A Hierarchical Algebraic Compression-Based Approach for Fast Numerical Solution of Hybrid Integral Equations and Many-Body Problems of Acoustic Scattering

Meydan Kaplan, Dan Last, and Yaniv Brick

School of Electrical Engineering, Faculty of Engineering, Ben-Gurion University of the Negev, Be'er Sheva, Israel

ybrick@bgu.ac.il

ABSTRACT

Integral equation and many-body problem modeling are of appeal for external acoustic wave problems, where the number of unknowns can be reduced to that of basis functions and particle moments defined on/assigned to only on the domains anomalous with respect to the background, which is otherwise modeled via the medium Green's function. While the downside of such modeling is the cost of computing, storing, and applying dense and large matrix operators, means for compressing these matrices have been developed, enabling fast solution at quasi-linear asymptotic complexity, e.g., [1]. That said, complex systems may involve multiple types of integral equations and corresponding kernels.

With the goal of accelerating the solution of various integral equations and many-body problems, our group developed a kernel-independent fast solver framework that relies on the hierarchical algebraic compression of system blocks [2]. In this framework, a system block, associated with a pair of basis and testing domains and an acoustic wave kernel, is partitioned into hierarchical-matrix blocks associated with the geometrical partitioning of the basis and testing function into cluster hierarchies. Hierarchical-matrix blocks that are identified as admissible for compression are then economically expressed by their butterfly approximation [3]. This multi-level algebraic representation of a block, unlike the simpler low-rank approximation, leads to asymptotic savings in memory (and as a result in computation time) for any type of oscillatory kernel, regardless of the problem size and topology.

The talk will review the compression strategy and its application to problems of coupled equations with multiple kernels. These include the fast iterative solution of systems arising from the discretization of hybrid integral equations for scattering by acoustically-large continuous objects and many-body problems describing the scattering by large discrete sets of particles exhibiting a Willis coupling. The tailoring of the compression and fast solver schemes to the specific formulations will be discussed and its performance will be demonstrated.

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Numerical and Theoretical Analysis for Optimization of a Thermo-Electric Generator Integrated with a Phase Change Material Heat Sink

Daniel Jalontzki[1], Moshe Bukai[2], Yoram Kozak[1]

[1] *School of Mechanical Engineering, The Fleischman Faculty of Engineering, Tel Aviv University, Tel Aviv, Israel*
[2] *Soreq Nuclear Research Center (SNRC), Yavne 81800, Israel*

danielj@mail.tau.ac.il

ABSTRACT

Power generation for isolated systems without any human contact, e.g., in deserts or outer space, is considered an outstanding engineering challenge. A possible solution for this engineering problem is a thermoelectric generator (TEG) integrated with a phase change material (PCM) heat sink, see Figure 1. The hot side of the TEG is subjected to a heat source, whereas the cold side of the TEG is attached to a finned PCM heat sink. Heat is conducted from the fins to the PCM, which melts and absorbs the heat. Thus, a relatively constant temperature difference can be maintained across the TEG for the heating period. This type of system was explored in the past, see, for instance [1,2]. However, simple design guides for an optimal heat sink fin array that achieves a maximum electrical energy output for given conditions still do not exist. In the current work, we carried out detailed 2-D and 3-D numerical simulations that predict the transient heat transfer and phase change processes associated with this special power generation system.

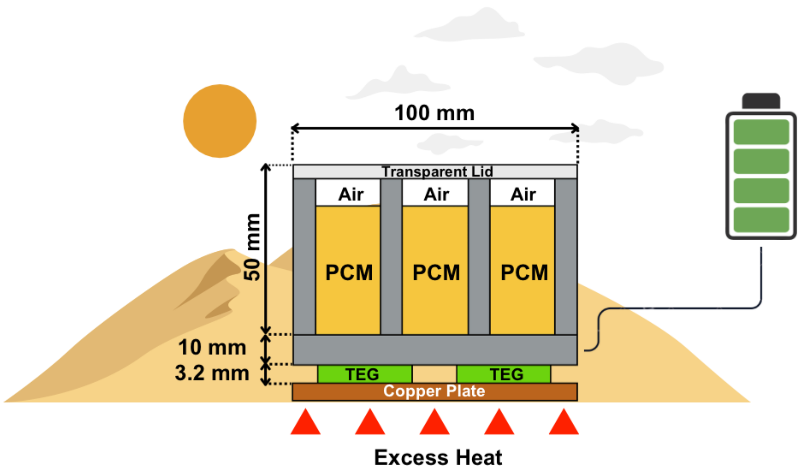

Figure 1: general schematics of the system.

