Hyper-Parameter analysis of Deep Auto Encoder for Flow Prediction

A PROJECT REPORT

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

BACHELOR OF TECHNOLOGY
IN
MECHANICAL ENGINEERING

Submitted by:

Prakrit Tyagi (2K17/ME/163)

Pranav Bahl (2K17/ME/164)

Under the supervision of

Prof. B.B. Arora

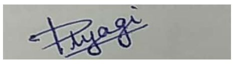
DEPARTMENT OF MECHANICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi 110042

JUNE, 2020

DEPARTMENT OF MECHANICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

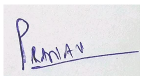
CANDIDATE'S DECLARATION

We, Prakrit Tyagi, Pranav Bahl, Roll No's – 2K17/ME/163, 2K17/ME/164 students of B.Tech (Mechanical Engineering),hereby declare that the project Dissertation titled "Hyper-Parameter analysis of Deep Auto Encoder for Flow Prediction" which is submitted by us to the Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of degree of Bachelor of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.



Place: Delhi

Prakrit Tyagi



Date: 31.05.2021

Pranav Bahl

DEPARTMENT OF MECHANICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

CERTIFICATE

I hereby certify that the Project Dissertation titled "Hyper-Parameter analysis of Deep Auto Encoder for Flow Prediction" which is submitted by Prakrit Tyagi, Pranav Bahl, Roll No's – 2K17/ME/163, 2K17/ME/164, Mechanical, Production and Industrial Department ,Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Bachelor of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi **Prof. B.B. Arora**

Date: 31.05.2021 **SUPERVISOR**

DEPARTMENT OF MECHANICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

ACKNOWLEDGEMENT

We wish to express our sincerest gratitude to Dr B.B. Arora for his continuous guidance and mentor-ship that he provided us during the project. He showed us the path to achieve our targets by explaining all the tasks to be done and explained to us the importance of this project as well as its industrial relevance. He was always ready to help us and clear our doubts regarding any hurdles in this project. Without his constant support and motivation, this project would not have been successful.

Place: Delhi — Prakrit Tyagi (2K17/ME/163)

Date: 31.05.2021 — Pranav Bahl (2K17/ME/164)

Abstract

Reducing the order of the system from high order dynamical space to a low dimensional subspace has been a challenging task and the models that achieve this are referred to Reduced Order Models (ROMs). Linear Projection methods have been used extensively in the past for building such ROMs, some common examples are POD,DMD etc. Though they have been successful in modelling several non-linear scenarios, their usage limits their applications pertaining to complex High order dynamical systems efficiently. In this study we aim to make use of advancement made in the field of Deep Learning to build a DL based ROM. We aim to probe the impact of hyper-parameters pertaining to flow prediction using deep autoencoders built with the help of artificial neural network. The parameters for our study that were used here were three different network sizes and two data sizes to compare the performance in flow prediction. Dataset for the Vorticity was generated using in-compressible URANS CFD solver icoFoam in an open-source CFD toolbox OpenFOAM. Von-Karman Vortex Street at Reynolds' number 100 around a bi-dimensional cylinder was simulated for our study.

Contents

Candidate's Declaration **ii**

Certificate **iii**

Acknowledgement **iii**

Abstract **iv**

Content **v**

List of Figures **vi**

List of Symbols, Abbreviations **vii**

1 INTRODUCTION **1**

2 LITERATURE REVIEW **3**

3 METHODOLOGY **6**
3.1 Bi-dimensional Flow Around Cylinder 6
3.1.1 Case Description 6
3.1.2 Hypotheses 6
3.1.3 Case Setup 7
3.1.4 Computational Mesh 8
3.1.5 Computational Model 9
3.1.6 Dataset 11
3.2 NOAA OISST V2 - Sea Surface Temp. Dataset 17
3.3 Machine Learning 18
3.3.1 Introduction 18
3.3.2 Neural Networks 19
3.3.3 ANN : Artificial Neural Network 21
3.3.4 Proposed Approach 23

4 RESULTS and DISCUSSION **25**
4.1 Effect of Network size 25
4.2 Effect of Training Data size 26

5 CONCLUSION AND FUTURE SCOPE **31**

List of Figures

2.1 Flow pattern generated around a cylinder for different reynolds number . . 4
2.2 Strouhal number versus Reynolds number for flow around a cylinder 5

3.1 Domain Description 7
3.2 Computational Mesh 9
3.3 Vorticity data on Computational Mesh Wireframe 10
3.4 Mathematical representation of Vorticity 12
3.5 Vorticity contour plot: Von Karman Street (time step 10) 13
3.6 Vorticity contour plot: Von Karman Street (time step 20) 13
3.7 Vorticity contour plot: Von Karman Street (time step 30) 13
3.8 Vorticity contour plot: Von Karman Street (time step 40) 14
3.9 Vorticity contour plot: Von Karman Street (time step 50) 14
3.10 Vorticity contour plot: Von Karman Street (time step 60) 14
3.11 Vorticity contour plot: Von Karman Street (time step 70) 15
3.12 Vorticity contour plot: Von Karman Street (time step 80) 15
3.13 Vorticity contour plot: Von Karman Street (time step 90) 16
3.14 Vorticity contour plot: Von Karman Street (time step 100) 16
3.15 Representation of Sea surface temperature contour plot 17
3.16 Artificial Neuron Structure 19
3.17 Activation Functions : Sigmoid, Identity and Step (From left to right) . . . 20
3.18 Auto-encoder Architecture 23
3.19 ReLU Activation Function 24

4.1 Effect of Network Size 25
4.2 Effect of data size: (a) plot for data size one (b) plot for data size two . . . 26
4.3 True Value of vorticity at time step 5 27
4.4 Predicted Value of vorticity at time step 5 27
4.5 True Value of vorticity at time step 50 28
4.6 Predicted Value of vorticity at time step 50 28
4.7 True Value of Sea surface temperature at time step 5 29
4.8 Predicted Value of Sea surface temperature at time step 5 29
4.9 True Value of Sea surface temperature at time step 50 30
4.10 Predicted Value of Sea surface temperature at time step 50 30

List of Symbols

r	Radius
v	Velocity
p	Ambient Pressure
α	Rate of momentum
η	adaptation step
W	Weight
w^t	State of vector at time t
e	Error
θ_ϕ	Network Parameters of decoder
θ_ψ	Network Parameters of encoder
ζ	Bottleneck Layer
ho	Output values
hi	Input values
θ_j	Threshold values
wih	Weighted correction between neuron i of the input layer and neuron j of the hidden layer
who	Weighted correction between neuron j of the hidden layer and neuron k of the output layer
N_input	Input parameters
N_hidden	Number of units in hidden layer
$N_classes$	Number of output of the problem
exp	Exponent
i_j	Input features
o	Output features

Chapter 1

INTRODUCTION

Advances in Machine Learning over the past decade has made it a popular field among the scientific community. It has found wide range of applications in fields such as robotics, neurobiology, economics and financial prediction, system dynamic modeling, prediction, etc.. A large role played in the explosive growth of machine learning is of availability of data and increase in computing resources which has yielded a reliable technique that has found plethora of applications.

In the era of computing, simulation has become essential for scientific progress. It plays an important role in decision making through prediction, helps in design by simulating a model over time and presents results for analysis, thus to achieve accurate simulation results a great emphasis is placed on model reliability. To achieve this it is necessary to use high spatial-temporal resolution models of the system for computation. This can be computationally expensive requiring hundreds of computing cores and time consuming making it unsuitable for real time applications requiring quick feedback.

Simulation is essentially for solving partial differential equations through iterative algorithms (deterministic or heuristic) by incorporating conditions. The models of systems used in simulations are essentially group of partial differential equations know as full order model (FOM). Full order model if used will be computationally expensive therefore reduced order model (ROM) is a technique aim at replacing the FOM by a reduced order model (ROM), which has a lower dimension but still able to describe the model of the problem described by the FOM. The basic assumption underlying the construction of such a ROM is that the solution of a PDE, lies on a low-dimensional set embedded in this space. This ROM is used to solve for solution in low dimension and then the solution is increased to FOM dimensions. This technique can be solved using a special type of artificial neural network called Deep Autoencoder. The neural network structure is such that it is able to reduce the dimension of the input and then reverse the dimension again. This has various application, in particular it is able to solve non-linear problems through composition of hidden layer and thus not restrict us to linear spaces.

Autoencoder is a neural network than can learn to imitate its input and output the same input data. Here we make use of an Auto-encoder Neural Net to learn the spatial and temporal distribution of flow and give satisfactory results with low error when compared to CFD results. This is a slight deviation from general usage of autoencoder and our efforts are to make use of advancements that have been made in the Neural networks or Deep Learning methods to build an efficient ROM (Reduced order Model) that would be able to capture the High Order Dynamics effectively and represent it in reduced latent space capturing the essential features and thereby reconstructing high order snapshot for the next time step. This paper presents results for comparisons with different hyper-parameters. Three different network sizes are used and following this different data sizes were used for training and comparison was made among them. Below is the generalized mathematical foundation of our model which presents the w^{t+1} predicted vectorized state, the model and its parameters $\varphi(;\theta_\varphi)$ and the input to the model i.e. the current time step w_t. 'e' represents the error term generated by model corresponding to the actual true state, hence predicted state is represented as $\hat{w}^{t+1}$ and the True state as w^{t+1}.

$$w^{t+1} = \varphi(w_t;\theta_\varphi) + e \tag{1.1}$$

$$e = w^{t+1} - \hat{w}^{t+1} \tag{1.2}$$

The report is organised as follows. The literature review is presented in **Chapter 2: Literature Review**. The problem formulation and Methodology is described in **Chapter 3: Methodology**. The evaluation of results are presented in **Chapter 4: Results** and conclusions are presented in **Chapter 5: Conclusion**.

Chapter 2

LITERATURE REVIEW

Advances in Machine Learning techniques has made its usage reliable and economical and opened plethora of applications in fields of robotics , neuro science, economic and financial prediction, system dynamic modeling and prediction etc.. Autoencoder is one such technique which learns by itself to represent large data in reduced form. This is advantageous as using low dimensional data for analysis and calculation is efficient, computationally economical and reduces cost. Therefore this technique has found extensive usage in flow reconstruction, reduced-order modeling [1], prediction of fluid flow dynamical system [2] and flow prediction [3].

Computational fluid dynamics is the go to technique for simulating fluid flow but it is computationally expensive and if a users has inadequate resources, he/she will find it difficult to simulate and innovate. However, CFD has found its application across various engineering disciplines such as Aerospace industry, Heating and Ventilation applications, Flows corresponding to cardiovascular operation, Fluid machinery etc [4]. The need for such simulation often requires very high temporal and spatial resolution and hence the high order dynamics are simulated using Full-order-Models (FOMs) which are various numerical methods such as Finite Volume Method (FVM), Finite Element Method (FEM) etc. which are based on the governing equations (Partial Differential Equations). These models hence hinders its use in Multi-query [5, 6] scenarios which require rapid simulation result generation. The application of building large scale dynamical systems to simulate highly complex and non-linear flows seems to be failing in its use without taking a lot of computational burden. Hence there is an inherent need to represent higher order dynamics in reduced representations, which could be further used to evolve dynamics and when required can be reconstruct back to it's high-order form. These techniques are often referred to as Reduced-order-Models (ROMs) and many academicians have made their contributions in the past to model such techniques [7, 8, 9, 10]. Building ROMs is not an easy task, since the models doesn't perform well in situations where the dynamical systems are complex since the parameters aren't robust enough. There are various projection based methods which have been introduced in the past which makes use of linear basis to form basis functions with help of snapshots generated using FOMs. These methods have found its acceptance among many researchers, such as Proper Orthogonal Decomposition(POD) [11, 12, 13], Dynamic mode Decomposition(DMD) [14, 15], Koopman Theory [16, 17] etc.

Proper Orthogonal Decomposition method is a method to decompose a physical vector field representing a physical phenomenon into a composition of deterministic functions that each reflect some part of total fluctuating kinetic energy. Through this method the hope is to find obscure hidden structures in any phenomenon that are difficult to observe and define. Dynamic mode Decomposition is similarly to POD i.e it is used to analyse dynamics of complex non-linear phenomenon that are difficult to observe and define. If given a temporal set of data, DMD computes a set of modes each of which is associated with a fixed oscillation frequency and decay/growth rate. These set of modes with their parameters help in extracting information about dynamics. Koopman Theory is an formulation of study of dynamical system through data-driven analysis. Provided a set of time-series data that is arranged in a vector space the Koopman operator gives a linear transformation of this vector. It can be seen a lifting of the dynamics from the state space into the space of observables.

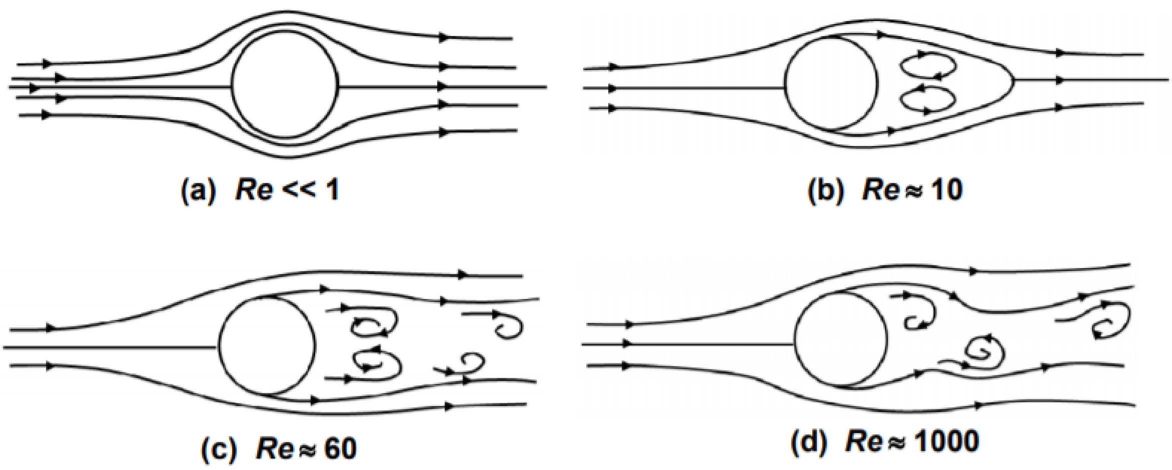


Figure 2.1: Flow pattern generated around a cylinder for different reynolds number

In this project we aim to estimate the spatial and temporal distribution of flow around a cylinder. Flow around a cylinder generates intriguing pattern in the wake of the cylinder. This is a popular phenomenon to simulate and test your algorithms. Flow patterns generated around a circular cylinder immersed in a uniform flow are shown in figure 2.1 [18].

A Kármán vortex street (or a von Kármán vortex street) is a repeating pattern of swirling vortices, caused by a process known as vortex shedding. It is formed in the wake of the flow around a bluff body.When the Reynold's number exceeds about 30, the two vortices formed behind the body gets stretched and are washed down. At the place of these two vortices, two new are formed and the process continues. The shape of every streamline is symmetrical not only around the cylinder's upper to lower side, but also around its front to rear. Karman gave the explanation for this phenomenon and according to him there are two possible configuration of the vortex trail i.e. symmetrical and the staggered configuration. Formation is dependent on Reynold's number of the flow, as the Reynolds number increases, the length of the vortex increases, at less than 5 Re no shedding, 5 to about 40 Re fixed symmetrical vortex, above 90 Re alternating vortices shedding starts. As shown in figure 2.1 the vortex The frequency of the shedding is directly proportional to the Dimensionless quantity "Strouhal Number" The Von Karman vortex streets are as a consequence of Stroual instability, which occurs on the transition between laminar and turbulent flows. Thus, this instability is linked with the Reynolds dimensionless number which determines the stability and the flow type. The variation of strouhal number versus reynolds number is shown in figure 3.3 [19]

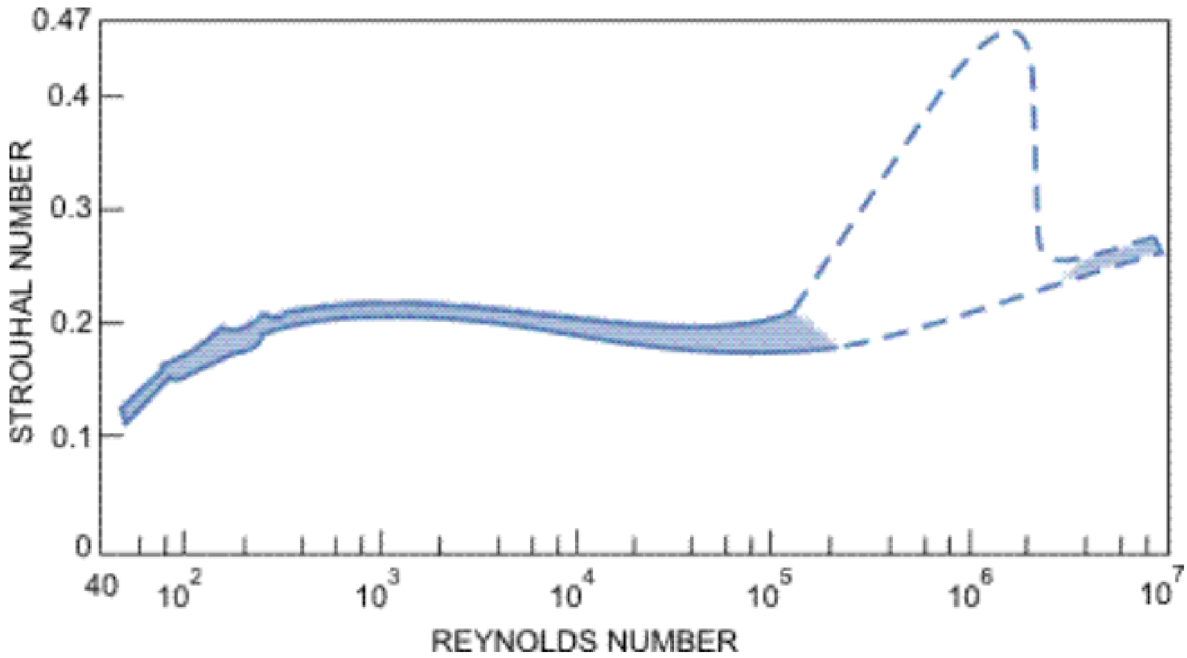


Figure 2.2: Strouhal number versus Reynolds number for flow around a cylinder

Chapter 3

METHODOLOGY

3.1 Bi-dimensional Flow Around Cylinder

3.1.1 Case Description

The analysis is based on the flow around a bluff body i.e. 2d circular cylinder. The specifics of the given case presented here is the two-dimensional or bi-dimensional mathematical modelling of laminar flow around this body which is in-compressible in nature. The model generated is made possible with the help of OpenFOAM version 7 tool-box. The mesh generated here for our case has specific high-resolution on the targeted areas wherein the effects of viscous nature is more dominant. The computational fluid dynamics (CFD) simulations are generated here for Reynolds Number 100, and visible vortices within the flow can be seen in the form of vortex shedding. We have constantly maintained decent qualitative metrics for our simulation case such as Mesh quality, Courant Number etc. Given the correct initial conditions for our simulation case , OpenFOAM have been able to accurately model our case of 2D Von Karman Vortex Shedding with correct Strouhal Number.

