

# Proper Orthogonal Decomposition Analysis of Separated and Reattached Pressure Gradient Turbulent Flows

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DOI: 10.2514/1.40095

**In this paper, the proper orthogonal decomposition was used to analyze velocity data obtained in turbulent flow downstream of a transverse square rib attached to the lower walls of parallel-walled asymmetric diverging and converging channels. The velocity measurements were obtained using a particle image velocimetry. The proper orthogonal decomposition results demonstrate that the energetic structures in the flow contribute most to Reynolds shear stress and least to transverse normal stress. The implications of these observations to the large-scale anisotropy are discussed. Significant differences are observed in the reconstructed Reynolds stress profiles at the center of the separated shear layer and those close to the reattachment point. The results also indicate that contribution of the energetic structures to the Reynolds stresses is higher at the upstream section of the ribs than in the separated layer. This was attributed to a more uniform energy distribution among the proper orthogonal decomposition modes in the separated shear layer than in the upstream section. The distributions of the mean velocity, mixing length, and eddy viscosity at selected locations were also analyzed. The mixing-length profiles in the inner region of the separated shear layer do not follow the well-documented linear profile reported for simple near-wall turbulent flows.**

## I. Introduction

SEPARATED and reattached flows have been the subject of intense research due to their practical importance in diverse fluid engineering applications. For example, flows over and around wall-mounted obstacles or through orifices are frequently encountered in practice, examples being heat exchangers and combustors. Separated and reattached flows are also used as a prototypical shear flow to conduct fundamental near-wall turbulence research. A wide range of simple laboratory geometries such as the backward-facing step (Bradshaw and Wong [1]), forward-facing step (Abu-Mulawah [2]), transverse square rib (Abdalla et al. [3]), splitter plate (Ruderich and Fernholz [4]), and blunt plate (Kiya and Sasaki [5]) have been used to study separated and reattached flows. These studies have shed light on the different regimes of the flow according to Reynolds number and boundary conditions (aspect ratio, blockage, freestream turbulence intensity, etc.). The investigations have been conducted using various pointwise techniques such as hot wire and laser Doppler anemometry and whole-field techniques such as particle image velocimetry (PIV). In most of these studies, the mean velocities and one-point turbulent statistics were obtained to study the salient features of the velocity field. A summary of previous studies on separated reattached flows, their Reynolds number, experimental technique, and relevant quantities are summarized by Shah [6] and Shah and Tachie [7].

The existence of coherent structures is one of the most important features of the turbulent flows (Kline et al. [8]). The essential flow physics are believed to be buried within coherent structures or eddies that are characterized by organized motions. It is generally believed that a better understanding of coherent structures is the key to understanding turbulence and its control (Kostas et al. [9]). An

in-depth knowledge of coherent structures would also offer the possibility of clarifying the physical mechanism through which turbulent energy is dissipated into heat. The implications for turbulence control include the reduction of the skin friction in wall-bounded flows, the delay of separation in wake flows, and the enhancement of mixing in free shear. In spite of concerted research on coherent structures over the past decades, they are relatively less understood compared with one-point turbulent statistics. As rightly noted by Moin and Moser [10], the present knowledge of organized motions has seldom been used in turbulence theories or quantitative models of turbulence. This was attributed to lack of quantitative definition of organized structures and an objective means for assessing their contribution to turbulence stresses and their importance in the production of turbulence.

The process of identifying and describing coherent structures has been a very challenging undertaking because they are, more often than not, hidden among the incoherent turbulent motions (Kostas et al. [9]). With the advent of increasing computing power, a large volume of flow data can now be collected to study turbulence in its full complexity. Hence, to extract the most useful structural information about the physical processes, this large volume of data must be summarized in a concise manner. A variety of statistical techniques such as two-point correlation and conditional or phase-averaging techniques have been used to study coherent structures (Moin and Moser [10]). The proper orthogonal decomposition (POD) has emerged as a powerful statistical technique for extracting dominant features and identifying coherent structures. The POD technique is first introduced in turbulence research by Lumley [11], in an attempt to systematically identify coherent structures in the turbulent flows, and subsequently by Sirovich [12] and Berkooz et al. [13]. The POD can effectively compress and summarize large quantities of data so that the most useful information about the physical processes occurring may be extracted (Kostas [14]). More important, the contribution of the extracted eddies to turbulence stresses and turbulence production can be determined.

In principle, the POD decomposes a series of experimental or numerical measurements into a number of modes that make up an orthonormal basis spanning the entire data set. The POD captures the most energetic and hence largest structures of the flow in the first modes. In other words, if the dynamics of the flow is dominated by a few large flow structures, the data can be represented satisfactorily using only a few of the first modes. The POD analysis requires the knowledge of two-point spatial correlation function. This would require the use of multipoint measurement techniques such as rakes

Presented as Paper 4347 at the 5th AIAA Theoretical Fluid Mechanics Conference, Seattle, WA, 8 June 2023–8 June 2026; received 28 July 2008; revision received 10 February 2009; accepted for publication 18 February 2009. Copyright © 2009 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved. Copies of this paper may be made for personal or internal use, on condition that the copier pay the \$10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0001-1452/09 and \$10.00 in correspondence with the CCC.

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