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Generalized Navier-Stokes Equations in Distortion Gravity: A Geometric Approach to Fluid Dynamics

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Abstract

We derive a generalization of the Navier-Stokes equations by incorporating the distortion fields of Distortion Gravity, a metric-affine theory of gravity in which the affine connection carries independent dynamics. Starting from the covariant conservation of the energy-momentum tensor in the presence of torsion and non-metricity, we perform a non-relativistic expansion and obtain modified fluid equations. The new terms include a Lorentz-like force due to axial torsion, an effective pressure modified by the non-metricity vector, and a geometric viscosity independent of velocity gradients. We discuss possible physical implications for turbulence, astrophysical accretion disks, and primordial cosmology. The results provide a new framework for studying fluids in strong gravitational regimes where quantum effects of the connection become relevant.

1 Introduction

The Navier-Stokes equations are the cornerstone of classical fluid dynamics, describing the motion of viscous fluids in a wide range of physical contexts. However, in regimes where gravitational effects are strong — such as near black holes, in the early universe, or in compact stars — the interplay between fluid motion and the geometry of spacetime becomes crucial. General relativity (GR) describes gravity as the curvature of spacetime, but its connection is assumed to be the Levi-Civita one, torsion-free and metric-compatible.

Distortion Gravity (DG) [1] generalizes GR by promoting the affine connection to an independent field. The distortion tensor $D^{\lambda}_{\mu\nu} = \Gamma^{\lambda}_{\mu\nu} - \bar{\Gamma}^{\lambda}_{\mu\nu}$ decomposes into a trace vector V_μ (non-metricity), an axial vector a_μ (torsion), and a traceless part $q^{\lambda}_{\mu\nu}$. The theory is ghost-free, renormalizable, and offers a natural framework for quantum gravity.

In this work, we extend the fluid dynamics to incorporate the distortion fields. We derive the generalized Navier-Stokes equations from first principles, showing how torsion and non-metricity modify the conservation laws and introduce new dissipative and transport phenomena. The resulting equations may be relevant for understanding turbulence in strong gravitational fields, the dynamics of accretion disks, and the evolution of primordial fluids.

2 Distortion Gravity: A Brief Review

We work in a metric-affine spacetime (M, g, Γ), where the metric $g_{\mu\nu}$ and the connection $\Gamma^{\lambda}_{\mu\nu}$ are independent. The distortion tensor is defined as

$$D^{\lambda}_{\mu\nu} = \Gamma^{\lambda}_{\mu\nu} - \bar{\Gamma}^{\lambda}_{\mu\nu},$$

where $\bar{\Gamma}$ is the Levi-Civita connection. The irreducible decomposition of D yields

$$D^{\lambda}_{\mu\nu} = \frac{1}{3}\delta^{\lambda}_{\mu} V_\nu + \frac{1}{3}\delta^{\lambda}_{\nu} V_\mu - \frac{1}{3} g_{\mu\nu} V^\lambda + \varepsilon^{\lambda\rho}{}_{\mu\nu} a_\rho + q^{\lambda}_{\mu\nu}.$$

The fields V_μ and a_μ satisfy Proca-type equations:

$$\Box V_\mu - \nabla_\mu \nabla_\nu V^\nu + m_V^2 V_\mu = J_\mu,$$

$$\Box a_\mu - \nabla_\mu \nabla_\nu a^\nu + m_a^2 a_\mu = K_\mu,$$

where J_μ and K_μ are source currents from matter fields.

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3 Covariant Conservation of the Energy-Momentum Tensor

For a perfect fluid, the energy-momentum tensor is

$$T^{\mu\nu} = (\rho + p)u^\mu u^\nu + pg^{\mu\nu},$$

where ρ is the energy density, p the pressure, and u^μ the four-velocity. In metric-affine gravity, the conservation law is modified:

$$\nabla_\mu T^{\mu\nu} = -\frac{1}{2}\left(D^\nu_{\mu\lambda}T^{\mu\lambda} - D^\lambda_{\mu\lambda}T^{\mu\nu}\right).$$

Substituting the decomposition of D, and using the equations of motion for V_μ and a_μ, we obtain the non-conservation of energy and momentum. This leads to source terms in the fluid equations.

4 Non-Relativistic Expansion

We perform a non-relativistic expansion in powers of v/c, with $u^\mu \simeq (1, \mathbf{v}/c)$. Keeping terms up to first order in v/c and linear in the distortion fields, we obtain the following results.