Our simulations revealed that for a given fin array, there is an optimal heat flux that leads to a maximum electrical energy output. Guided by these detailed simulation results, we developed a simplified quasi-steady model that can quickly determine the optimal heat flux for given system conditions. Also, according to our optimization results, we designed and manufactured a new experimental setup that will be used in the near future to further validate our model predictions and explore the system performance.

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Matrix-Free Multigrid for the Elastic Helmholtz Equation
מולטיגריד נטול-מטריצות למשוואת הלמהולץ האלסטית

Rachel Yovel[1], Eran Treister[1]

רחל יובל[1], ערן טרייסטר[1]

[1] *Department of Computer Science, Ben-Gurion University, Beer Sheva, Israel*

[1]*המחלקה למדעי המחשב, אוניברסיטת בן-גוריון, באר שבע, ישראל*

yovelr@bgu.ac.il

ABSTRACT

The Helmholtz equation arises in modeling wave propagation in the frequency domain. The acoustic Helmholtz equation models acoustics and electromagnetics, while the elastic Helmholtz equation models wave propagation in solids, such as the earth's sub-surface. Both are difficult to solve numerically, as the discrete linear system is huge, indefinite, and ill-conditioned. The elastic version amplifies these difficulties both because of its larger size (as a system of PDEs) and its more complicated physics.

We present an efficient matrix-free geometric multigrid method for the elastic Helmholtz equation, and a suitable discretization. Many discretization methods had been considered in the literature for the Helmholtz equations, as well as many solvers and preconditioners, some of which are adapted for the elastic version of the equation. However, there is very little work considering the reciprocity of discretization and a solver. We take steps towards bridging this gap, as our discretization is chosen to fit the solver.

Our multigrid method is based on the shifted Laplacian approach, together with approaches used for linear elasticity. Our discretization for the elastic Helmholtz equation is inspired by an existing fourth-order stencil for acoustic Helmholtz. Using two-grid local Fourier analysis, we validate the compatibility of our discretization with our solver and tune a choice of weights for the stencil that optimize the convergence rate of the multigrid cycle. The resulting discretization reduces numerical dispersion, and hence improves the coarse grid correction. We show, numerically and theoretically, that our discretization allows the use of less grid points per shear wavelength without deteriorating the performance. It results in a scalable multigrid preconditioner that can tackle large real-world 3D scenarios.

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Israel Association for Computational Methods in Mechanics

Faculty of Engineering Sciences, Ben-Gurion University of the Negev, Beer Sheva, Israel

Block-Gauss-Seidel Vanka Smoother: Immersed Boundary Add-on and Application to Multiphase Flows

Mukesh Kumar, Yuri Feldman

[1] *Department of Mechanical Engineering, Ben Gurion University, Beer Sheva, Isreal*
mukesh@post.bgu.ac.il

ABSTRACT

We present a robust numerical algorithm for simulating multiphase flow problems with high-density ratios in arbitrary geometries. The method integrates a single-fluid framework using the volume-of-fluid (VOF) algorithm [1] to simulate multiple immiscible fluids and employs a direct forcing immersed boundary (IB) method [2] to enforce the kinematic constraints of no-slip on the surface of immersed bodies. The algorithm utilizes the developed Block-Gauss-Seidel Vanka-IB smoother for incompressible multiphase flows on a staggered grid. The algorithm's performance is enhanced by utilizing a direct MUMPS solver. A high-resolution upwind-biased scheme (Cubic Upwind Interpolation) [3] is used to discretize convective fluxes, eliminating the need for pressure and velocity interpolation. The solution of momentum, pressure, and fluid volume fraction equations throughout the entire domain eliminates the need for pressure and velocity interpolation — a common source of spurious oscillations in sharp interface-immersed boundary methods. The results obtained by applying the developed methodology to the solution of representative canonical configurations are presented.

