INTERACTION OF FREE-STREAM TURBULENCE WITH A TURBULENT BOUNDARY LAYER

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by

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Certificate

This is to certify that the thesis entitled **"Interaction of Free-stream Turbulence with a Turbulent Boundary Layer"** being submitted by **Mr. Chandrahas S. Shet** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** in Applied Mechanics department is a bonafide record of original research work carried out by him under our supervision in conformity with rules and regulations of the institute. The results contained in this thesis have not been submitted, in part or in full, to any other University or Institute for the award of any Degree or Diploma.

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Abstract

We present measurements of a zero external pressure gradient two-dimensional (2D) turbulent boundary layer (TBL) on a flat plate in the presence of grid-generated (passive or active grid) isotropic free-stream turbulence (FST), as well as in the absence of any grid. Free-stream intensities were approximately 0.3%, 4.8% and 9.3% for the no grid, passive grid and active grid cases respectively, at the start of the boundary-layer. The free-stream Taylor's microscale based Reynolds number is about 490 and 120 for the active grid and passive grid cases respectively. The measurements were made using hot-wire anemometry (HWA) and two-dimensional particle image velocimetry (PIV).

We present an optimized procedure for generating isotropic, homogeneous, high intensity turbulent flow behind an active grid. Isotropy in FST is first rigorously established in the present set-up before conducting the boundary layer (BL) measurements. Experimental investigation to check the validity of the Taylor's 'frozen' turbulence hypothesis for high intensity turbulence is also discussed.

The experimental investigations on FST-TBL interactions confirm that, at a fundamental level, the presence of the FST increases the growth rate of the TBL and the wall shear stress. The effect of FST extends deep into the TBL, affecting the wall region as well as the small scale statistics throughout the boundary layer; the greater the free stream turbulence intensity, the deeper is the extent where it influences the TBL. A comprehensive set of statistics like velocity spectra, velocity correlation maps, and velocity PDFs of various kinds, as well as velocity profiles, both from HWA and PIV measurements, are presented to support and quantify this view. Changes in the structural organization of the TBL because of the FST are discussed.

We educe the interacting structures of the FST and TBL using kinetic energy (KE) maps and proper orthogonal decomposition (POD). The data is used to propose a mechanism of growth enhancement observed in the TBL in the presence of FST. Very large scale structures, of sizes 2δ or more, spanning regions across the boundary layer interface nearly up to the wall are seen to drive the interaction. We propose and evaluate an engulfment and diffusion model of the BL-FST interaction and model the growth of the boundary layer.

सार

हम एक शून्य बाहरी प्रेशर ग्रेडिएंट दो-आयामी (2D) तुर्बुरबुलेंट बाउंड्री लेयर (TBL) चपती प्लेट पर के माप प्रस्तुत करते हैं ग्रिड जनित आइसोट्रोपिक फ्री-स्ट्रीम टर्बुलेंस (पैसिव/एक्टिव ग्रिड) (FST) की उपस्थिति में, साथ ही साथ किसी ग्रिड के अनुपस्थिति में। फ्री-स्ट्रीम तीव्रता बाउंड्री लेयर के शुरू में लगभग 0.3%, 4.8% और 9.3% थी बिना ग्रिड, पैसिव ग्रिड और एक्टिव ग्रिड मामले क्रमशः। फ्री-स्ट्रीम टेलर का माइक्रोस्कैल आधारित रेनॉल्ड्स संख्या 490 और 120 थी एक्टिव ग्रिड और पैसिव ग्रिड मामले क्रमशः। माप किया गया था हॉट-वायर एनेमोमेट्री (HWA) और दो-आयामी पार्टिकल इमेज वेलोसिमेट्री (PIV) का उपयोग से।

हम एक्टिव ग्रिड के पीछे आइसोट्रोपिक, सजातीय, उच्च तीव्रता तुर्बुलेंट बहे पैदा करने के लिए एक अनुकूलित प्रक्रिया प्रस्तुत करते हैं। वर्तमान प्रयोगिक व्यवस्था में, फ्री-स्ट्रीम टर्बुलेंस में आइसोट्रॉपी पहले सख्ती से स्थापित की जाती है बाउंड्री लेयर (BL) माप आयोजित करने से पहले । उच्च तीव्रता की टर्बुलेन्स के लिए टेलर का 'फ्रोजेन' टर्बुलेन्स हाइपोथिसिस की वैधता की प्रायोगिक जाँच की चर्चा भी की गई है।