3.1.2 Hypotheses

The following are the hypotheses considered for our case of simulation, which comprehends the simplicity or straight-forwardness of our problem with respect to extremely complex Non-Linear problems.

1. The flow is Incompressible in nature, with no variations in the density.
2. The flow is Laminar in nature, with no lateral mixing of fluid layers.
3. The fluid is newtonian in nature.

4. The flow is 2-Dimensional in nature, with no gradients in the z-direction.
5. The gravitational effects on our fluid flow is negligible.

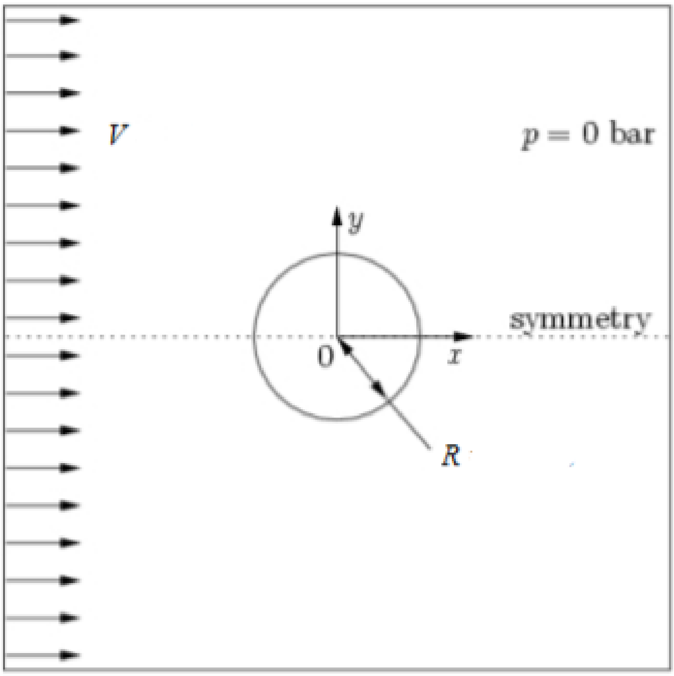


Figure 3.1: Domain Description

3.1.3 Case Setup

The CFD setup generated here makes use of bluff body which is 2-Dimensional in nature and represents physically a circular object placed in a flow. The diametre of the circular object is 0.1 m and the velocity of the flow from the inlet is of constant speed 1 m/s, following which the outlet is kept at Ambient condition of the pressure. The solution for the simulation is not an analytical one and henceforth the behaviour of the flow is governed by the governing equations of the system and the dimensionless number representation corresponding to the problem. The fluidic behaviour is high Non-linear in nature and the dependency of the system is dependent on the Reynolds number of the flow. The viscous behavior of the fluid can be observed wherein the boundary layer detachment is seen as an existential phenomena because of the adverse pressure gradient. A widely known phenomenon takes place due to the symmetry of the system i.e. Von karman vortex street, which is observable in the form of alternate shedding of the vortices behind the body. The dimensionless number associated with the shedding of these vortices is Strouhal Number.

1. The Continuity Equation :

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{3.1}$$

2. The Momentum Equation :

$$\frac{\partial u}{\partial \tau} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \frac{1}{Re}(\frac{\partial^2 u}{\partial^2 x} + \frac{\partial^2 u}{\partial^2 y}) \tag{3.2}$$

$$\frac{\partial v}{\partial \tau} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \frac{1}{Re}[\frac{\partial^2 v}{\partial^2 x} + \frac{\partial^2 v}{\partial^2 y}] \tag{3.3}$$

3. The Reynolds Number :

$$Re = \frac{\rho V L}{\mu} \tag{3.4}$$

4. The Strouhal Number :

$$St = \frac{wD}{2\pi U} \tag{3.5}$$

As stated above the CFD modelling of the problem defined was done using OpenFOAM. The solver that was used here under the regime of the tool-box is called icoFoam. The icoFoam solver used here is an incompressible solver of the Navier-stokes equations and the method involved in solving these equation is called Pressure Implicit with Splitting Operator - PISO Algorithm. This solver has proved to be an effecient and accurate solver for such kind of problems before as well.

3.1.4 Computational Mesh

The mesh was generated here to cater the problem defined as above. The bidimensional cylinder here has a diameter of 0.1 metre with the flow of fluid coming from the +x direction and following this leaving at an Ambient pressure at the outlet. The order of the problem has dependency on the size of the boundary layer and corresponding to this, certain sections of the mesh were created with high-resolution discretizations. The theoretical version of such discretization strategy often refers to using equally sized grid-points and small enough to capture relevant features.

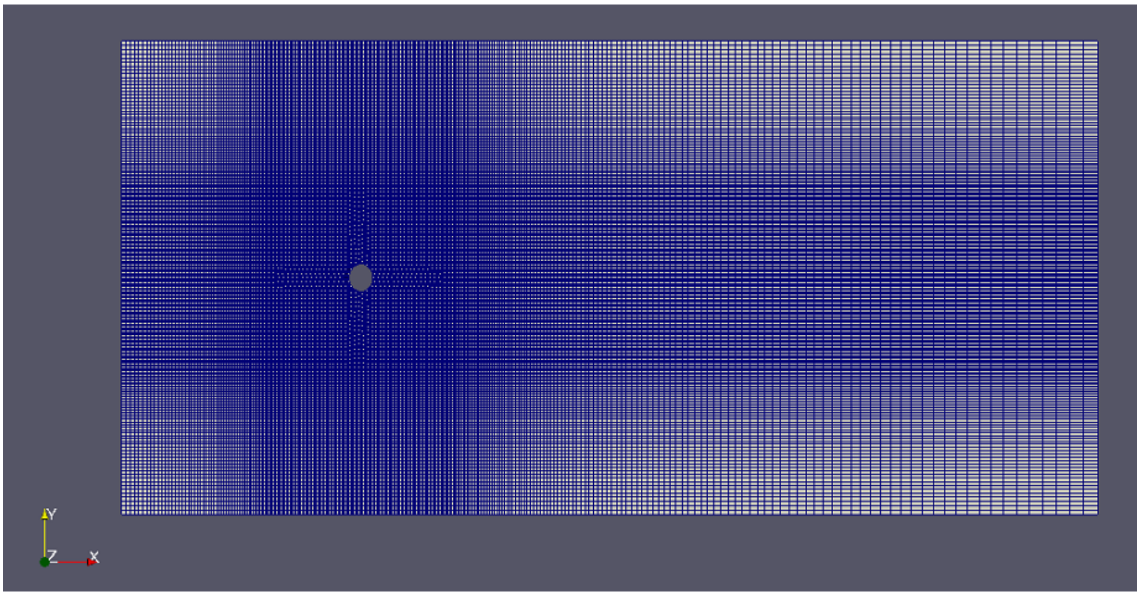


Figure 3.2: Computational Mesh

Since to enhance the computational burden from the system we make use of the variation in resolution, without compromising on losing of relevant features. The fineness of the mesh around the cylinder is more than the other spatial-domain since it needs to capture the boundary layer prevalent features. The blockMeshDict in the directory /system is used to generate /constant/PolyMesh for mesh. The following mesh has been defined with the help of six different patches i.e. Top, Bottom, Inlet, Outlet, Cylinder and FrontAndBack of the respective domain. The development of the fine mesh around the cylinder was done using feature arc instruction of the blockMesh utility. The cylinder patch was defined as wall and FrontAndBack patch was defined as empty for the sake of bi-dimensionality of the problem. The patch instruction were passed for the inlet and the outlet section of the problem and as such no information is specified since then we can use it for instructing the flow at specified initial conditions. As discussed before the resolution of the mesh around the cylinder is increased as for efficient capturing of the boundary layer and hence fluid elements near edges which are smaller are restricted as a consequence.

3.1.5 Computational Model

The description of the model used in our case could be fundamentally drawn from the files situated at directories /0 and /constant and /system. The discussion of these respective files would be made in the consequent sections explaining the descriptions of the models and their usage. The files are corresponding to the version 7 of OpenFOAM CFD toolBox. In the /0 directory the files that are present are the files corresponding to the /0/p

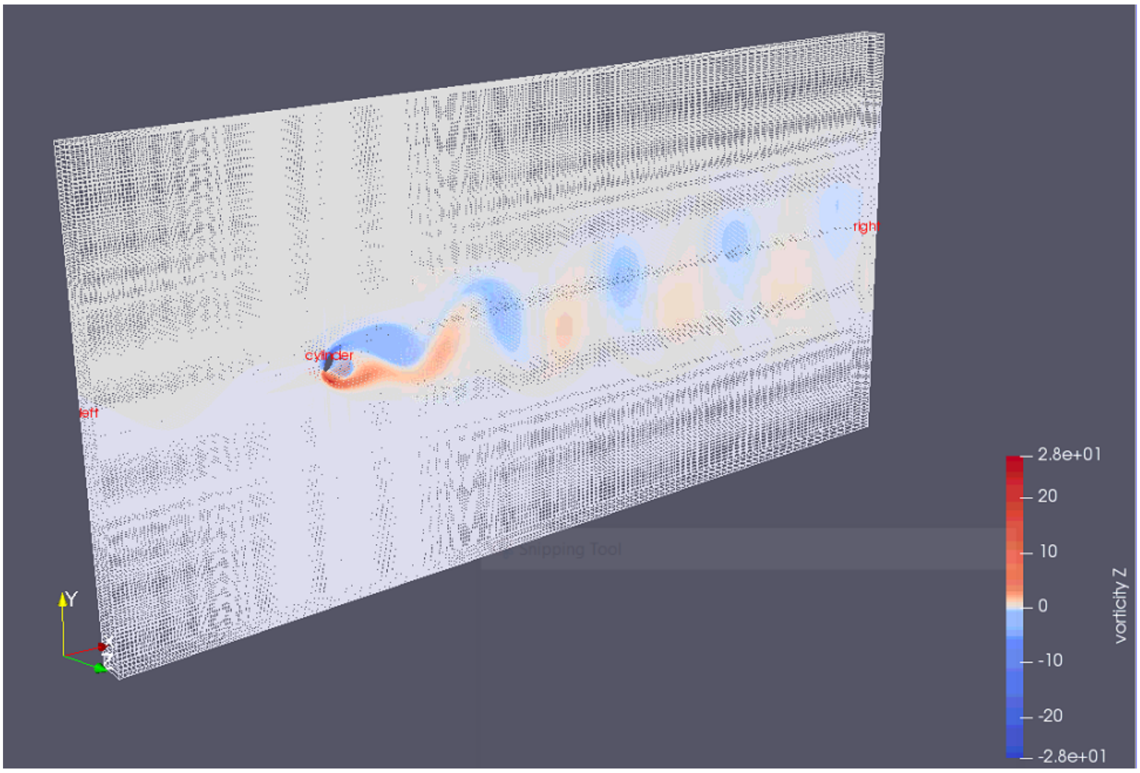


Figure 3.3: Vorticity data on Computational Mesh Wireframe

and /0/U and hence as the name suggests contains the information corresponding to initial conditions of the respective boundaries. The following is the bifurcations made :

1. Patch : Top and Bottom - symmetryPlane condition

2. Patch : Front and Back - empty condition

3. Patch : Inlet and Outlet - freeStreamPressure condition

The patch freeStreamPressure leads to the constant setting of the inlet with the negligible gradient with the corresponding outlet hence providing an absolute critical environment for the flow of the fluid. The next file which contains the initial conditions for the velocity contains information corresponding to the uniform velocity directed from the -x direction of the spatial domain to the +xdirection of the domain. The internalField term inside the file contains the information corresponding the quantitative measure of the uniform velocity to be given as the input. The dynamic viscosity of the fluid is adjusted as such that the inlet velocity with its value form the required Reynolds number of 100. Again the conditions corresponding to the boundaries were made as follows :

1. Patch - Top and Bottom - symmetryPlane Condition

2. Patch - Front and Back - empty Condition

3. Patch - Cylinder - noSlip Condition

The empty condition as usual has been used here to direct the system to a bi-dimensional form and the cylinder has been initiated here with the noSlip condition of OpenFOAM so as to direct zero velocity at this patch through-out leading to the formation of a boundary layer. The next file corresponding to the modelling of the system are /constant. There are two files namely in this directory i.e. /constant/RASProperties and /constant/transportProperties. The file RASproperties as the name suggests is used to define the Reynolds Averaged Model and can be used to flag the model to be used in the case of simulation. Since our simulation setup corresponds to the laminar flow, we set the system by writing the flag as laminar. The constantly printing of the coefficients can also be adjusted here. The next file that we have in this directory is transportProperties which contains the information corresponding to the property of the fluid i.e. kinematic viscosity which is dynamic viscosity divided by the density of the fluid and can be altered to adjust the Reynolds number. Next in the queue comes the /system directory which contains the files that directs the code to run in a particular way. /system/controlDict implements the code to run with a certain time-step and controls the total iterations to run for the simulation and also has the command over the writing of the data. The solver is also to be mentioned in this file i.e. for our case icoFoam. We set the time-step accordingly for the system taking help of the courant number. The start-time of the simulation is kept as 0 and final as 10 seconds. The simulation start is also kept as the start-time at the starting and as latest-time in the middle of simulations. The write-interval option is also presented in the controlDict file, and can be set accordingly. /system/fvSchemes file directs the cfd code to use which schemes whether it be discretization schemes or the interpolation schemes. GaussLinearOrthogonal function has been used for the laplacian schemes section. The file /system/fvSolutions contains which solvers to use for solving the CFD problem. The solver for the velocity section used here is PBiCG and the preconditioner used corresponding to it is DILU. Since PISO solver is used here hence we have nNonOrthogonalCorrectors at constant value 3 which helps in getting more features get captured by our simulation.

3.1.6 Dataset

The cylinder has a diameter of a unit along with its distance corresponding to the centre from the inlet is 8 units and from the outlet is 25 units. Boundary conditions of the domain corresponds to the unit velocity from inlet and pressure of 0 at the outlet. A no-slip BC has been initiated for the circular body. The simulation carried out here is of Unsteady RANS simulation using OpenFOAM. The solver used here is icoFoam which is an incompressible Navier-stokes solver. There is an inherent need for extracting relevant features/information from the corresponding data-set and hence we only concentrate our study around the formation of vortices and its shedding, henceforth we look forward to cut-out the part of the data for relevant understanding of the system. The cut-out stretch that has been proposed her contains the spatial domain with stretch in the y-direction from - 2 unit to the + 2 unit and following this in the x-direction the stretch starts from 0 unit to +16 unit. The following cut-out stretch has data in an unstructured form and hence a MATLAB code was written to use linear-interpolant to distribute data uniformly in the space and thereby facilitating in even distribution of wieghts and biases throughout domain. The uniformly distributed data has data has quantitative features of 80 points in the y-domain and 320 points in the x-direction and the data used here is Z-Vorticity data. Other from the computation of the rate of the flow and the wall shear stress calculation the voticity of the fluid can generated with the help of OpenFOAM utility. The vorticity of the fluid can be presented as a pseudovector field that comprehends the circular motion of the fluid locally with respect to some reference point. The vorticity of the fluid can be represented mathematically as below, which basically the curl of the velocity field.

$$\vec{\omega} = \nabla \times \vec{v} = \left(\frac{\partial}{\partial x} \quad \frac{\partial}{\partial y} \quad \frac{\partial}{\partial z} \right) \times \left(v_x \quad v_y \quad v_z \right)$$

$$= \left(\frac{\partial v_z}{\partial y} - \frac{\partial v_y}{\partial z} \qquad \frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x} \qquad \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y} \right)$$

Figure 3.4: Mathematical representation of Vorticity

As suggested our current case is a 2-Dimensional or bi-dimensional flow the curl of the velocity field with be with respect to the x-direction and the y-direction and hence curl would automatically mean the magnitude of the vector to be in the z-direction and hence the vectors are perpendicular to the state of the system.