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Matrix Equations Models for Solving The Dynamic Response of Inelastic Cantilever Structures

Assaf Shmerling

Department of Civil and Environmental Engineering, Ben-Gurion University of the Negev, Beer-Sheva, Israel

assafs@bgu.ac.il

ABSTRACT

This work presents a matrix equations model approach for analyzing the dynamic response of cantilever structures. The method can be used to assess the linear-elastic or inelastic response of buildings with symmetric or anti-symmetric floorplans. The proposed model constitutes an alternative to finite-element analysis and a valuable tool for introducing two-dimensional and three-dimensional cantilever structures to control the theory's state-space representation and structural dynamics' equation of motion. The model regards the stiffness and mass matrices. The proposed displacement-related stiffness matrix of cantilever elements satisfies the elemental boundary conditions while deriving a symmetric stiffness matrix. The linear-elastic response analysis is performed in displacement coordinates. However, the inelastic response analysis is conducted in bending curvature coordinates to coop with smooth hysteretic models that refer to the relation between the bending moment and the bending curvature through the bending stiffness. The transformation from displacement coordinates to bending curvature coordinates is explained. In the case of buildings with an anti-symmetric floorplan, the Direct Stiffness Method (DSM) is employed to transfer the cantile-ver elements from their local coordinates into the global degree-of-freedom (DOF) system. The numerical accuracy of the matrix equations model is examined, and its reliability is showcased.

Phase field method for fracture of brittle materials implemented with polygonal finite elements

Timo Saksala[1], Mahmood Jabareen[2]

[1] *Faculty of Built Environment, Tampere University, Tampere, Finland*
[2] *Faculty of Civil and Environmental Engineering, Technion-Israel Institute of Technology, Haifa, Israel*

timo.saksala@tuni.fi

ABSTRACT

Phase field method has become a popular approach to model fracture in computational mechanics. Its attraction stems from the ability to simulate crack initiation, propagation, and branching without the need for ad-hoc criteria. Moreover, with this method, cracks are tracked automatically by the propagation of a smooth crack field on a fixed mesh. However, the major shortcoming is the computational labor due to dense meshes required to reach convergence.

In this study, we present some preliminary results on an implementation of the phase field method with polygonal finite elements. We aim at modelling fracture propagation in brittle materials, such as rocks and concrete. Therefore, we adopt the so-called hybrid formulation of the phase field theory, which enables using a Mohr-Coulomb type of crack driving force to correctly model brittle materials under compression. While hybrid formulations are variationally inconsistent, they are computationally cheap since they allow to use a linear balance of momentum equation within the robust staggered scheme to solve the coupled system for the phase field and the displacement field.

The phase field method is implemented with 2D polygonal finite elements based on the Wachspress interpolation functions. As numerical examples, we solve the typical testcase of a notched sample under mode I and II loadings. Finally, a slope stability problem is solved as an engineering application.

In-Plane vs. Out-Of-Plane S-Waves in High Symmetry Phononic Crystals

Ilaie Nadejde[1], Pavel I. Galich[1]

[1] *Faculty of Aerospace Engineering, Technion-Israel Institute of Technology, Haifa, Israel*