एक मौलिक स्तर पर FST-TBL इंटरैक्शन की प्रायोगिक जांच इसकी पुष्टि करती है, फ्री-स्ट्रीम टर्बुलेंस की उपस्थिति तुर्बुरबुलेंट बाउंड्री लेयर की विकास दर को बढ़ाती है और वाल शियर स्ट्रेस भी बढ़ाती है। फ्री-स्ट्रीम टर्बुलेंस का प्रभाव दीवार क्षेत्र को प्रभावित करते हुए तुर्बुरबुलेंट बाउंड्री लेयर में गहरा होता है, साथ ही साथ सीमा स्तर पर छोटे पैमाने के आँकड़े को प्रभावित करता है। अधिक तीव्रता की टर्बुलेन्स से, और गहरी सीमा जहां यह प्रभाव को प्रभावित करता है। आँकड़ों का एक व्यापक सेट जैसे वेलोसिटी स्पेक्ट्रा, वेलोसिटी कॉरिलेशॅन मैप्स और विभिन्न प्रकार के वेलोसिटी पीडीएफ़ (PDFs), HWA और PIV दोनों का उपयोग से इस दृश्य का समर्थन और परिमाण करने के लिए प्रस्तुत किए जाते हैं।

फ्री-स्ट्रीम टर्बुलेंस के कारण तुर्बुरबुलेंट बाउंड्री लेयर के संरचनात्मक संगठन में परिवर्तन पर चर्चा की जाती है। हम गतिज ऊर्जा (KE) और प्रॉपर ओर्थोगोनल दीकॉम्पॅज़िशन (POD) का उपयोग करते हुए फ्री-स्ट्रीम टर्बुलेंस और तुर्बुरबुलेंट बाउंड्री लेयर की परस्पर क्रिया संरचनाओं को संपादित करते हैं। फ्री-स्ट्रीम टर्बुलेंस की उपस्थिति में तुर्बुरबुलेंट बाउंड्री लेयर में वृद्धि देखी गई और इसका समर्थन के लिए डेटा का उपयोग से एक तंत्र का प्रस्ताव किया जाता है। बहुत बड़ा स्केल संरचना, आकार 2δ या अधिक, सीमा परत इंटरफ़ेस के पार क्षेत्रों फैले लगभग दीवार तक इंटरेक्शन को चलाने हुए देखा जाता है। हम प्रस्तावित करते हैं और मूल्यांकन करते हैं: BL-FST इंटरएक्शन के संलग्न और प्रसार (एंगुलफ्मेंट एंड डिफ़्यूज़न्) मॉडल और बाउंड्री लेयर के विकास का मॉडल।

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Nomenclature

$(dP/dX)_\infty$	External pressure gradient
α	$(\equiv \frac{V_{tip}}{<U>} = \frac{2\pi\Omega C}{<U>})$ Wing tip speed ratio
β	$(\equiv (\frac{(\left\langle u^2 \right\rangle^{1/2} / \langle U \rangle)_\infty}{L_\infty^u/\delta_{995}+2})$ Empirical parameter
β'	Porosity of the grid
ΔC_f	$(\equiv C_f - C_{f_o})$ Fractional change in the skin friction coefficient
Δt	Time delay between successive calls to the random number generator
$\Delta t'$	Separation time between the dual images
δ^*	Displacement thickness
$\delta_{995} \equiv \delta$	Boundary layer thickness defined by the position at which $U/\langle U \rangle = 0.995$
ϵ	Dissipation rate
ϵ_{rms}	r.m.s. error in the PIV measurements
η	$(\equiv (\frac{\nu^3}{\epsilon})^{1/4})$ Kolmogorov microscale
λ	$(\equiv \frac{2\Pi}{k})$ Wavelength
λ	Taylor micro-scale
λ_1	$(\equiv \frac{2\Pi}{k_1})$ Longitudinal wavelength
$\langle \nu_T \rangle_\delta$	Average turbulent diffusivity at a location x
$\langle U \rangle$	Mean velocity in x or X direction
$\langle uv \rangle$	Reynolds shear stress
$\langle V \rangle$	Mean velocity in Y direction
μ	Dynamics viscosity of the fluid
ν	$(\equiv \mu/\rho)$ Kinematic viscosity

Ω	Mean winglet rotational speed (r.p.s.)
Π	Coles parameter
ρ or ρ_a	Density of air
ρ_o	Mass density of the manometer liquid
ρ_{uv}	cross-correlation coefficient
$\sigma^{'}$	Solidity of turbulence generating grid
$\tau^{'}$	Time constant representing lag of the pressure measurement system under dynamic conditions
τ_w	Wall shear stress
θ	Momentum thickness
$\theta(y)$	Angle of tilt in the correlation maps
θ_1	Mean rotation angle between change of direction
C	Constant in logarithmic law of BL velocity profile
C	Winglet chord length
$C_{11}(0,r,0)$	Transverse correlation based on two-point measurements
$C_{22}(0,r,0)$	Longitudinal correlation based on two-point measurements
C_{f_o}	Value of skin friction coefficient for the no grid case
C_f	($\equiv \frac{2\tau_w}{\rho_a <U>^2_\infty}$) Skin friction coefficient
$C_{ij}(\boldsymbol{r})$	Correlation coefficient based on multi-point measurements
$C^S_{uu}(r)$	Spatial correlation function
$C^T_{uu}(\tau)$	Temporal correlation function
D	Outer diameter
d	Inner diameter
$d^{'}$	Diameter of the pressure measurement tube
d_g	Size of the grid rod
$f(r)$	Autocorrelation coefficient
$F_{11}(k_1)$	Longitudinal power spectra
$F_{22}(k_1)$	Transverse power spectra
G	Clauser shape parameter

