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Technical Comments

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Comment on "Rotational Effects on the Boundary-Layer Flow in Wind Turbines"

D. H. Wood*
University of Newcastle,
Newcastle, New South Wales 2308, Australia

IN Ref. 1, a numerical solution of the three-dimensional laminar boundary-layer equations is described in blade-fixed coordinates for a generic rotating blade subjected to a prescribed pressure distribution. Dumitrescu and Cardos[1] show that boundary-layer separation can be delayed by the effects of rotation, principally through the action of the Coriolis force. This action is claimed to explain the phenomena of "stall delay" on wind turbine blades whereby the (usually turbulent) boundary layer stays attached at angles of attack that would cause stall on the corresponding airfoil section. The paper concludes by rejecting Wood's alternative explanation for stall delay[2] in terms of modifications to the external inviscid flow. The main purpose of these comments is to demonstrate that that rejection is invalid. Many studies of stall delay have appeared in the 13 years since Ref. 2 was published, and this discussion will trace briefly the history of the developing ideas on this very important topic.

When the blade-fixed boundary integral analysis of Ref. 2 was undertaken, the state of knowledge of stall delay was poor. Partly on the grounds of expediency, because it is more difficult to analyze the boundary-layer flow, Wood started from the fundamental assumption that, if a significant reduction occurred in the adverse pressure gradient on the blade's suction surface when compared to an airfoil at the same angle of attack, then it is unnecessary to seek the explanation for stall delay within the boundary layer. In turn, this assumption was motivated by two considerations: First, to leading order, boundary layers simply respond to the pressure gradient imposed on them. Second, it seemed unlikely that the Coriolis force, which, by the no-slip condition, is zero at the blade surface (in blade-fixed coordinates) could cause separation as effectively as an adverse pressure gradient, which is felt equally across a boundary layer (in the absence of significant streamline curvature) and, hence, is felt in much greater relative terms near the wall. The results of the computations described in Ref. 2 showed significant reductions in the imposed adverse pressure gradient and thus were consistent with the fundamental assumption.

Boundary integral analysis naturally includes the effects of the Coriolis and centrifugal forces on the inviscid flow, and it is well known that wind turbines typically produce only a small amount of swirl in the air passing over them: In terms of standard blade element theory, the rotational induction factor is usually small and negligible. Thus, the centrifugal force is nearly balanced by the Coriolis force at the edge of the boundary layer. This fixes their relative magnitude for boundary-layer analysis and provides an alternative statement to the order of magnitude estimate of Eq. (19) of Ref. 1. Furthermore, the near cancellation of centrifugal and Coriolis forces in the inviscid flow leaves the ratio r/c, where r is the radius and c is the chord, as the natural scaling parameter for stall delay according to the fundamental assumption. Note that r/c is inversely proportional to the local solidity, and so this explanation for stall delay is ultimately one of interference between adjacent blades and implies, inter alia, that stall delay can occur on a stationary blade. In this context, an airfoil can be considered as a blade element for which $r/c \to \infty$.

An important early experimental study of stall delay was by Ronstan,[3] who compared rotating blade pressure distributions to those obtained on a stationary blade, up to an angle of attack of 30.4 deg. At this high angle, the nonrotating blade had stalled, whereas the rotating blade had not. Unfortunately, in view of the arguments given earlier, the nonrotating blade was tested separately in a wind tunnel, and so was not part of a turbine rotor. Thus, there was no interference with adjacent blades. These experimental pressure distributions are reproduced in Sec. 3.12 of Ref. 4 along with the early data correlation of Snel et al.,[5] which gives the increment in section lift coefficient due to rotation in terms of r/c only. Such a correlation cannot be adequate because it implies that the Coriolis force can delay separation on a stationary blade. The more recent work of Du and Selig[6,7] considers the effects of rotation. Unfortunately the data correlation of Ref. 7 is not well behaved as the tip speed ratio $\lambda \downarrow 0$, probably because it results from considering only the boundary-layer flow. If, however, the fundamental assumption is correct and the external inviscid flow is also modified to reduce the blade's adverse pressure gradient, then the rotational effects within the boundary layer will be of higher order. Dumitrescu and Cardos[1] did not consider modifications to the inviscid flow, and therefore, their rejection of this possibility is invalid.

The more recent experiment of Schreck and Robinson[8] compared the pressures on rotating and stationary rotors (not isolated blades) and showed conclusively that rotation leads to more stall delay than does interference on its own.

The comparison of airfoil and blade element performance is complicated by a fundamental difference that has yet to be seriously addressed: There can be no net upwash for a blade. In other words, the circulation in the air passing over a blade can only be generated downstream of the leading edge, whereas about half the circulation of an airfoil occurs upstream (the upwash) and half downstream (the downwash). This difference, which was first demonstrated by Taylor[9] in 1915, using a typically simple and elegant argument, may well be important at the high values of lift and circulation that result from stall delay. Furthermore, the effects of the difference should scale on r/c. These effects are automatically captured by a boundary integral analysis, and so they may be responsible for some of the differences in the pressure distributions computed by Wood.

In summary, it appears that there are possibly two distinct physical mechanisms for explaining stall delay: the reduction of the adverse pressure gradient imposed by the external inviscid flow and the action of the Coriolis and centrifugal forces within the boundary layer. Both appear, in general, to scale on the parameter r/c, but we do not yet have an adequate explanation for this unusual situation, nor are we able to determine the relative importance of the two mechanisms in a given situation. The work of Ref. 1 and others are providing valuable information on boundary layer behavior but extreme care should be taken in generalizing their results.

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*Conjoint Associate Professor, School of Engineering.

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S. Aggarwal
Associate Editor