-charge electrokinetic flow, potentially causing a distortion of both the strength and frequency dispersion predicted for pure induced-charge effects. We compare the 'wall effects' of conducting walls- where the applied field is normal to the surface - to insulating walls – in which case the applied field is parallel to the substrate. This work is of both fundamental and practical importance and may be used to further refine non-linear electrokinetic theory and optimize the flow parameters of electroossmotic pumps and the mobility of electrokinetically driven micromotors or carriers in lab-on-a-chip analysis systems.

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A wave action equation for water waves propagating on vertically sheared flows

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The coexistence of motions of different scales in oceans and other natural water basins presents a challenge for their dynamic modeling. For water waves on currents, an asymptotic procedure exploiting the separation of scales allows the modeling of two motions of a qualitatively different nature, the fast shortwaves on the surface and the dynamics of the slow, long currents.

Most wave forecast models are based on the wave action equation which is a conservation equation which takes into account the propagation of the wave energy in geographic space, shoaling, refraction, diffraction and also source terms which account for generation, wave-wave interactions and dissipation of the energy.

Water waves almost always propagate on currents with a vertical structure such as currents directed towards the beach accompanied by an under-current directed back toward the deep sea or wind-induced currents which change magnitude with depth due to viscosity effects. On larger scales they also change their direction due to the Coriolis force as described by the Ekman spiral. This implies that the existing wave models, which assume vertically-averaged currents, is an approximation which is far from realistic.

In recent years, ocean circulation models have significantly improved with the capability to model vertically-sheared current profiles in contrast with the earlier vertically-averaged current profiles. Further advancements have coupled wave action models to circulation models to relate the mutual effects between the two types of motion. Restricting wave models to vertically-averaged current profiles is obviously problematic in these cases and the primary goal of this work is to derive and examine a general wave action which accounts for this shortcoming.

Combining two previous theoretical approaches [Voronovich, 1976; Skop, 1987], the developed wave action formulation greatly improves the representation of linear wave-current interaction in the case of tidal inlets, wind-induced currents, storm surges and undertow currents. In contrast to the case of vertically averaged ambient currents, the structure of the oscillatory flow under the wave depends on the current's vertical structure. Locally, this structure relates to the solution of the Rayleigh equation with appropriate surface and bottom boundary conditions, an essential step for creating an applicable explicit wave action formulation. For an arbitrary current profile the Rayleigh equation boundary-value problem does not have an exact analytical solution asymptotic solutions must be employed.

Two approximations are made to the new formulation; one assuming a small current, gradient and curvature, the Skop [1987] approximation, the other assuming no shear. The accuracy of these approximations are analysed numerically to determine the improvement of the shear to no shear approximations over the exact solutions to the group velocity Cg and the invariant Ivs. A two-layer profile and also a countercurrent

vertical velocity profile were examined to determine the range of validity of the approximations for simple wave-current interaction problems.

Under the assumptions of a small current, small current gradient and small curvature, to the leading order, the new wave action formulation gives the same results as the noshear formulation which is based on the famous work of Bretherton and Garrett [1968] and that the existing models need alter only their value of the current to be taken at the surface, rather than a depth-averaged value.

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Evolution of a turbulent patch in dilute water-polymer solutions

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Drag reduction effect by dilute polymer solutions was discovered back in 1946 by B.A.Toms, but the mechanism is not explained thoroughly despite the enormous progress in understanding the near wall turbulent boundary layer flow in pipes or channels. One of the main problems is relatively poor understanding of dilute polymer solutions and inter-scale transfer of energy in turbulent flows. The problem intensifies in the case of turbulent entrainment across turbulent/non-turbulent interfaces on the boundaries of turbulent jets, wakes or mixing layers. The polymer is sought to alter this region of flow significantly due to the large gradients at the interface and strong interaction of multiple scales - large scales that deflect the interface and the small scales that diffuse the vorticity and strain.

