

Numerical Analysis of Massive Separation Control on Turbomachine Blades Using Synthetic Jet

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Abstract

The study of massive separation control using synthetic jet based on the computation of RANS equations is carried out in this work.

Above of all, the performance of turbulence models is discussed. A revised k- ϵ model is proposed as the known turbulence models perform poor in reproducing the flow of airfoil at pre-stall or stall angle of attack. The modified turbulence model is validated on an NACA63₃-018 airfoil under the Reynolds number of 300,000. Good agreement with the experimental data is obtained. Therefore, the modified turbulence model is adopted to simulate the excitation of synthetic jet.

The systematical investigation of the synthetic jet is conducted on the same NACA63₃-018 airfoil at stall angle of attack. The result shows that the jet is effective in controlling the massive separation. The large separation region cannot be completely removed by the synthetic jet. However, the flow structure can be regularized. The airfoil drag can be reduced by 22% when the frequency of excitation has a value between 1.5 and 2 times the characteristic frequency of $f_c = u_\infty / (C \cos \alpha)$, where u_∞ is the free stream velocity, C the chord, and α the angle of attack. The characteristic frequency relates to a time scale of the main flow passing through the airfoil in flow direction. The jet intensity has little influence on the frequency range of efficient excitation. But the extent of the variations of lift and drag is large with intensive jet. Moreover, the best effect of excitation can be achieved when the synthetic jet locates at the natural separation point.

The behavior of synthetic jet in controlling the massive separation on turbomachine blades is studied through an unconventional axial stator-rotor arrangement. The stator and rotor blades are constructed from NACA63₃-018 airfoil with stagger angles of 50 degrees. The result shows that the synthetic jet is efficient in controlling the massive separation in cascade flow when the frequency of excitation has a value between 1.5 and 2 times the characteristic frequency. The large separation can be transformed into several small separation bubbles. The drag of stator and rotor blades can be reduced by 50% and the loss of total pressure can be reduced to about one-third.

Numerische Analyse zur Beeinflussung der massiven Ablösung an den Schaufeln von Turbomaschinen mit künstlich erzeugtem Strahl

Zusammenfassung

In der vorliegenden Arbeit werden Untersuchungen zur Beeinflussung der massiven Ablösung mithilfe eines künstlich erzeugten, pulsierenden Strahls durchgeführt, die auf der numerischen Berechnung der RANS Gleichungen basiert.

Zunächst wird die Frage der Turbulenzmodelle behandelt. Es wird ein modifiziertes $k-\epsilon$ Modell vorgeschlagen, da die üblichen Turbulenzmodelle für die Strömung um ein Profil bei ablösenahen oder zur Ablösung führenden Anstellwinkeln schlecht geeignet sind. Das modifizierte Turbulenzmodell wird an einem NACA63₃-018 Profil bei einer Reynoldszahl von 300.000 validiert. Es wurde eine gute Übereinstimmung mit experimentellen Daten erzielt. Das modifizierte Turbulenzmodell wurde daher auch verwendet, um die Beeinflussung der Ablösung durch einen künstlich erzeugten Strahl zu simulieren.

Die systematische Untersuchung der Wirkung des künstlich erzeugten Strahls erfolgt für das gleiche NACA63₃-018 Profil bei Anstellwinkeln, die zu massiver Ablösung führen. Die Ergebnisse zeigen, dass der künstlich erzeugte Strahl sehr effektiv in der Beeinflussung der massiven Ablösung ist. Das große Ablösungsgebiet kann von dem künstlich erzeugten Strahl nicht vollkommen unterdrückt werden, jedoch kann die Strömungsstruktur im gewünschten Sinne verändert werden. Der Widerstand des Profils kann um bis zu 22% reduziert werden, wenn die Frequenz des künstlich erzeugten Strahls einen Wert zwischen dem 1,5 bis 2fachen der charakteristischen Frequenz $f_c = u_\infty / (C \cos \alpha)$ hat, wobei u_∞ die Geschwindigkeit der Zuströmung ist, C die Sehnenlänge des Profils und α dessen Anstellwinkel. Die charakteristische Frequenz bezieht sich auf ein Zeitmaß, das der Zeit für die Passage der Hauptströmung um das Profil in Strömungsrichtung entspricht. Die Pulsationsamplitude des künstlich erzeugten Strahls hat nur geringen Einfluss auf den Frequenzbereich, in dem eine effiziente Beeinflussung der Ablösung erfolgt. Jedoch ist das Maß der Veränderungen von Auftrieb und Widerstand groß bei höherer Pulsationsamplitude. Weiterhin kann der beste Effekt einer Beeinflussung erzielt werden, wenn der künstliche Strahl am Ort des natürlichen Ablösungspunkts erzeugt wird.