ilaienadejde@campus.technion.ac.il

ABSTRACT

The study of elastic wave propagation in periodic materials known as phononic crystals (PnCs) has drawn significant attention in recent years due to advancements in fabrication technologies and computational tools. PnCs are structures characterized by specific 2D or 3D geometric designs that create a periodic impedance contrast, which can manipulate the propagation of elastic waves in solids. The phononic band structure of a PnC is typically determined by its geometry, topology, and symmetry, with higher symmetries leading to an increased likelihood of achieving a complete omnidirectional phononic bandgap [1] - a frequency gap in the phononic band structure where elastic wave propagation is forbidden for all wavevectors. Exploiting more complex symmetries and geometric features can lead to even wider bandgaps, giving rise to different acoustic devices that exploit a specific range of prohibited frequencies for acoustic isolation or filtering. In our recent study[2], we push the limits of complete omnidirectional bandgaps by unveiling an extremely wide bandgap of 124 % for the nonsymmorphic p4gm symmetry group design. This design greatly exceeds symmorphic p4mm-group PnC designs, as the nonsymmorphic plane groups have the advantage of potentially yielding wider bandgaps due to "band-sticking" [3]. We numerically compute the bandgap for a family of designs via finite elements, using the eigenfrequency analysis method and transmission loss simulations. We determine the band gap by scanning the Irreducible Brillouin Zone (IBZ) contour. Since the p4gm unit cell exhibits high-symmetry points, the IBZ alone is sufficient to acquire a complete description of the wave vectors corresponding to the allowed propagation frequencies within the PnC. We explore both P- and S-wave propagations and uncover distinctions between the mode types. We reveal differences between in-plane and out-of-plane S-wave propagation and investigate these both numerically and experimentally. Our findings indicate that by utilizing out-of-plane S-waves, it is possible to alter the attenuation characteristics of the same PnC structure, which opens up novel possibilities for manipulating elastic wave propagation for various applications.

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Numerical models of left ventricular expanders for heart failure: Optimization of functionality and durability

Gil Marom

School of Mechanical Engineering, The Fleischman Faculty of Engineering, Tel Aviv University, Tel Aviv, Israel

maromgil@tauex.tau.ac.il

ABSTRACT

Left ventricular (LV) expanders are spring-like devices that are specifically dedicated for the treatment of heart failure with preserved ejection fraction (HFpEF). They are intended to mechanically facilitate outward ventricular expansion during cardiac relaxation, thus enhancing the LV filling. First, we modeled device implantation in different configurations in HFpEF-induced porcine-specific hearts. We evaluated cardiac performance for several scenarios and compared them to the preimplantation and healthy (pre-induction) configurations to determine device effectiveness and potential use. The device has successfully increased the ventricular volume without hindering heart contraction. The end-systolic pressure-volume ratio was also improved. The EF remained within preserved values for all scenarios, demonstrating the device's safety profile. Arm rotation and device stiffness reduction have improved device performance without diminishing the compensatory high LV pressures. The device caused an increase in stress levels during diastole, with minor effects during systole. Then, we aimed at evaluating the effect of such devices implanted inside a generic model of a diseased human heart with hypertrophied and stiffened LV myocardium. This model was used for optimization of the shape, size, and material of the device by testing several configurations. The effect of the various devices on cardiac function was quantified by physiological parameters throughout the cardiac cycle, with a focus on systolic behavior. Finally, fatigue analyses were performed on the optimal design to assess the long-term impact and durability of the device. All expander device designs showed a positive impact on heart function. The results also revealed that cobalt-chromium alloys seem to be more appropriate than nickel-titanium for this type of application. The fatigue analysis, of the most optimized configuration, revealed that the device might not be capable of withstanding 10 years of heart cycles, but it can endure 2.5 years. This study indicates that the use of LV expanders may be used with caution in HFpEF and other diseases of cardiac stiffening. Although the EF and overall systolic function were preserved, the diastolic impact of the device should be more carefully assessed. Interestingly, even devices with a 2.5-year durability may still be beneficial for patients with severe cardiac stiffening, like in HFpEF, who typically have a shorter life expectancy. Further patient-specific analysis is needed to check the device in the context of clinical needs.

From Micro to Macro: Multiscale Analysis of 3D Collagen Network

Daria Orlova[1], Igor Berinskii[1]

[1] *School of Mechanical Engineering, The Fleischman Faculty of Engineering, Tel Aviv University, Tel Aviv, Israel*

dariaegorova@mail.tau.ac.il

ABSTRACT

Collagen fibers, a primary structural protein in the extracellular matrix, provides essential scaffolding for tissues. Functionally, these fibers are essential for providing mechanical support, ensuring tissues like tendons effectively transfer force from muscles to bones. Moreover, collagen is a dynamic component that plays a crucial role in mediating cell signaling, influencing various cellular behaviors and functions.

