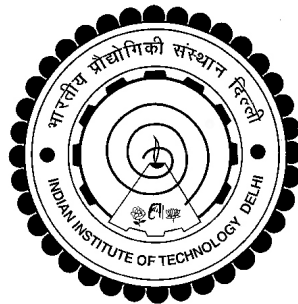


DIRECT NUMERICAL SIMULATION OF TRANSITIONAL AND TURBULENT FLOWS IN A SQUARE DUCT

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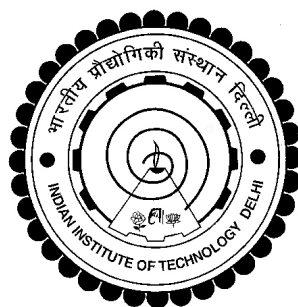
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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy
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Certificate

This is to certify that the thesis entitled “**Direct Numerical Simulation of transitional and turbulent flows in a square duct**”, being submitted by **Hamid Hassan Khan** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy**, is a record of the bonafide research carried out by him which has been prepared under our supervisions in conformity with the rules and regulations of the Indian Institute of Technology Delhi. The research reports and results presented in the thesis has not been submitted for any degree or diploma in any other university or institute.

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HAMID HASSAN KHAN

Abstract

Applications of duct flow are ubiquitous in oil and gas pipelines, heat exchangers, turbo-machinery and nuclear engineering. The understanding of transition and turbulent flow in ducts is hailed as an important problem in industrial applications and scientific research. A non-circular duct with square cross-sectional geometry often shares interesting flow phenomena as compared to the pipe and channel flow. The in-depth perspective of the underlying dynamics of transition and turbulent flow in a square duct is still evolving and yet to be fully understood.

The overall aim of the thesis is to develop an optimized DNS solver and study the underlying dynamics of transitional and turbulent flow coherent motion in an infinite and finite length square duct. The DNS solver is optimized on an MPI parallel platform using a cubic (or 3D) domain decomposition technique, array operation, user-interface and parallel input/output. The parallel performance analysis of the optimized DNS solver on the multiprocessor computing system (PADUM supercomputer) shows 80% efficiency.

The DNS solver numerically investigates the transition and turbulent flow in an infinite length (or periodic boundary condition in streamwise direction) square duct. The thesis demonstrate the organized motion of the flow regimes below the frictional Reynolds number of the fully turbulent flow. The transitional flow is coined as “minimal and marginal” flows. The vortex-detection technique unveil hairpin vortices in fully and minimal turbulent flow in the square duct. Bursting of streaks is detected with variable interval time average, and the evolution of hairpin vortices has also been addressed. Turbulent intensities and energy spectra are reported and compared between the minimal,

marginal and fully turbulent flow. The minimal turbulence in a square duct indicates transitional turbulent flow characteristics like lesser occurrence of ejection and sweep, intermittent bursting events, and steeper variation of energy spectrum as compared to fully turbulent energy spectrum distribution.

The coherent structures are identified through the spatial and temporal analysis of Proper Orthogonal Decomposition (POD) modes. Analysis of two sets of POD data is performed. In obtaining the first set, POD is performed on the combined fluctuating velocity vector, while for the second set, only the fluctuating velocity along the y- or z-direction is used. It was found that the first two most energetic spatial POD modes are the streamwise-independent or non-propagating roll modes. The third and fourth most energetic modes are observed to be streamwise-dependent, propagating modes. The spatio-temporal analysis of POD modes confirms the presence of traveling waves in the square duct, and its average speed is also calculated. The POD of the second dataset showed only propagating modes, and no non-propagating modes were found. These propagating modes are also rotationally symmetric. It has been shown that there is an energy exchange between non-propagating modes and propagating modes. The flow dynamics of the first four reconstructed POD modes portray the self-sustaining turbulence mechanism in a square duct. The structures obtained from the first POD dataset reconstruction of 10% energy show well-organized hairpin vortices. Furthermore, the dataset reconstructed from modes containing 35% energy, gives detailed information on the coherent structures aligned along the wavy streamwise direction.