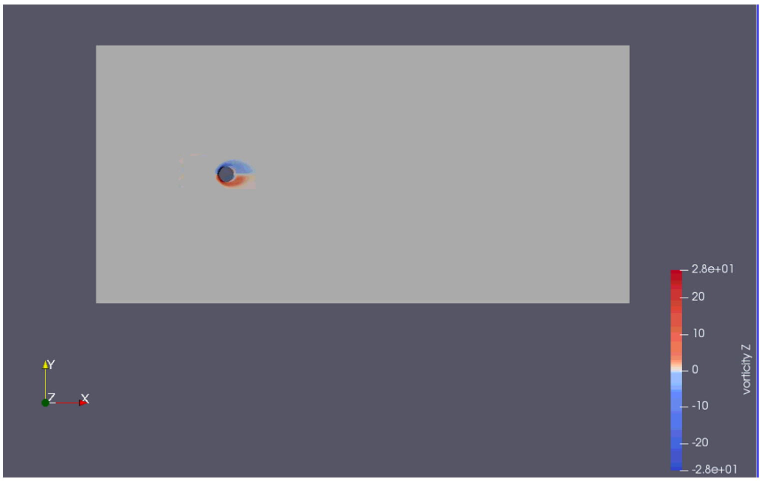


Figure 3.5: Vorticity contour plot: Von Karman Street (time step 10)

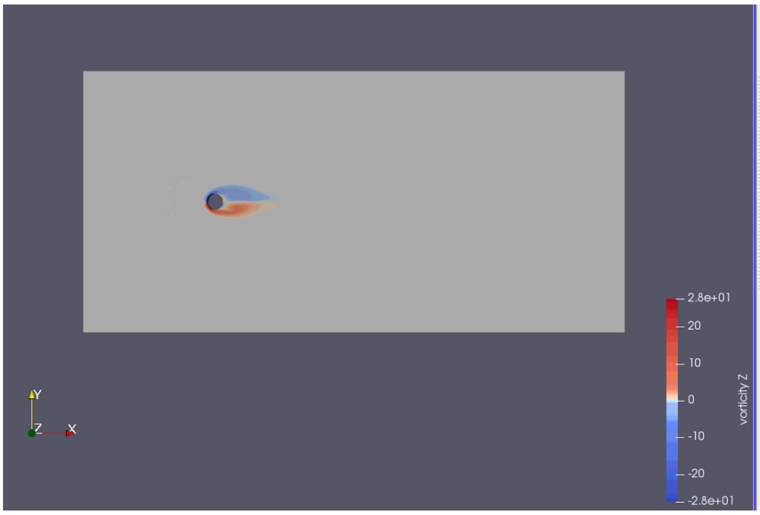


Figure 3.6: Vorticity contour plot: Von Karman Street (time step 20)

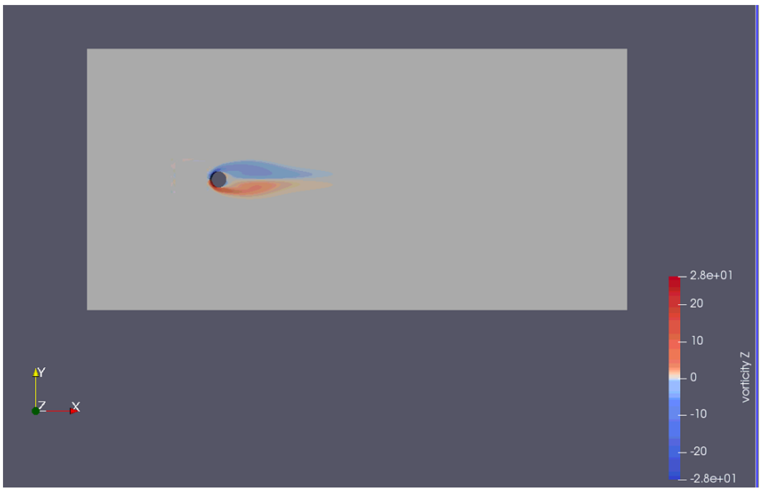


Figure 3.7: Vorticity contour plot: Von Karman Street (time step 30)

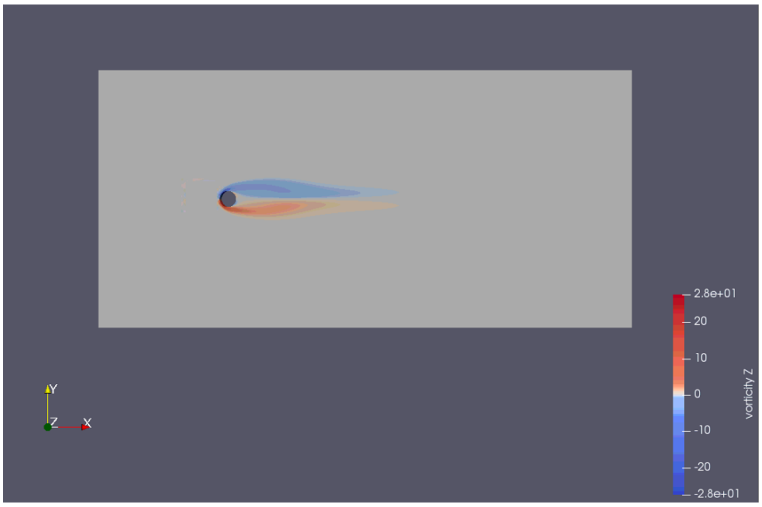


Figure 3.8: Vorticity contour plot: Von Karman Street (time step 40)

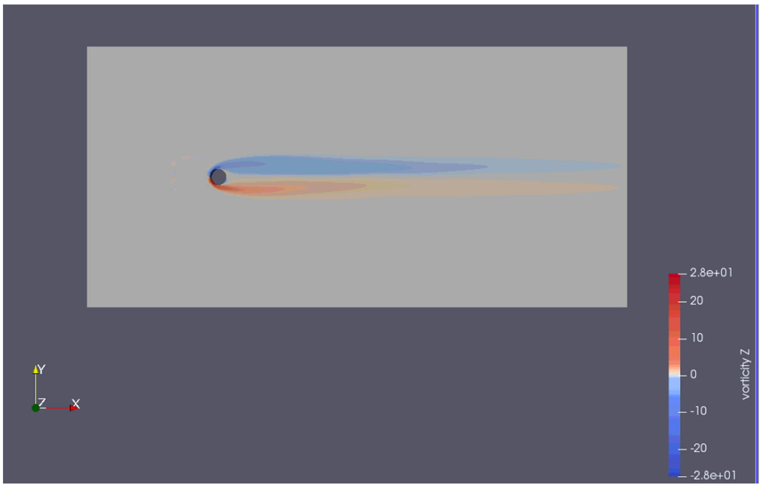


Figure 3.9: Vorticity contour plot: Von Karman Street (time step 50)

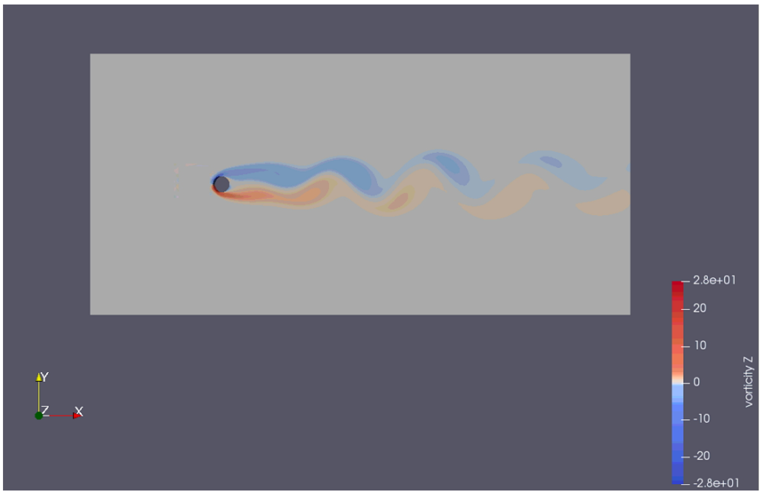


Figure 3.10: Vorticity contour plot: Von Karman Street (time step 60)

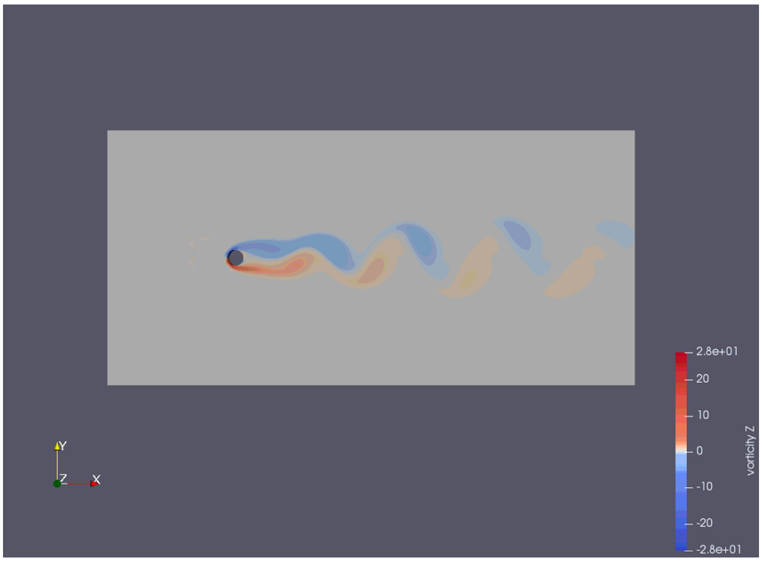


Figure 3.11: Vorticity contour plot: Von Karman Street (time step 70)

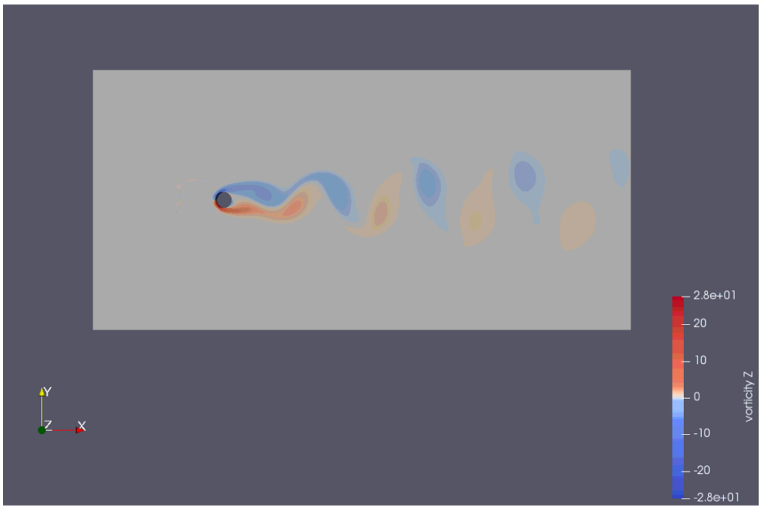


Figure 3.12: Vorticity contour plot: Von Karman Street (time step 80)

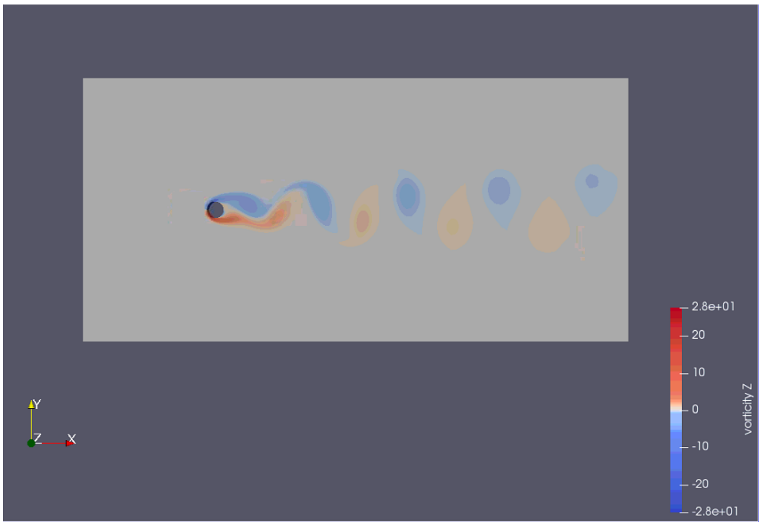


Figure 3.13: Vorticity contour plot: Von Karman Street (time step 90)

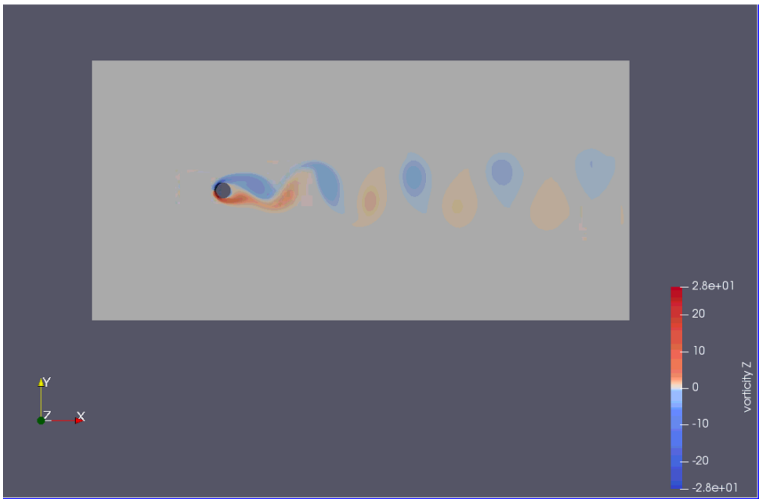


Figure 3.14: Vorticity contour plot: Von Karman Street (time step 100)

3.2 NOAA OISST V2 - Sea Surface Temp. Dataset

As the proof of concept and generalization of our machine learning technique, we test our approach on an another well-known highly-nonlinear data i.e. Sea Surface Temperature (SST) dataset. SST Data is made publicly available and uploaded by the Physical Sciences Division at National Oceanic and Atmospheric Administration (NOAA). The data is made available by the respective organization after the analysis of in-situ and satellite observation of the Sea surface temperature by the help of ship-buoys and expensive satellites. The resolution of the data available corresponding to the variable 'time' or as we call it the temporal resolution of the data is Weekly data, Monthly data and monthly long-term mean data. The resolution corresponding corresponding to the spatial domain is of 1 deg latitude and 1 deg longitude, which translates to 180 x 360 grid points. Since our earth constitutes of 360 deg longitude and 180 deg latitude the above described data covers all the spatial domain of the earth along with the sea and the surface. The surface data here is represented as a large number meaning no existential sea surface temperature. In this study we make use of weekly mean data from the year 1990 on-wards. This resolution for the temporal dependency was used since the time-steps corresponding to other temporal resolution were either in very large quantity or else in shortage for the training of the model. The data is said to be centred around Wednesday for this period, meaning the features corresponding to the whole week were centered for a single point in the time space.

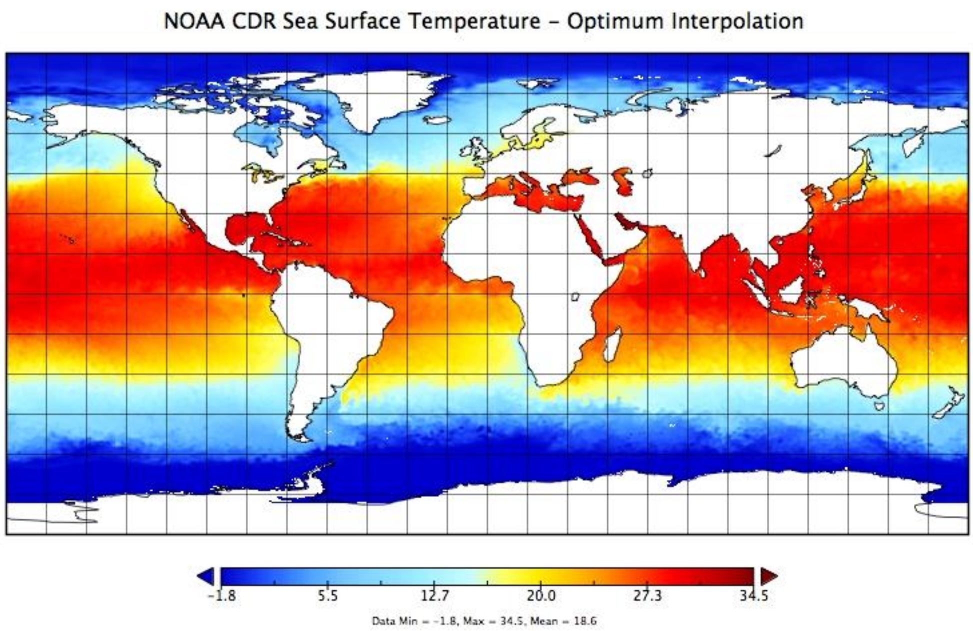


Figure 3.15: Representation of Sea surface temperature contour plot

Data for initial 400 weeks was chosen as the training data-set for our machine learning model. Following 100 weeks data was chosen as validation data-set for recommending the system as valid for its application to the real world data for predicting, and following 200 weeks of the data was used for the testing of the model's accuracy. The problem description here is to reconstruct the SST data on the time-step t+1 with the input to the model at time-step at t, henceforth making an model recursively predicting the next time-steps.