The intricate network of collagen fibers in tissues forms a highly interconnected system, highlighting the tissue's structural resilience. This complexity, especially when considering interactions between collagen fibers or with cells, presents challenges for detailed analyses.

Our study presents a homogenization framework designed for intricate 3D collagen-based fibrous networks with varying degrees of connectivity (C = 7 and 4), aiming to bridge the gap between micro-to-macro scale material behavior. Central to this study is the numerical strategy focused on the computational homogenization of the RVE, integrating boundary periodicity and uniaxial loading to derive effective elastic properties.

Through systematic evaluations, we derived an average stress-stretch curve, revealing the material's behavior at the micro-scale. The behavior was best represented by several hyperelastic models for both highly connected and more physiologically representative collagen networks with reduced connectivity, aligning closely with discrete experimental results. Collectively, these insights provide a solid foundation for advancing our understanding of collagen mechanics, setting the stage for more nuanced analyses, especially in contexts simulating cellular interactions within collagen matrices.

Identifiability of soft tissue constitutive parameters from *in-vivo* macro-indentation[1]

Zohar Oddes and Dana Solav

Faculty of Mechanical Engineering, Technion-Israel Institute of Technology, Haifa, Israel

zohar.oddes@campus.technion.ac.il

ABSTRACT

Reliable identification of soft tissue material parameters is frequently required in a variety of applications, particularly for biomechanical simulations using finite element analysis (FEA). However, determining representative constitutive laws and material parameters is challenging and often comprises a bottleneck that hinders the successful implementation of FEA. Soft tissues exhibit a nonlinear response and are commonly modeled using hyperelastic constitutive laws. *In-vivo* material parameter identification, for which standard mechanical tests (e.g., uniaxial tension and compression) are inapplicable, is commonly achieved using finite macro-indentation test. Due to the lack of analytical solutions, the parameters are commonly identified using inverse FEA (iFEA), in which simulated results and experimental data are iteratively compared. However, determining what data must be collected to accurately identify a *unique* parameter set remains unclear.

The presented work investigates the sensitivities of two types of measurements: indentation force-depth data (e.g., measured using an instrumented indenter) and full-field surface displacements (e.g., using digital image correlation). To eliminate model fidelity and measurement-related errors, we employed an axisymmetric indentation FE model to produce synthetic data for four 2-parameter hyperelastic constitutive laws: compressible Neo-Hookean, and nearly incompressible Mooney-Rivlin, Ogden, and Ogden-Moerman models. For each constitutive law, we computed the objective functions representing the discrepancies in the reaction force, the surface displacement, and their combination, and visualized them for hundreds of parameter sets, spanning a representative range as found in the literature for the bulk soft tissue complex in human lower limbs. Moreover, we quantified three identifiability metrics, which provided insights into the uniqueness (or lack thereof) and the sensitivities. This approach provides a clear and systematic evaluation of the parameter identifiability, which is independent of the selection of the optimization algorithm and initial guesses required in iFEA. Our analysis indicated that the indenter's force-depth data, despite being commonly used for parameter identification, was insufficient for reliably and accurately identifying both parameters for all the investigated material models and that the surface displacement data improved the parameter identifiability in all cases, although the Mooney-Rivlin parameter s remained poorly identifiable. Informed by the results, we then discuss several identification strategies for each constitutive model. Finally, we openly provide the codes used in this study, to allow others to further investigate the indentation problem according to their specifications (e.g., by modifying the geometries, dimensions, mesh, material models, boundary conditions, contact parameters, or objective functions).

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µFEA OF A RABBIT FEMUR
µFEA לעצם ירך של ארנב

Shani Martinez Weissberg and Zohar Yosibash

Computational Mechanics and Experimental Biomechanics Lab, School of Mechanical Eng, The Fleischman Faculty of Engineering, Tel Aviv University, Tel Aviv, Israel. sm2@mail.tau.ac.il

ABSTRACT

Given the ethical and practical limitations of conducting preliminary medical studies on humans, New Zealand White (NZW) rabbits serve as a common model for treatment validation. An important such medical study is radiation therapy on bones with tumors, which may increase the risk of fracture, especially in the femur.