Laminar to turbulent flow transition in a finite length square duct has been carried out for the first time by imposing novel spatio-temporal finite amplitude inlet disturbance on the laminar flow. A short-duration narrow ring inlet disturbance is used, and it elucidates the most exciting dynamics of laminar to turbulence transition in a square duct. A short-duration inlet disturbance is imposed on the laminar flow at upper and lower transitional range bulk Reynolds number 2260 and 1540, respectively. The laminar flow at upper and lower transitional range Reynolds number is similar to marginal and minimal turbulent

flow in a square duct. A disturbance applied on the upper transitional range laminar flow propagates downstream, giving puff (transition) and slug (turbulent) flow phenomena similar to pipe flow. However, at the lower transitional range, inlet disturbance shows only a puff-like structure. The mean secondary flow is obtained by the time and space average of the puff and slug region. The four vortex secondary flow is observed in a puff region with two vortex on each vertical/horizontal wall, while conventional eight vortex is observed in the slug region. The transition (puff) flow coherent structures show the presence of dual-type hairpin structures. The dual-type coherent structures consist of conventional forward and non-convention reverse hairpin vortices. The high-speed streaks from the inlet disturbance play a role in the formation of the reverse hairpin. The turbulent kinetic energy indicates that the conventional $-5/3$ spectra for slug (turbulent) flow and -2 energy spectra for puff (transition) flow because of the flow's intermittency at the transition. We now confirm that the novel inlet disturbance through narrow ring captures laminar to turbulent transition.

सार

डक्ट फ्लो के अनुप्रयोग तेल और गैस पाइपलाइनों, हीट एक्सचेंजर्स, टर्बो-मशीनरी और परमाणु इंजीनियरिंग में सर्वव्यापी हैं। नलिकाओं में संक्रमण और अशांत प्रवाह की समझ औद्योगिक अनुप्रयोगों और वैज्ञानिक अनुसंधान में एक महत्वपूर्ण समस्या के रूप में है। वर्ग क्रॉस-अनुभागीय ज्यामिति के साथ एक गैर-परिपत्र डक्ट अक्सर पाइप और चैनल प्रवाह की तुलना में दिलचस्प प्रवाह की घटनाओं को साझा करता है। एक वर्ग वाहिनी में संक्रमण और अशांत प्रवाह की अंतर्निहित गतिशीलता का गहन परिप्रेक्ष्य अभी भी विकसित हो रहा है और अभी तक पूरी तरह से समझा नहीं जा सका है।

थीसिस का समग्र उद्देश्य एक अनुकूलित डीएनएस सॉल्वर विकसित करना और एक अनंत और सीमित लंबाई वर्ग वाहिनी में संक्रमणकालीन और अशांत प्रवाह सुसंगत गति के अंतर्निहित गतिशीलता का अध्ययन करना है। DNS सॉल्वर को MPI समानांतर प्लेटफॉर्म पर क्यूबिक (या 3D) डोमेन अपघटन तकनीक, सरणी ऑपरेशन, उपयोगकर्ता और इंटरफ़ेस का उपयोग करके अनुकूलित किया गया है और समानांतर इनपुट / आउटपुट। मल्टीप्रोसेसर कंप्यूटिंग सिस्टम (PADUM सुपर कंप्यूटर) पर अनुकूलित DNS सॉल्वर का समानांतर प्रदर्शन विश्लेषण 80% दक्षता दर्शाता है।

DNS सॉल्वर संख्यात्मक रूप से संक्रमण और अशांत प्रवाह की एक अनंत लंबाई (या स्ट्रीमवाइज दिशा में आवधिक सीमा स्थिति) वर्ग वाहिनी की जांच करता है। थीसिस पूरी तरह से अशांत प्रवाह के घर्षण रेनॉल्ड्स संख्या के नीचे प्रवाह शासनों के संगठित गति को प्रदर्शित करता है। संक्रमणकालीन प्रवाह को "न्यूनतम और सीमांत" प्रवाह के रूप में गढ़ा गया है। भंवर का पता लगाने की तकनीक स्क्वायर डक्ट में पूरी तरह से और न्यूनतम अशांत प्रवाह में हेयरपिन भंवर का अनावरण करती है। स्ट्रीक के फटने का पता वैरिएबल इंटरवल टाइम एवरेज से लगाया जाता है, और हेयरपिन भंवरों के विकास को भी संबोधित किया गया है। टर्बुलेंट तीव्रता और ऊर्जा स्पेक्ट्रा की रिपोर्ट की जाती है और न्यूनतम, सीमांत और पूरी तरह से अशांत प्रवाह के बीच तुलना की जाती है। एक वर्ग वाहिनी में न्यूनतम अशांति संकेत के रूप में संक्रमण और प्रवाह की कम घटना, आंतराधिक फटने की घटनाओं, और ऊर्जा स्पेक्ट्रम की तुलना में भिन्नता जैसी संक्रमणकालीन अशांत प्रवाह विशेषताओं को इंगित करता है पूरी तरह से अशांत ऊर्जा स्पेक्ट्रम वितरण।