3.3 Machine Learning

3.3.1 Introduction

This section will briefly cover the specifics related to machine learning algorithm and how do they function. The increase in the existential use of data-driven algorithm over the course of whole globe has increased dramatically, the one good reason for the following could be the huge rise in the production of data. The focus of this subject is to study and analyse the data generated and develop algorithms that can help in understanding such data. The primary task defined is to find a function that can map the input features X to output Y i.e. the predictions of the function. Machine learning tasks can be classified into different sites of applications such as classification problem or prediction of the state, irrespective of the application the accuracy of the system is to be measured and calibrated accordingly. Hence there has to be a performance measure that has to be present for an algorithm to develop the model as accurate as possible. Machine learning techniques are often subdivided on the basis of the optimization problem or the kind of training required to optimize the algorithm's weights and biases. These are called namely, Supervised method of learning, Unsupervised method of Learning and Reinforcement strategy for learning. The first case of supervised methodology as the name suggests makes use of the data-set that are labeled in nature i.e. a corresponding has a particular output. Such techniques are made use of wherein the input to the model and output to the model are available in large quantities and the focus is on reducing the error between the predicted output by the model to the respective input. Next in the queue come the unsupervised learning technique, which makes use of unlabeled data-sets that has no input-output pair to reduce some error associated with the predicted state, rather the focus is more on the discovering of the similarity or cluster formation among the data and seek useful information out of it. Reinforcement techniques are rather based on the feedback-loop of the system wherein the function is trained on the whole ideology of reward based system , as every action has its own set of consequence. The amount of the data around us is tremendous and it is the prerogative of the system to derive useful information/inferences out of it. In today's age of Internet, Internet of Things, Sensors etc every hour unimaginable amount of data is generated. Hence there is an inherent need for developing algorithms that helps us understand Non-linear complex phenomena of the world accurately.

3.3.2 Neural Networks

Neurons

This section will present intricate details pertaining to modern day deep learning technique known as Neural Networks that are artificially generated. The discussion starts with inheriting the design of the biological neurons that are present in the human brain. These biological neurons are said be extensively interconnected and forms the basic cell for processing the information presented. They are composed of the biological terms associated as follows, dendrites, soma and the axon. Each of these have their own function associated with respect to the biological entity i.e. in case of dendrites they send electrical signals to soma with the help of extremely dense interconnected branches.

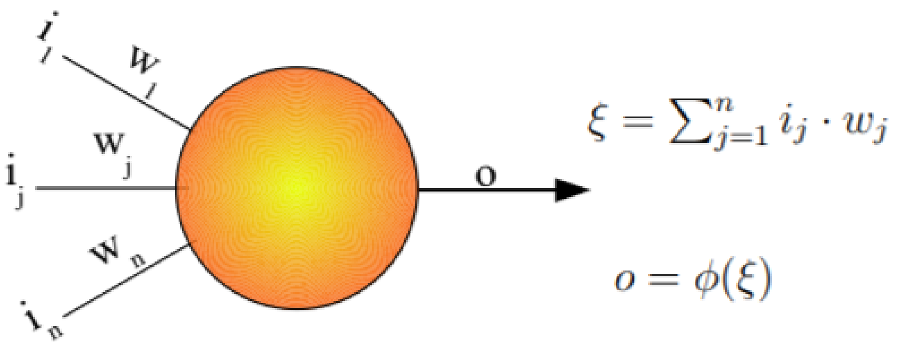


Figure 3.16: Artificial Neuron Structure

All the information is processed in the Central part of the neuron i.e. soma , the activity next performed by axon is to take away signal from the soma. Similar is the way that an artificial neuron is generated i.e. some input features are given to a artificial neuron and the function is to output a data after the processing of the input data. The working is presented in the most simple form that is the input data is multiplied by the weight they hold to the answer processed and also if an extra bias associated, for that an additional term. The whole processed data after this is passed onto the activation function, which is a source for adding non-linearity in the system. Without the advent or use of activation function it isn't possible for the system to add non-linearity in the problem and hence a linear function is what will be left in the end. There have been several instances in the past that has shown that single layer of the neuron can depict or approximate any kind of a function with a certain level of accuracy.

$$\phi_{sig}(\xi) = \frac{1}{1 + \exp(-\xi)} \tag{3.6}$$

$$\phi_{id}(\xi) = \xi \tag{3.7}$$

$$\phi_{step}(\xi) = \begin{cases} 1, & \xi > 0 \\ 0, & \text{otherwise,} \end{cases} \tag{3.8}$$

Optimization Algorithm

The optimization problem posed on the algorithm is of a popularly known algorithm i.e. Back-propagation algorithm. The fundamental required necessity for the algorithm is a derivative based function. As the derivative is calculated as parameter to reach near the global optimum. Several Activation function used here are corresponding to the differentiable functions such as the sigmoid function, ReLU, Tanh etc.

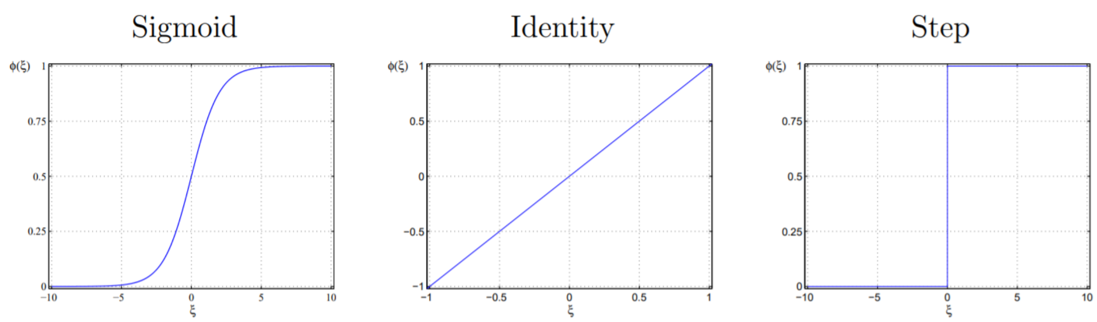


Figure 3.17: Activation Functions : Sigmoid, Identity and Step (From left to right)

The activation functions to be used are corresponding to the kind of application we intend to apply it for, example if the value is corresponding to true or false and henceforth sigmoid function would be used to limit the value between 0 and 1. For tanh, varied data is required for normalized value between 1 and -1. The common problem pertaining to both of these problem is the fact that the curve for the function near the end has infinitely small values which leads to very small updating of the given function's weight. This leads to very popular choice of the activation function i.e. ReLU that helps in rapid simulation rates and higher computational efficiency pertaining to easy update of the given weights of the system.

3.3.3 ANN : Artificial Neural Network

This section contains the information pertaining to the network topology of the multi-layer network with layers of neurons connected with respect to each other and the processing of the information takes place between the layers, adding extra non-linearity to the system along with enhancing the complexity of the data-driven model to better capture the system relevant features. There are three components to this type of network namely, the first layer then the hidden layer following which there is an output layer. The input layer processes the input to the system wherein the number of neurons used here is equal to the number of the features. Following this we tend to make use of the input information processed to pass on the information to the hidden layers thereby increasing processing the information even-more and hence-forth modelling our complex function.

The output layer in the one which hence collects the information from the processed output of the hidden layers in the action and hence the output layer is the one that finally processes and outputs the data in the number of features expected out of the model in the number of output neurons. The process of calibrating the weights of the system in order to make the model is done with the help of training procedure. The process begins with the random initialization of the weights and thereby the back-propagation and the gradient-descent algorithm comes in and the weights and the biases are updated accordingly. The below are the respective equations presented wherein the weights are multiplied with the respective features and the bias is added. Following this the activation function is applied to the system of output and results are derived.

$$ii_i = io_i = x_i \tag{3.9}$$

$$hi_j = \sum_{i=1}^{Ninputs} wih_{i,j} \cdot x_i + \theta_j \tag{3.10}$$

$$ho_j = \frac{1}{1 + \exp(-hi_j)} \tag{3.11}$$

Here now comes our discussion pertaining to the updating of the system of equations with their respective weights with the help of the Back-propagation which is essentially applied in almost all the supervised trained algorithm. The process essentially contains a minimization or optimization problem of a error function associated with the input and the output of the system. The true output is essentially compared with predicted output and residual generated is used for the back-propagation algorithm. The following are the systems of equation which are used to implement this. Below are the given weight adjustment strategy adopted. The adaptation rate and the momentum rate has been mentioned in the given problem.

$$Error(x) = \frac{1}{2} \cdot \sum_{c=1}^{N_c} (d_c(x) - y_c(x))^2 \tag{3.12}$$

$$W(t+1) = W(t) - \eta \frac{\partial Error}{\partial W}(t) + \alpha \cdot (W(t) - W(t-1)) \tag{3.13}$$

$$\frac{\partial Error}{\partial W}(t) = \frac{\partial Error}{\partial who_{j,k}}(t) = -\delta_k \cdot ho_j \tag{3.14}$$

$$\delta_k = (d_k - y_k) \cdot (1 - y_k) \cdot y_k \tag{3.15}$$

$$\frac{\partial Error}{\partial W}(t) = \frac{\partial Error}{\partial wih_{i,j}}(t) = -\left(h0_j \cdot (1 - ho_j) \cdot \sum_{h=1}^{Noutput} \delta \cdot who_{j,h} \right) \cdot x_i \tag{3.16}$$

The following are applied to the the data-sets that majoritarian are divided into three major parts that is the training set, Validation set and the test set. The training set is essentially used to calibrate or update the weights of the system and the Validation set is hence used for selection of the best network configuration to be applied to the generalized schemes. Finally the test set is used to refer the accuracy of the model crated here. Essentially the part of the data used as Training set and the Validation set are known as Learning set of the data and the rest is Test set. The major problem with network that may propose over-fitting at times because of the added non-linearity. Hence regularization of the model is to be done or the complexity of the system needs to be reduced by reducing the network's neurons per-say.

3.3.4 Proposed Approach

In this section, we will put forward the details of the framework for Deep Learning based model which can be used as a Reduced Order Model for predicting future time steps of the High Order Model with less computational efforts. The model is based on a Linear Auto-encoder approach which makes use of encoder and decoder architecture for reducing the number of computational nodes. The approach is used to learn the reduced latent subspace through a non-linear approach which helps in reducing the loss of information with comparison to its counterparts such as Proper Orthogonal Decomposition (POD), DMD, Petrov-Gaalerkin approach etc. which on other hand uses linear approach for the aforementioned function. Training of the model uses vectorized form of data $\tau = [\tau_1, \tau_2, \tau_3, ..., \tau_n] \in N_t$ which represents the data over t time steps. The state vector represented as $w \in N_w$ and predicted data as $\tau = [\tau_1 + 1, \tau_2 + 1, \tau_3 + 1, ...]$ The expression of the predicted state variable at time step "t+1" is as presented below.

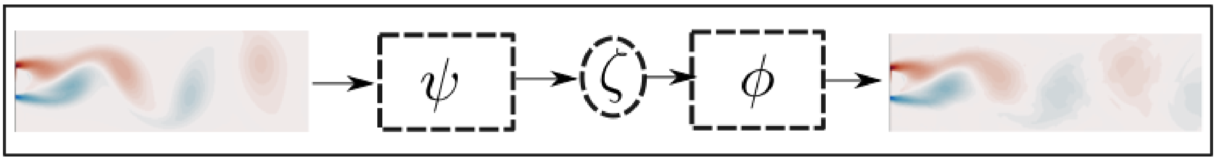


Figure 3.18: Auto-encoder Architecture

$$\zeta = \psi(w_t; \theta_\psi) \tag{3.17}$$

$$\phi(\zeta) = \hat{w}^{t+1} \tag{3.18}$$

$$\hat{w}^{t+1} = \phi(\psi(w_t; \theta_\psi); \theta_\phi) \tag{3.19}$$

Where the $\phi(; \theta_\phi)$ represents the decoder network which projects the reduced latent space back to the original high order space with θ_ϕ being its network parameters to optimize. The $\psi(w_t; \theta_\psi)$ network represents the encoder which reduces the previous time step's high order data to a nonlinear reduced subspace with θ_ψ being the network parameters to optimize. We present in the paper following using this architecture that non-linear approach to project is an efficient method in comparison to it's counter-parts. The optimization of the network has been carried out using Mean Squared Error (MSE) approach for the optimization of the network parameters. The mathematical formulation has been presented below, wherein the "e" represents the difference between the predicted and the true state vector.

$$\alpha = min\frac{1}{N-1}\sum_{n=0}^{N-1}\|e\|_2^2 \tag{3.20}$$

$$\alpha = min\frac{1}{N-1}\sum_{n=0}^{N-1}\left\|w^{t+1} - \phi(\psi(w_t))\right\|_2^2 \tag{3.21}$$

The Auto-encoder approach as stated in this paper involves the use of a deep neural network containing neurons which in the first place are reduced as moving in the forward layers and then increased, so as to reconstruct the next time step. There are two split parts which are referred to as encoder and decoder wherein the encoder compresses the data, thereby performing the function of a Reduced-order-Model and then the decoder reconstructing the reduced state back to the high order output. During the training phase of the architecture, input to the encoder is the vectorized form of the flow-field at the time step "t" and the label corresponding to the output of the decoder is the vectorized form of the flow field at time step "t+1". The Auto-encoder architecture mentioned in the paper has 5 layers of neural network with 3 hidden layers and 3rd layer being the bottle-neck layer. The activation function used here for the purpose of adding non-linearity to the ANN was chosen as ReLU. Linear activation is used in the end layer for predicting the vectorized form of the fluid flow prediction. ReLU has been used here since it is computationally less expensive. The mathematical formulation of ReLU function has been presented below.

$$F(x) = Max(0, x) \tag{3.22}$$

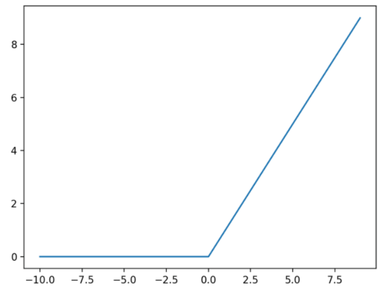


Figure 3.19: ReLU Activation Function

The training of the network has been carried out with the help of ADAM Optimizer with a learning rate of 0.01. The parameters corresponding to encoder and decoder are represented as θ_ψ and θ_ϕ which are optimized with the help of ADAM algorithm. For regularization of the network we use L^2 regularization to eradicate the possibility of over-fitting. Weight decay of 0.5 have been used here so as to regularize the network.

Chapter 4

RESULTS and DISCUSSION

4.1 Effect of Network size

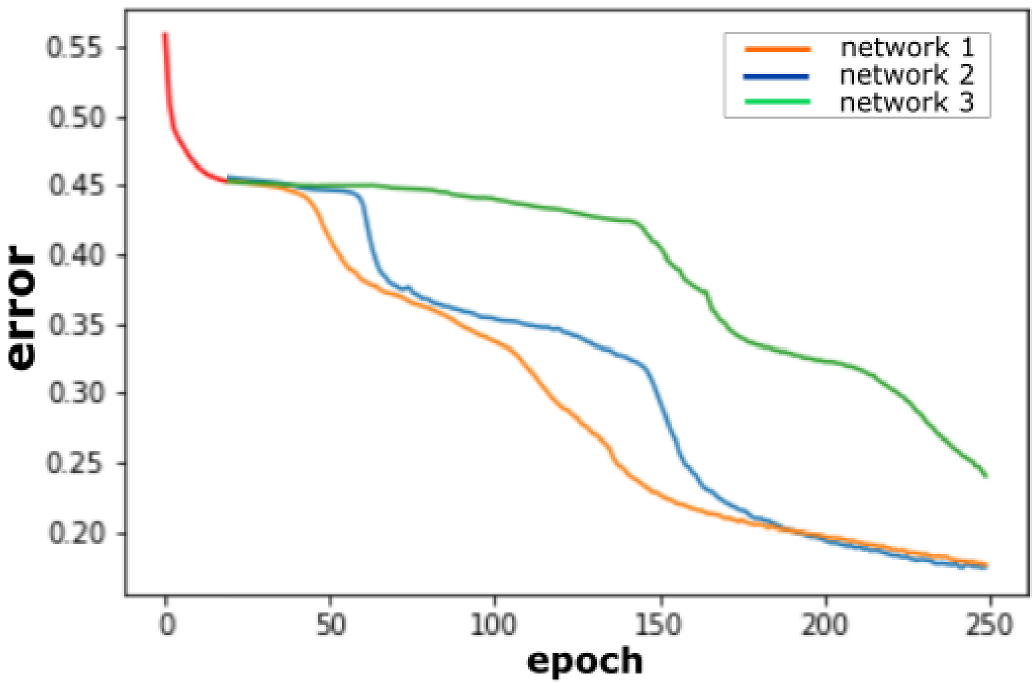


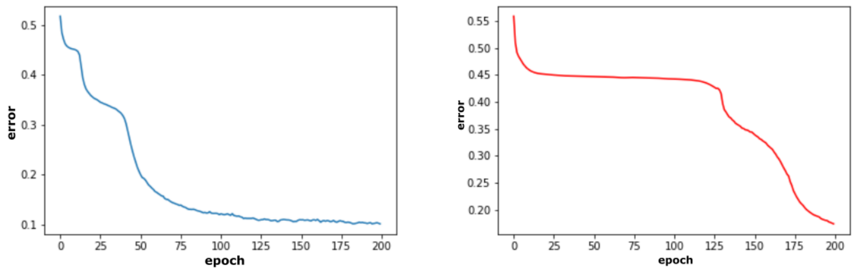
Figure 4.1: Effect of Network Size

In this section we present the effect of network size during training. Three network architecture were chosen with hidden layers as given network:1 [200,100.200], network:2[100,50.100] , network:3 [50,25.50] .The data set of Von Karman street was used in training process. The data size contained 400 time steps and each architecture was trained on it. Vorticity data at 25600 data points was used as input. The number of epoch $n_{epoch} = 250$. It can be seen in fig:4.1 that as the network size was increased i.e neuron were increased in the hidden layer the training error decreased sharply in case of network one (orange) and in case of network three (green) it decrease sharply in initial epochs but then on it got stuck in local minimum and the error decreased very slowly, this is due to under-fitting.

