Scaling Laws for Testing Airfoils Under Heavy Rainfall

Alan J. Bilanin*
Continuum Dynamics, Inc., Princeton, New Jersey

Subscale test data have shown that airfoils operating in a simulated heavy-rain environment can experience significant performance penalties. The physical mechanism resulting in this performance penalty has yet to be conclusively identified. Therefore, the extrapolation of subscale data to full-scale conditions must be undertaken with extreme caution since complete scaling laws are unknown. This paper discusses some of the technical issues that must be addressed and resolved prior to extrapolating the performance of full-scale airfoils from subscale test data. A set of scaling laws is suggested based on the neglect of thermodynamic interactions between the droplets and the air/water vapor phase.

Nomenclature

a =isentropic acoustic speed
c =airfoil chord
C_d =drag coefficient
C_L =lift coefficient
c_v =specific heat at constant volume
D =drop diameter
h_{fg} =latent heat of vaporization of water
ℓ =mean distance between droplets
m =mass
M =Mach number
$n(D)$ =raindrop size spectrum
n_0 $=8\times10^3\ \mathrm{m}^{-3}\mathrm{mm}^{-1}=n_{0fs}$
N =aerodynamic force
ND =droplet number density
p =pressure
R =rainfall rate, mm/h, or gas constant
T =temperature
u_i =velocity vector
U_∞ =flight speed
V =volume or droplet impact velocity
V_T =drop terminal velocity
W_L =liquid water content, g/m^3
We =Weber number
x,y,z =Cartesian coordinate system
α =angle of attack
β =impact angle
γ =ratio of specific heat
θ =contact angle
A =reciprocal of rain spectrum scale
μ =absolute viscosity
υ =kinematic viscosity
ρ =density
σ =surface tension
τ =shear stress
Φ =velocity potential

Subscripts

a =air
fs =full scale
ss =subscale
s =solid
v =vapor
w =water

Introduction

THE National Aeronautics and Space Administration (NASA) and other agencies are currently conducting studies on the performance penalties that might occur when airfoils operate under heavy-rain conditions. The studies to date are primarily of an experimental nature and, for practical reasons, are conducted at subscale. Since incorrect extrapolation of test results to full scale can seriously impact performance predictions, it is critical to have in hand detailed scaling laws. These laws will assure that tests conducted at subscale are relevant to the performance of aircraft.

The effect of rainfall about aircraft has received considerable attention in the literature. However, the bulk of this work is concerned with rain erosion resulting from high-speed droplet impacts with the aircraft surface.' The first reported investigation of the effect of heavy rain on the performance of aircraft was published in 1941 by Rhode.[2] In this report, the author concludes that the added drag of rain impacting the aircraft exacted the greatest performance penalty, but that this penalty did not seem to be a safety concern. This conclusion, however, was reached without considering the decreased performance margins that exist during landing. This author has been unable to find any additional published work until 1983 when Luers and his colleague Haines published two articles discussing heavy rain penalties on aircraft,[3,4] followed by a subsequent article by Luers.[5] The conclusion of this work was that, under extremely heavy rain, the rain-roughened wing could suffer a decrease in stall angle with maximum lift coefficient reductions of 30%. In the same time period, Calarese and Hankey[6] published an analytic study showing that, under heavy-rain conditions, the lift of an airfoil actually increased. However, their analysis neglected the droplet interactions with the wing surface and the resulting splash-back and surface roughing effects.

The remaining published investigations on performance penalties associated with operation under heavy-rain conditions were presented at an AIAA meeting in 1985. They include the results of a recent test program conducted by NASA[7,8] on a flapped NACA 64-210 section. These tests confirm at subscale that performance penalties can occur when the airfoil is operating in very severe rainfall. Another paper demonstrates that under heavy-rain conditions, laminar airfoils such as those used on gliders, but tested at subscale, are also susceptible to a performance penalty.'

It is clear from the above that performance penalties on airfoils have been identified in subscale tests. Therefore, it is of great importance that scaling laws be developed to aid in the extrapolation of these data to full-scale. This paper at-

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*Senior Associate. Member AIAA.