Die Beeinflussung der massiven Ablösung an den Schaufeln von Turbomaschinen mithilfe eines künstlich erzeugten Strahls wurde am Beispiel einer unkonventionellen Sator-Rotor-Anordnung untersucht. Die Sator- und Rotorschaukeln sind NACA63₃-018 Profile mit Staffelungswinkeln von 50 Grad. Das Ergebnis zeigt, dass an den Satorschaufeln künstlich erzeugte Strahlen sehr wirksam zur Unterdrückung der massiven Ablösung in dem

Gitter dienen können, wenn die Pulsationsfrequenz einen Wert zwischen dem 1,5 und 2fachen der charakteristischen Frequenz hat. Das große Ablösegebiet kann dadurch in mehrere kleinere Ablösungsblasen umgewandelt werden. Der Widerstand der Stator- und Rotorscheaufeln kann um 50% und der Totaldruckverlust kann auf ungefähr ein Drittel reduziert werden.

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Nomenclature

Latin Characters

A	Coefficient Matrix
C	chord length
Cd	Drag coefficient
Cd _{msr}	Mean square root of drag coefficient
Cl	Lift coefficient
Cl _{msr}	Mean square root of lift coefficient
Cp	Pressure coefficient
Cr	Lift-to-drag ratio
D _{ij}	Strain-rate tensor
f	Frequency or integrand
f _c	Characteristic frequency
f _p	Dimensionless parameter
f _r	Frequency of main flow
f _{shear}	Frequency of shear-layer instability
f _v	Vortex-shedding frequency
g _i	Gravitational acceleration in tensor notation
h	Riblet height
k	Turbulent kinetic energy
l	Length scale
L	Lower triangular matrix
N	Residuum Matrix
n	Distance from wall
n ⁺	Dimensionless wall distance, $n^+ = \rho u_\tau n / \mu$
\vec{n}	Outward unit face area vector
p	Pressure
Q	Integral source or source vector
Re	Reynolds number
s	Spanwise distance of riblets
S	Strain-rate tensor invariant or surface of control volume
St	Strouhal number, $St = fC \sin \alpha / u_\infty$

t	Time
T	Averaging time interval
T_e	Period of excitation
T_f	Main flow period
T_u	Degree of turbulence, $T_u = \sqrt{k}/u_\infty$
U	Upper triangular matrix
U_0	Jet intensity
\vec{u}	Velocity vector
u_i	Velocity in tensor notation
\bar{u}_t	Mean velocity parallel to wall
u_{jet}	Jet velocity perpendicular to boundary
V	Control volume
x_i	Position vector in tensor notation
y	Distance from wall
y^+	Dimensionless wall distance, $y^+ = \rho u_\tau y / \mu$

Greek Characters

α	Angle of attack
β	Blending factor
C_ε	Model constant
$C_{\varepsilon 1}$	Model constant, 1.44
$C_{\varepsilon 2}$	Model constant, 1.92
C_μ	Model constant, 0.09
δ_{ij}	Kronecker symbol
ΔP	Coefficient of total pressure loss
ε	Dissipation of turbulent kinetic energy
ϕ	General dependent variable or phase of excitation
$\tilde{\phi}$	Normalized general variable
Φ	Variable vector
γ	Model constant, $\gamma = \delta_{ij}$
Γ	Diffusion coefficient
λ	Coefficient
μ	Dynamic viscosity

μ_t	Eddy viscosity
ν	Kinematic viscosity
ρ	Fluid density
$-\overline{\rho u_i u_j}$	Reynolds stress tensor
σ_ε	Model constant, 1.3
σ_k	Model constant, 1.0
τ_{ij}	Stress tensor
τ_w	Shear stress at wall
u_τ	Shear velocity, $u_\tau = \sqrt{\tau_w / \rho}$
ω	Frequency of large eddies
Ω	Mean vorticity tensor invariant
L_ε	Length scale
P_θ	Dimensionless parameter
q_ϕ	Source

Subscripts

0	Initial value
∞	Reference value
C	Central
D	Downstream
in	Inlet
m _{sr}	Mean square root
n	Time step
out	Outlet
P	Cell P
U	Upstream
w,e,s,n	West, east, south, and north cell-face, respectively
W,E,S,N	West, east, south, and north neighboring cell, respectively

Superscripts

–	Averaged value
′	Fluctuating of mean value
C	Convection

D	Diffusion
n	Time level

Abbreviations

AOA	Angle Of Attack
CDS	Central differencing scheme
CFD	Computational Fluid Dynamics
CH	Chien low-Reynolds-number turbulence model
CV	Control Volume
DNS	Direct Numerical Simulation
FV	Finite Volume
JL	Jones-Launder low-Reynolds-number turbulence model
KL	Kato-Launder modification
LES	Large-Eddy Simulation
LS	Launder-Sharma low-Reynolds-number turbulence model
NOR	Conventional modeling
QUICK	Quadratic Upwind Interpolation for Convective Kinematics
RANS	Reynolds Averaged Navier-Stokes method
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations
SMART	Sharp and Monotonic Algorithm for Realistic Transport
UDS	Upwind Differencing Scheme
WS	Wang-Stoffel modification

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