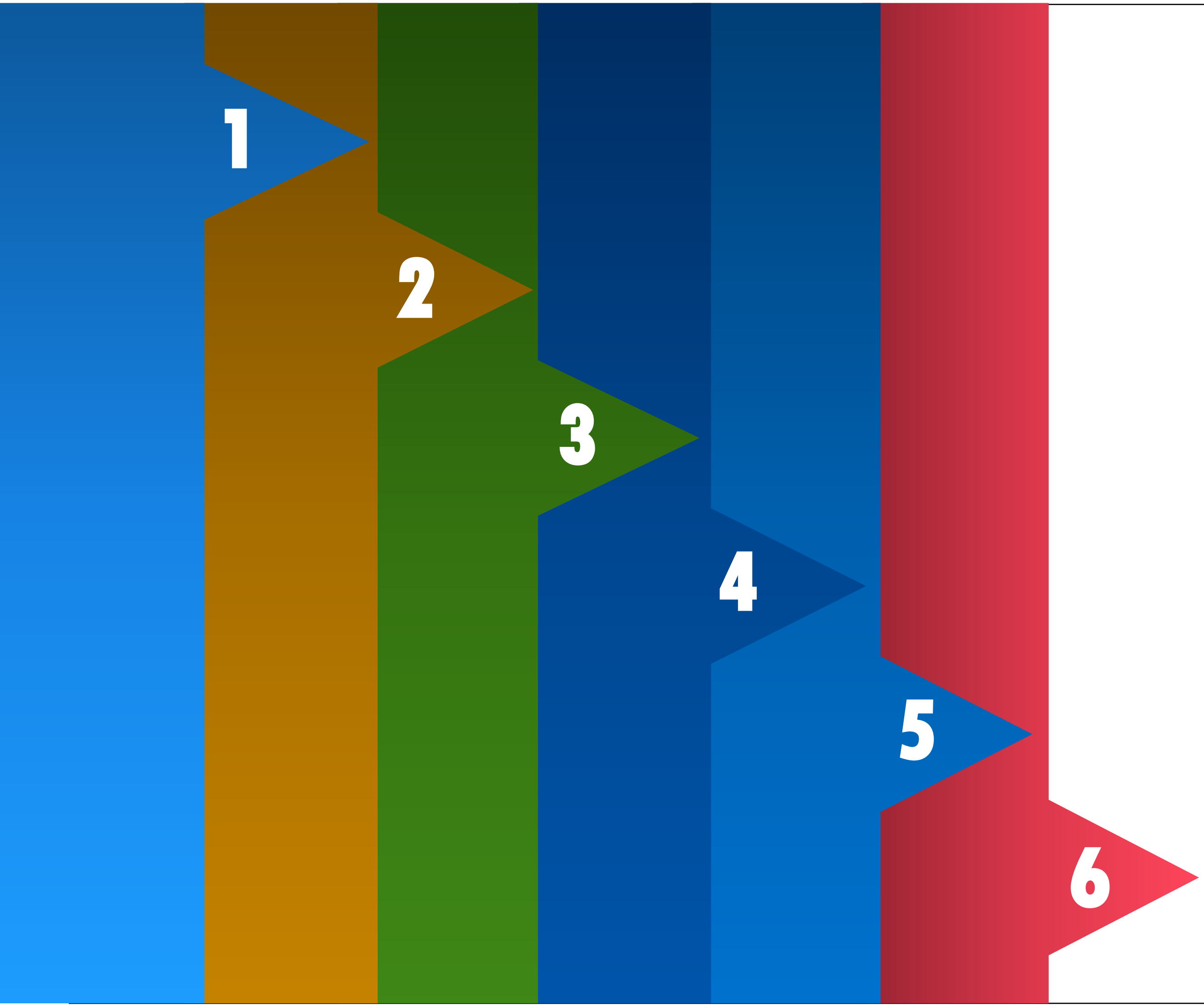
Analysis of Regression Models for estimating the main bearing loads of wind turbines

Master Thesis
Mithun Nagesh Shet
Aachen, 12.08.2022

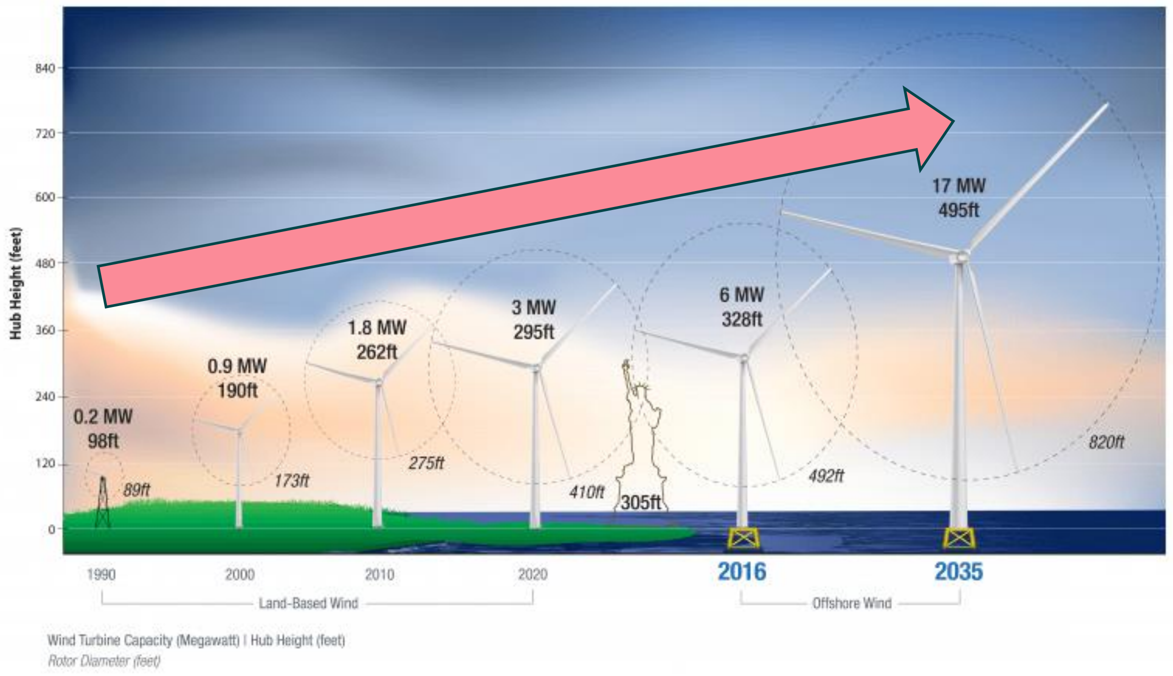
CWD Chair for Wind Power Drives | RWTH AACHEN UNIVERSITY

