Progress in Aerospace Sciences 52 (2012) 30–47

Contents lists available at SciVerse ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

Towards Large Eddy Simulation of gas turbine compressors

W.A. McMullan [1], G.J. Page *

Department of Aeronautical & Automotive Engineering, Loughborough University, Leicestershire LE11 3TU, United Kingdom

ARTICLE INFO

Available online 1 April 2012

Keywords:
Large Eddy Simulation
Computational fluid dynamics
Gas turbine
Turbomachinery

ABSTRACT

With increasing computing power, Large Eddy Simulation could be a useful simulation tool for gas turbine axial compressor design. This paper outlines a series of simulations performed on compressor geometries, ranging from a Controlled Diffusion Cascade stator blade to the periodic sector of a stage in a 3.5 stage axial compressor. The simulation results show that LES may offer advantages over traditional RANS methods when off-design conditions are considered – flow regimes where RANS models often fail to converge. The time-dependent nature of LES permits the resolution of transient flow structures, and can elucidate new mechanisms of vorticity generation on blade surfaces. It is shown that accurate LES is heavily reliant on both the near-wall mesh fidelity and the ability of the imposed inflow condition to recreate the conditions found in the reference experiment. For components embedded in a compressor this requires the generation of turbulence fluctuations at the inlet plane. A recycling method is developed that improves the quality of the flow in a single stage calculation of an axial compressor, and indicates that future developments in both the recycling technique and computing power will bring simulations of axial compressors within reach of industry in the coming years.

Contents

1. Introduction

In modern engineering practice an increasing emphasis is being placed on the role of Computational Fluid Dynamics (CFD) in the design process. In order for a CFD tool to be an effective part of the design environment it must provide highly accurate

* Corresponding author. Tel.: +44 1509 227205.
E-mail address: G.J.Page@lboro.ac.uk (G.J. Page).
[1] Current address: Department of Engineering, University of Leicester, Leicestershire LE1 7RH, United Kingdom.

0376-0421/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.paerosci.2011.12.002

Nomenclature

α	low pass filter smoothing factor
$\overline{\varpi}$	total pressure loss coefficient
β	flow inlet angle
Δt	numerical time step
$\varDelta$	filter width
δ,δ^*	boundary layer thickness and displacement thickness
κ	Von Karman constant 0.41
μ_t	RANS turbulent viscosity
μ_{sgs}	subgrid scale viscosity
ω	vorticity, rotational speed
ρ	density
A^+	Van Driest constant 26.0
A_{ij}	flux Jacobian
c	blade chord
C_p	pressure coefficient
C_s	Smagorinsky model constant
E	total energy per unit volume
F,G	flux vectors
L^{lp}	pseudo-Laplacian
L_Z	spanwise extent
l_{bl}	Baldwin–Lomax length scale
l_{smag}	Smagorinsky length scale
M	Mach number
n	normal vector
P	total pressure
p	static pressure
Q	state vector
Q_m	low pass filtered running mean of state vector
r	normal distance from surface of blade
Re	Reynolds number
S_{ij}	strain rate tensor
t	time
u,v,w	Cartesian components of velocity
$u_i,\overline{u}_i,u'_i$	instantaneous, mean and fluctuating velocity components
U_n	face normal velocity component
u_t	velocity component tangential to blade
V_{in}	inlet velocity magnitude
V_{ref}	reference inlet velocity magnitude
x,y,z	Cartesian components of position
x^+,y^+,z^+	distance in wall units

solutions to the flow problem in question within an acceptable timeframe – typically results are required within an overnight run. For gas turbine compressor components the CFD methods employed in industry have been centred around solution of Reynolds-Averaged Navier Stokes (RANS) equations. Whilst the capability of RANS to produce rapid flow solutions over a range of performance characteristics is highly desirable for industry, it is known to be deficient in key areas; first, RANS solutions often fail to converge at off-design conditions; the lack of confidence in the CFD solutions can restrict the design space. Second the ensemble-averaged RANS data does not give any information on the time-dependent structure within the flow. Experimental evidence suggests that organised streamwise vorticity may play an important role in the evolution of the near-wall flow [1,2]. This is frequently referred to as Görtler vorticity and this array of streamwise vorticity is more easily observed on the concave pressure surface of a turbine. The absence of this structure from RANS solutions may lead to an inaccurate description of the boundary layer flow and therefore the loss mechanisms in the turbomachine.

In order to improve the understanding of the physical processes which lead to loss in gas turbines, a computational method which provides an accurate representation of the flow physics is required. Such a methodology demands both a high spatial resolution to capture the structure in the flow and a time-accurate description of the physical processes. Direct Numerical Simulation (DNS), in which all of the scales of motion are resolved, produces the most accurate numerical representation of fluid flow phenomena, but this high level of accuracy is achieved at a high computational cost. The Reynolds numbers involved in practical gas turbine designs renders the use of DNS impractical in these flow configurations for many years to come, hence other time-dependent simulation techniques must be used. The two most viable alternatives are Large Eddy Simulation (LES) and Detached Eddy Simulation (DES). In the DES method, the boundary layer is modelled using a RANS method, and the larger scales of motion away from walls are solved explicitly using a LES-type approach. Whilst DES is viable for high Reynolds number external aerodynamics where the boundary layers are very thin compared to the geometry, its application to internal flows in turbomachinery is less beneficial. As was stated above the role of organised vorticity near to the wall appears to play an important role in the development of the boundary layer on blade surfaces, and DES will fail to resolve this structure as the boundary layer is assumed to be steady. In order to model these correlated fluctuations an interface treatment between the RANS and LES layers is required, which must be capable of generating correlated fluctuations that accurately model the organised vorticity. In Large Eddy Simulation, however, all scales of motion above a characteristic filter width are resolved, hence a well-refined grid near to the wall will capture the organised vorticity in the boundary layer. This paper, therefore, will exclusively consider numerical methods where the boundary layer is spatially well-resolved.

Early studies into flows relevant to turbomachinery using LES were restricted to simple geometries at modest Reynolds numbers. The laminar separation and transition to turbulence of a boundary layer have been simulated both on a flat plate [3] at a Reynolds number of 350,000 and on a geometry that includes a curved leading edge [4] at a Reynolds number of 3500 based on leading edge radius. In both cases the simulation results compared well with experiment and elucidated the transition mechanism in the flow. Wake-induced transition of a flat-plate boundary layer has been simulated numerically [5] at a Reynolds number of 150,000 with the transition mechanism captured in the simulation comparing very favourably with experiment. More recent studies into natural transition have shown that mode interaction plays an important role in the transition process [6], but the meshing requirements for these simulations mean that the simulation of natural transition will be restricted to simple geometries for the foreseeable future.

Published research which has focused on simulations of flows in turbomachinery geometries has generally been restricted to the mid-span of blades in linear cascades. Whilst computationally expensive, DNS has been performed for turbine cascades at transitional Reynolds numbers [7]. LES of turbine cascades have been performed at conditions that match reference DNS data [8], and it was found that the LES predicted a transition on the suction side of the blade due to impinging wakes that was delayed by some 10% when compared to the DNS. This was attributed to the