सुसंगत ऑर्थोगोनल अपघटन (POD) मोड के स्थानिक और लौकिक विश्लेषण के माध्यम से सुसंगत संरचनाओं की पहचान की जाती है। POD डेटा के दो सेटों का विश्लेषण किया जाता है। पहला सेट प्राप्त करने में, POD को संयुक्त उतार-चढ़ाव वाले वेग सदिश पर किया जाता है, जबकि दूसरे सेट के लिए केवल y - या के साथ उतार-चढ़ाव वाला वेग होता है। z - दिशा का उपयोग किया जाता है। यह पाया गया कि पहले दो सबसे ऊर्जावान स्थानिक POD मोड स्ट्रीम-इंडिपेंडेंट या नॉन-प्रॉपगेटिंग रोल मोड हैं। तीसरे और चौथे सबसे ऊर्जावान मोड को स्ट्रीम-निर्भर, प्रचार मोड के रूप में देखा जाता है। पीओडी मोड के स्थानिक-लौकिक विश्लेषण, स्क्वायर डक्ट में यात्रा तरंगों की उपस्थिति की पुष्टि करता है, और इसकी औसत गति भी गणना की जाती है। दूसरे डेटासेट के POD ने केवल प्रचार मोड दिखाए, और कोई भी गैर-प्रचार मोड नहीं मिला। ये प्रचार मोड भी घूर्णी रूप से सममित हैं। यह दिखाया गया है कि गैर- प्रचार मोड और प्रचार मोड के बीच एक ऊर्जा विनिमय है। पहले चार खंगाले POD मोड के प्रवाह की गतिशीलता आत्मनिर्भर अशांति तंत्र को दर्शाती है एक वर्ग वाहिनी में। 10% ऊर्जा के पहले POD डेटासेट पुनर्निर्माण से प्राप्त संरचनाएं सुव्यवस्थित हेयरपिन भंवर दिखाती हैं। इसके अलावा, डेटासेट 35% ऊर्जा वाले मोड से पुनः निर्मित होता है, सुसंगत संरचनाओं पर विस्तृत जानकारी देता है जो लहराती सुव्यवस्थित दिशा के साथ संरेखित है।

पहली बार एक परिमित लंबाई के वर्ग वाहिनी में 'लामिना से अशांत प्रवाह संक्रमण' का अध्ययन किया गया है, लामिना के प्रवाह पर नए spatio- टेम्पोरल परिमित आयाम इनलेट अशांति का उपयोग करके। एक छोटी अवधि की संकीर्ण रिंग इनलेट disturbance का उपयोग किया जाता है, और यह एक वर्ग डक्ट में अशांति के संक्रमण के लिए लामिना के सबसे रोमांचक गतिशीलता को स्पष्ट करता है। एक छोटी अवधि की इनलेट disturbance को क्रमशः ऊपरी और निचले संक्रमणकालीन रेंज बल्क रेनॉल्ड्स नंबर 2260 और 1540 पर लामिना के प्रवाह पर लगाया जाता है। ऊपरी और निचले संक्रमणकालीन रेंज में लामिना का प्रवाह रेनॉल्ड्स संख्या एक वर्ग वाहिनी में सीमांत और न्यूनतम अशांत प्रवाह के समान है। ऊपरी संक्रमणकालीन रेंज पर एक अशांति लागू होती है लामिना का प्रवाह नीचे की ओर फैलता है, जिससे पफ (संक्रमण) और स्लग (अशांत) प्रवाह की घटनाएँ पाइप के प्रवाह के समान होती हैं। हालांकि, कम संक्रमणकालीन सीमा पर, इनलेट की गड़बड़ी केवल एक पफ-जैसी संरचना को दर्शाती है। औसत माध्यमिक प्रवाह पफ और स्लग क्षेत्र के समय और स्थान के औसत से प्राप्त होता है। चार भंवर माध्यमिक प्रवाह है प्रत्येक ऊर्ध्वाधर दीवार पर दो भंवर के साथ एक पफ क्षेत्र में पाया जाता है, जबकि पारंपरिक आठ भंवर स्लग क्षेत्र में पाया जाता है। संक्रमण (पफ) प्रवाह सुसंगत संरचनाएं दोहरे प्रकार के हेयरपिन संरचनाओं की उपस्थिति दर्शाती हैं। दोहरे प्रकार के सुसंगत संरचनाओं में पारंपरिक आगे और गैर-सम्मेलन रिवर्स हेयरपिन भंवर शामिल हैं। उच्च गति इनलेट disturbance से लकीरें रिवर्स हेयरपिन के गठन में एक भूमिका निभाती हैं। अशांत गतिज ऊर्जा इंगित करती है कि स्लग (अशांत) प्रवाह के लिए पारंपरिक $-5/3$ स्पेक्ट्रा और पफ (संक्रमण) प्रवाह के लिए -2 ऊर्जा स्पेक्ट्रा -- संक्रमण पर प्रवाह की रुकावट के कारण पाया जाता है। अब हम पुष्टि करते हैं कि संकीर्ण रिंग के माध्यम से नए इनलेट की disturbance से लामिना - अशांत संक्रमण को पकड़ लेती है।