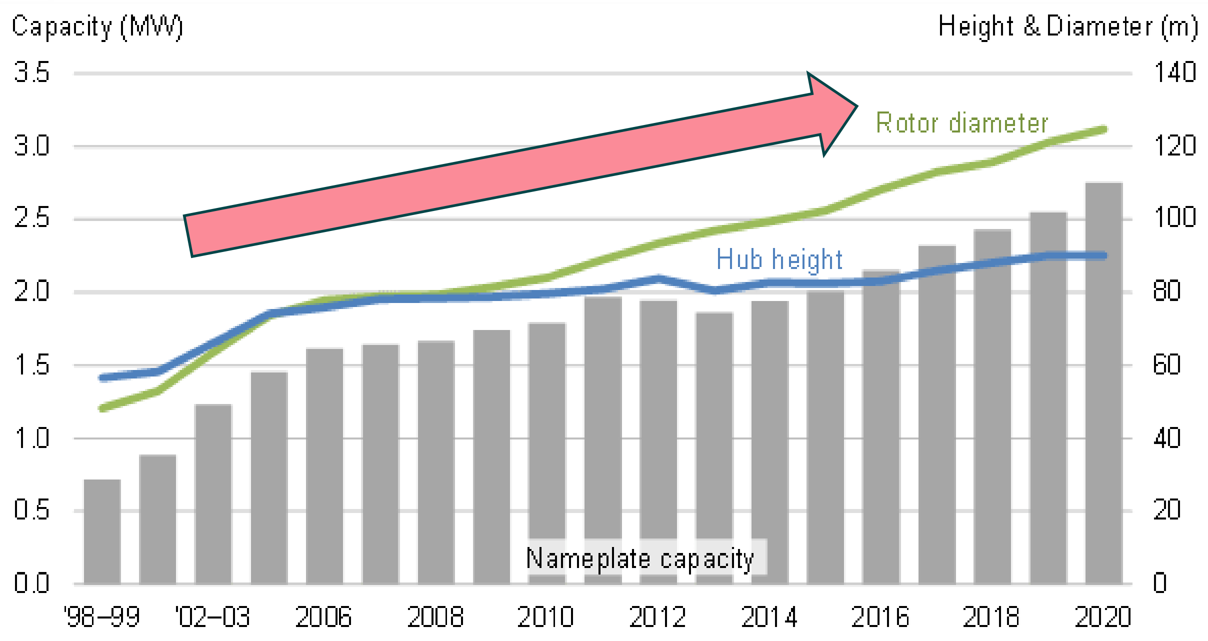
Structure



MOTIVATION

Motivation

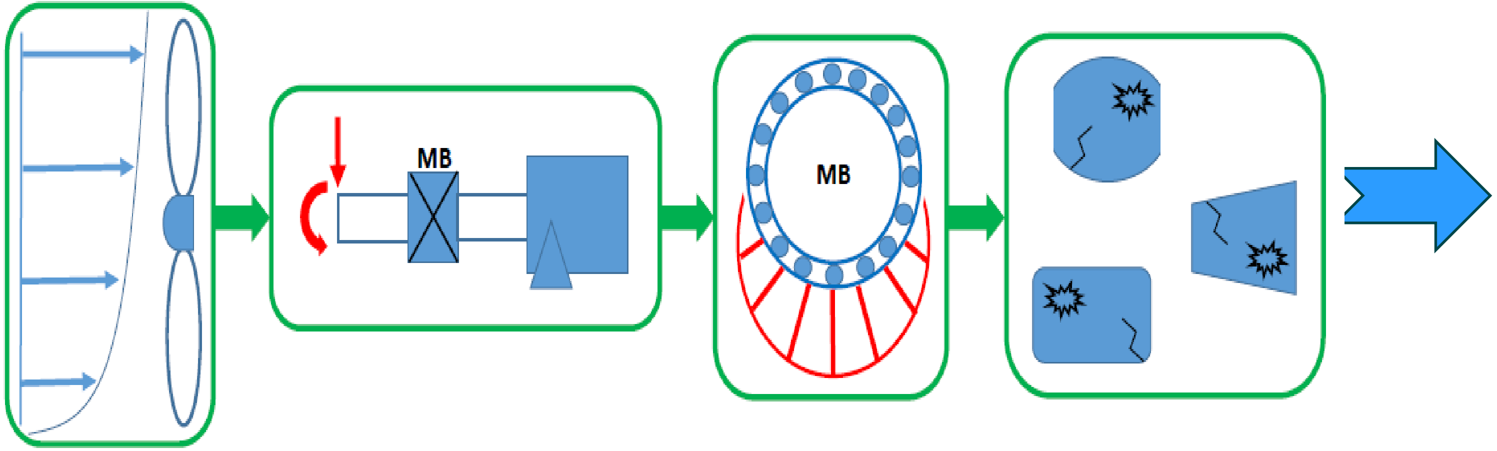




- Wind is set for largest increase in renewable energy generation growing by 275TW by 2021.
- The trend shows that there is substantial increase in diameter of turbine blades and size of hub every decade by an amount of 40 percent every decade.
- This increased size has significantly increased the torque and non torque loads.

Source : Office of energy efficiency and renewable energy

Motivation



High Operation cost and less service life

- Under ideal conditions, lifespan of wind tubine is around 20 years.
- In actual , the wind turbine lasts for about 6 years.

Reason:

- Fatigue mechanism
- Wear and tear due to bearing misalignment
- Bearing unseating, skewing and sliding due to high axial to radial loads.

Solution:

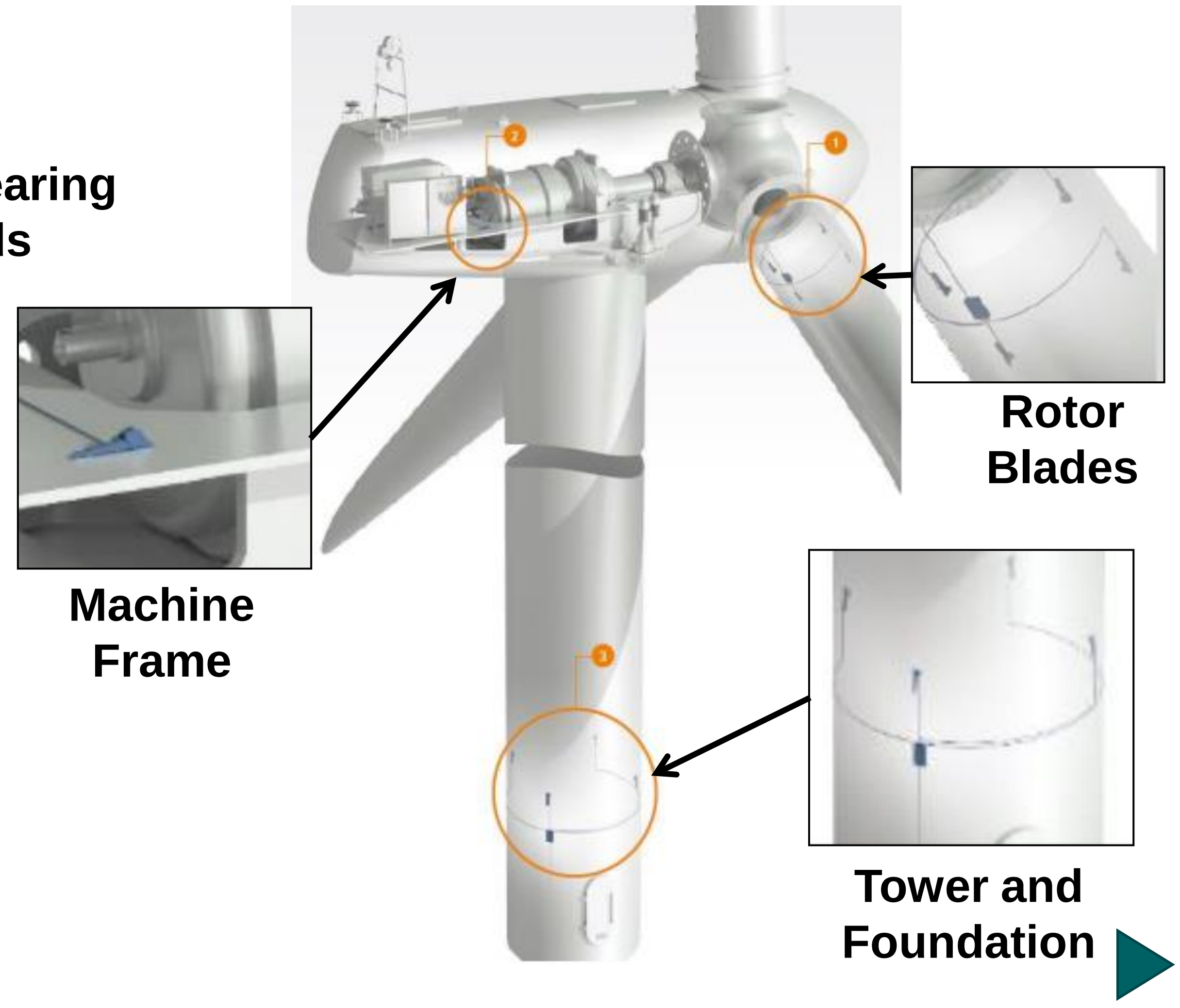
Load monitoring system to monitor loads and send signals prior to observed failures.