4.1 Modified Continuity Equation

The component $\nu = 0$ of the conservation equation yields

$$\boxed{\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = -\rho V^0}$$

where V^0 is the time component of V^μ. This indicates that non-metricity can create or destroy mass density, a novel effect absent in classical hydrodynamics.

4.2 Generalized Navier-Stokes Equation

The spatial components $\nu = i$ give the momentum equation:

$$\boxed{\rho\left(\frac{\partial\mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \eta\nabla^2\mathbf{v} + \left(\zeta + \frac{1}{3}\eta\right)\nabla(\nabla\cdot\mathbf{v}) + \mathbf{F}_{\text{dist}}}$$

with the distortion force

$$\boxed{\mathbf{F}_{\text{dist}} = \rho\left(\mathbf{E}_V + \mathbf{v}\times\mathbf{B}_a\right) + \nabla(\rho\Phi_V) - \frac{\eta}{2}\left(\nabla\times\mathbf{a} + \nabla V^0\right) - \rho\,\mathbf{v}\cdot\nabla\mathbf{V}}$$

where we have defined:

$$\mathbf{E}_V = -\nabla V^0 - \partial_t\mathbf{V}, \qquad \mathbf{B}_a = \nabla\times\mathbf{a}, \qquad \Phi_V = V^0 + \mathbf{v}\cdot\mathbf{V}.$$

5 Interpretation of the New Terms

5.1 Lorentz-like Force

The terms $\rho\mathbf{E}_V$ and $\rho\mathbf{v}\times\mathbf{B}_a$ have the same structure as the Lorentz force, with the distortion fields replacing the electromagnetic ones. Torsion behaves as a magnetic-like field that deflects fluid motion.

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5.2 Effective Pressure

The term $\nabla(\rho\Phi_V)$ can be absorbed into an effective pressure:

$$p_{\text{eff}} = p - \rho\Phi_V.$$

This introduces a velocity-dependent pressure, leading to non-linear instabilities.

5.3 Geometric Viscosity

The term $-(\eta/2)(\nabla\times\mathbf{a}+\nabla V^0)$ represents a viscosity that depends on the gradients of torsion and non-metricity. This is a purely geometric dissipation mechanism, active even in the absence of velocity gradients.

5.4 Drag Force

The term $-\rho\,\mathbf{v}\cdot\nabla\mathbf{V}$ describes the dragging of the non-metricity field by the fluid: a moving fluid feels a resistance if $\mathbf{V}$ varies spatially.

6 Vorticity Equation

Taking the curl of the Navier-Stokes equation yields the generalized vorticity equation:

$$\boxed{\frac{\partial\omega}{\partial t}+\nabla\times(\omega\times\mathbf{v}) = \nu\nabla^2\omega+\nabla\times\left(\frac{\mathbf{F}_{\text{dist}}}{\rho}\right)}$$

where $\omega = \nabla\times\mathbf{v}$ is the vorticity. The term $\nabla\times(\nabla\times\mathbf{a})$ can generate vorticity even in an initially irrotational fluid, provided the torsion field has non-zero Laplacian.

7 Physical Implications

7.1 Turbulence in Strong Gravitational Fields

The geometric viscosity term provides a new dissipation channel in turbulent flows, potentially altering the Kolmogorov cascade in environments where torsion is significant (e.g., near black holes).

7.2 Accretion Disks

In accretion disks around compact objects, strong gravitational gradients may generate torsion fields. The generalized Navier-Stokes equations could modify the angular momentum transport and the disk's thermal structure.

7.3 Primordial Cosmology

In the early universe, torsion and non-metricity could have been generated by quantum fluctuations. The vorticity source term may explain the origin of cosmic rotation, leaving observable imprints in the cosmic microwave background.

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7.4 Experimental Prospects

Laboratory experiments with rotating fluids in strong magnetic fields could test the Lorentz-like force due to torsion, by measuring deviations from classical fluid behavior.

8 Conclusions

We have derived a generalization of the Navier-Stokes equations in the framework of Distortion Gravity. The new equations incorporate contributions from the torsion and non-metricity fields, leading to a Lorentz-like force, an effective pressure, a geometric viscosity, and a drag force. These terms may have significant implications for astrophysical and cosmological fluid dynamics. Future work will explore numerical simulations and potential observational signatures.

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