An experimental study has been performed to characterize the basic mechanisms of turbulent entrainment in water - poly(ethylene oxide) solutions, alongside the benchmark case of the fresh water. A new experimental setup was developed to create a spherical localized turbulent patch, thus isolating the polymer effect far from the boundaries with negligible wall friction effects, as opposed to the previously utilized 2D space-filling planar oscillating grids. The setup enables a direct comparison of the results with the direct numerical simulations. We have also developed a system of a repetitive, automatic and consistent solution mixing and performed a large set of particle image velocimetry (PIV) measurements.



Figure 1: Field-average-kinetic-energy per unit mass of the PIV acquired velocity fields for several liquid solutions of PEO at three different agitation frequencies.

The evolution of the turbulent kinetic energy (per unit mass) was obtained from PIV realizations and its ensemble average is shown in Figure 1. The patch life cycle

comprises of three phases of initial growth, a steady state and the decay phase after the forcing ceased. The direct polymer effect is in every stage, from a reduced growth rate, to monotonically decreasing energy levels at steady state and a reduced decay rate, with increasing polymer concentration (0 ppm is a freshwater benchmark case).

Figure 2 shows vorticity fields of water and 10 ppm polymer at 6.9 Hz agitation frequency after 5 sec. (in the steady state phase). From enstrophy(vorticity squared) fields we could deduce the position of the sharp interface between the turbulent patch and its surrounding fluid. We observe a smaller patch, much smoother interface and the depletion of the length scales separation. An algorithm for patch interface detection is proposed and successfully applied to the PIV measurements, revealing the change in energy transfer towards and across the interface, along with additional physical measures of the patch evolution. The results will be used in developing an improved models of turbulent entrainment and possibly implemented in the applications that require a precise control of localized mixing rates.



Figure 2: Vorticity magnitude comparison example of water (0 ppm) and 10 ppm polymer at 6.9 Hz agitation frequency at t = 5 sec.

Consistent nonlinear deterministic and stochastic evolution equations for deep to shallow water wave shoaling

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One-dimensional deterministic and stochastic evolution equations are derived for the dispersive nonlinear waves while taking dissipation of energy into account. The deterministic nonlinear evolution equations are formulated using operational calculus by following the approach of Bredmose *et al.* (2005). Their formulation is extended to include the linear and nonlinear effects of wave dissipation due to friction and breaking. The resulting equation set describes the linear evolution of the velocity potential for each wave harmonic coupled by quadratic nonlinear terms. These terms describe the nonlinear interactions between triads of waves, which represent the leading-order nonlinear effects in the near-shore region. The equations are translated to the amplitudes of the surface elevation by using the approach of Agnon and Sheremet (1997) with the correction of Eldeberky and Madsen (1999).

The only current possibility for calculating the surface gravity wave field over large domains is by using stochastic wave evolution models. Hence, the above deterministic model is formulated as a stochastic one using the method of Agnon and Sheremet (1997) with two types of stochastic closure relations (Benney and Saffman's, 1966, and Hollway's, 1980). These formulations cannot be applied to the common wave forecasting models without further manipulation, as they include a non-local wave shoaling coefficients (i.e., ones that require integration along the wave rays). Therefore, a localization method was applied (see Stiassnie and Drimer, 2006, and Toledo and Agnon, 2012). This process essentially extracts the local terms that constitute the mean nonlinear energy transfer while discarding the remaining oscillatory terms, which transfer energy back and forth.

One of the main findings of this work is the understanding that the approximated non-local coefficients behave in two essentially different manners. In intermediate water depths these coefficients indeed consist of rapidly oscillating terms, but as the water depth becomes shallow they change to an exponential growth (or decay) behavior. Hence, the formerly used localization technique cannot be justified for the shallow water region. A new formulation is devised for the localization in shallow water, it approximates the nonlinear non-local shoaling coefficient in shallow water and matches it to the one fitting to the intermediate water region. This allows the model behavior to be consistent from deep water to intermediate depths and up to the shallow water regime.