Table of Contents

Certificate	i
Acknowledgements	iii
Abstract	v
Table of Contents	ix
List of Figures	xiii
List of Tables	xxi
Nomenclature	xxiii
1 Introduction	1
1.1 Background	1
1.2 Motivation	3
1.2.1 Why transition to turbulent flow?	3
1.2.2 Why transition and turbulent flow in square duct?	4
1.3 Literature review	6
1.3.1 Turbulent flow in a square duct	6
1.3.2 Laminar to turbulent flow transition in a duct	9
1.3.3 Turbulent Structures in wall-bounded flow	13
1.3.4 Conclusion from literature survey	17

1.4	Problem Description	18
1.5	Objectives	19
1.6	Organization of the thesis	19
2	Numerical Methodology	23
2.1	Governing Equation	24
2.2	Computational Scheme and Numerical Discretization	25
2.2.1	Simplified Marker and Cell Scheme (SMAC)	25
2.2.2	Spatial and Temporal Discretization	27
2.2.3	Solution of transport equations and PPE equations	30
2.3	General-purpose Code optimization	32
2.3.1	Arrays operation	32
2.3.2	User-Interface and Specific algorithm	33
2.3.3	Parallel Implementation	34
2.3.4	Parallel Input/Output operation	39
2.4	Summary	40
3	Validation and Parallel Performance	43
3.1	Hydrodynamic developing flow in a Square duct	43
3.1.1	Problem Description and Boundary condition	43
3.1.2	Validation	44
3.2	Turbulent flow in a Square duct	47
3.2.1	Problem Description and Boundary condition	47
3.2.2	Validation	49
3.3	Parallel Performance	50
3.3.1	Speedup and Efficiency	50
3.4	Summary	53
4	Flow characterization	55

4.1	Turbulent statistics	56
4.1.1	Mean flow	57
4.1.2	Turbulence intensities	57
4.1.3	Mean streamwise momentum budget	61
4.2	Organized motion	64
4.2.1	Instantaneous flow	64
4.2.2	Quadrant Analysis	68
4.2.3	Bursting Events	70
4.2.4	Coherent Structures	72
4.2.5	Streaks eduction	76
4.3	Turbulent kinetic energy spectra	78
4.4	Summary	80
5	POD analysis	83
5.1	Snapshot POD technique	84
5.2	POD analysis of fully turbulent flow	87
5.2.1	Eigen Mode	88
5.2.2	Temporal coefficient	91
5.2.3	Self-sustenance	101
5.2.4	Reconstructed coherent structures	103
5.3	Effect of Reynolds number	104
5.3.1	Eigen mode	105
5.3.2	Temporal coefficient	108
5.4	Summary	119
6	Role of Inlet disturbance	123
6.1	Finite amplitude inlet disturbance	125
6.2	Continuous narrow ring inlet disturbance	128
6.3	Short-time inlet disturbance	130

6.3.1	Disturbance imposed on laminar flow at upper transition range Re	131
6.3.2	Disturbance imposed on laminar flow at lower transition range Re	137
6.3.3	Turbulence Statistics	140
6.3.4	Coherent Structures	141
6.3.5	Energy spectra of transition to turbulent flow	143
6.4	Summary	145
7	Conclusions and Future Work	147
7.1	Conclusions	147
7.2	Future work	150
	Appendices	151
A	Methods for Vortex Identification	151
B	Streak eduction procedure	155
C	Turbulent kinetic energy spectra	157
	Bibliography	159