BACKGROUND

Background

Strains → **Strain Gauge** → Main Bearing loads

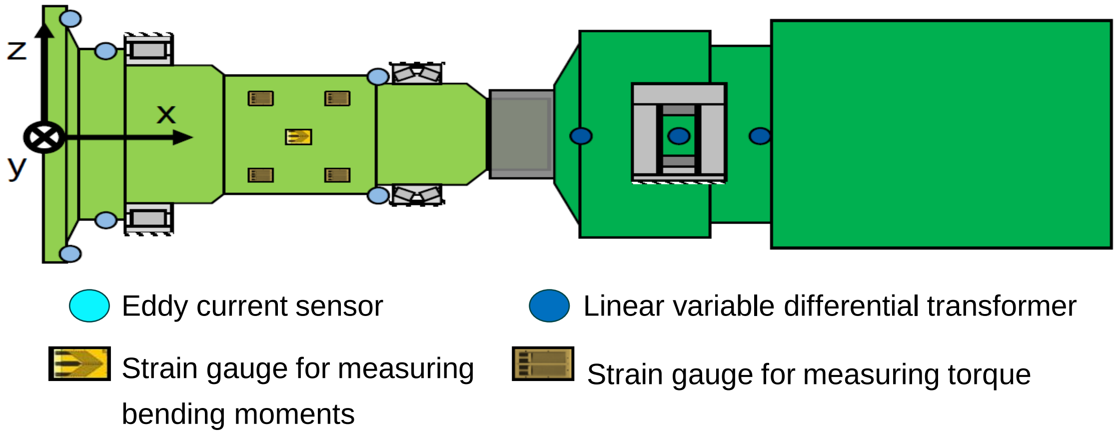
- Currently **strain based load estimation** is used.
- Measurement based on linear relationship between strains and loads.
- Vulnerable to calibration error and signal drift.
- Limited lifetime.
- A better technology is necessary which is **long-lasting** and **robust.**



