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Investigation and Application of Laser Doppler Velocity Profile Sensors toward Measurements of Turbulent Shear Flows

M.Sc. Katsuaki Shirai

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Abstract

Fluid flows are ubiquitous in our daily life from our internal biomechanical activities to meteorological phenomena. Most of flows around us are in turbulence, which is crucial for high rate of transfer and mixing of momentum and heat through fluid flows. In industry, turbulence is purposely utilized for efficient mixing of momentum and heat. Turbulent flows consist of thousands of vortices in nature with a wide range of scales in time and in space. Energy produced in large scales is transferred into small scale until it finally dissipates into heat. Resolving flow velocities over a wide range with a small uncertainty remains still a challenge in fluid mechanics even with currently available measurement techniques. Especially, the lack of spatial resolution in the measurement techniques severely restricts us from investigating flow phenomena occurring at small spatial scales in high Reynolds turbulent shear flows.

Laser Doppler anemometry (LDA) has been used as a non-invasive single-point measurement technique of local flow velocities for over 40 years. The technique has a spatial resolution of around 30 μm and the measurement uncertainty of 0.3 % in a best case. Main advantages of this technique are the relatively high spatial resolution and small measurement uncertainty for a wide range of flow velocities. However, the spatial resolution is still not sufficent to capture the fine scale structures of turbulent flows.

The purpose of this thesis work is to provide a new measurement technique with a spatial resolution sufficiently high compared to the smallest spatial scale of turbulence together with a small uncertainty of velocity measurements. The new measurement technique is aimed to the investigations of fine scale structures in turbulent shear flows. The present thesis reports on the investigations and applications of novel laser Doppler velocity profile sensors for the study of fluid flows. This new sensor achieves a spatial resolution in the range of 10^{-6} m with a measurement uncertainty in the range of 10^{-4} at the same time. Hence, the uncertainties are at least one magnitude of order smaller than those of conventional LDA. The high spatial resolution and small measurement uncertainty are achieved without reducing the size of the measurement volume compared to conventional LDA. As the new sensor provides both velocities and positions of individual tracer particles passing through the measurement volume, high spatially resolved velocity profile along one-dimensional line is captured without the needs of any preliminary assumptions on the flow. This feature of the sensor could provide new opportunities for demanding investigations of complex turbulent shear flows at high Reynolds numbers such as in highly three-dimensional or separated flows where no analogy is established.

Fundamentals of the velocity profile sensor were investigated before they are applied to real fluid flows. The spatial resolution and measurement uncertainty were evaluated based on theory and experiments. Due to the unique features of the sensor, adaptive signal processing techniques and statistical analysis methods were developed for velocity measurements in fluid flows. New calibration method was proposed for minimizing the systematic uncertainty of the sensor, since the resulting measurement uncertainty is ultimately determined by calibration process. Feasibility of the sensors were confirmed in two types of laminar flows: uniform laminar flow and laminar boundary layers. In the uniform laminar flow, the measurement uncertainty was compared directly to the ones with hot-wire anemometry and a conventional LDA. In the laminar boundary layers, Blasius velocity profiles were captured by the new sensors until very close to the wall.

The new sensors were applied in a fully developed two-dimensional turbulent channel flow for fundamental study of turbulence. The resulting turbulence statistics of the streamwise velocity in the near-wall region showed comparable behaviors of the available direct numerical simulation (DNS) data. Moreover, the higher order moments measured with the new sensors exhibited consistent dependencies on the Reynolds number. The Reynolds number dependency was also observed in DNS studies of channel flows and this clearly demonstrated the high capability of the new sensor. The sensor was further extended for two types of new measurements. One was spatially resolved local flow accelerations and the other was two-point velocity correlations for the first time. Feasibilities were studied with experiments including the measurements of local flow acceleration in a stagnation flow and two-point spatial correlation in a turbulent wake flow.

In conclusion, powerful potentials of the sensor were demonstrated for spatially high resolved measurements of flow velocities with a small measurement uncertainty. The featured information of high spatially resolved flow velocities inside the measurement volume should bring new insights on various types of complex turbulent shear flows, which are not resolvable with any other conventional measurement techniques.