We also tested this for Sea Surface Temperature data set and found the same result.

4.2 Effect of Training Data size

In this section we present the effect of data size during training. The data set of Von Karman street was used in training process. Two data sizes were used with size one having 921 time steps and size two having 400 timestamps for the training set. Vorticity data at 25600 data points was used as input. The number of epoch $n_{epoch} = 250$. It can be seen in fig:4.2 that with training with larger data size fig:4.2a the error decreased rapidly but with smaller data size fig:4.2b the error plateaued because it got stuck locally. Below from fig fig:4.3 to fig:4.6 is spatial representation of predicted output compared with true values in the case data size two for Von Karman flow and from fig:4.7 to fig:4.10 is spatial representation of predicted output compared with true values for Sea surface temperature data set.



(a) (b)

Figure 4.2: Effect of data size: (a) plot for data size one (b) plot for data size two

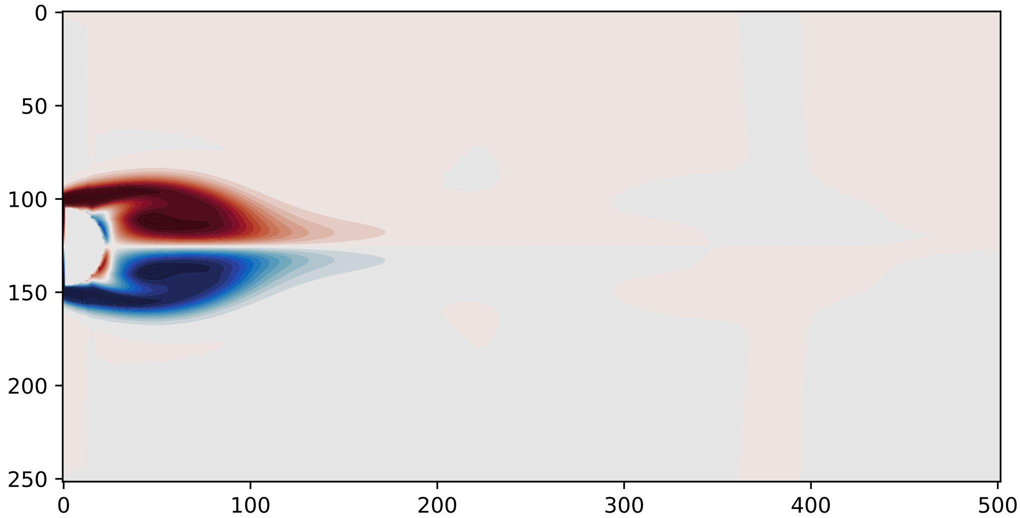


Figure 4.3: True Value of vorticity at time step 5

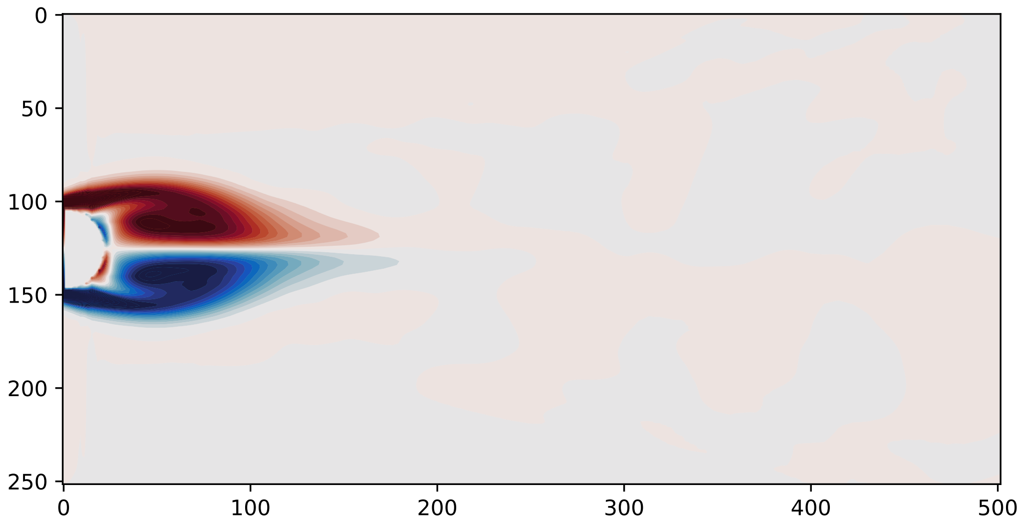


Figure 4.4: Predicted Value of vorticity at time step 5

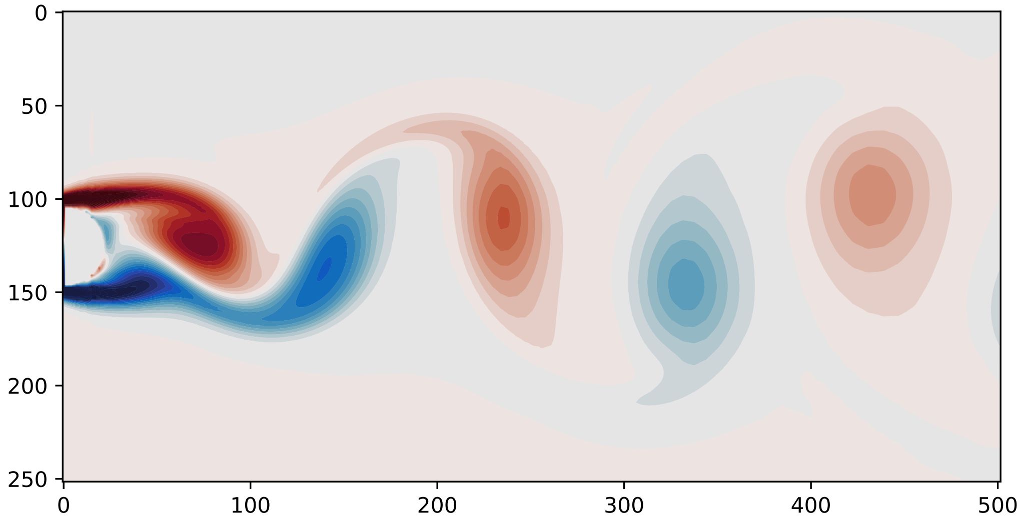


Figure 4.5: True Value of vorticity at time step 50

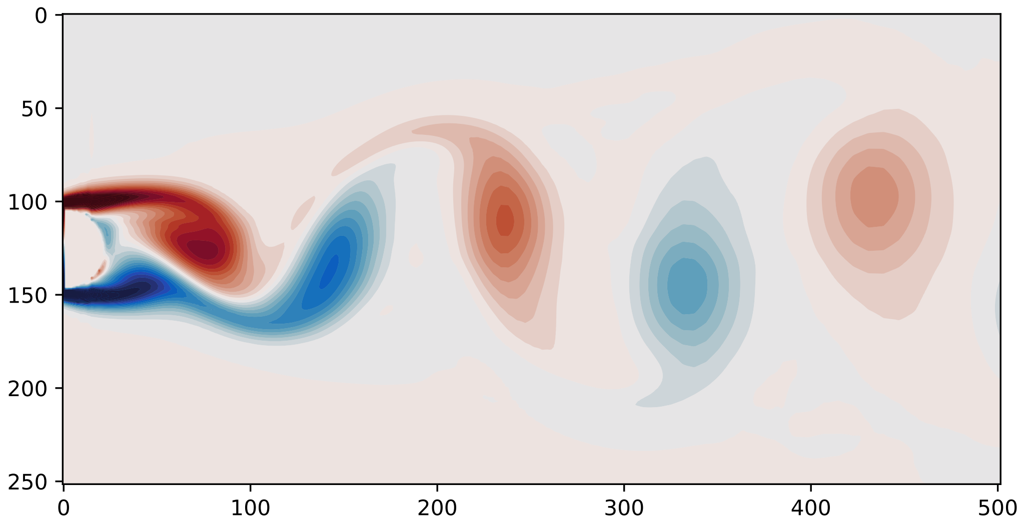


Figure 4.6: Predicted Value of vorticity at time step 50

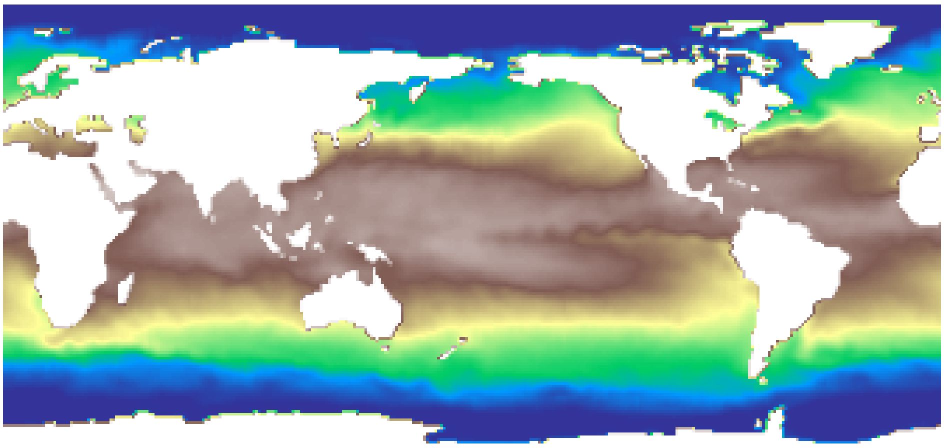


Figure 4.7: True Value of Sea surface temperature at time step 5

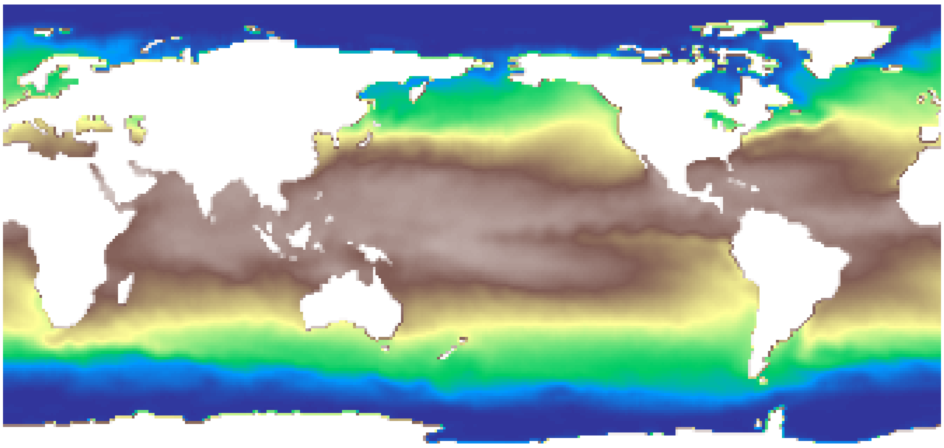


Figure 4.8: Predicted Value of Sea surface temperature at time step 5

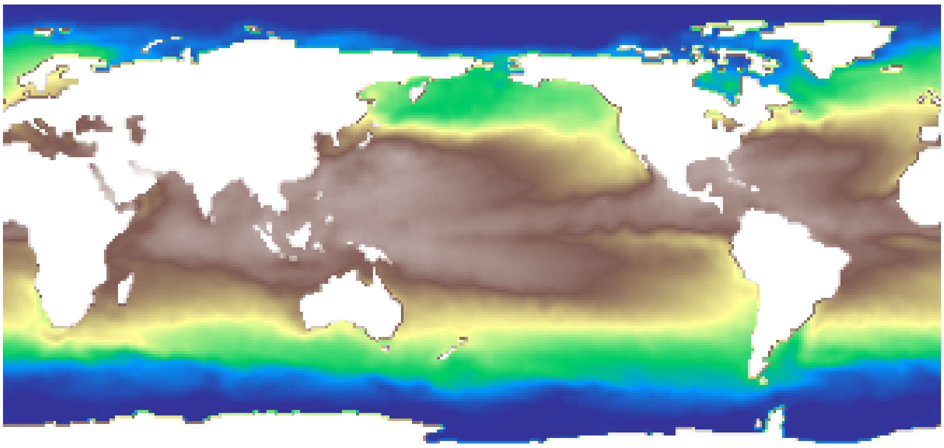


Figure 4.9: True Value of Sea surface temperature at time step 50

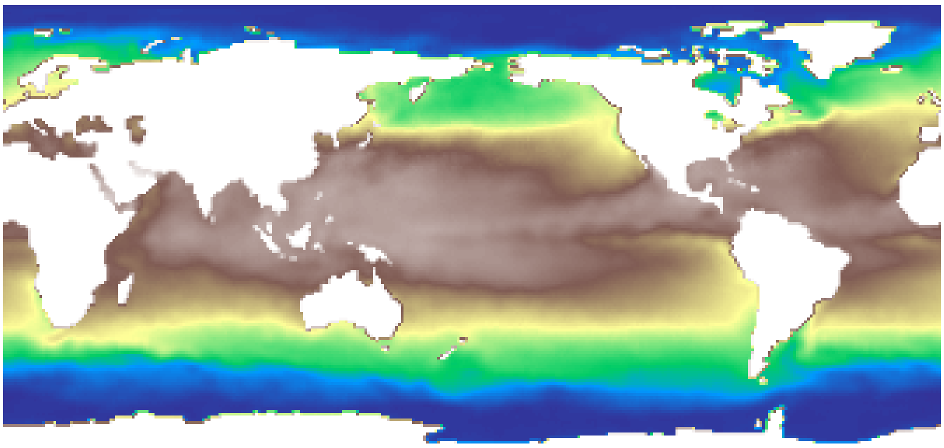


Figure 4.10: Predicted Value of Sea surface temperature at time step 50

Chapter 5

CONCLUSION AND FUTURE SCOPE

This paper presents the Hyper-parameters comparison between different Auto-encoder architectures and there comparison pertaining to each other. This paper presents a Deep learning based Reduced order Model (ROM) which is expected to reduce the losses in the information and extract only relevant data in the bottleneck layer so as to reconstruct the high order dynamics efficiently from the reduced state.We were successful in coding and simulating the encoder algorithm through cloud service provided by google (google colab). The training time was practical and the dataset was of normal size making the solution feasible. We have made comparison between network architectures wherein the following conclusion was made, i.e. the training error sharply decreased as we increased the network size, which has its underlying reason for added non-linearity in the network but also leads to a relatively more computationally expensive model to its counter-part architecture. Following this we also make comparison between increased size of dataset and lower amount of dataset which were generated with the help of different time-steps. It was seen and concluded that a larger dataset helped in converging to the solution much rapidly and easily in comparison to the shorter dataset. The numerical Accuracy of Deep learning Autoecnoder is of order of magnitude higher than than provided by linear ROMs.

As for the future scope of the project instead of using artificial neural network we can use conversational neural network and work out the same problems. Combining this machine learning method with something more deterministic can we future work, where we can combine neural network power of approximating functions with physical dynamical equations to achieve convergence and to solve problems that have non-linear equations describing their motion. This way we can aim to reduce computation time to train the neural network and get better accurate results.

Bibliography

[1] R. Maulik, B. Lusch, and P. Balaprakash, "Reduced-order modeling of advection-dominated systems with recurrent neural networks and convolutional autoencoders," *Physics of Fluids*, vol. 33, no. 3, p. 037106, 2021.

[2] L. Agostini, "Exploration and prediction of fluid dynamical systems using auto-encoder technology," *Physics of Fluids*, vol. 32, no. 6, p. 067103, 2020.

[3] N. B. Erichson, M. Muehlebach, and M. W. Mahoney, "Physics-informed autoencoders for lyapunov-stable fluid flow prediction," *arXiv preprint arXiv:1905.10866*, 2019.

[4] K. Pragati, H. Sharma *et al.*, "Concept of computational fluid dynamics (cfd) and its applications in food processing equipment design." *Journal of Food Processing and Technology*, vol. 3, no. 1, 2012.

[5] K. Lee and K. T. Carlberg, "Model reduction of dynamical systems on nonlinear manifolds using deep convolutional autoencoders," *Journal of Computational Physics*, vol. 404, p. 108973, 2020.

[6] S. Fresca, A. Manzoni *et al.*, "A comprehensive deep learning-based approach to reduced order modeling of nonlinear time-dependent parametrized pdes," *Journal of Scientific Computing*, vol. 87, no. 2, pp. 1–36, 2021.