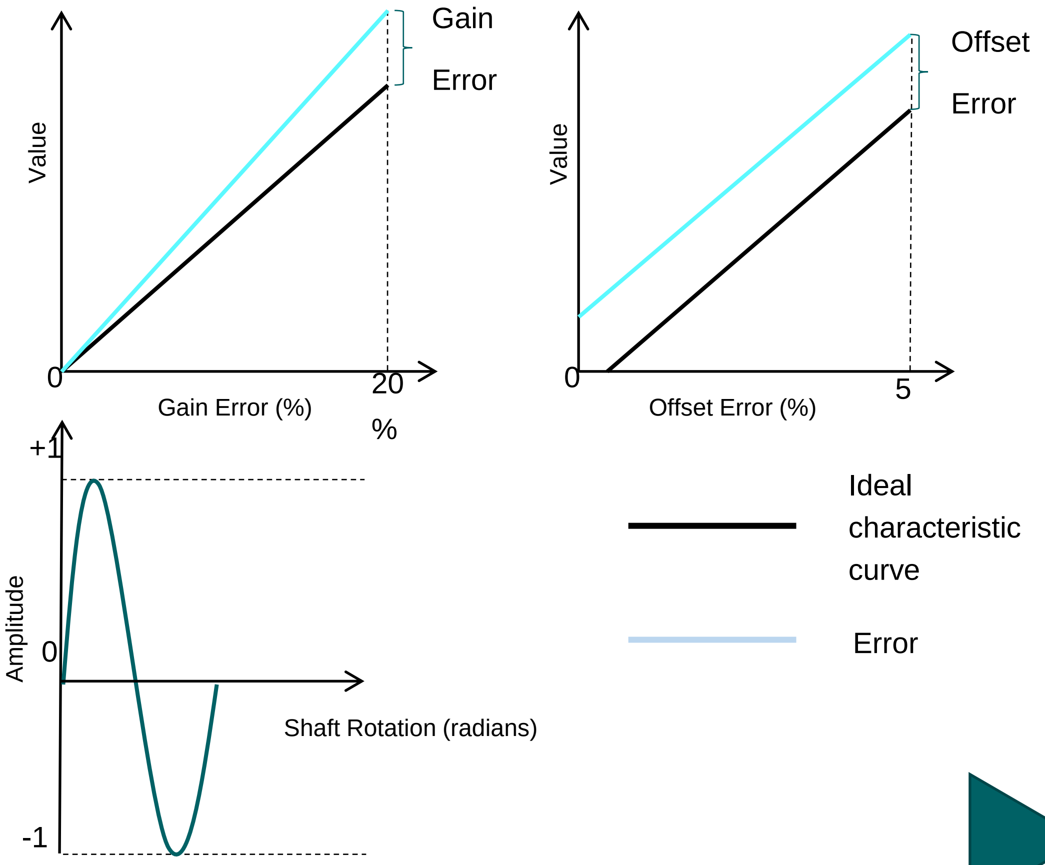
Source : Leine Linde Systems

OBJECTIVE

Objective



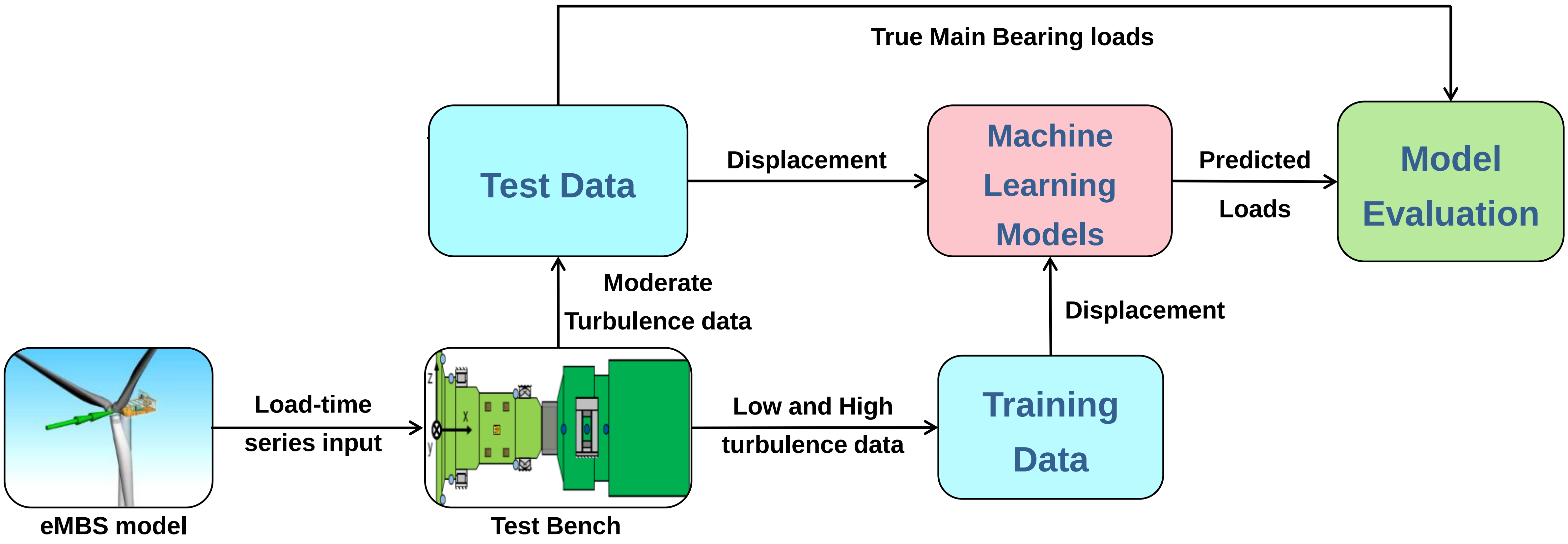
Model Robustness



- Replacing the traditional method of using strain gauges by machine learning models.
- Training, building and testing the models from displacement signals recorded by Eddy current sensors to predict loads.
- Checking robustness of models to errors like **Gain error, Offset error and sinewave error.**

METHODOLOGY

Methodology

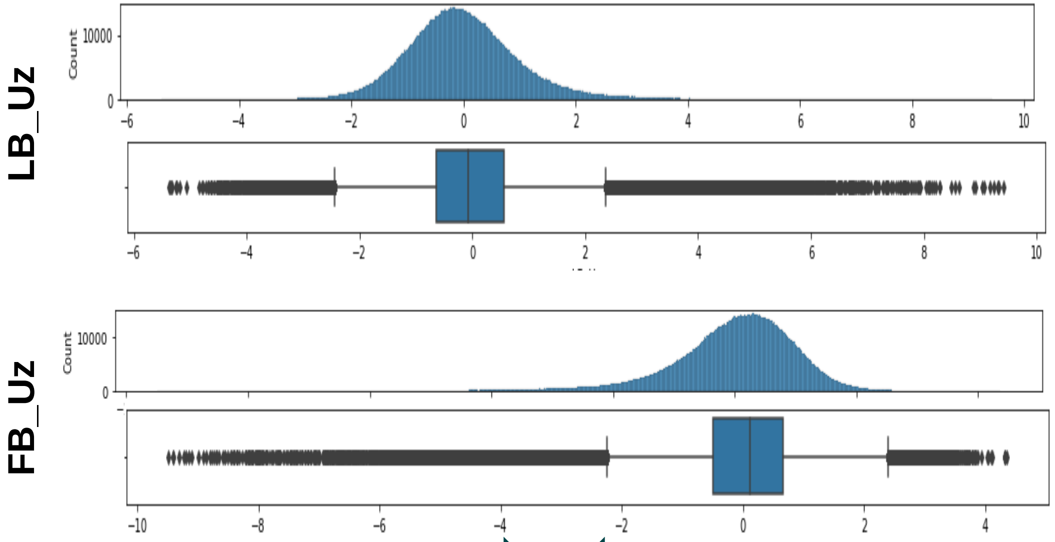


EDA and Feature Engineering

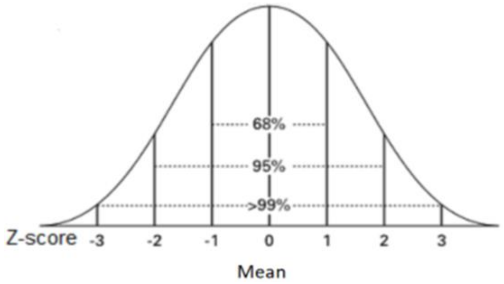
Variables study

Independent Variables		Response Variable
Fixed Bearing (FB)	Loose Bearing (LB)	Main Bearing Loads
Linear Displacements	Linear Displacements	Fixed Bearing Loads
x direction - FB_Ux y direction - FB_Uy z direction - FB_Uz	x direction - LB_Ux y direction - LB_Uy z direction - LB_Uz	x direction - FB_Fx y direction - FB_Fy z direction - FB_Fz
Angular Displacements	Angular Displacements	Loose Bearing Loads
y axis - FB_PHIy z axis - FB_PHIz	y axis - LB_PHIy z axis - LB_PHIz	y direction - FB_Fy z direction - FB_Fz

Outlier Detection



Normalization



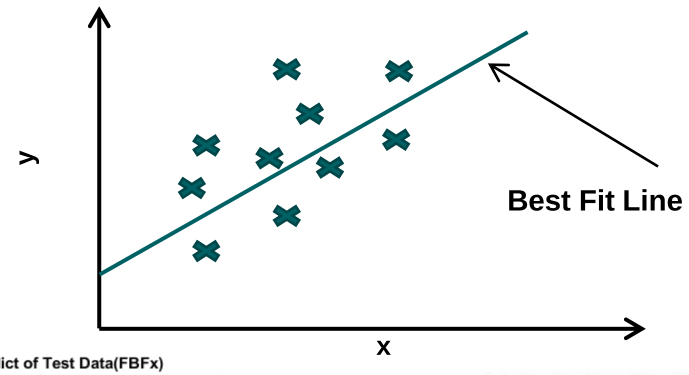
$$z = \frac{x - \mu}{\sigma}$$

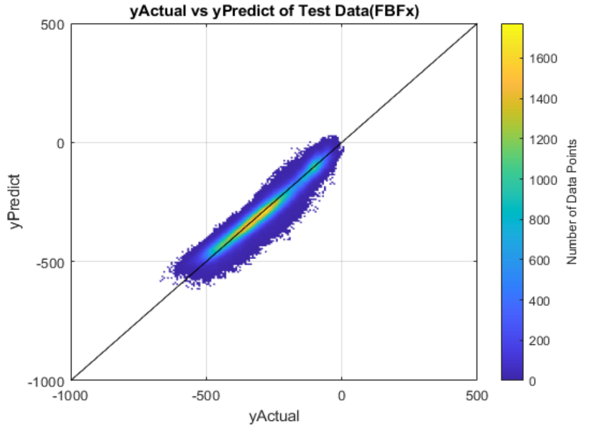
$\mu =$ Mean
$\sigma =$ Standard Deviation

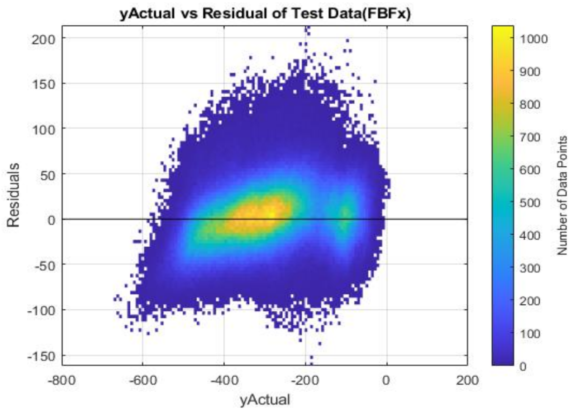
- Performance of regression models depend on quality of data and outliers can lead to high variance.
- The training data was split in **80% for training** and **20 % for validation**.
- The data was normalized using **Z-score** method.

