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A discontinuous Galerkin method for nonlinear shear-flexible shells

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Abstract

In this paper, a discontinuous Galerkin method for a nonlinear shear-flexible shell theory is proposed that is suitable for both thick and thin shell analysis. The proposed method extends recent work on Reissner-Mindlin plates to avoid locking without the use of projection operators, such as mixed methods or reduced integration techniques. Instead, the flexibility inherent to discontinuous Galerkin methods in the choice of approximation spaces is exploited to satisfy the thin plate compatibility conditions a priori. A benefit of this approach is that only generalized displacements appear as unknowns. We take advantage of this to craft the method in terms of a discrete energy minimization principle, thereby restoring the Rayleigh-Ritz approach. In addition to providing a straightforward and elegant derivation of the discrete equilibrium equations, the variational character of the method could afford numerous advantages in terms of mesh adaptation and available solution techniques. The proposed method is exercised on a set of benchmarks and example problems to assess its performance numerically, and to test for shear and membrane locking.

Keywords: shells, discontinuous Galerkin, locking, variational

1. Introduction

Shell structures are perhaps the most challenging setting for numerical analysis in solid mechanics. The primary difficulty encountered is *locking*, wherein the approximation power of the numerical method diminishes as the shell thickness is reduced. The problem is similar to that faced in nearly incompressible elasticity. Shear-flexible shell theories are generally formulated with two kinematic fields: the displacement of the shell mid-surface, and some representation of the rotation of fibers originally transverse to the shell surface. The root of the locking problem is that when standard finite element interpolations are used for both fields, the pair of approximations spaces taken together do not represent the thin-shell limit well. In particular, this incompatibility prevents the transverse shear strains from vanishing, leading to spurious shear energy. The problem is exacerbated as the shell thickness t tends to zero, since the bending energy is smaller than the transverse shear energy by a factor of t^2, and the spurious shear energy caused by the incompatibility of the discrete function spaces becomes dominant.

The goal for numerical analysis of shear-flexible plates and shells is a method that converges uniformly with respect to the thickness, while remaining simple. These requests are somewhat antagonistic, and the search for acceptable compromises has generated a large body of literature (see the review by [1] and the references therein). Most approaches operate on the shear energy by replacing the rotations in the shear strain term with some lower order projection. There are two main techniques applied to effect this projection: one avenue followed has been mixed methods, in which the shear strain is added as an unknown, such as [2, 3, 4, 5, 6] for Reissner-Mindlin plates, and the well-known MITC elements [7, 8, 9] that extend this idea to curved shells. The other main approach, popular in commercial finite element codes, is to use a reduced

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