This paper presents large-scale parallel computational fluid dynamics simulations for the Stratospheric Observatory for Infrared Astronomy (SOFIA). SOFIA is an airborne, 2.5-m infrared telescope mounted in an open cavity in the aft fuselage of a Boeing 747SP. These simulations focus on how the unsteady flow field inside and over the cavity interferes with the optical path and mounting structure of the telescope. A temporally fourth-order accurate Runge–Kutta, and a spatially fifth-order accurate WENO-5Z scheme were used to perform implicit large eddy simulations. An immersed boundary method provides automated gridding for complex geometries and natural coupling to a block-structured Cartesian adaptive mesh refinement framework. Strong scaling studies using NASA's Pleiades supercomputer with up to 32 k CPU cores and 4 billion computational cells show excellent scaling. Dynamic load balancing based on execution time on individual adaptive mesh refinement (AMR) blocks addresses irregular numerical cost associated with blocks containing boundaries. Limits to scaling beyond 32 k cores are identified, and targeted code optimisations are discussed.