Linear and Polynomial Regression

Linear Regression for FB_Fx



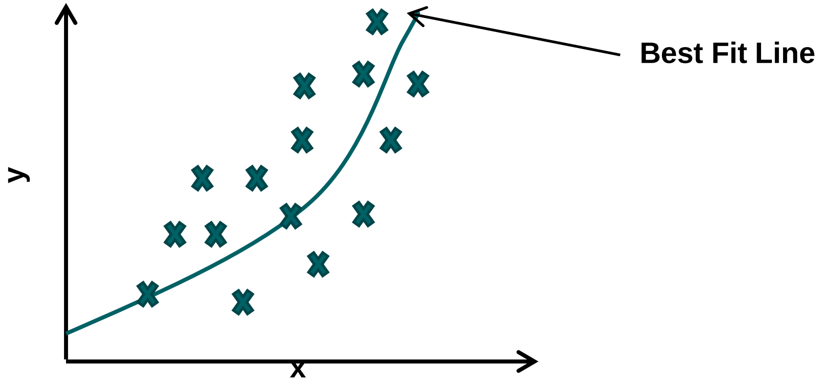


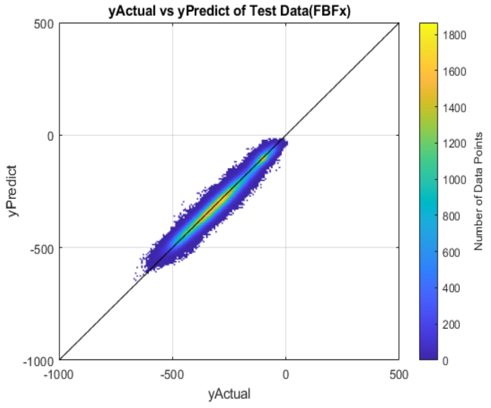


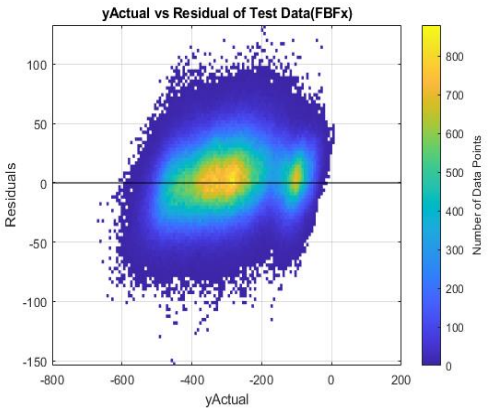
MAE	MSE	RMSE	R2
22.7565	856.9163	29.2731	0.9392

- Simple model and used as reference.
- Residual error range
- **-120kN to +180kN**.

Polynomial Regression for FB_Fx





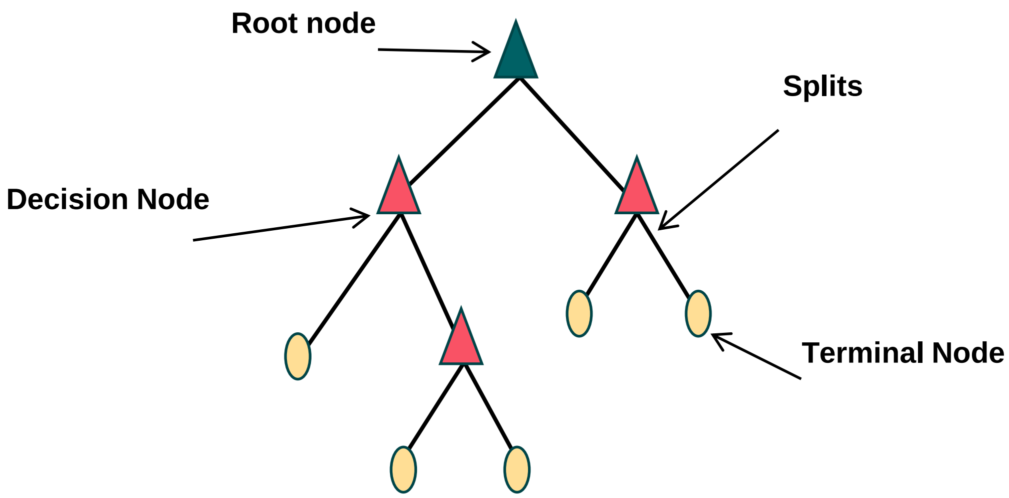


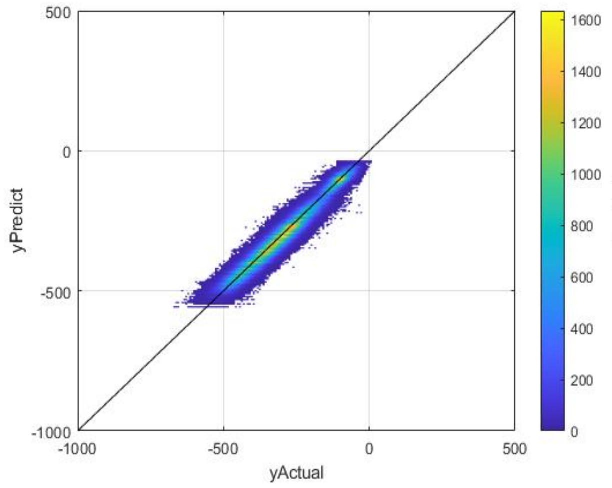
MAE	MSE	RMSE	R2
18.9258	574.4274	23.9672	0.9593

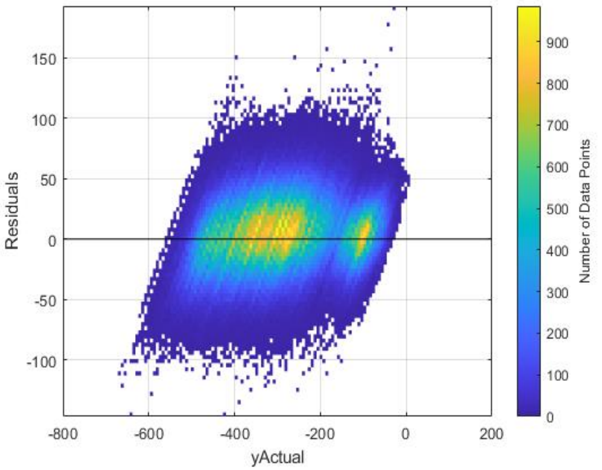
- Residual error range **-100kN to +100kN**.

Regression Tree Model

EDA
LPR
TM
SVR
GPR
EBT
ANN







- Flexibility to capture nonlinear predictor-response relationship.
- Minimum leaf size set at 35 to 40 for balanced fit.
- Residual error varying between **±110kN** with high density points found at around **±25kN**