[7] Z. Bai, "Krylov subspace techniques for reduced-order modeling of large-scale dynamical systems," *Applied numerical mathematics*, vol. 43, no. 1-2, pp. 9–44, 2002.

[8] I. Akhtar, J. Borggaard, J. A. Burns, H. Imtiaz, and L. Zietsman, "Using functional gains for effective sensor location in flow control: a reduced-order modelling approach," *Journal of Fluid Mechanics*, vol. 781, p. 622, 2015.

[9] D. J. Lucia, P. S. Beran, and W. A. Silva, "Reduced-order modeling: new approaches for computational physics," *Progress in aerospace sciences*, vol. 40, no. 1-2, pp. 51–117, 2004.

[10] F. Fang, C. Pain, I. Navon, G. Gorman, M. Piggott, P. Allison, P. Farrell, and A. Goddard, "A pod reduced order unstructured mesh ocean modelling method for moderate reynolds number flows," *Ocean modelling*, vol. 28, no. 1-3, pp. 127–136, 2009.

[11] G. Berkooz, P. Holmes, and J. L. Lumley, "The proper orthogonal decomposition in the analysis of turbulent flows," *Annual review of fluid mechanics*, vol. 25, no. 1, pp. 539–575, 1993.

[12] P. Holmes, J. L. Lumley, G. Berkooz, and C. W. Rowley, *Turbulence, coherent structures, dynamical systems and symmetry.* Cambridge university press, 2012.

[13] N. Aubry, P. Holmes, J. LUMLEY, E. Stone *et al.*, "The dynamics of coherent structures in the wall region of a turbulent boundary layer," *Journal of Fluid Mechanics*, vol. 192, no. 1, pp. 115–173, 1988.

[14] J. L. Proctor, S. L. Brunton, and J. N. Kutz, "Dynamic mode decomposition with control," *SIAM Journal on Applied Dynamical Systems*, vol. 15, no. 1, pp. 142–161, 2016.

[15] G. Tissot, L. Cordier, N. Benard, and B. R. Noack, "Model reduction using dynamic mode decomposition," *Comptes Rendus Mécanique*, vol. 342, no. 6-7, pp. 410–416, 2014.

[16] I. Mezić, "Analysis of fluid flows via spectral properties of the koopman operator," *Annual Review of Fluid Mechanics*, vol. 45, pp. 357–378, 2013.

[17] S. L. Brunton, B. W. Brunton, J. L. Proctor, and J. N. Kutz, "Koopman invariant subspaces and finite linear representations of nonlinear dynamical systems for control," *PloS one*, vol. 11, no. 2, p. e0150171, 2016.

[18] W. F. Hughes, J. A. Brighton, and N. Winowich, *Schaum's outline of fluid dynamics.* McGraw Hill Professional, 1999.

[19] R. Blevins, "Flow-induced vibrations van nostrand reinhold," *New York*, 1990.

turnitin

Hyper_Parameter_analysis_of_Deep_Auto_Encoder_for_Flow_Prediction.pdf
May 31, 2021
6223 words / 30634 characters

Pranav Bahl

Hyper_Parameter_analysis_of_Deep_Auto_Encoder_for_Flow...

Sources Overview

Prof. B.B. Arora

Pranav Bahl 2K17/ME/164

Prakrit Tyagi 2K17/ME/163

5%
OVERALL SIMILARITY

1	University of Aberdeen on 2020-12-21	SUBMITTED WORKS	<1%
2	Stefania Fresca, Luca Dede', Andrea Manzoni. "A Comprehensive Deep Learning-Based Approach to Reduced Order Modeling of Nonli...	CROSSREF	<1%
3	Southern Federal University on 2015-04-07	SUBMITTED WORKS	<1%
4	archive.org	INTERNET	<1%
5	digitalcommons.usu.edu	INTERNET	<1%
6	University of Sydney on 2021-05-14	SUBMITTED WORKS	<1%
7	Deze Zeng, Peng Li, Song Guo, Toshiaki Miyazaki, Jiankun Hu, Yong Xiang. "Energy Minimization in Multi-Task Software-Defined Sens...	CROSSREF	<1%
8	Cranfield University on 2013-11-11	SUBMITTED WORKS	<1%
9	Universiti Kebangsaan Malaysia on 2011-08-20	SUBMITTED WORKS	<1%
10	University of Aberdeen on 2011-05-16	SUBMITTED WORKS	<1%
11	"Convective Heat and Mass Transfer in Porous Media", Springer Science and Business Media LLC, 1991	CROSSREF	<1%
12	Imperial College of Science, Technology and Medicine on 2012-09-14	SUBMITTED WORKS	<1%
13	University of Northumbria at Newcastle on 2021-05-20	SUBMITTED WORKS	<1%
14	eprints.soton.ac.uk	INTERNET	<1%
15	ir.cwi.nl	INTERNET	<1%
16	Mohammed Zaki. "ADMIT", Proceedings of the eighth ACM SIGKDD international conference on Knowledge discovery and data mining...	CROSSREF	<1%

Excluded search repositories:

- None

Excluded from Similarity Report:

- None

Excluded sources:

- None

Hyper-Parameter Analysis of Deep Auto Encoder for Flow Prediction

Prakrit Tyagi, Pranav Bahl and B B Arora

May 21, 2021

Hyper-Parameter analysis of Deep Auto Encoder for Flow Prediction

Prakrit Tyagi[1], Pranav Bahl[1], and BB Arora[2]

Delhi Technological University, Delhi 110042, India

Abstract. Reducing the order of the system from high order dynamical space to a low dimensional subspace has been a challenging task and the models that achieve this are referred to Reduced Order Models (ROMs). Linear Projection methods have been used extensively in the past for building such ROMs, some common examples are POD,DMD etc. Though they have been successful in modelling several non-linear scenarios, their usage limits their applications pertaining to complex High order dynamical systems efficiently. In this study we aim to make use of advancement made in the field of Deep Learning to build a DL based ROM. We aim to probe the impact of hyper-parameters pertaining to flow prediction using deep autoencoders built with the help of artificial neural network. The parameters for our study that were used here were three different network sizes and two data sizes to compare the performance in flow prediction. Dataset for the Vorticity was generated using in-compressible URANS CFD solver icoFoam in an open-source CFD toolbox OpenFOAM. Von-Karman Vortex Street at Reynolds' number 100 around a bi-dimensional cylinder was simulated for our study.

Keywords: Deep Autoencoder · Von Karman Vortex Street · Hyper-pararmeters.

1 Introduction

Advances in Machine Learning techniques has made its usage reliable and economical and opened plethora of applications in fields of robotics , neuro science, economic and financial prediction, system dynamic modeling and prediction etc.. Autoencoder is one such technique which learns by itself to represent large data in reduced form. This is advantageous as using low dimensional data for analysis and calculation is efficient, computationally economical and reduces cost. Therefore this technique has found extensive usage in flow reconstruction, reduced-order modeling [1], prediction of fluid flow dynamical system [2] and flow prediction [3].

Computational fluid dynamics is the go to technique for simulating fluid flow but it is computationally expensive and if a users has inadequate resources, he/she will find it difficult to simulate and innovate. However, CFD has found its application across various engineering disciplines such as Aerospace industry, Heating and Ventilation applications, Flows corresponding to cardiovascular operation, Fluid machinery etc [4]. The need for such simulation often requires

Certificate of ICAPIE-2021 Paper

mail.google.com/mail/u/0/?tab=rm&ogbl#inbox/FMfcgxwLttCBWNcTtnlfRTxXZvgpWjfn

Gmail

Search mail

Compose

Inbox 69

Starred

Snoozed

Important

Sent

Drafts 54

Categories

Meet

New meeting

Join a meeting

Hangouts

Prakrit

Yogesh Kumar
You: https://meet.google.com/gyi-tnc

Rishabh Tyagi
You: https://skribbl.io/?QVNDCrYQx

Sujit PB
You: Congratulations Sir. However r

Priyam Gupta
You: https://meet.google.com/grj-ydr

23 of 1,050

Certificate of ICAPIE-2021 Paper ID: 415

Inbox ×

ICAPIE DTU

to Arora, pranavbahl_2k17me164, me

Thu, 13 May, 17:53

Dear Author(s),

Please find attached the certificate of your paper accepted in ICAPIE-2021, which will be published in **Lecture Notes in Mechanical Engineering**, **a Scopus Indexed publication of Springer.**

Thanks for your support to ICAPIE-2021.

--

With Regards

Prof. Ranganath M Singari

Conference Chair

ICAPIE - 2021

Email- icapie.dtu@gmail.com

> *"Bring your Ideas..Share your Time....Showcase your Abilities.."*

> **ICAPIE CONNECTS ALL DESIGNERS, ENGINEERS AND MANAGERS ON A SINGLE PLATFORM**

Activate Windows

Go to Settings to activate Windows.

TECHNOSCIENCE

ICAPIE 2021

Program name

6th International Conference on Advanced Production and Industrial Engineering

Program Description

June 18-19, 2021

Fees breakup(Round 2) :

Students(UG/PG/Ph.D) : 6000
Faculty : 7500
Delegates from Industry/R& D Centers : 8000
Fee beyond 10 pages : 500/page

Name of the organizer:

Centre for Advanced Production and Industrial Engineering Research (CAPIER) ,Delhi Technological University, Delhi

Contact Us:

icapie.dtu@gmail.com

₹ 6000.00

Payment Successful!

Thank you for registration in ICAPIE 2021.

Share Your Experience

Payment ID: pay_H7ASC01XApKfE5
A confirmation email has been sent to you

Springer

ICAPIE DTU

tribologyinindustry
Journal of the Serbian Tribology Society

FME TRANSACTIONS

Certificate

Dear Author(s): Prakrit Tyagi, Pranav Bahl and Bb Arora

Paper ID: 415

Paper Title: Hyper-Parameter analysis of Deep Auto Encoder for Flow Prediction

This is to enlighten you that the above manuscript has been appraised by the editors of LNME and is accepted for the **6th International Conference on Advanced Production and Industrial Engineering (ICAPIE)- 2021 to be held during June 18-19, 2021**. The paper is recommended for publication in **Lecture Notes in Mechanical Engineering (Scopus Indexed publication of Springer Nature), ISSN: 2195-4356**. The manuscript has been submitted to Springer in May 2021 and will be online during October 2021.

Finally, the team of CAPIER DTU and ICAPIE-2021 would like to extend congratulations to you.

Prof. Ranganath M Singari
(Conference Chair, ICAPIE-2021)

Dr. Harish Kumar
(Convener, ICAPIE-2021)

Publishing Agreement

SPRINGER NATURE

for Contributions in Collected Works

This Publishing Agreement (this "**Agreement**") has been approved by and entered into between:

[Prakrit Tyagi Delhi Technological University, Delhi Pranav Bahl Delhi Technological University, Delhi BB Arora Delhi Technological University, Delhi)]
(the "**Author**")
whereas, in the event that the Author is more than one person, **[Prakrit Tyagi]** serves as corresponding author (the "**Corresponding Author**")

on the one part and

Springer Nature Singapore Pte Ltd.
152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

(the "**Publisher**")

on the other part;
together hereinafter referred to as the "**Parties**".

The Publisher intends to publish the Author's contribution in a collected work provisionally entitled:

Advances in Mechanical Engineering and Technology: Proceedings of 6th International Conference on Advanced Production and Industrial Engineering (ICAPIE) - 2021

(the "Work")
edited by: **Ranganath M. Singari, Pavan Kumar Kankar, Girija Moona**
(the "Editor")

The Publisher intends to publish the Work under the imprint Springer.

The Work may be published in the book series **Lecture Notes in Mechanical Engineering**.

1. Contracting Authors

When the Author is more than one person then, unless otherwise indicated in this Agreement or agreed in writing by the Publisher:
(a) the expression "**Author**" as used in this Agreement will apply collectively for all such persons (each a "**co-author**");
(b) the Corresponding Author hereby warrants and represents that all co-authors of the contribution have expressly agreed that the Corresponding Author has full right, power and authority to sign this Agreement on their behalf, that the Corresponding Author is entitled to act on their behalf, and that they shall be bound by the Corresponding Author, with respect to all matters, responsibilities, notices and communications related to this Agreement; the Corresponding Author shall obtain authorisations and make them available to the Publisher on request; and
(c) each co-author is jointly and severally responsible for the Author's obligations under this Agreement which apply to each co-author individually and to the co-authors collectively and the Publisher shall not be bound by any separate agreement or legal relationship as between the co-authors.

2. Subject of the Agreement

2.1 The Author will prepare a contribution provisionally entitled:
[Hyper-Parameter analysis of Deep Auto Encoder for Flow Prediction]
The expression "**Contribution**" as used in this Agreement means the contribution as identified above, and includes without limitation all related material delivered to the Publisher by or on behalf of the Author whatever its media and form (including text, graphical elements, tables, videos and/or links) in all versions and editions in whole or in part.

2.2 The Contribution may contain links (e.g. frames or in-line links) to media enhancements (e.g. additional documents, tables, diagrams, charts, graphics, illustrations, animations, pictures, videos and/or software) or to social or functional enhancements, complementing the Contribution, which are provided on the Author's own website or on a third party website or repository (e.g. maintained by an institution) subject always to the Author providing to the Editor, at the latest at the delivery date of the manuscript for the Contribution, an accurate description of each media enhancement and its respective website or repository, including its/their owner, nature and the URL. The Publisher is entitled to reject the inclusion of, or suspend, or delete links to all or any individual media enhancements.

2.3 In the event that an index is deemed necessary, the Author shall assist the Editor in its preparation (e.g. by suggesting index terms), if requested by the Editor.

3. Rights Granted

3.1 The Author hereby grants to the Publisher the perpetual, sole and exclusive, worldwide, transferable, sub-licensable and unlimited right to publish, produce, copy, distribute, communicate, display publicly, sell, rent and/or otherwise make available the Contribution in any language, in any versions or editions in any and all forms and/or media of expression (including without limitation in connection with any and all end-user devices), whether now known or developed in the future, in each case with the right to grant further time-limited or permanent rights. The above rights are granted in relation to the Contribution as a whole or any part and with or in relation to any other works.
Without limitation, the above grant includes: (a) the right to edit, alter, adapt, adjust and prepare derivative works; (b) all advertising and marketing rights including without limitation in relation to social media; (c) rights for any training, educational and/or instructional purposes; and (d) the right to add and/or remove links or combinations with other media/works.
The Author hereby grants to the Publisher the right to create, use and/or license and/or sub-license content data or metadata of any kind in relation to the Contribution or parts thereof (including abstracts and summaries) without restriction.
The Publisher also has the right to commission completion of the Contribution in accordance with the Clause "**Author's Responsibilities – Delivery and Acceptance of the Manuscript**" and of an updated version of the Contribution for new editions of the Work in accordance with the Clause "**New Editions**".

3.2 The copyright in the Contribution shall be vested in the name of the **Author**. The Author has asserted their right(s) to be identified as the originator of the Contribution in all editions and versions, published in all forms and media. The Author agrees that all editing, alterations or amendments to the Contribution made by or on behalf of the Publisher or its licensees for the purpose of fulfilling this Agreement or as otherwise allowed by the above rights shall not require the approval of the Author and will not infringe the Author's "moral rights" (or any equivalent rights). This includes changes made in the course of dealing with retractions or other legal issues.

4. Self-Archiving and Reuse

4.1 **Self-Archiving**: The Publisher permits the Rights Holder to archive the Contribution in accordance with the Publisher's guidelines, the current version of which is set out in the **Appendix "Author's Self-Archiving Guidelines"**.

4.2 **Reuse**: The Publisher permits the Author to copy, distribute or otherwise reuse the Contribution, without the requirement to seek specific prior written permission from the Publisher, in accordance with the Publisher's guidelines, the current version of which is set out in the **Appendix "Author's Reuse Rights"**.

5. The Publisher's Responsibilities

5.1 Subject always to the other provisions of this Clause below, the Publisher will undertake the production, publication and distribution of the Contribution and the Work in print and/or electronic form at its own expense and risk within a reasonable time after acceptance of the Work unless the Publisher is prevented from or delayed in doing so due to any circumstances beyond its reasonable control. The Publisher shall have the entire control of such production, publication and distribution determined in its sole discretion in relation to any and all editions and versions of the Contribution and the Work, including in respect of all the following matters:
(a) distribution channels, including determination of markets;
(b) determination of the range and functions of electronic formats and/or the number of print copies produced;
(c) publication and distribution of the Contribution, the Work, or parts thereof as individual content elements, in accordance with market demand or other factors;
(d) determination of layout and style as well as the standards for production;
(e) setting or altering the list price, and allowing for deviations from the list price (if permitted under applicable jurisdiction);
(f) promotion and marketing as the Publisher considers most appropriate.

5.2 All rights, title and interest, including all intellectual property or related rights in the typography, design and/or look-and-feel of the Contribution shall remain the exclusive property of and are reserved to the Publisher. All illustrations and any other material or tangible or intangible property prepared at the expense of the Publisher including any marketing materials remain, as between the Parties, the exclusive property of the Publisher. The provisions of this subclause shall continue to apply notwithstanding any termination of, and/or any reversion of rights in the Contribution to the Author, under this Agreement.