g	Acceleration due to gravity
$g(r)$	cross-correlation coefficient
H	($\equiv \frac{\delta^*}{\theta}$) Shape parameter
I_{uv}	($\equiv u_{rms}/v_{rms}$) Anisotropy ratio
k	Cross-sectional area of the manometer tube
k	Von Kármán constant
k	Wave number ($\equiv \frac{2\pi f}{U}$)
K, Ku, Kv	Kurtosis factor ($\frac{u^4}{(u^2)^2}$, $\frac{v^4}{(v^2)^2}$)
k_1	Longitudinal wave number
k_t	Diameter of the BL trip wire
L	Eulerian integral length scale
L	Length of the contraction section
l	Integral length scale
l/d	Ratio of the active length to the diameter
l'	Length of the pressure measurement tube
l_{11}	Longitudinal length scale calculated using longitudinal autocorrelation function
l_{22}	Transverse length scale calculated using transverse autocorrelation function
L^u_∞	Free-stream length scale
M	Mesh width of turbulence generating grid
n	Exponent in decay law
p_2	Absolute pressure at the end of the tubing
r	Spatial separation
R_λ	($\equiv \frac{u_{rms}\lambda}{\nu}$) Reynolds number based on Taylor's micro-scale
R_l	($\equiv u_{rms}l/\nu$) Turbulence Reynolds number
R_o	($\equiv \frac{<U>}{\Omega M}$) Rossby number
Re_τ	($\equiv \delta u_\tau/\nu$) Reynolds number based on skin friction velocity
Re_θ	($\equiv \frac{<U>\theta}{\nu}$) Reynolds number based on momentum thickness

Re_c	$(\equiv U_k k_t/\nu)$ Transitional critical Reynolds number
Re_M	$(\equiv \frac{<U>M}{\nu})$ Mesh Reynold's number
Re_x	$(\equiv \frac{<U>_\infty x}{\nu})$ Local Reynolds Number
S, Su, Sv	Skewness factor $(\frac{u^3}{(u^2)^{3/2}}, \frac{v^3}{(v^2)^{3/2}})$
T	Cruise time
T	Eulerian integral time scale
T	Torque required by the stepper motors
t	Time
Tu	$(\equiv u_{rms}/\langle U\rangle)$ Turbulence Intensity
Tu_x	FST intensity at the measurement location 'x'
U	Local streamwise mean velocity
u	Fluctuating velocity in X direction
U_∞	Free-stream mean velocity
u_τ	Frictional velocity
U_c	Convection velocity
$u_d^S or u_d^T$	Decorrelation velocity
U_k	Velocity one diameter away from the wall, in the absence of the BL trip wire
u_p	Pressure velocity scale
u_{rms} *or* $u^{'}$	RMS u
V	Initial closed volume
v	Fluctuating velocity in y or Y direction
v_{rms} *or* $v^{'}$	RMS v
V_{tip}	Speed of the active grid winglet at its tip
X	Downstream coordinate
x	Distance downstream from the boundary layer plate leading edge
X_{LE}	Distance of leading edge from the grid
y or Y	Wall normal coordinate
z or Z	Transverse coordinate

Acronym

AC	Alternating current
A/D	Analog to digital
A or AG	Active grid
BL	Boundary layer
BNC	Bayonet Neill-Concelman
CTA	Constant temperature anemometer
DAQ	Data acquisition
DC	Direct current
DR or D	double-random
FR	Fully random
FS	Free-stream
FS	Full scale
FST	Free-stream turbulence
HEPA	High efficiency particulate absolute
HWA	Hot wire anemometry
HW	Hot wire anemometry
IC	Integrated circuit
ID	Internal diameter
I/O	Input/Output
KE	Kinetic energy
LC	Least count
LDA	Laser Doppler anemometry
LES	Large eddy simulation
LSB	Low-swirl burner
NUSS	NetScanner Unified Startup Software
OD	Outer diameter
OFI	Oil-film interferometry
OHR	Overheat ratio for hot wire
PCI	Peripheral Component Interconnect (hardware bus)
PDF	Probability density function
P or PG	Passive grid
PIV	Particle image velocimetry
PLIF	Planar laser-induced fluorescence

POD	Proper orthogonal decomposition
PVC	Polyvinyl chloride
RAM	Random-access memory
r.p.s.	Revolutions per second
SHC	Shielded cable
SLS	Selective laser sintering
SLS	Selective laser sintering
SR or S	Single-random
SS	Stainless steel
SSH	Simultaneous sampling and hold
TBL	Turbulent boundary layer
TKE	Turbulent kinetic energy
TH	Taylor's 'frozen' turbulence hypothesis
THI	Instantaneous Taylor's hypothesis
UPS	Uninterrupted power supply
WC	Water column
ZPG	Zero-pressure gradient

Subscripts

∞	Free-stream value
d	Decorrelation velocity

Superscripts

$+$	Quantity normalized by the frictional velocity
S	Spatial correlation
T	Temporal correlation