Finite element (FE) analyses based on clinical computer tomography (CT) scans (referred to as CTFEA) have gradually gained recognition as a technology that provides insight into the mechanical response of long bones at the organ (whole bone) scale. However, clinical CT resolution cannot reproduce the trabecular morphology or determine accurately the cortex thickness of the rabbit bone. Notably, recent research indicates that CTFEA may also provide inaccurate predictions of human long bone failure load, in areas where large trabecular bone volume is surrounded by a thin cortex layer [1-3].

To capture the detailed rabbit femoral architecture, micro-computed tomography (µCT) scans are essential. In their pioneering paper, van Rietbergen et. al [4] introduce the voxel-based micro finite element (µFE) that converts each voxel in µCT images into a micro-mechanical model. µFE is being used routinely on small bone pieces (usually trabecular tissues), however, a µFE model of an entire bone is of an order of hundreds of millions of degrees of freedom (DOFs) and, therefore requires designated µFE solvers for analyzing these large µFE models.

The presentation outlines the step-by-step process (see Fig. 1) to create patient-specific µFE models of an entire rabbit femur, resulting in FE models of hundreds of millions of DOFs. The workflow begins with µCT imaging, followed by segmentation using MIA [5] (open-source software for medical image analysis). Subsequently, SimpleWare software is used for the generation of the 3D µFE model. The final step is a designated FE open-source library MFEM (Modular Finite Element Methods) [6] used to solve the system of equations and thereafter post-processing the results consisting of over 125 million DOFs.

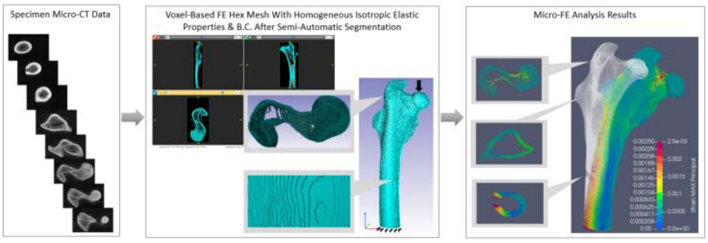

Fig. 1 – Rabbit femur µFE model flow work.

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Challenges in modeling, verification and validation of metal forming processes

Elad Priel[1,2]

[1] *Nuclear Research Center Negev-NRCN, Be'er-Sheva, Israel*
[2] *Center for Thermo-Mechanics and Failure of Materials, Department of Mechanical Engineering, Shamoon College of Engineering, Be'er-Sheva, Israel*

eladp@sce.ac.il

ABSTRACT

Metal forming processes are integral to modern manufacturing, facilitating the transformation of metal into desired shapes and forms through significant plastic deformation. These processes, whether conducted at room temperature (cold forming) or elevated temperatures (hot forming), are essential for various industries, from automotive to aerospace. However, the large forces involved in metal forming can lead to tool failure, defective products, and material loss. Computational modeling, particularly through the finite element method, offers a powerful approach to address these challenges by designing robust tools, predicting component failure, and optimizing process parameters.

This tutorial talk provides a comprehensive overview of computational modeling in metal forming, focusing on its challenges, methodologies, and applications. We begin with an introduction to different metal forming processes and common failure mechanisms encountered in industrial settings. Emphasis is placed on the nonlinear nature of these processes, characterized by large deformations, material plasticity, and frictional effects.

Key aspects of computational methodology, including the determination of temperature-dependent flow stress and friction coefficients, are discussed in detail. We highlight the importance of incorporating thermal-mechanical coupling in simulations, especially in scenarios where temperature significantly influences material behavior.

Through examples, ranging from extrusion to multi-step rolling processes and micro-mechanical modeling of metallic powder compaction, we demonstrate the versatility of finite element analysis in modeling complex metal forming operations. Attention is given to proper verification and validation practices to ensure the reliability and accuracy of computational models.

Finally, current challenges in modeling metal forming processes, such as addressing process-induced changes in material microstructure and ductile failure, are addressed, pointing towards avenues for future research and development in computational mechanics. This tutorial aims to provide attendees with a comprehensive understanding of computational modeling in metal forming and its implications for advancing manufacturing processes.