5.3 Without prejudice to the Publisher's termination and other rights hereunder including under the Clause "**The Author's Responsibilities**", it is agreed and acknowledged by the Parties that nothing in this Agreement shall constitute an undertaking on the part of the Publisher to publish the Contribution unless and until: (i) any and all issues in relation to the Work (including all necessary revisions, consents and permissions) raised by the Publisher have been resolved to the Publisher's satisfaction, and (ii) the Publisher has given written notice of acceptance in writing of the final manuscript of the entire Work to the Editor. If following (i) and (ii) above the Publisher has not published the Contribution in any form within a reasonable period and the Author has given written notice to the Publisher requiring it to publish within a further reasonable period and the Publisher has failed to publish in any form, then the Author may terminate this Agreement by one month's written notice to the Publisher and all rights granted by the Author to the Publisher under this Agreement shall revert to the Author (subject to the provisions regarding any third party rights under any subsisting licence or sub-licence in accordance with the Clause "**Termination**").
The Author may also give such written notice requiring publication on the same terms as above if the Publisher has published the Contribution but subsequently ceases publishing the Contribution in all forms so that it is no longer available.
This shall be the Author's sole right and remedy in relation to such non-publication and is subject always to the Author's continuing obligations hereunder including the Clause "**Warranty**".

6. The Author's Responsibilities

6.1 ***Delivery and Acceptance of the Manuscript***

6.1.1 The Author shall deliver the Contribution to the Editor (or, if requested by the Publisher, to the Publisher) on or before Delivery Date (the "**Delivery Date**") electronically in the Publisher's standard requested format or in such other form as may be agreed in writing with the Publisher. The Author shall retain a duplicate copy of the Contribution. The Contribution shall be in a form acceptable to the Publisher (acting reasonably) and in line with the instructions contained in the Publisher's guidelines as provided to the Author by the Publisher. The Author shall provide at the same time, or earlier if the Publisher reasonably requests, any editorial, publicity or other information (and in such form or format) reasonably required by the Publisher. The Publisher may exercise such additional quality control of the manuscript as it may decide at its sole discretion including through the use of plagiarism checking systems and/or peer review by internal or external reviewers of its choice. If the Publisher decides at its sole discretion that the final manuscript does not conform in quality, content, structure, level or form to the stated requirements of the Publisher, the Publisher shall be entitled to terminate this Agreement in accordance with the provisions of this Clause.

6.1.2 The Author must inform the Publisher at the latest on the Delivery Date if the sequence of the naming of any co-authors entering into this Agreement shall be changed. If there are any changes in the authorship (e.g. a co-author joining or leaving), then the Publisher must be notified by the Author in writing immediately and the Parties will amend this Agreement accordingly. The Publisher shall have no obligation to consider publication under this Agreement in the absence of such agreed amendment.

6.1.3 If the Author fails to deliver the Contribution in accordance with the provisions of this Clause above by the Delivery Date (or within any extension period given by the Publisher at its sole discretion) or if the Author (or any co-author) dies or becomes incapacitated or otherwise incapable of performing the Author's obligations under this Agreement, the Publisher shall be entitled to either:
(a) elect to continue to perform this Agreement in accordance with its terms and the Publisher may commission an appropriate and competent person (who, in the case of co-authors having entered into this Agreement, may be a co-author) to complete the Contribution; or
(b) terminate this Agreement with immediate effect by written notice to the Author or the Author's successors, in which case all rights granted by the Author to the Publisher under this Agreement shall revert to the Author/Author's successors (subject to the provisions of the Clause "**Termination**").

6.1.4 The Author agrees, at the request of the Publisher, to execute all documents and do all things reasonably required by the Publisher in order to confer to the Publisher all rights intended to be granted under this Agreement.

6.1.5 The Author warrants that the Contribution is original except for any excerpts from other works including pre-published illustrations, tables, animations, text quotations, photographs, diagrams, graphs or maps, and whether reproduced from print or electronic or other sources ("**Third Party Material**") and that any such Third Party Material is in the public domain (or otherwise unprotected by copyright/other rights) or has been included with written permission from or on behalf of the rights holder (and if requested in a form prescribed or approved by the Publisher) at the Author's expense unless otherwise agreed in writing, or is otherwise used in accordance with applicable law. On request from the Publisher, the Author shall in writing indicate the precise sources of these excerpts and their location in the manuscript. The Author shall also retain the written permissions and make them available to the Publisher on request.

6.2 ***Approval for Publishing***

6.2.1 The Author shall proofread the page proofs for the Contribution provided by or on behalf of the Publisher, including checking the illustrations as well as any media, social or functional enhancements and give approval for publishing, if and when requested by the Publisher. The Author's approval for publishing is deemed to have been given if the Author does not respond within a reasonable period of time (as determined by the Publisher) after receiving the proofs nor contacts the Publisher within three days after receipt of the last of three reminders sent by the Publisher via email. The Publisher shall not be required to send a second set of corrected proofs unless specifically requested by the Author in writing but in any event no further amendments may be made or requested by the Author.
In the event of co-authors having entered into this Agreement the Publisher shall send the page proofs to the Corresponding Author only and all persons entering into this Agreement as Author agree that the Corresponding Author shall correct and approve the page proofs on their behalf.

6.2.2 If the Author makes changes other than correcting typographical errors, the Author shall bear all the Publisher's costs of such alterations to proofs including without limitation to alterations to pictorial illustrations. The Publisher shall have the right to charge and invoice these costs plus value added or similar taxes (if applicable) through its affiliated company Springer Nature Customer Service Center GmbH or Springer Nature Customer Service Center LLC, respectively, to the Author, payable within 14 days of receipt of the invoice.

6.3 ***Cooperation***

Without prejudice to the warranties and representations given by the Author in this Agreement, the Author shall cooperate fully with the Editor and the Publisher in relation to any legal action that might arise from the publication or intended publication of the Contribution and the Author shall give the Publisher access at reasonable times to any relevant accounts, documents and records within the power or control of the Author.

7. Warranty

7.1 The Author warrants and represents that:
(a) the Author has full right, power and authority to enter into and perform its obligations under this Agreement; and
(b) the Author is the sole legal owner of (and/or has been fully authorised by any additional rights owner to grant) the rights licensed in the Clause "**Rights Granted**" and use of the Contribution shall in no way whatever infringe or violate any intellectual property or related rights (including any copyright, database right, moral right or trademark right) or any other right or interest of any third party subject only to the provisions in the Clause "**The Author's Responsibilities**" regarding Third Party Material (as defined above); and
(c) the Contribution shall not contain anything that may cause religious or racial hatred or encourage terrorism or unlawful acts or be defamatory (or contain malicious falsehoods), or be otherwise actionable, including, but not limited to, any action related to any injury resulting from the use of any practice or formula disclosed in the Contribution and all of the purported facts contained in the Contribution are according to the current body of research and understanding true and accurate; and
(d) there is no obligation of confidentiality owed in respect of any contents of the Contribution to any third party and the Contribution shall not contain anything which infringes or violates any trade secret, right of privacy or publicity or any other personal or human right or the processing or publication of which could breach applicable data protection law and that informed consent to publish has been obtained for all research or other featured participants; and
(e) the Contribution has not been previously licensed, published or exploited and use of the Contribution shall not infringe or violate any contract, express or implied, to which the Author, or any co-author, who had entered into this Agreement,is a party and any academic institution, employer or other body in which work recorded in the Contribution was created or carried out has authorised and approved such work and its publication.

7.2 The Author warrants and represents that the Author, and each co-author who has entered into this Agreement, shall at all times comply in full with:
(a) all applicable anti-bribery and corruption laws; and
(b) all applicable data protection and electronic privacy and marketing laws and regulations; and
(c) the Publisher's ethic rules (available at https://www.springernature.com/gp/authors/book-authors-code-of-conduct), as may be updated by the Publisher at any time in its sole discretion. The Publisher shall notify the Author in the event of material changes by email or other written means
(the "**Applicable Laws**").
If the Author is in material breach of any of the Applicable Laws or otherwise in material breach of accepted ethical standards in research and scholarship, or becomes the subject of any comprehensive or selective sanctions issued in any applicable jurisdiction (e.g. being subject to the OFAC sanctions list) or if, in the opinion of the Publisher, at any time any act, allegation or conduct of or about the Author prejudices the production or successful exploitation of the Contribution and the Work or brings the name and/or reputation of the Publisher or the Work into disrepute, or is likely to do so, then the Publisher may terminate this Agreement in accordance with the Clause "**Termination**".

7.3 The Publisher reserves the right to amend and/or require the Author to amend the Contribution at any time to remove any actual or potential breach of the above warranties and representations or otherwise unlawful part(s) which the Publisher or its internal or external legal advisers identify at any time. Any such amendment or removal shall not affect the warranties and representations given by the Author in this Agreement.

8. Author’s Discount and Electronic Access

8.1 The Author, or each co-author, is entitled to purchase for their personal use the Work and other books published by the Publisher at a discount of 40% off the list price, for as long as there is a contractual arrangement between the Author and the Publisher and subject to any applicable book price law or regulation. The copies must be ordered from the affiliated entity of the Publisher (Springer Nature Customer Service Center GmbH or Springer Nature Customer Service Center LLC, respectively). Resale of such copies is not permitted.

8.2 The Publisher shall provide the electronic final published version of the Work to the Author, provided that the Author has included their e-mail address in the manuscript of the Contribution.

9. Consideration

9.1 The Parties agree that the Publisher's agreement to its contractual obligations in this Agreement in respect of its efforts in considering publishing and promoting the Contribution and the Work is good and valuable consideration for the rights granted and obligations undertaken by the Author under this Agreement, the receipt, validity and sufficiency of which is hereby acknowledged by the Author. The Parties expressly agree that no royalty, remuneration, licence fee, costs or other moneys whatsoever shall be payable to the Author.

9.2 The Publisher and the Author each have the right to authorise collective management organisations ("**CMOs**") of their choice to manage some of their rights. Reprographic and other collectively managed rights in the Contribution ("**Collective Rights**") have been or may be licensed on a non-exclusive basis by each of the Publisher and the Author to their respective CMOs to administer the Collective Rights under their reprographic and other collective licensing schemes ("**Collective Licences**"). Notwithstanding the other provisions of this Clause, the Publisher and the Author shall each receive and retain their share of revenue from use of the Contribution under Collective Licences from, and in accordance with, the distribution terms of their respective CMOs. To the fullest extent permitted by law, any such revenue is the sole property of the Publisher and the Author respectively and, if applicable, the registration and taxation of that revenue is the sole responsibility of the respective recipient party. The Publisher and the Author shall cooperate as necessary in the event of any change to the licensing arrangements set out in this Clause.

10. New Editions

10.1 The Publisher has the sole right to determine whether to publish any subsequent edition of the Work containing an updated version of the Contribution, but only after reasonable consultation with the Author. Once notified by the Publisher that an update of the Contribution is deemed necessary, the Author agrees to deliver an updated manuscript in accordance with the terms of the Clause "**The Author's Responsibilities**" and the other relevant provisions of this Agreement, together with the material for any new illustrations and any other supporting content including media enhancements, within a reasonable period of time (as determined by the Publisher) after such notification. Substantial changes in the nature or size of the Contribution require the written approval of the Publisher at its sole discretion. The terms of this Agreement shall apply to any new edition of the Work that is published under this "**New Editions**" Clause.

10.2 If the Author, for whatever reason, is unwilling, unable or fails (including as a result of death or incapacity) to submit an updated manuscript that meets the terms of this Agreement within the above stated period, then the Publisher is entitled to revise, update and publish the content of the existing edition or to designate one or more individuals (which, where co-authors have entered into this Agreement, may be one or more of the co-authors) to prepare this and any future editions provided that the new editions shall not contain anything that is a derogatory use of the Author's work that demonstrably damages the Author's academic reputation. In such case, the Author shall not participate in preparing any subsequent editions. The Author agrees that the Publisher shall be entitled but not obliged to continue to use the name of the Author on any new editions of the Work together with the names of the person or persons who contributed to the new editions. Should the Author or the Author's successors object to such continuing use then they must notify the Publisher in writing when first contacted by the Publisher in connection with any new edition.

11. Termination

11.1 In addition to the specific rights of termination set out in the Clause "**The Publisher's Responsibilities**" and the Clause "**The Author's Responsibilities**", either Party shall be entitled to terminate this

Agreement forthwith by notice in writing to the other Party if the other Party commits a material breach of the terms of the Agreement which cannot be remedied or, if such breach can be remedied, fails to remedy such breach within 45 days of being given written notice to do so.

11.2 Termination of this Agreement, howsoever caused, shall not affect:
(a) any subsisting rights of any third party under any licence or sub-licence validly granted by the Publisher prior to termination and the Publisher shall be entitled to retain its share of any sum payable by any third party under any such licence or sub-licence;
(b) except where stated otherwise in this Agreement, any claim which either Party may have against the other for damages or otherwise in respect of any rights or liabilities arising prior to the date of termination;
(c) the Publisher's right to continue to sell any copies of the Work which are in its power, possession or control as at the date of expiry or termination of this Agreement for a period of six months on a non-exclusive basis.

12. General Provisions

12.1 This Agreement, and the documents referred to within it, constitute the entire agreement between the Parties with respect to the subject matter hereof and supersede any previous agreements, warranties, representations, undertakings or understandings. Each Party acknowledges that it is not relying on, and shall have no remedies in respect of, any undertakings, representations, warranties, promises or assurances that are not set forth in this Agreement. Nothing in this Agreement shall exclude any liability for or remedy in respect of fraud, including fraudulent misrepresentation. This Agreement may be modified or amended only by agreement of the Parties in writing. For the purposes of modifying or amending this Agreement, "in writing" requires either a written document signed by both the Parties or an electronic confirmation by both the Parties with DocuSign or a similar e-signature solution. Any notice of termination and/or reversion and, where applicable, any preceding notices (including any requesting remediable action under the Clause "**Termination**") must be provided in writing and delivered by post, courier or personal delivery addressed to the physical address of the relevant Party as set out at the beginning of this Agreement or any replacement address notified to the other Party for this purpose. All such notices shall become effective upon receipt by the other Party. Receipt is deemed to have taken place five working days after the respective notice was sent by post or left at the address by courier or personal delivery. If the Publisher is the terminating Party the notice need only be provided to the address of the Corresponding Author. If the Author is the terminating Party a copy of the notice must also be sent to the Publisher's Legal Department located at Heidelberger Platz 3, 14197 Berlin, Germany.

12.2 Nothing contained in this Agreement shall constitute or shall be construed as constituting a partnership, joint venture or contract of employment between the Publisher and the Author. No Party may assign this Agreement to third parties but the Publisher may assign this Agreement or the rights received hereunder to its affiliated companies. In this Agreement, any words following the terms "include", "including", "in particular", "for example", "e.g." or any similar expression shall be construed as illustrative and shall not limit the sense of the words preceding those terms.

12.3 If any difference shall arise between the Author and the Publisher concerning the meaning of this Agreement or the rights and liabilities of the Parties, the Parties shall engage in good faith discussions to attempt to seek a mutually satisfactory resolution of the dispute. This Agreement shall be governed by, and shall be construed in accordance with, the laws of Choose an item.. The courts of Choose an item. shall have the exclusive jurisdiction.

12.4 A person who is not a party to this Agreement (other than an affiliate of the Publisher) has no right to enforce any terms or conditions of this Agreement. This Agreement shall be binding upon and inure to the benefit of the successors and assigns of the Publisher. If one or more provisions of this Agreement are held to be unenforceable (in whole or in part) under applicable law, each such provision shall be deemed excluded from this Agreement and the balance of the Agreement shall remain valid and enforceable but shall be interpreted as if that provision were so excluded. If one or more provisions are so excluded under this Clause then the Parties shall negotiate in good faith to agree an enforceable replacement provision that, to the greatest extent possible under applicable law, achieves the Parties' original commercial intention.

The Corresponding Author signs this Agreement on behalf of any and all co-authors.

Signature of Corresponding Author:

Tyagi

....