The essential difference between the shallow and intermediate nonlinear shoaling physics is explained via the dominating class III Bragg resonances phenomenon. By inspecting the resonance conditions and the nature of the dispersion relation, it is

shown that unlike in the intermediate water regime, in shallow water depths the formation of resonant interactions is possible without taking into account bottom components.

Various simulations of the model were performed for the cases of intermediate, and shallow water, overall the model was found to give good results in both shallow and intermediate water depths. Figure 1, presents an experimental set-up of Stiassnie and Drimer (2006) for investigating infra-gravity wave evolution. Stiassnie and Drimer's unpublished experimental results for nonlinear subharmonic infra-gravity wave generation resulting from bi-chromatic wave generation are given in Figure 2 together with numerical results of various stochastic and deterministic models.



Figure 1: The experimental setup of Stiassnie and Drimer (2006). The experiment was conducted in a 45 meter wave flume. Twenty wave gages are used for acquiring four surface elevation measuring points as indicated on the figure. All units are in millimeters.



Figure 2: Evolution of the of sub-harmonic infra-gravity wave (with period of 132 sec) due to subharmonic interactions of bi-chromatic waves (with periods of 11sec and 12sec). Two different cases were simulated, for an initial amplitude of 0,04 cm (left pannel) and for one of 0,02 cm (right pannel). The circle symbols represent the unpublished experimental results of Stiassnie and Drimer. The numerical results are described as follows, dash-dot line (1): Stiassnie and Drimer (2006); dashed line (2): Toledo and Agnon (2012); solid line (3): present work. The shaded area and dotted line (4) represent the ensemble of the deterministic solutions of Kaihatu and Kirby (1995) and their average respectively

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Acoustic spreading of thin films of water – balancing capillary, viscous, and vibrational mechanisms

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Substrate vibrations at frequencies comparable to HF and VHF radio frequencies and in contact with a liquid film generate flow at micron and submicron scales, leading under appropriate conditions to the spreading of micron thick liquid films; this spreading mechanism is known as Acoustic Spreading. This spreading mechanism is thought as a way of manipulating liquids and especially water, a natural carrier of biological and biochemical agents, on microfluidic platforms. Previous studies of acoustic spreading concentrated on a fully wetting model liquid – silicon oil – where spreading was found easy to initiate as long as liquid and substrate vibrations are in contact. Water films under similar conditions, however, were observed to spread to a minute extent and only under high power levels that further invoke intense capillary instabilities and liquid atomization.

In this presentation we will use theory and experimental evidence to discuss the physical mechanisms associated with acoustic spreading of water films. We will highlight mechanisms associated with acoustic spreading of liquids with arbitrary surface tension, and we will show the balance between the different mechanisms is encapsulated within one dimensionless number whose value determines whether spreading is to take place and, subsequently, the rate of liquid spreading. We will further elucidate the discrepancy, observed in earlier literature, between the response of oil and deionized water to acoustic excitation, highlighting an intermediate region, where precise manipulation of the rate and direction of liquid spreading is achieved by carefully balancing the governing mechanisms.

Various Issues Raised by the Mechanics of an Octopus's Arm

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The arm of the octopus serves as an example of a manipulator possessing an infinite number of degrees of freedom as it has no rigid links. For this reason studying mechanical models of the octopus's arm is of interest from both the theoretical and practical points of view.

The arm of an octopus contains five groups of muscle fibers: longitudinal fibers, two groups of mutually orthogonal transverse fibers, and two groups of right handed and left handed helicoidal fibers (see Figure 1). When the muscles are inactive, the material that makes up the arm does not support shear statically. In addition, the material shows very little compressibility which is therefore usually neglected. Such a structure is referred to a *mascular hydrostat*. The elephant trunk and the human tongue may serve as other examples of organs that have the structures of muscular hydrostats. (See a detailed study in Kier and Stella, 2007.) Thus, we assume that 5 distributed intertwined muscle fibers groups are embedded in the arm and that the total mixture is incompressible.



Figure 1: An illustration of the morphology of an octopus's arm.

