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Title

An adjoint-based approach for finding smooth surface waviness tolerances for natural laminar flow design

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Abstract

An adjoint-based methodology is proposed and tested to find tolerances for manufacturing natural laminar flow (NLF) surfaces subjected to smooth surface waviness type of excrescences. The main goal is to find the manufacturing tolerances based on the largest allowable waviness profile with minimum $L2$-norm of surface deformations that might cause early transition due to the existence of waviness on the airfoil. The growth of convectively unstable disturbances is computed by solving Euler, compressible boundary layer (BLE), and parabolized stability equations (PSE). The gradient of the kinetic energy of disturbances in the boundary layer (E) with respect to surface grid point deformations is calculated by solving adjoints of PSE, BLE, and Euler equations, and it is validated with finite difference method. Then, for specific flight conditions and a disturbance mode, using the gradient ascent and the SLSQP methodologies, the waviness profile with minimum $L2$-norm of surface deformations that causes a specific increase in the maximum value of N-factor, ΔN, is found and the tolerances for assuring NLF are calculated based on such worst-case scenario. Finally, numerical tests are performed using the NLF(2)-0415 airfoil to specify tolerance levels for ΔN up to 2.0 for different flight conditions. All simulations are carried out at Mach number equal to 0.5 for Reynolds numbers between 9×10^6 and 15×10^6 and for smooth waviness profiles with different ranges of wavelengths of waviness on airfoil.
The results obtained show how the tolerance decreases with an increase in Reynolds number, where the thickness of the BL plays a significant role, and how it decreases with a decrease in wavelengths of surface waviness on airfoil due to the level of adverse-favorable pressure gradients. It also has been shown that the SLSQP is the only one, out of the two, capable of informing the largest allowable deformation profile, with minimum L2-norm of surface deformation, at the cost of additional computational time compared to the gradient ascent approach, which informs tolerances within an error of less than 10% but in a shorter time frame.