MAE	MSE	RMSE	R2
20.6247	681.8551	26.1124	0.9516

EDA
LPR
TM
SVR
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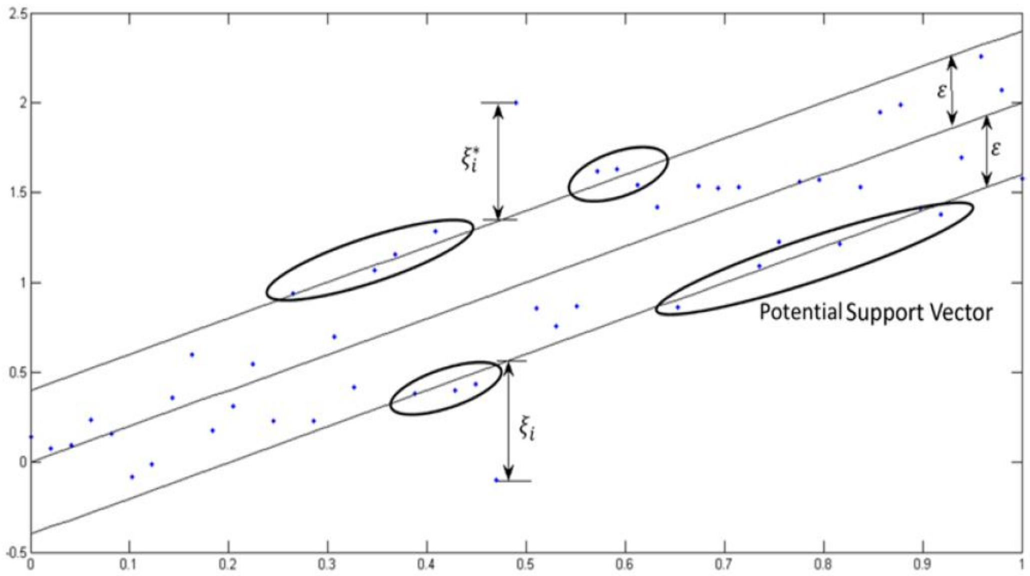
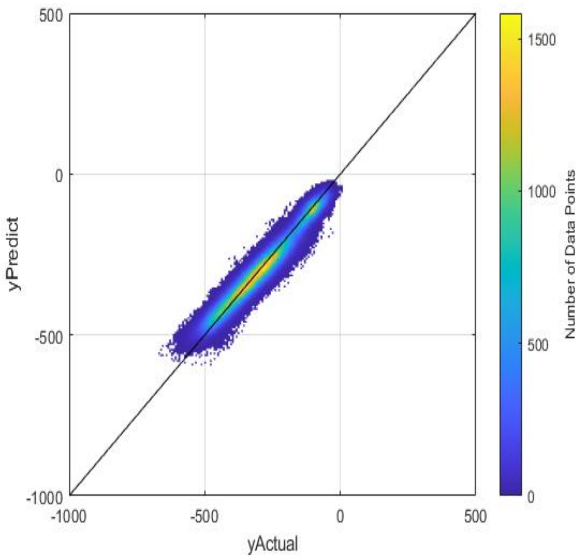
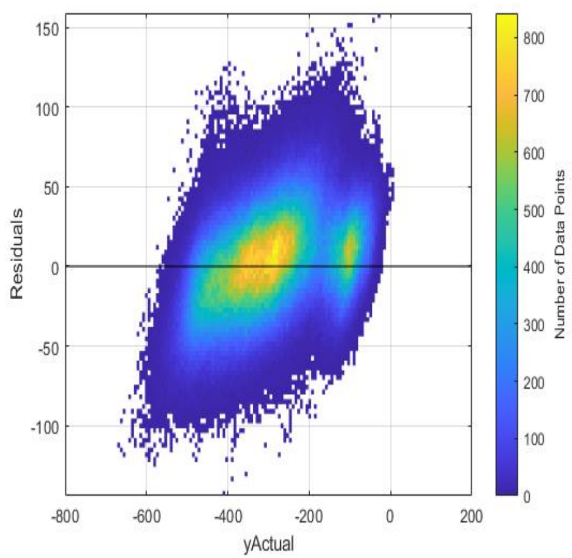
Support Vector Regressor







- Consists of Є tube which reformulates the optimization problem to find best tube that approximates continuous valued function.
- The kernel was set as polynomial of order 2.
- The residual error varied between **±120kN** with high density of points seen around **±35kN**.

MAE	MSE	RMSE	R2
22.3663	796.6266	28.2246	0.9435

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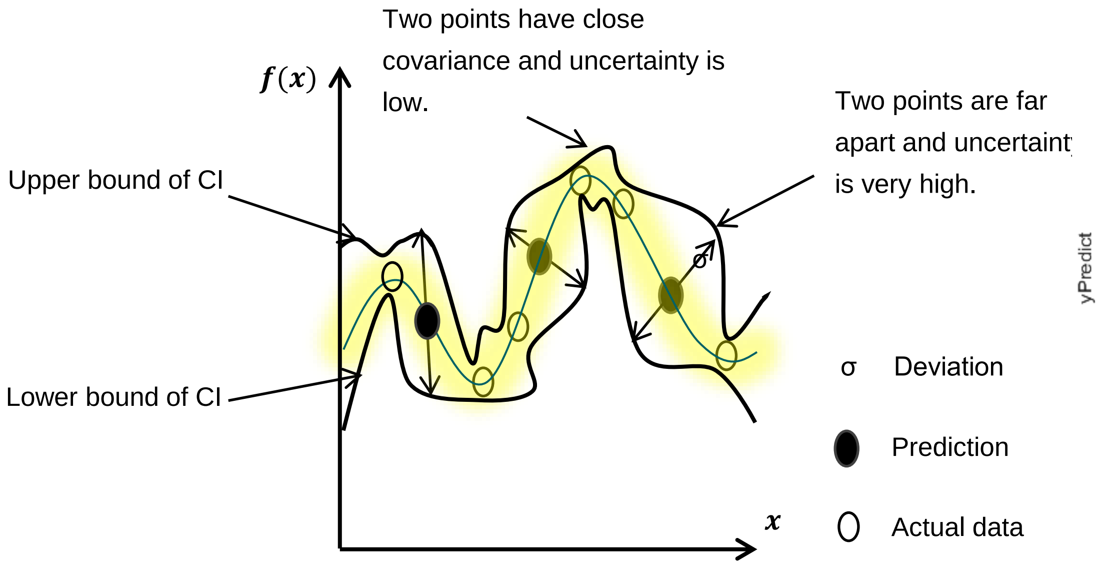
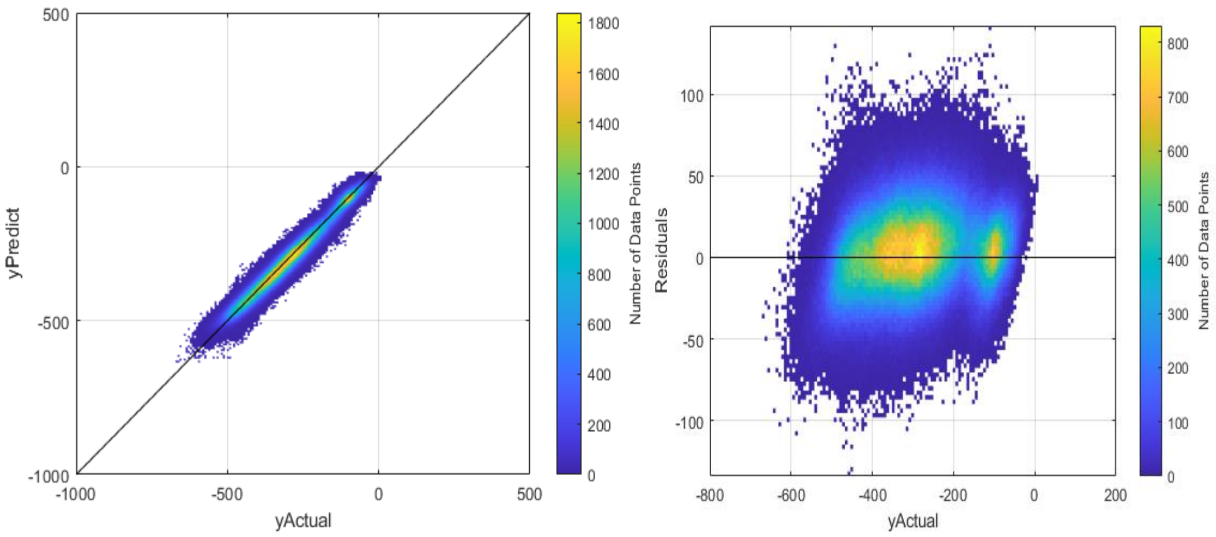
Gaussian Process Regressor