In a study of the mechanics of the octopus's arm, one should try to explain how the arm operates without having a rigid skeleton and in spite of the fact that muscle fibers can apply tension and cannot apply compression. As an elementary oversimplified example, using incompressibility, the arm can extend and can apply longitudinal compression by contracting the transverse muscle groups.

The structure of the arm raises some theoretical questions. For example, since the space of the values of the stress tensor at a point, the space of 3×3 symmetric

tensors, is 6-dimensional, can it be spanned by a collection of 6 stress tensors corresponding to tensions in 6 fiber bundles? In other words, we look for the conditions such that for 6 vectors, w_n , n = 1, ..., 6, the tensors $w_n \otimes w_n$ be linearly independent. Since the fibers may be only in tension, one would like to describe the collection stresses that result from tension in the fibers only (rather than compression). Next, taking incompressibility into consideration, one would like to find conditions for the geometry of a collection of 5 vectors, w_m , m = 1, ..., 5, so that the tensors $w_m \otimes w_m$ together with the identity tensor *I* span the space of symmetric tensors. It is also observed that for an unloaded activated arm to be in equilibrium with nonvanishing hydrostatic pressure, the identity tensor should be representable as a linear combination of $w_m \otimes w_m$, m = 1, ..., 5, so that the space of symmetric tensors cannot be spanned.

For the stress analysis of the arm, a constitutive model of the muscle fibers should be incorporated. In order to make use of available data on the mechanical properties of muscle fibers, we conceive the following scenario. From a reference configuration which is not activated, the arm is deformed to an intermediate configuration in an unloaded motion for which the activation of the muscles is negligible. At this intermediate configuration, the muscles are activated isometrically. Then, under fixed activation of the muscles, the arm is loaded externally undergoing a passive small deformation which is superimposed on the arm foregoing large deformation. Linearization of the constitutive relations in a neighborhood of the prestressed activated muscles shows how geometric stiffness enables the arm to support external loading even with a smaller number of muscle groups.

In the analysis, a fiber bundle is represented by a vector field whose magnitude is the density of the fibers. Various kinematic relations for the fiber density vector fields are presented. In fact, from the general geometric point of view, the fiber density is better described as a differential 2-form.

As another interesting question we consider regarding the geometry of the fibers is: what is the angle between the helicoidal fibers and the axis of the arm for which the length of the helicoidal fibers will be minimal. In such a case, both extension of the arm and its contraction will cause the helicoidal fibers to extend. Thus, tension in the helicoidal fibers will resist both an extension and a contraction of the arm without activating either the longitudinal muscles or the transverse fibers.

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Creeping annular flow within an elastic shell

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The study deals with the fluid-structure-interaction problem of longitudinal annular flow about a rigid axisymmetric centre-body externally interfaced by an elastic shell. The configuration models a slender structure with a deformable elastic boundary which may be controlled via internal pressure. The gap between the centre-body and enclosing shell may be initially filled with a thin fluid layer or devoid of it. We employ elastic shell theory and the lubrication approximation to show that the problem is governed by a forced nonlinear diffusion equation in fluid pressure,

$$\frac{\partial p}{\partial t} - \frac{1}{12} \frac{\partial}{\partial z} \left\{ \frac{\partial p}{\partial z} (\lambda + p - p_e)^3 \right\} \sim \frac{\partial p_e}{\partial t} . \tag{1}$$

where λ is the ratio of fluid film layer to characteristic radial deformation, and p_e is external pressure. Passing λ to the limit, $\lambda \rightarrow 0$, represents the case of an advancing liquid front in an initially unpenetrated interface and degenerates Eq. (1) into the porous medium equation (PME),

$$\frac{\partial p}{\partial t} - \frac{1}{12} \frac{\partial}{\partial z} \left\{ \frac{\partial p}{\partial z} p^3 \right\} \sim 0 , \qquad (2)$$

in the case of an unforced structure. The PME has been studied extensively over the past decades; it exhibits self-similar weak solutions with compact support and finite speed of propagation. The characteristic source solution of the PME (Barenblatt 1952),

