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Stability of weak confined wake behind a cylinder in fully developed turbulent channel flow

T Vijaya Kumar[a], P.K. Sen[b]*, S.V Veeravalli[b] and Munendra Kumar[a]

[a]Delhi Technological University, Delhi 110042, India
[b]Indian Institute of Technology Delhi, New Delhi -110016, India

Abstract

The motivation for the study of instability of turbulent wake flow in a confined turbulent channel was multi-fold. First, the instability of confined wake flows has not been studied much. Second, confined wakes are found to retain their mean velocity profile for a considerable downstream distance. Third, wakes have two points of inflection, one each on either side of the centre line. The basic aim of the present study was to investigate the correlation between the turbulence in the wake region and the inflection points in the wake region using stability theory. The wake behind a cylinder of diameter d in a turbulent channel with half width h, is a weak confined wake when $d/h \approx 0.2$. Thus, $d/h = 0.2$ was chosen for the present work. Experimental results are obtained by introducing organized disturbances in the wake and tracking these downstream. Theoretical results were obtained by solving the Orr-Sommerfeld equation by numerical methods.

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Keywords: Stability theory; weak wake; inflection point; Karman vortices; turbulence tuner

1. Introduction

The basic task of hydro-dynamic stability theory is to explain all possible phases of transition from the laminar flow regime into the turbulent one in various dynamic systems of fluid mechanics. For near wall turbulence, the process of formation of lift-up and bursting of streaks has qualitative similarity to that of transition in a macroscopic perspective. This, and other examples like free shear flows, lead to interest in study of turbulence by asking the question: Are hydrodynamic instability mechanisms relevant in turbulent flows? In this context researchers have

* Corresponding author. Tel.: +91 9810846032
E-mail address: pksen@am.iitd.ac.in; pksen45@hotmail.com

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explored stability theory for studying some aspects of turbulence. Our present study focuses on a confined weak wake in fully developed turbulent channel flow.

The main difference between wakes and other flows, like wall bounded flows, and other free shear flows, is the presence of the Karman vortex street which persists as the primary feature of disturbance in the flow even in the turbulent regime. Compared with wall bounded flows, free shear flows are highly unstable due to the presence of inflection point in the velocity profile and the associated inviscid instability.

A weak wake is one wherein the minimum velocity is only 10% smaller than the maximum velocity, that is where the maximum defect of the velocity is around 10% of the free stream velocity. Different sizes of cylinders were tried in the turbulent channel and it was found that if the cylinder diameter *d* is large as compared to the channel width (e.g. d/h = 0.4) the Karman vortices help in quickly filling up the wake and even within a downstream distance of 10*d*, the wake ceases to exists.

When the cylinder diameter was d= 8mm, i.e. 10% of the channel width, a weak wake defined as above was obtained, which persisted for a long distance in the downstream direction. The experimental and the theoretical efforts in the present work was to study the stability of this wake to organised disturbances, and also study its capacity to sustain turbulence. Thus the propagation of organised disturbances along this wake was studied.

Nomenclature

C	Constant	h	Channel half width
Re	Reynolds number	R_{flow}	Flow Reynolds number
U_o	Centreline velocity	U	Instantaneous velocity
$\overline{U}$	Mean velocity	F_{11}	Longitudinal spectrum
F_{1R}	Cross-spectrum	$c=c_r+ic_i=\beta/\alpha$	Wave speed, complex
c_r	Wave speed, real	c_g	Group velocity
x	Down stream distance	$x^* = x/\sigma$	Normalised downstream distance
y	Distance across the channel from the wall		
u, v, w	Velocity fluctuations		
$\hat{u}(y)$	Amplitude of fluctuation velocity from Orr-Sommerfeld (OS) solution		
$\widetilde{u}$	rms velocity component due to organized disturbance		
U_{rms}	rms velocity of turbulence in the presence of cylinder		
U_{rmso}	rms velocity of turbulence in the absence of cylinder (free stream turbulence)		
$u_r = \sqrt{(U_{rms}^2 - U_{rmso}^2)}$	Excess rms velocity of turbulence in the wake		
σ	Half width of Gaussian distribution , distance from inflection point to centre of channel		
α	Wave number	$\beta = 2\pi f$	Circular frequency
$\beta = \beta_r + \beta_i$	Complex frequency		
μ	Dynamic viscosity	ρ	Density
θ	Phase angle	ψ	Disturbance stream function
ϕ	Amplification function of ψ	rms	Root mean square

2. Relevant Literature

The connection between stability theory and turbulent shear flow was first studied by Landau [1] based on a nonlinear stability model; however this model did not prove to be a suitable model for turbulence. Next, Malkus [2] studied the role of the turbulent mean velocity profile in the Orr-Sommerfeld equation. He proposed that if the mean velocity profile typical of wall-bounded turbulent flows is used in the solution of the classical Orr-Sommerfeld equation, then the profile would prove to be marginally or neutrally stable at the existing Reynolds number. Reynolds & Tiederman [3] proved that the Malkus theory was not valid by performing detailed calculations for a fully developed channel. Later on Reynolds continued work in the area of stability theory applied to fully developed wall turbulence along with Hussain, Hussain & Reynolds [4-5-6]. Initially they started with experiments by introducing controlled, weak, organised disturbances in a fully developed turbulent channel. Reynolds & Hussain [7] also did the theoretical investigations for this problem. Based on their three-way decomposition, they derived the disturbance equation as an extended Orr-Sommerfeld equation. However, neither theoretically nor