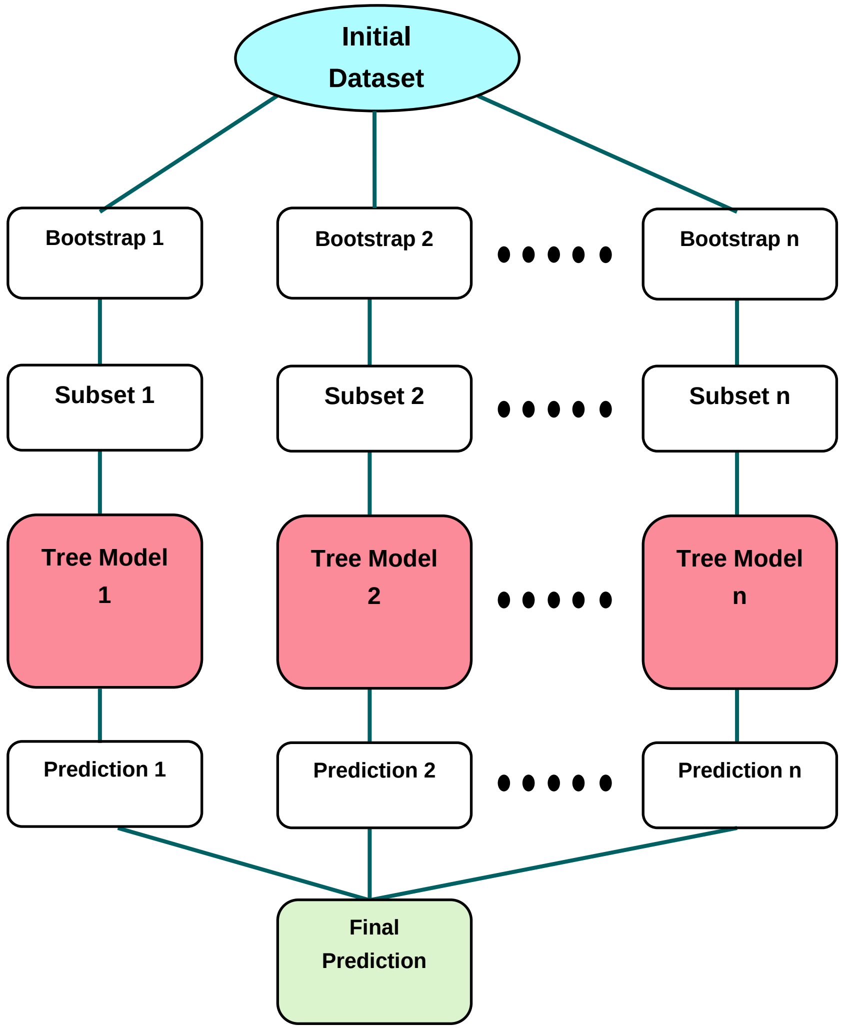


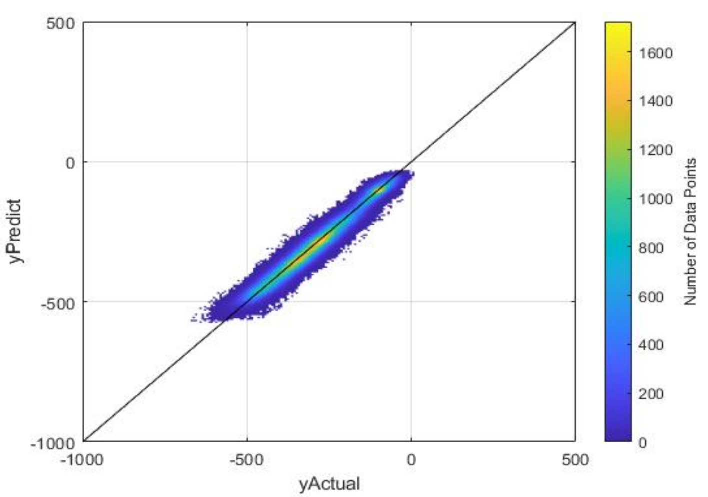


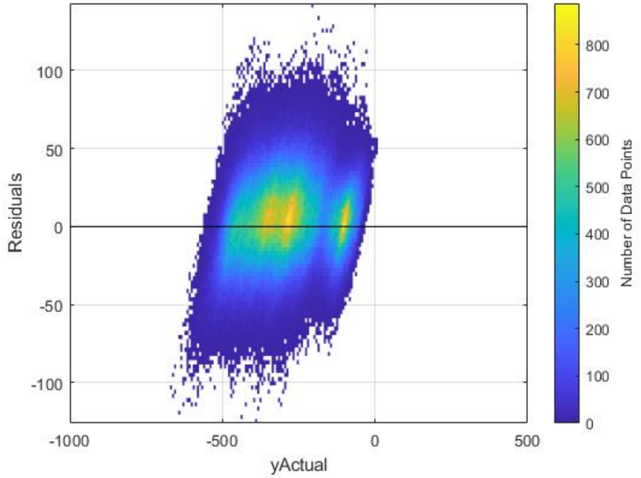
- Gaussian process regression (GPR) models are nonparametric kernel based probabilistic models.
- Kernel function used is squared exponential based on the data distribution.
- The residual error varies between **±95kN** with high density of points seen around **±25kN**.