$$p(z,t) = t^{-k} \left[\left(1 - \frac{k(m-1)}{2m} \frac{z^2}{t^{2k}} \right)_+ \right]^{\frac{1}{m-1}}$$

with = 4, k = 1/5 and $u_+ = \max(u, 0)$, represents an inlet pressure pulse input into the system at t = 0. Additional solutions of the flow-field and solid-deformation for various time-varying inlet pressure and external forces are explored in the study. The presented interaction between viscosity and elasticity may be applied to fields such as soft-robotics and micro-autonomous-systems.

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Propagation of elastic waves in highly deformable composite materials

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The propagation of acoustic waves in elastic materials has been investigated intensively (see, for example, Hussein et al, 2014; and references therein) because the understanding of the phenomenon is of great importance for a huge variety of applications. The areas of applications include nondestructive material testing, ultrasonic transducers, vibration dumpers, wave-guides, acoustic mirrors and filters. Recently, a new class of manmade acoustic metamaterials has attracted considerable attention. The remarkable properties of these metamaterials originate in their microstructure, a proper choice of which may result in phononic band-gaps.

Moreover, soft metamaterials, due to their capability to sustain large deformations, open the promising opportunities of manipulating acoustic properties via deformation. Applied deformations influence the wave propagation twofold: first, as a material undergoes deformations its microstructure evolves; second, local deformations that the material experiences lead to change of the local properties (for instance, local softening/hardening). It is worth mentioning that soft biological tissues often can be found in similar, pre-deformed or pre-stressed conditions due to, for example, growth, damage or remodeling. Consequently, it is important to account for these effects in another acoustic based application – ultrasound testing.

To account for the finite deformation non-linear effects as well for the material nonlinearity, we analyze the wave propagation in terms of incremental small-amplitude motions superimposed on a finitely deformed state (Truesdell and Noll, 1965).

The material heterogeneity together with the deformations gives rise to the possibility of elastic instability development (Rudykh and deBotton, 2012). This phenomenon can be used to trigger sudden and reversible pattern transformation which is accompanied by changes in acoustic properties. Here we specially focus on the influence of instability-induced interfaces on elastic wave propagation in finitely deformed layered materials.

The onset of instability in initially deformed interfacial layers occurs when a critical compressive strain or stress is achieved (Li et al, 2013). Continuation of compression beyond the critical strain leads to an increase in the wrinkle amplitude of the interfacial layer. This, in turn, gives rise to the formation of a system of periodic scatterers, which interfere with wave propagation. It is shown that the topology of wrinkling interfacial layers can be controlled by deformation and used to produce band-gaps and to filter undesirable frequencies (Rudykh and Boyce, 2014). Remark that the mechanism of frequency filtering is effective even for composites 2

with similar or identical densities. Since the microstructure change is reversible, the technology can be used for tuning and controlling wave propagation by use of deformation without any damage to the pattern.

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Micromechanics of soft layered composites: analysis, simulations and experimental studies.

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Motivated by designing bio-inspired light-weight flexible protective systems (for body armor applications), we study deformable layered materials reminiscent of the structures present on teleost fish species (e.g., zebrafish Danio rerio and Arapaima gigas) [1]. These materials comprise soft matrix and stiffer layers. The overlapping stiff scales are embedded in a soft tissue such that the composite material can provide protection while also undergoing large deformations when subjected to a penetrating loading (such as a bullet, knife, or a powerful animal bite). Moreover, the layered materials hold a great potential for a large variety of applications including noise reduction [2] and actuation [3]. Here, we analyze the influence of microstructure parameters on the performance of the composites. We derive an analytical solution for the multilayered structure accounting for large deformations. The solution predicts the mechanical response of the media as a function of the layer inclination angle, constituent volume fractions and properties [1]. To capture the effects of localized deformation (for example, in case of penetrating loading), we develop a finite element numerical model of the structure and loading conditions. Physical prototypes of the composites are fabricated by three-dimensional printing. The prototypes are subjected to mechanical loadings and the local deformation mechanics of the layered structure are measured using digital image correlation. The measured mechanical response, macroscopic as well as local, is found to be in good agreement with the simulations as well as with analytical predictions. Moreover, the results provide a detailed picture of the composite deformation mechanisms, which consist of matrix shear, stiff plate rotation and bending, depending on the microstructural parameters and loadings. Understanding the key mechanisms and parameters is an important step towards designing materials with a large variety of functionalities.