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List of Symbols, Scripts and Acronyms

Alphabet

symbol	meaning	unit
A	slope of linear fit (Chap. 3)	Hz/m
	or coefficient in Taylor expansion (Chap. 7)	m^{-3}
	or amplitude of signal (App. C)	V
a	Lagrangian acceleration	m/s^2
B	intercept of linear fit	Hz
C	tolerance from mean value	a.u.
D	beam distance	m
d	fringe spacing	m
d_p	particle diameter	m
e	basis of natural logarithm (mathematical constant)	-
F	force	N
F_D	drag force	N
F_L	lift force	N
FF	flatness factor (kurtosis)	-
f_{AOM}	AOM frequency	
f_c	cut-off frequency	Hz
$f_{carrier}$	carrier frequency	Hz
f_D	Doppler frequency	Hz
f_{rot}	rotational frequency	Hz
f_s	sample rate	Hz
H	channel full-height	m
h	channel half-height	m
I	irradiance (optical intensity)	W
I_0	incident light intensity	W
i	integer	-
j	integer	-
k	wave number	m^{-1}
L	representative length scale (Chap. 1)	m
	or working distance of sensor (Chap. 5 and App. C)	m
l	dimension of measurement volume	m

l_τ	viscous length scale	m
M	number of measurement trial (Chap. 3)	-
M^2	beam quality parameter defined in ISO 11146 [107]	-
M_p	Mie parameter (App. A)	-
M_n	normalized n-th order central moment	-
m	refractive index (App. A)	m
N	number of points for a single Doppler burst signal	m
	(Chap. 2, App. C)	-
	or total number of pinholes (Chap. 3)	-
	or total number of data samples (App. B)	-
N_f	number of fringes inside the measurement volume	-
n	integer	-
$O(\ )$	order of magnitude	-
P	point (Chap. 2)	-
	pressure (Chap. 4)	Pa
P_w	static pressure at the wall	Pa
Q	total uncertainty	a.u.
q	quotient	m
R	correlation coefficient	-
Re	Reynolds number	-
Re_d	Re based on wire diameter (Chap. 7)	-
Re_p	Re based on particle (App. A)	-
Re_x	Re based on the distance from the leading edge	-
Re_τ	Re based on friction velocity and channel half-width	-
r	radius or radial distance	m
r_0	exact calibration radius (Chap. 3)	m
s	slot (Chap. 7)	-
	relative slip velocity (App. A)	m/s
SF	skewness factor	-
SNR	signal-to-noise ratio defined in Eq.(C.4)	dB
SNR^*	variation of signal-to-noise ratio defined in Eq.(2.14)	-
T	duration of signal sample	s
	or integral time (Chap. 7)	s
T_b	duration of Doppler burst signal	s
TI	turbulence intensity	-
ΔT	time difference of successive burst signals	s
t	time	s
U	representative velocity (Chaps. 1 and 6)	m/s
	or mean velocity in streamwise direction (Chaps. 4 and 5)	m/s
U_f	fluid velocity (App. A)	m/s
U_p	particle velocity (App. A)	m/s
U_∞	free stream velocity	m/s
u	velocity of tracer particle (Chap. 2)	m/s
	or streamwise velocity (Chap. 4)	m/s
	or rms velocity in streamwise direction (Chap. 5)	m/s

u'	fluctuating velocity in streamwise direction	m/s
u_n	n-th order central moment	-
V	mean velocity in wall-normal direction	m/s
v	rms velocity in wall-normal direction	m/s
	or wall-normal velocity (Chaps. 4 and 5)	m/s
$\vec{u}$	velocity vector in general	m/s
v'	fluctuating velocity in wall-normal direction	m/s
Vis	visibility (modulation depth)	m/s
W	mean velocity in spanwise direction	m/s
w	rms velocity in spanwise direction	m/s
w_0	diameter of beam waist	m
x	streamwise axis	m
	streamwise distance from the leading edge (Chap. 4)	m
	general position (Chap. 7)	m
y	axis perpendicular to the beam plane (Chap. 2)	m
	or wall-normal axis (Chap. 4 and 5)	m
z	optical axis (Chap. 2)	m
	or spanwise axis (Chaps. 4 and 5)	m
z_0	parameter defined in Eq.(C.11)	m
z_R	Rayleigh range	m
z_w	position of beam waist	m

