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Maxwell viscoelasticity at large strains and rotations

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We analyse the behaviour of three Maxwell models under simple shear up to large strains: the classic small-strain model (SS), a model using Jaumann's co-rotational stress rate to account for rigid-body rotations (MJ), and a new model for finite viscoelastic transformations (FT) using a logarithmic co-rotational stress rate and the Hencky strain tensor. The former two models have been used most commonly in computational geodynamics and structural geology. However, only the new FT model satisfies the notions of frame indifference and consistency in terms of energy conservation. Therefore, discrepancies and errors can be expected at high non-coaxial strains with significant elastic stress contributions in the SS and MJ models.

To test this hypothesis, we compare these three models over the parameter space relevant to lithospheric deformation. The relevant material properties are parameterized in terms of the Weissenberg number W, defined here as the product of the Maxwell relaxation time and the characteristic strain rate. All models yield practically identical results at $W \leq 0.1$. In other words, if elastic stresses are negligible compared to viscous ones, the mathematically simple SS model performs sufficiently well. However, in the W-interval]0.1;10], important differences are observed. The SS model overestimates shear stresses significantly because it ignores the principle of frame indifference. As a result, large errors in the energy balance occur. The MJ model dissipates elastic energy erroneously due to artificial oscillatory terms and hence violates the notion of energy conservation. Since the first law of thermodynamics is at the heart of continuum mechanics, the MJ model appears to be unsuited for modeling large non-coaxial deformations in geomaterials. The FT model overcomes these problems and provides an energetically consistent approach to modeling large non-coaxial viscoelastic deformation. Therefore, it is expected to be of great use to viscoelasticity problems in forward models of, for example, shear zones, folds, or strongly sheared and bending lithospheric plates.