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Adjoint methods for efficient stellarator optimization and sensitivity analysis[1]

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The design of modern stellarators often employs gradient-based optimization to navigate the high-dimensional spaces used to describe their geometry. However, computing the numerical gradient of a target function with respect to many parameters can be expensive. The adjoint method allows these gradients to be computed at much lower computational cost and without the noise associated with finite differences. This technique has been employed widely in automotive and aerodynamic engineering, and we present the first applications to stellarator design. An adjoint method has been implemented in the stellarator coil design code REGCOIL, allowing for optimization of the coil-winding surface with analytic gradients to obtain improved coil shapes with minimal field error. An adjoint drift kinetic equation has also been implemented in the SFINCS code to compute gradients of moments of the distribution function, such as the bootstrap current, with respect to geometric parameters. We apply this method for optimization of neoclassical quantities without inherent assumptions on the collisionality or radial electric field. Furthermore, we present an adjoint method for obtaining the gradients of functions of MHD equilibria, such as the rotational transform or magnetic well, with respect to the shape of the plasma boundary or coils, providing an order $10^2 - 10^3$ reduction in cost. In addition to gradient-based optimization, we use the derivatives obtained from the adjoint method for local sensitivity analysis. For example, derivatives from REGCOIL inform where the normal field error is most sensitive to displacements of coils. Similarly, derivatives computed from SFINCS inform where the bootstrap current is most sensitive to perturbations of the field strength. These local sensitivity calculations provide quantification of engineering tolerances and insight into optimization.

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