a.u. = arbitrary unit

Greek symbol	meaning	unit
α	half-angle of beam crossing	rad
β	tilt angle of a calibration object to y-axis	rad
Δ	displacement	m
δ	total uncertainty	a.u.
ϕ	scattering angle with respect to the incident light	rad
Γ	Gamma function	-
η	nondimensional parameter for Blasius solution	-
κ	von Kármán constant	-
Λ	summation defined by Eq.(3.31)	-
λ	wavelength	m
	or Taylor microscale (Chap. 7)	m or s
μ	(dynamic) viscosity	Pa·s
μ_f	(dynamic) viscosity of fluid (App. A)	Pa·s
ν	kinematic viscosity	m^2/s
π	ratio of the circumference of a circle to its diameter (mathematical constant)	-
θ	tilt angle of particle trajectory to fringe surface	rad
ρ	density	kg/m^3

ρ_f	fluid density (App. A)	kg/m^3
ρ_p	particle density (App. A)	kg/m^3
Σ	summation	-
σ	uncertainty in a sense of standard deviation	a.u.
	or noise variance (Chap. 2)	a.u.
τ	time	s
τ_0	characteristic time	s
τ_w	wall shear stress	Pa
ϕ	deviation angle from the rotation center (Chap. 3)	rad
	or scattering (App. A)	rad
Ψ	stream function	-
ω	angular velocity	rad·s
ω_c	critical angular velocity	rad·s
ξ	scattering angle	rad

Subscripts

symbol	meaning
0	initial or reference value
1	channel 1 or beam 1 (only in App. C)
2	channel 2 or beam 2 (only in App. C)
b	burst signal
c	critical value
cal	calibration value
$circ$	circumferential value
D	Doppler frequency or drag force (only in App. A)
est	estimated value
exp	value obtained in experiment
f	flow or fluid value
fit	fit value
$Gauss$	Gaussian value
i	index
j	index
max	maximum value
$mean$	mean value
$meas$	measurement value
min	minimum value
N	total number of pinholes in multiple pinhole calibration method
n	integer
p	particle
$real$	real value
rms	root mean square
rot	rotational value
s	sample
std	standard deviation

temp	temporal value
theo	theoretical value
true	true value
var	variance
w, *wall*	wall value
z	optical axis
+	normalized value with wall-variables

Acronyms

abbreviation	meaning
ASME	Americal Society of Mechanical Engineers
AOM	Acousto-Optic Modulator
CCD	Charge-Coupled Device
CFD	Computational Fluid Dynamics
CMOS	Complementary Metal Oxide Semiconductor
CRLB	Cramer-Rao Lower Bound
CTA	Constant Temperature Anemometer
DEHS	DiEthyl-Hexyl-Sebacate
DGV	Doppler Global Velocimetry
DNS	Direct Numerical Simulation
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
GUM	Guide to the expression of Uncertainty in Measurement
HFA	Hot-Film Anemometry
HWA	Hot-Wire Anemometry
ISO	International Organization for Standardization
LDA	Laser Doppler Anemometry
LDV	Laser Doppler Velocimetry
LES	Large Eddy Simulation
LIF	Laser Induced Fluorescence
MEMS	Micro Electro-Mechanical Systems
MOEMS	Micro Opto-Electro-Mechanical Systems
MM	Multi Mode
PDF	Probability Density Function
PDV	Planar Doppler Velocimetry
PIV	Particle Image Velocimetry
PTV	Particle Tracking Velocimetry
QDT	Quadrature Demodulation Technique
RANS	Reynolds Averaged Navier-Stokes
SM	Single Mode
SNR	Signal-to-Noise Ratio
WDM	Wavelength Division Multiplexing