List of Figures

1.1	(a) Osborne Reynolds tank (Jackson and Launder, 2007) (b) Sketch of flow regimes (Barkley, 2016).	2
1.2	(a) 19th-century laboratory: sketch of Reynolds performing experiment (b) questions of today: Yamal-Europe natural gas pipeline (McKeon, 2010).	3
1.3	Comparison of flow behavior (a) pipe flow (El Khoury et al., 2013) (b) square duct flow (present work).	5
1.4	Schematic diagram of a square duct and the mean eight-vortex secondary flow of Prandtl's second kind.	5
1.5	(a) History of the typical coherent motion in wall-bounded turbulence. (b) The sketch in black frame (top left) adopted from Song (2014) shows the streak formation process. Schematic diagram of organized motion in a wall-bounded turbulent flow (right); modified from Salim et al. (2016) . The sketch in red frame (bottom left) self-sustaining near-wall turbulence cycle proposed by Hamilton et al. (1995)	14
1.6	Schematic diagram of a square duct having (a) period boundary in the axial direction ($L/h=4\pi$), and (b) inlet and outlet boundary ($L/h=100$).	18
2.1	Chart showing different features discussed in this chapter.	24
2.2	Flow chart for Simplified Marker and Cell (SMAC).	25
2.3	Simplified GMRES algorithm from White (2015)	32

2.4	Schematic of parallel architectures (Left(a)) shared-memory; (Right(b)) distributed-memory.	35
2.5	(a)Computational Domain. The domain decomposition technique (b) Slab (1D) decomposition, (c) Pencil (2D) decomposition, and (d) Cubic (3D) decomposition.	36
2.6	Schematic diagram of domain decomosition and communication between processor.	37
2.7	The schematic diagram of the parallel HDF5 implementation layer. . . .	39
2.8	The schematic diagram of the skeleton of the collective parallel HDF5 API.	40
3.1	Schematic diagram of a square duct.	44
3.2	(a) Contours of the axial velocity in the streamwise plane and (b) Center-line axial velocity.	45
3.3	The developing flow velocity profile at (a) $x/Re = 0.0075$ and (b) $x/Re = 0.02$; the fully developed profile at (c) $x/re = 0.12$	46
3.4	Schematic diagram of a square duct.	47
3.5	Comparison of present DNS results of mean velocity profile with reference DNS data of Gavrilakis (1992) (a)streamwise velocity at $z = 0.05$, (b)streamwsie velocity at $z = 0.5$, (c)lateral velocity at $z = 0.08$ and (d) lateral velocity at $z = 0.4$. Mean velocities are rescaled with centerline mean velocities.	48
3.6	Comparison of present DNS results of turbulent intensities with reference DNS data of Gavrilakis (1992) (a) u_{rms} , (b) v_{rms} and (c) w_{rms}	48
3.7	Speedup of the 3D DNS solver.	51
3.8	Efficiency of the 3D DNS solver.	52
3.9	Scaling of fluid solver on PADUM (HPC system of IIT Delhi) for $1536*128*128$ grids.	52
4.1	Chart showing different features discussed in this chapter.	55

4.2	Eight-vortex mean secondary flow and streamwise flow contours (a) $Re_\tau = 100$ (b) $Re_\tau = 160$ (c) $Re_\tau = 300$	58
4.3	(a,b) Mean streamwise velocity profile (c,d) Mean wall-normal velocity profile at different Re_τ	59
4.4	Turbulence intensities at different frictional Reynolds number along wall bisector (a) u_{rms} (b) w_{rms}	59
4.5	The Reynolds stress terms $\overline{u'u'}$, $\overline{v'v'}$, $\overline{w'w'}$, $\overline{u'v'}$, $\overline{u'w'}$ and $\overline{v'w'}$ (From left to right) at $Re_\tau = 100, 160$ and 300 (From top to bottom). (dark and light contours shows the maximum and minimum value, respectively).	60
4.6	Mean streamwise momentum budget distribution at different locations and frictional Reynolds number. —: $\bar{v} \frac{\partial \bar{u}}{\partial y} + \bar{w} \frac{\partial \bar{u}}{\partial z}$; - - - - -: $-\frac{\partial \overline{u'v'}}{\partial y}$; - . - . - . -: $-\frac{\partial \overline{u'w'}}{\partial z}$;: Viscous Diffusion.	62
4.7	Time series of instantaneous vorticity contours on cross-flow plane (YZ-plane) represents mushroom-like structures at (a) $Re_\tau = 100$, (b) $Re_\tau = 160$ and (c) $Re_\tau = 300$	66
4.8	Comparison of instantaneous vorticity contours on streamwise plane at (a) $Re_\tau = 100$, (b) $Re_\tau = 160$ and (c) $Re_\tau = 300$. Time series of instantaneous vorticity contours on streamwise plane at (d) $Re_\tau = 100$ and (e) $Re_\tau = 160$	67
4.9	Instantaneous distributions of (u', w') near viscous sublayer (a-c) and in buffer layer (d-f): (a,d) $Re_\tau = 100$ (b,e) $Re_\tau = 160$ (c,f) $Re_\tau = 300$	69
4.10	Comparison of turbulent burst events at the buffer layer (a) $Re_\tau = 100$ (b) $Re_\tau = 160$ (c) $Re_\tau = 300$	72
4.11	The iso-surface of swirling strength colored with streamwise velocity (a) $Re_\tau = 100$ (b) $Re_\tau = 300$ (the isosurface of the swirling strength are 25% of its maximum value).	73