PRAKRIT TYAGI

[Name of Author]

Date: 18|05|2021

For internal use only:

Order Number: 89125542

GPU/PD/PS: 3/59/8130

ER_Book_Contributor_CAL_ST_EN - Contract Express V.0.5

Scopus Search Sources Lists SciVal ↗ KB

Source details

Lecture Notes in Mechanical Engineering

Scopus coverage years: from 2013 to Present

Publisher: Springer Nature

ISSN: 2195-4356 E-ISSN: 2195-4364

Subject area: Engineering: Automotive Engineering | Engineering: Mechanical Engineering | Chemical Engineering: Fluid Flow and Transfer Processes | Engineering: Aerospace Engineering

Source type: Book Series

View all documents > | Set document alert | Save to source list | Source Homepage

CiteScore 2019
0.5

SJR 2019
0.165

SNIP 2019
0.275

CiteScore | CiteScore rank & trend | Scopus content coverage

i Improved CiteScore methodology

CiteScore 2019 counts the citations received in 2016-2019 to articles, reviews, conference papers, book chapters and data papers published in 2016-2019, and divides this by the number of publications published in 2016-2019. Learn more >

CiteScore 2019

CiteScoreTracker 2020

0.5 = 1,947 Citations 2016 - 2019 / 3,662 Documents 2016 - 2019

Calculated on 06 May, 2020

0.7 = 4,541 Citations to date / 6,974 Documents to date

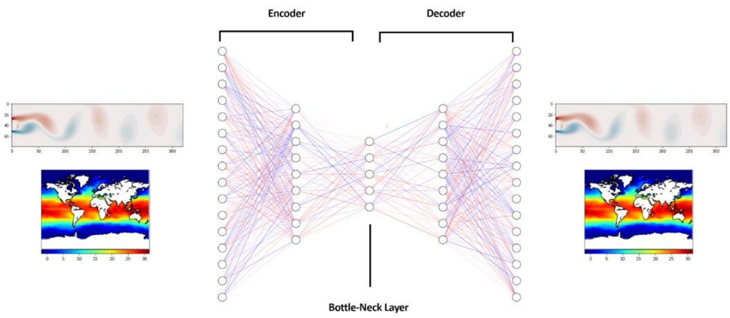
Last updated on 06 April, 2021 • Updated monthly

CiteScore rank 2019

Category	Rank	Percentile
Engineering — Automotive Engineering	#70/91	23rd
Engineering — Mechanical Engineering	#486/585	17th
Chemical		

View CiteScore methodology › CiteScore FAQ › Add CiteScore to your site

Hyper-Parameter analysis of Deep Auto Encoder for Flow Prediction



Pranav Bahl
Undergraduate Student
Delhi Technological University
(Formerly Delhi College of Engineering)

Prakrit Tyagi
Undergraduate Student
Delhi Technological University
(Formerly Delhi College of Engineering)

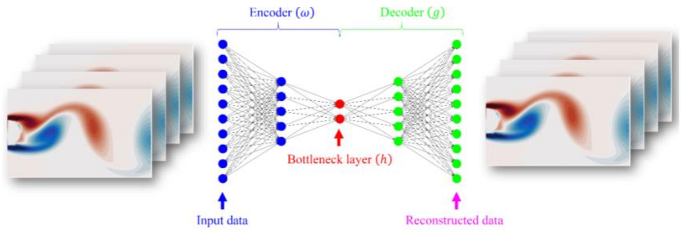
Faculty Mentor: Dr. BB Arora
Professor
Delhi Technological University
(Formerly Delhi College of Engineering)

Outline

- Motivation
- Problem Statement
- Formulation
- Results
- Conclusion

Motivation

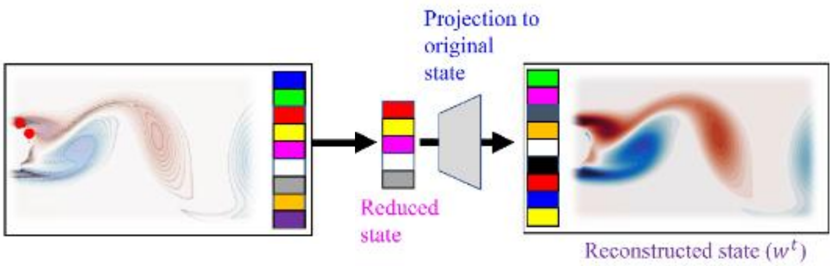
- Fluid Flow prediction is computationally expensive when using iterative algorithms for solving parametric equation.
- Explosion of data and available computation resource has made machine learning appealing.
- Machine learning can help solve most challenging nonlinear problems in feasible manner that classically take enormous amount of time and computation .
- Challenges:
  - Low availability of data
  - Data is noisy



Problem Statement

To analyse the effect of changing hyper-parameters values in accuracy of prediction.

- Consider a problem of predicting flow pattern if given information about existing condition, spatial and temporal features of flow.
- Autoencoder modelled with three hidden layer plus input and output layer is to be trained on vorticity data of flow around a cylinder and on sea surface temperature data.
- The trained model must be able to predict future flow pattern accurately.
- Compare results for each case of hyperparameters.



Formulation: Autoencoder

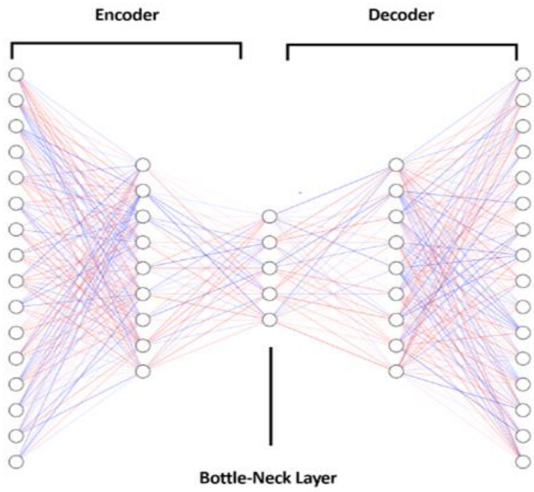
- Artificial Neural Network is a computational model consisting of various neurons or functional nodes.
- The input data is multiplied to corresponding weights and an bias is added following which an activation function is applied to the whole output of the neuron to add the nonlinearity to the function
- A loss function is decided at the end of the network as a means to optimize the parameters of the model.

Remark 1: A situation where $g(\omega(\xi)) = \xi$ everywhere needs to be avoided [33]. In other words, the training algorithm is designed in such a way to restrict direct copying of the input.

Remark 2: In AE, the dimensionality of the latent space $h \in \mathbb{R}^h$ is generally much smaller than the dimensionality of the input variable $\xi \in \mathbb{R}_N$, $h \ll N$. Therefore, h can be thought of as a reduced-order representation of ξ.

Remark 3: When the decoder g is linear, and $\mathcal{L}$ is a mean-squared error, an AE learns to span the same subspace as principal component analysis.

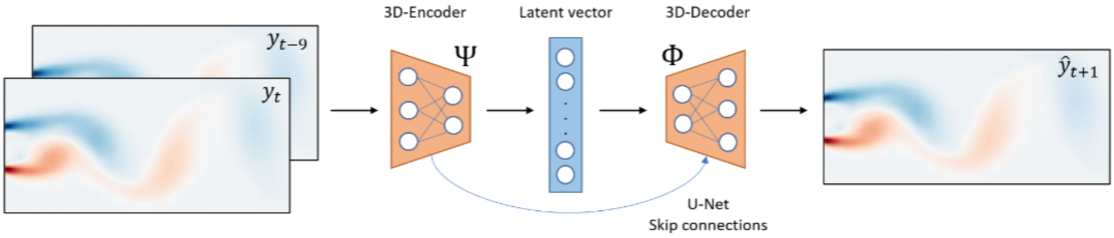
Remark 4: AE with nonlinear encoder ω and nonlinear decoder g learns a nonlinear reduced-



$$h = \omega(\xi), \ \hat{\xi} = g(h),$$

$$\alpha = \arg\min_{\alpha} \mathcal{L}(\xi_t, g(\omega(\xi)); \alpha),$$

Formulation: Proposed Approach



Mapping Data from Input to the Reduced State and back to Original state

$$\phi(\zeta) = \hat{w}^{t+1} \qquad \zeta = \psi(w_t; \theta_\psi)$$

Predicting the state of the vector from a given input

$$\hat{w}^{t+1} = \phi(\psi(w_t; \theta_\psi); \theta_\phi)$$

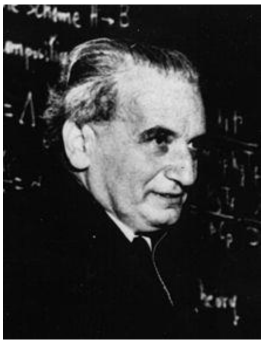
Relative Error : Quantitative Metric for measuring Accuracy

$$\alpha = min \frac{1}{N-1} \sum_{n=0}^{N-1} \|e\|_2^2$$

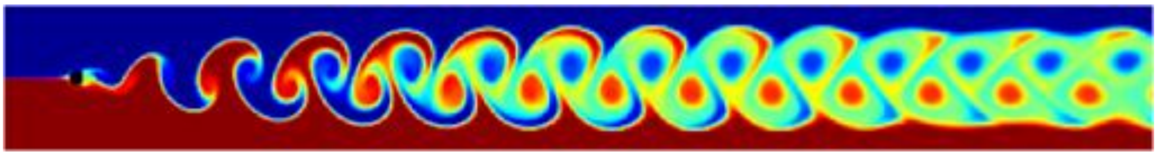
$$\alpha = min \frac{1}{N-1} \sum_{n=0}^{N-1} \left\| w^{t+1} - \phi(\psi(w_t)) \right\|_2^2$$

Von Karman Vortex Street

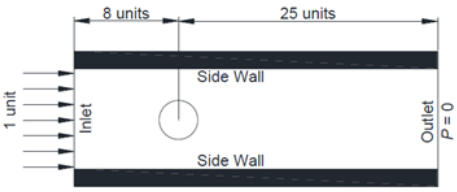
1) A Kármán vortex street (or a von Kármán vortex street) is a repeating pattern of swirling vortices, caused by a process known as vortex shedding. It is formed in the wake of the flow around a bluff body.
2) When the Reynold's number exceeds about 30, the two vortices formed behind the body gets stretched and are washed down. At the place of these two vortices, two new are formed and the process continues.
3) Karman gave the explanation for this phenomenon and according to him there are two possible configuration of the vortex trail i.e. symmetrical and the staggered configuration.
4) Formation is dependent on Reynold's number of the flow, less than 5 no shedding, 5 to about 40 fixed symmetrical vortex, above 90 alternating vortices shedding starts.
5) The frequency of the shedding is directly proportional to the Dimensionless quantity "Strouhal Number"

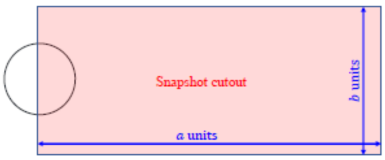


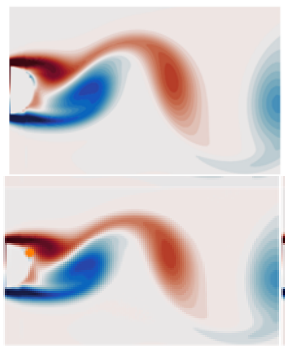
Theodore von Kármán



Numerical Experiment (OpenFOAM)







Periodic Vortex Shedding

- The overall problem domain is discretized into 63420 elements with finer mesh near the cylinder. Time step δt = 0.02 units is considered.
- Training: 180 Snapshots ; Valid: 60 , Test: 60
- Separation b/w snapshots: 10 δt
- Reynolds Number : 190
- 168 * 251 points in X and Y direction
- a = 6 units ; b = 4 units

- **Solver**: Incompressible Laminar Navier Stokes solver based on PISO Algorithm -- **IcoFoam** solver (OpenFOAM)
- No Slip boundary condition at body.
- Inlet Velocity : 1 unit ; Outlet Pressure: 0

$$\nabla \cdot \mathbf{u} = 0$$

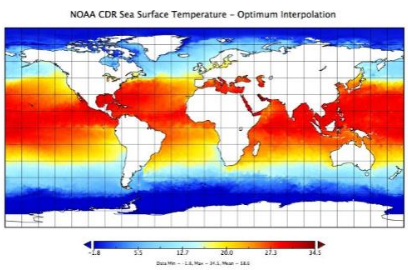
$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) - \nabla \cdot (\nu \nabla \mathbf{u}) = -\nabla p$$

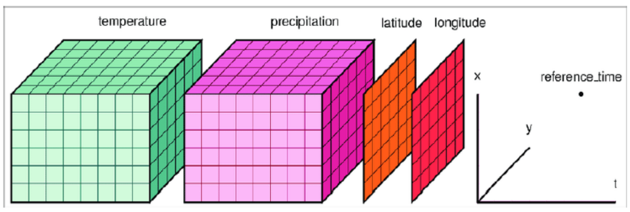
Ref 1: Nirmal J. Nair and Andres Goza. Leveraging reduced-order models for state estimation using deep learning. Journal of Fluid Mechanics, 897:R1, 2020.

Ref 2: Kumar, Yash, Pranav Bahl, and Souvik Chakraborty. "State estimation with limited sensors--A deep learning based approach." arXiv preprint arXiv:2101.11513 (2021).

Dataset : NOAA OISST V2 - Sea Surface Temperature

1) NOAA (OI) Sea Surface Temperature V2 data-set has been made publicly available by the Physical sciences division at NOAA.
2) The temporal resolutions available for the data-set are weekly, monthly and monthly long-term mean data.
3) The weekly-data is centered on Wednesday for the brief period of 1990-2020 and on Sunday for the period of 1981-1989.
4) The spatial resolution of the data is 1-deg latitude and 1-deg longitude leading to 180 x 360 grid points. This was chosen as the High Resolution Data.
5) The spatial resolution of the data 2-deg latitude and 2-deg longitude leading to 90 x 180 grid points was chosen as the Low Resolution Data.
6) Training 400 snapshots : Monthly data (1984 – 2021)
7) Training : 1500 snapshots : Weekly Data (1990 – 2021)





Hoyer, Stephan & Hamman, Joseph. (2017). xarray: N-D labeled Arrays and Datasets in Python. Journal of Open Research Software. 5. 10.5334/jors.148.

Simulation Results

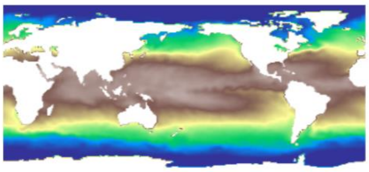


Figure 4.7: True Value of Sea surface temperature at time step 5

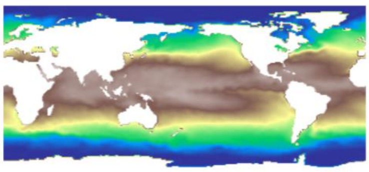


Figure 4.8: Predicted Value of Sea surface temperature at time step 5

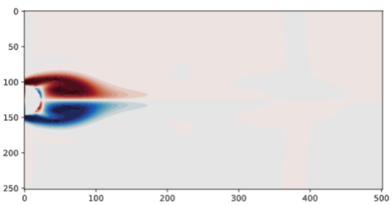


Figure 4.3: True Value of vorticity at time step 5

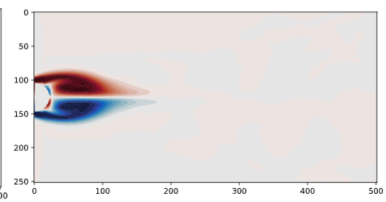


Figure 4.4: Predicted Value of vorticity at time step 5

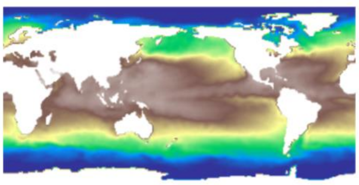
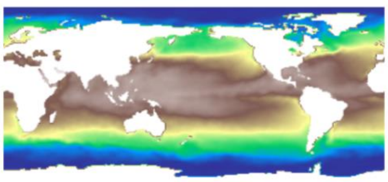


Figure 4.9: True Value of Sea surface temperature at time step 50



igure 4.10: Predicted Value of Sea surface temperature at time step 50

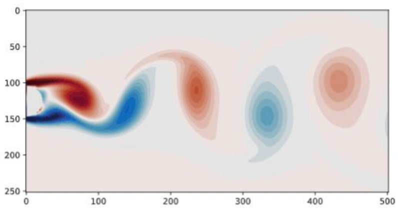


Figure 4.5: True Value of vorticity at time step 50

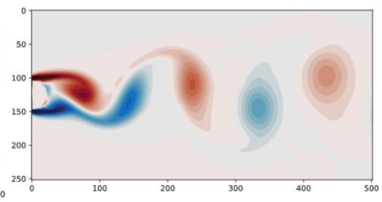
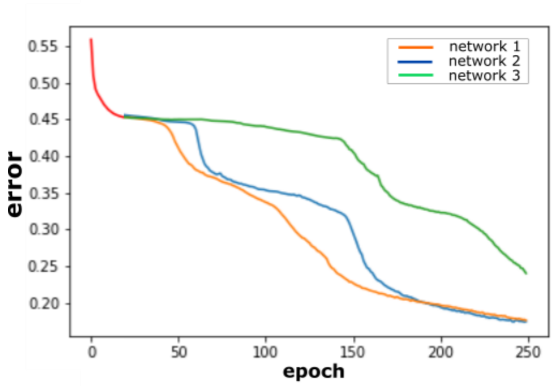


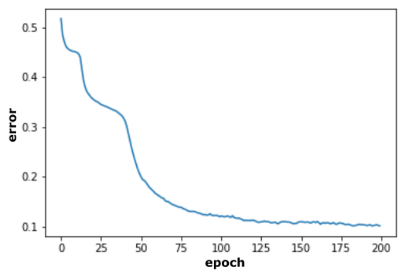
Figure 4.6: Predicted Value of vorticity at time step 50

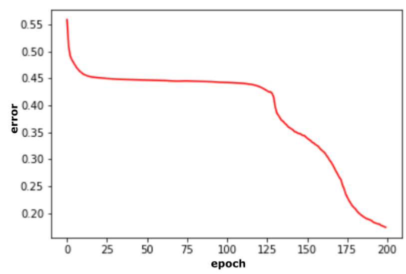
Simulation Results

Effect of Network size

Effect of Data size







Conclusion and Future Work

We have made comparison between network architectures wherein the following conclusion was made,

- The training error sharply decreased as we increased the network size, which has its underlying reason for added non-linearity in the network but also leads to a relatively more computationally expensive model to its counterpart architecture.
- Following this we also make comparison between increased size of dataset and lower amount of dataset which were generated with the help of different time-steps. It was seen and concluded that a larger dataset helped in converging to the solution much rapidly and easily in comparison to the shorter dataset.
- Make use of autoencoder based 3D-UNets to generate reduced order models and to use this reduced state to predict future timesteps presents a novel and effective solution for reducing computational runtimes of CFD simulations.