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Viscous-poroelastic interaction as mechanism to create adhesion in frogs' toe pads

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The toe pads of frogs consist of soft hexagonal structures and a viscous liquid contained between and within the hexagonal structures. It has been hypothesized that this configuration creates adhesion by allowing for long range capillary forces, or alternatively, by allowing for exit of the liquid and thus improving contact of the toe pad. In this work we suggest interaction between viscosity and elasticity as a mechanism to create temporary adhesion, even in the absence of capillary effects or van der Waals forces. We initially illustrate this concept experimentally by a simplified configuration consisting of two surfaces connected by a liquid bridge and elastic springs. We then utilize poroelastic mixture theory and model frog's toe pads as an elastic porous medium, immersed within a viscous liquid and pressed against a rigid surface. The flow between the surface and the toe pad is modeled by the lubrication approximation. Inertia is neglected and analysis of the elastic-viscous dynamics yields a governing partial differential equation describing the flow and stress within the porous medium. Several solutions of the governing equation are presented and show a temporary adhesion due to stress created at the contact surface between the solids. This work thus may explain how some frogs (such as the torrent frog) maintain adhesion underwater and the reason for the periodic repositioning of frogs' toe pads during adhesion to surfaces.



lubrication region (red dashed)

Figure 1. Illustrative description of the model consisting of a poroelastic material (dotted area) connecting a rigid body and a lubrication region (red dashed). The poroelastic material is axi-symmeteric with radius r_0 , height h and external axial force f_e acting on the rigid body.

Modeling Ductile Fracture Toughness and Fracture Surface Roughness

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Two fundamental questions in the mechanics and physics of fracture are:

- 1. What is the relation between a material's microstructure and its resistance to crack growth?
- 2. What is the relation between a material's microstructure and the roughness of the fracture surface?

From those two question, an obvious corollary question arises :

What is the relation, if any, between a material's crack growth resistance and the roughness of the corresponding fracture surface?

I will discuss results of 3D finite element calculations of mode I ductile crack growth aimed at addressing these questions. A material length scale is explicitly introduced via a discretely modeled microstructural feature, such as the spacing of second phase particles that nucleate voids or the mean grain size and grain boundary's thickness. In the calculations, ductile fracture of structural metals by void nucleation, growth and coalescence is modeled using an elastic-viscoplastic constitutive relation for a progressively cavitating plastic solid. Quantitative measures of crack growth resistance and of the statistics of the fracture surface roughness will be presented and related to the nature of the ductile crack growth process. Finally some possible correlations between the fracture toughness and fracture surface roughness will be discussed.

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Wavelet Analysis of Microscale Strains

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Recent experiments and numerical simulations provide numerous observations on the microstructure and deformation of polycrystals. These show how confined bands of deformation percolate in a complex way across various grains. Such information is represented as samples on grids, and, in turn, creates huge data sets. The extensive size of data in this form renders identifying key features difficult, and the cost of digital storage expensive. To represent, analyze, and predict strain fields with localized features, we use wavelets: multiresolution functions, which are localized both in frequency and real domains. By way of example, we focus on pseudo-elastic polycrystals, capable of recovering strains beyond an apparent elastic limit. I will show how wavelets efficiently represent experimental and simulated strains of Ni-Ti, while reducing data size by two orders of magnitude. More importantly, I will show how the compact wavelet representation captures the essential physics within. Finally, I will discuss how to use insights gained to improve specific experimental and computational methods.