4.12	Evolution of hairpin-like structures (a-h) at minimal ($Re_\tau = 100$) turbulent flow colored with stretching (red) and compression (blue) at increasing time instant from $t+\delta t^+$ to $t+8\delta t^+$, with an time interval between frames $\delta t^+ \approx 10$ (the isosurface of the swirling strength are 25% of its maximum value).	75
4.13	Contour plots of streamwise velocity fluctuations on horizontal plane close to wall (a) $Re_\tau = 100$ (b) $Re_\tau = 160$ (c) $Re_\tau = 300$	77
4.14	Histograms of low speed streak strength (a) $Re_\tau = 100$ (b) $Re_\tau = 160$ (c) $Re_\tau = 300$	78
4.15	Energy spectra for minimal, marginal and fully turbulent flow.	79
5.1	Chart showing different features discussed in this chapter.	84
5.2	Iso-surfaces of streamwise velocity fluctuation (a) reconstructed from first 5003 POD modes containing 90% of energy (b) DNS data. (the light surface is positive and the dark surface is negative).	87
5.3	Energy (eigenvalue) spectra for first 100 Modes in a square duct.	89
5.4	(a) Energy distribution of first 20 modes, (b) Distribution of cumulative Energy.	89
5.5	Iso-surfaces of constant streamwise fluctuating velocity of first four most energetic POD modes (a) Mode 1, (b) Mode 2, (c) Mode 3 and (d) Mode 4 (the light surface is positive and the dark surface is negative).	91
5.6	Temporal spectra of Turbulent Kinetic Energy.	92
5.7	(a) Temporal evolution of third and fourth POD coefficient (b) third and fourth POD coefficient scatter plot.	93
5.8	Eigenfunction ϕ_u of the most energetic propagating mode in the x-direction at three direction location (a) $y=0.5, z=0.5$ (b) $y=0.25, z=0.5$ and (c) $y=0.25, z=0.25$	94
5.9	Temporal evolution of first two POD coefficient of (a) ϕ_v and (b) ϕ_w . Iso-surfaces of (c) ϕ_v and (d) ϕ_w of the first two POD modes (the light surface is positive and the dark surface is negative).	95

5.10	Contour lines of the most energetic pair mode on the same axial plane (a) ϕ_v at $z=0.5$ (b) ϕ_w at $y=0.5$, where black represents Mode 1 and grey represents Mode 2.	95
5.11	Contour lines of the most energetic pair mode on the same cross-sectional plane, where black represents Mode 1 and grey represents Mode 2.	96
5.12	Eigenfunction ϕ_v and ϕ_w of the most energetic propagating mode in the (a- c) y-direction and (d-f) z-direction, respectively, at three direction location (a,d) $y=0.5, z=0.5$ (b,e) $y=0.25, z=0.5$ and (c,f) $y=0.25, z=0.25$	97
5.13	Time evolution of modal energy (a) Energy $E(t)$, (b) Entropy $S(t)$, (c) $E(t)$ Vs $S(t)$ scatter plot, and (d) roll and propagating modes.	99
5.14	Time evolution of modal energy of most energetic roll and propagating modes.	100
5.15	Model for modal energy distribution among roll and propagating modes.	101
5.16	Iso-surfaces of streamwise velocity fluctuation reconstructed from the first four most energetic POD modes at increasing time instant (the light surface is positive and the dark surface is negative).	102
5.17	Iso-surfaces of swirling strength reconstructed from (a) 10% of energy (b) 35% of energy (c) 65% of energy (d) 90% of energy.	104
5.18	Energy (eigenvalue) spectra for first 100 Modes in a square duct.	105
5.19	Energy distribution of first 10 modes.	106
5.20	Iso-surfaces of streamwise velocity fluctuation containing 90% of energy reconstructed from (a) 1781 POD modes (minimal turbulent), (b) 3500 POD modes (marginal turbulent), and (c) 5003 POD modes (fully turbulent).	107
5.21	Iso-surfaces of constant streamwise fluctuating velocity of (a-c) Mode 1 & 2 and (d-f) Mode 3 & 4 at different Reynolds number (a,d) minimal turbulent, (b,e) marginal turbulent, (c,f) fully turbulent (the light surface is positive and the dark surface is negative).	109

