# Calculation of Unsteady Wake/Rotor Interaction

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**This paper presents a numerical analysis of wake/rotor interaction using a time-marching solution of the unsteady, nonlinear Euler equations. The incoming wakes are specified through the unsteady inflow boundary conditions. The lagged periodic boundary condition that arises due to unequal rotor/stator pitches is handled by a new technique that inclines the computational plane in time. Comparison of results for a flat-plate cascade with results using a linear analytic theory demonstrates the method's capability to accurately predict unsteady forces, moments, and radiated sound. Results are also presented for a low-speed turbine.**

## Nomenclature

*Variables*

$c$ = speed of sound
$C$ = axial chord length
$D$ = maximum wake velocity defect
$E, H$ = total energy and enthalpy, respectively.
$J_{\pm}$ = Riemann invariants
$p$ = pressure
$P_r, P_s$ = rotor and stator pitches
$q$ = speed
$u, v$ = velocity components
$U$ = upstream axial velocity
$V$ = wheel speed
$w_{1,2,3,4}$ = characteristic variables
$W$ = fractional wake width
$x, y$ = coordinates
$\alpha$ = flow angle
$\gamma$ = ratio of specific heats
$\rho$ = density
$\Delta T$ = time lag in periodic bc's
$\lambda$ = $\Delta T / P_r$
$\omega$ = frequency, $2\pi V / P_s$

*Subscripts*

$is$ = steady inlet variable in rotor frame
$inl$ = specified inlet variable in rotor frame
$iw$ = specified inlet variable in wake frame
$os$ = steady outlet variable in rotor frame

## I. Introduction

In the past, the calculation of the flow in turbomachinery has been based largely on the approximation that the flow in each stator or rotor row is steady in the frame of reference of the stator or rotor. In reality, the flow is inherently unsteady. In two dimensions, there are three dominant causes of unsteadiness. The first is wake/rotor interaction in which the wakes produced by a stator row are then swept downstream into the next rotor row. The second is vortex shedding at trailing edges. The third is the potential stator/rotor interaction in which the pressure field associated with the leading edge of a rotor sweeps past the trailing edge of an upstream stator, causing additional unsteadiness at the trailing edge and possibly affecting the vortex-shedding mechanisms.

The purpose of this paper is to present and evaluate a numerical method for the investigation of the wake/rotor interaction. In the future, this method will lead to a more complete analysis of the full, unsteady viscous stator/rotor interaction. The wake/rotor interaction problem is relatively simple because it is essentially inviscid, meaning that although viscous forces generated the stator wakes, the viscous forces are not particularly important in the dynamics of their subsequent interaction with the downstream rotor row. Thus, the problem can be modeled by solving the Euler equations for the inviscid flow through a rotor row, with the wakes being imposed through the unsteady inflow boundary conditions.

Another important reason for calculating wake/rotor interaction is to be able to predict noise generation. One of the questions in the development of counter-rotating propfans and ultra-high-bypass turbofans is the level of noise produced. If we assume that the fans are separated sufficiently so that they are outside each other's moving potential field, then one of the principal noise sources is the wake/rotor interaction since the wakes decay very little before entering the rotor passage. Because the fans are transonic and highly loaded, simple linear theories are inadequate, and so it is important to use the nonlinear, unsteady Euler equations to predict the noise generation and to check the accuracy on simple test cases for which linear theory is valid.

Experimental studies of wake/rotor interactions have been performed by Kerrebrock and Mikolajczak[1] for compressors, and by Binder et al.[2] and Hodson[3] for turbines. These studies show that the dominant effects are inviscid, with the leading order behavior being simply that the wake vorticity and entropy are convected by the mean flow. The next order effect is the wake migration, which is due to the fact that the wake acts as a "negative jet" relative to the mean flow, and so after the wake is cut into segments by the blade row, the segments migrate toward the pressure surface for compressors and the suction surfaces for turbines.

On the theoretical side, Smith[4] developed a linear theory for subsonic flow, in which he considered small perturbations about uniform flow past a flat plate cascade at zero incidence. The theory calculates the magnitudes of the unsteady lift, moment, trailing edge vortex sheet and radiated pressure waves, in response to either incoming wakes and pressure waves or blade flutter. The theory leads to an integral equation that must be solved numerically, and Whitehead has implemented this method in an extrememly fast program.[5] Unfortunately, Smith also showed that in experiments the steady-state loading significantly affects the results and so his theory is best applied in only lightly loaded cascades.

To calculate the nonlinear effects, one must turn to more recent computational methods. The most important work in this area is by Rai,[6] who has calculated the unsteady, viscous rotor/stator interaction using a sliding interface between grids that are fixed in the rotor and stator frames of reference. An

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