MAE	MSE	RMSE	Rsq
18.5603	553.0644	23.5173	0.9608

Ensemble Bagged Tree



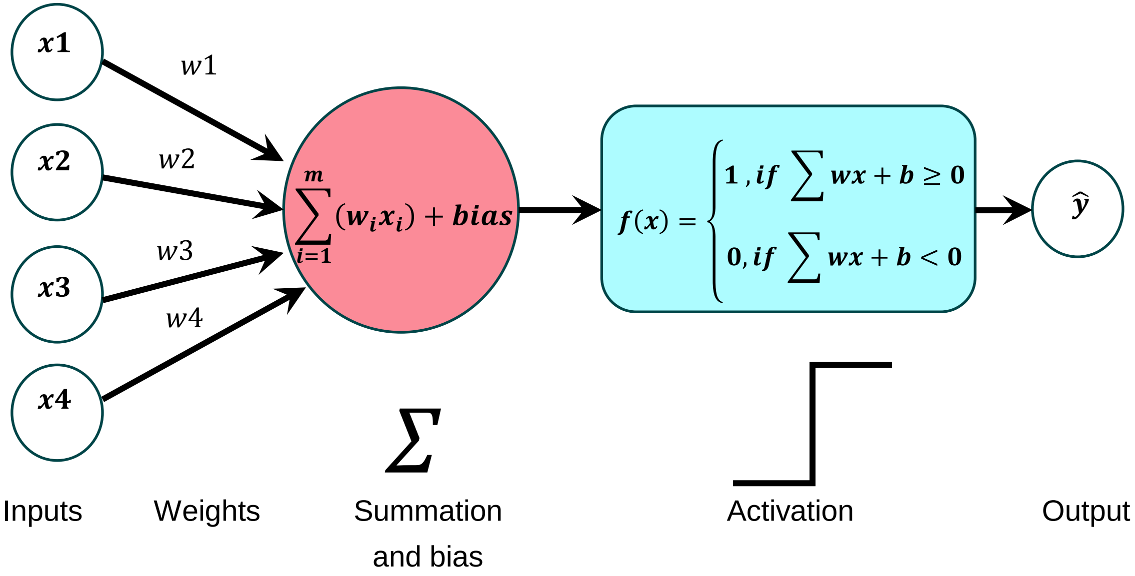


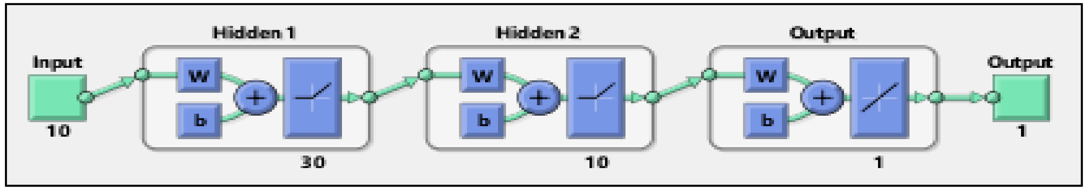


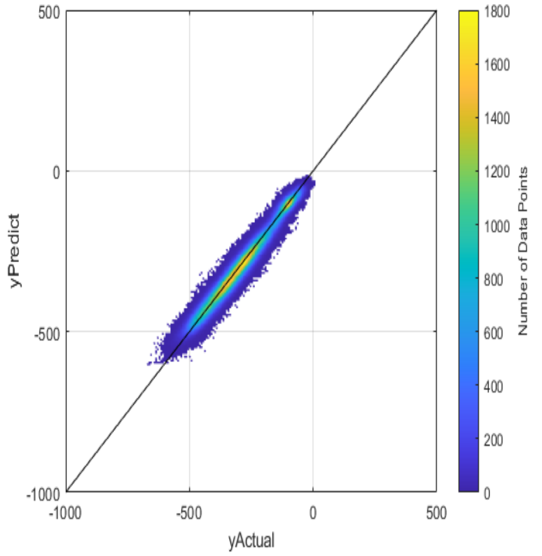
MAE	MSE	RMSE	R2
19.2415	594.3141	24.3786	0.9579

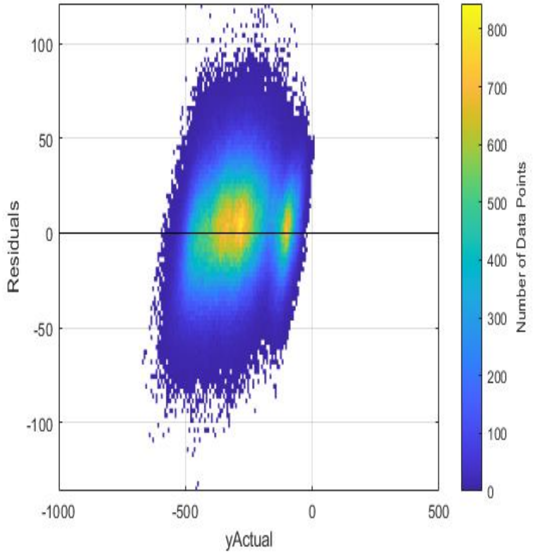
- A bagged ensemble tree is a machine learning algorithm where multiple tree models are trained to solve the same problem and combined to get better results.
- Bagged ensembles help to avoid the problem of overfitting.
- The model becomes resilient to generating errors.
- Residual error varying between **±90kN** with high density of points seen around **±20kN** .

Artificial Neural Network









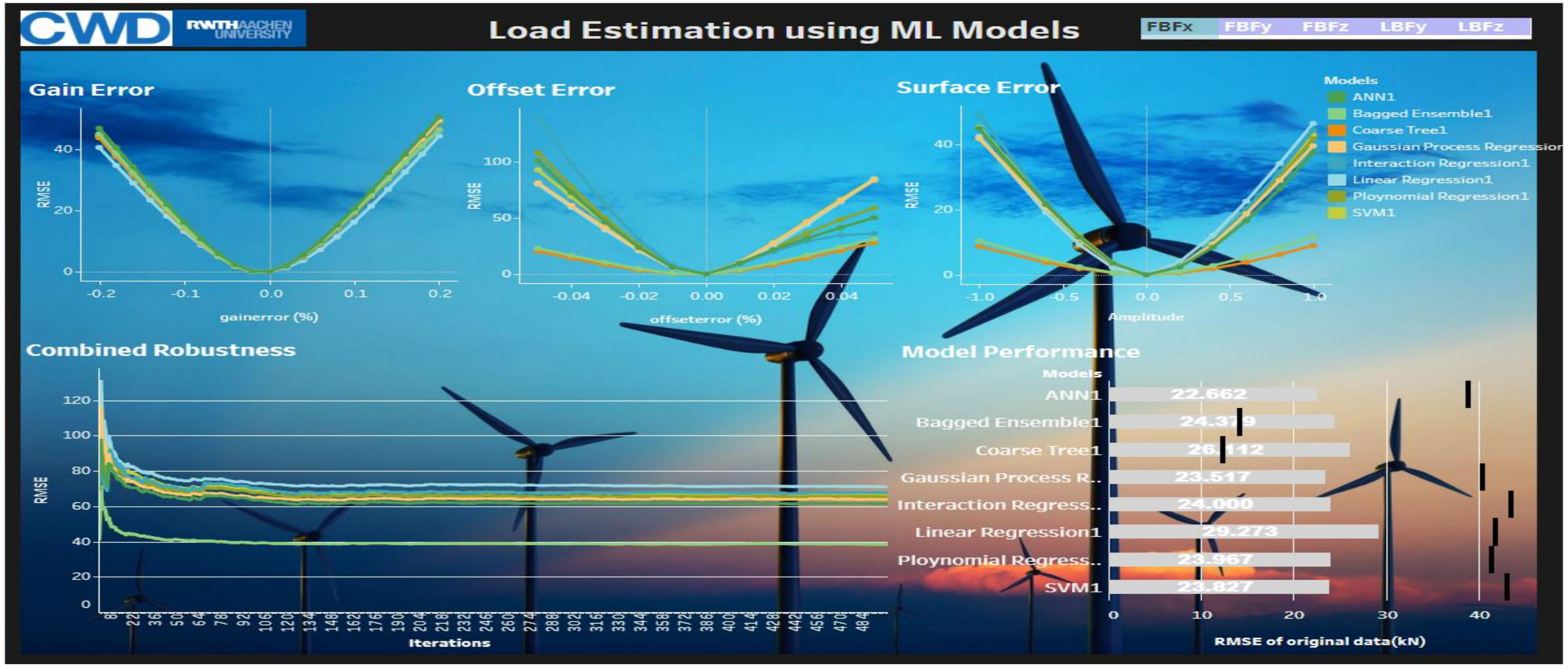
MAE	MSE	RMSE	R2
18.1189	527.1320	22.9594	0.9626

- To model a better nonlinear correlation between the displacements and the loads.
- The model was built with 2 hidden layers with RELU as activation function.

- Residual error varying between **±80kN** with high density of points seen around **±20kN** .

RESULT STUDY

Result Study



The results of each model and its performance for each main bearing loads is discussed in dashboard which can be accessed using below link.
https://public.tableau.com/views/Thesisresults_dashboard_v3/Dashboard1?:language=en-US&publish=yes&:display_count=n&:origin=viz_share_link

Summary and Outlook

Summary and Outlook

Summary:

- With approach presented in thesis, Regression models can estimate main bearing loads from displacement values with certain degree of error.
- Apart from linear model, all models could capture nonlinearity due to bearing surface and clearance with Bagged ensemble showing highest robustness.
- Bagged Tree ensemble model consistently showed strong robustness for all main bearing loads.
- ANN model showed good performance with original dataset and captured nonlinearity but was inconsistent in robustness test.
- Compromise made between the accuracy and robustness.

Outlook:

- Models can be further trained with dataset consisting all kinds of error for better performance to capture nonlinearities.
- Further study is needed on the minimum threshold for accuracy and robustness required to be implemented in real world.

Thank you for your attention.

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