5.22	Temporal evolution of third and fourth POD coefficient (a) minimal turbulent, (b) marginal turbulent, and (c) fully turbulent.	110
5.23	Eigenfunction ϕ_u of the most energetic POD modes at the centerline of the duct (a) minimal turbulent, (b) marginal turbulent , and (c) fully turbulent.	111
5.24	Temporal evolution of first two POD coefficient of (a-c) ϕ_v (d-f) ϕ_v for (a) minimal turbulent, (b) marginal turbulent, and (c) fully turbulent. . . .	112
5.25	Iso-surfaces of constant of (a-c) ϕ_v and (d-f) ϕ_w of the first two POD modes for (a,d) minimal turbulent, (b,e) marginal turbulent, (c,f) fully turbulent (the light surface is positive and the dark surface is negative).	113
5.26	Eigenfunction ϕ_v of the most energetic POD modes at the centerline of the duct (a) minimal turbulent, (b) marginal turbulent, and (c) fully turbulent.	114
5.27	Eigenfunction ϕ_w of the most energetic POD modes at the centerline of the duct (a) minimal turbulent, (b) marginal turbulent, and (c) fully turbulent.	115
5.28	Time evolution of modal energy of most energetic roll and propagating modes for (a) minimal turbulent, (b) marginal turbulent, and (c) fully turbulent.	117
5.29	Scatter plot between energy $E(t)$ and entropy $S(t)$ for (a) minimal turbulent, (b) marginal turbulent, and (c) fully turbulent.	118
5.30	Temporal spectra of (a) minimal turbulent, (b) marginal turbulent, (c) fully turbulent.	119
6.1	Chart showing different features discussed in this chapter.	125
6.2	(Left side) Schematic diagram of a inlet disturbed Square duct, (Right side) Sapio-temporal disturbance.	126
6.3	(a) Full cross-section inlet disturbance, (b) Ring type inlet disturbance. .	127

6.4	The effect of full cross-section continuous inlet disturbance on the base laminar showing instantaneous Y-vorticity on the mid XZ-plane at increasing time instant from $t+\delta t$ to $t+9\delta t$, with an time interval between frames $\delta t \approx 10$	128
6.5	Schematic diagram of continuous inlet disturbance.	129
6.6	The effect of continuous inlet disturbance on the base laminar showing instantaneous Y-vorticity on the mid XZ-plane at increasing time instant from $t+\delta t$ to $t+9\delta t$, with an time interval between frames $\delta t \approx 10$	129
6.7	The history of continuous inlet disturbance showing spatio-temporal variation of q at the centerline of the duct at disturbance amplitude (a) $O(Re^{-1})$ (b) $0.1 \times O(Re^{-1})$	130
6.8	Schematic diagram of short-duration inlet disturbance.	131
6.9	Iso-surface of streamwise vorticity colored with streamwise velocity at different time instant.	132
6.10	The history of short-duration inlet disturbance showing spatio-temporal variation of streamwise velocity at the centerline of the duct.	132
6.11	The history of short-duration inlet disturbance showing spatio-temporal variation of q at the centerline of the duct.	133
6.12	Instantaneous streamwise velocity on the mid XZ-plane at increasing time instant from $t+\delta t$ to $t+10\delta t$, with an time interval between frames $\delta t \approx 10$	134
6.13	Instantaneous Y-vorticity on the mid XZ-plane at increasing time instant from $t+\delta t$ to $t+10\delta t$, with an time interval between frames $\delta t \approx 10$	134
6.14	(a) Visualization of puff structure. Time history of isolated turbulent patches through a fixed location at a center line of a square duct (b,c) Schematic behaviour of puff and slug, (d,e) puff and slug indication from present DNS results.	136
6.15	Schematic diagram showing the selection of puff (P1 and P2) and slug (S1) region.	136

6.16	Mean secondary flow obtained from three different averaging locaion (a)P1 (X=40 to 50) (b)P2 (X=50 to 60) and (c)S1 (X=85 to 95).	137
6.17	The spatio-temporal variation of (a) streamwise velocity (b) q at the centerline of the duct at 1540 bulk Reynolds number.	138
6.18	Instantaneous streamwise velocity on the mid XZ-plane at increasing time instant from $t+\delta t$ to $t+9\delta t$, with an time interval between frames $\delta t \approx 10$	139
6.19	Time history of isolated turbulent patches through a fixed location at a center line of a square duct (a) puff and (b) puff splitting indication from present DNS results.	139
6.20	Time history of isolated turbulent patches through a fixed location at a center line of a pipe flow (a) puff and (b) puff splitting (adopted from Nishi et al. (2008)).	140
6.21	Turbulent statistics of puff and slug (a)mean streamwsie velocity profile (b) streamwise and (c) wall normal turbulent intensities.	141
6.22	Iso-surface of swirling strength colored with stretching (red) and compression. Enlarge view shows the forward hairpin vortices at the core and reverse hairpin vortices near the wall (the isosurface of the swirling strength are 25% of its maximum value).	143
6.23	Evolution of coherent structures at increasing non-dimensional time instant (a) 45, (b) 46, (c) 47, and (d) 48, (the isosurface of the swirling strength are 25% of its maximum value).	144
6.24	Turbulent kinetic energy spectra of puff and slug.	145

List of Tables

1.1	DNS of turbulent flow in a square duct	8
1.2	Puff and slugs comparison	10
1.3	The nature of investigation whether DNS (Direct Numerical Simulation) or Exp (experimental) is tabulated along with the location of disturbance like inlet and wall.	12
2.1	Hyperslab elements.	40
4.1	Parameters Setting.	56
5.1	Propagating u-Mode speed in x-direction.	96
5.2	Propagating speed of v-Modes in x-direction.	98
5.3	Propagating speed of w-Modes in x-direction.	98
5.4	Propagating u-Mode speed in x-direction.	115
5.5	Propagating v-Mode speed in x-direction.	116
5.6	Propagating w-Mode speed in x-direction.	116
6.1	Parameters Setting.	126
6.2	Short-duration narrow ring disturbance	131

Nomenclature

Notations

Δt	time step
$\Delta x^+, \Delta y^+, \Delta z^+$	wall units grid resolution in x, y, z direction
$ \omega_y^+ _{max}$	strength of low speed streak
$\mathbf{U}'$	corrected velocity
$\mathbf{U}^*$	predicted velocity vector
$\mathbf{U}^{n+1}$	new time level velocity vector
$\mathbf{U}^n$	previous time level velocity vector
a	POD or temporal coefficient
A_d	amplitude of disturbance
f	frequency
P'	corrected pressure
P^{n+1}	new time level pressure field
P^n	previous time level pressure field
u', v', w'	fluctuating velocities in x, y, z direction
u_0	base flow velocity
2D	two dimension
3D	three dimension
$\mathbf{F}$	source term
$\mathbf{U}$	velocity vector
$E(k)$	energy spectra

$E(t)$	Mode energy
h	square duct width
i, j, k	local grid indices
k	wave number
L	streamwise length of square duct
L_x, L_y, L_z	square duct length in x, y, z direction
N_x, N_y and N_z	numbers of grid points in x, y and z-direction
P	pressure
Pe	Peclet number
Q	column vector containing source terms
Re	Reynolds number
Re_τ	frictional Reynolds number
Re_b	bulk Reynolds number
$S(t)$	Mode entropy
t	time scale
U	mean speed of flow
u_τ	frictional velocity
u, v, w	velocity in x, y, z directions
x, y, z	direction in cartesian coordinate

Greek Symbols

α	eigenvector
η	Kolmogorov length scale
λ	eigenvalue
λ_r	real eigenvalue
λ_{ci}	swirling strength
ν	kinematic viscosity
ϕ	eigenfunction
ϕ_u, ϕ_v, ϕ_w	eigenfunction in x, y, z direction

ρ	density
τ_w	wall shear stress

Other Symbols

∇	gradient operator
∇^2	laplace operator
∂	partial derivative
∂^2	partial double derivative

Abbreviation

API	application programming interface
BC	boundary condition
CFL	CourantFriedrichsLewy condition
CPU	central processing unit
DNS	Direct Numerical Simulation
Exp	experiment
FDM	finite difference method
GMRES	Generalized Minimal Residual
HDF5	Hierarchical Data Format
IITD	Indian Institute of Technology Delhi
LDV	Laser Doppler Velocimetry
MPI	Message-Passing-Interface
PCPE	pressure correction poisson equation
PISO	Pressure-Implicit with Splitting of Operators
POD	proper orthogonal decomposition
PSB	periodic suction and blowing
RAM	Random-access memory
RSB	random suction and blowing
SIMPLE	semi implicit method for pressure linked equations
SIMPLEC	semi-implicit method for pressure linked equations-consistent

SMAC	simplified marker and cell
VITA	variable interval time average