NOISE FILTERING FOR ACCURACY IMPROVEMENT OF CONVEYOR BELT TYPE DYNAMIC WEIGHING SYSTEMS

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Degree of Master of Science in Industrial Automation

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Thesis/Dissertation submitted in partial fulfillment of the requirements for the degree Master of Science in Industrial Automation

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ABSTRACT

Conveyor belt-type checkweigher machines are important part of modern production factories. They are used to determine the weight of the different types of products without stopping the products on the weighing conveyor. The main challenge of dynamic weighing system is providing high measurement accuracy, while the checkweigher machine is running at high conveyor belt speeds. In this paper different types of noises such as electronic noises, motor vibration noises and noises due to natural frequencies are analyzed in frequency domain and it is discussed how digital filtering such as Notch filter, FIR lowpass, IIR lowpass are effective to obtain the required accuracy level. Then to achieve further accuracy level, system is modelled using first principles as spring-mass system as well as black box model. Finally, the selected model is used to apply Kalman filter. Then Kalman is selected as the best filtering method and applied to the real system and simulation and experimental results & conclusions are discussed in detailed.

Keywords: Check weigher, Frequency Analysis, Model based filtering, Notch filter, FIR lowpass, IIR lowpass, Kalman Filter, Black box model

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1. INTRODUCTION

In modern factories, checkweighers have become critical quality control machine. Check weighing is an automated process, which weighs the product while it is in motion. It normally runs without any manual intervention of operator. There is significant difference between static weighing and dynamic weighing. In static weighing, weight of the product is determined at standstill whereas in dynamic weighing, weight of the product is determined while it is moving on conveyor. Loadcells are commonly used in both weighing systems. However, in dynamic weighing the weight signal may not reach the steady state hence the weight is assessed by using different filtering methods. There are number of factors which can influence dynamic weighing, some are relatively minor, but others can be problematic to getting an accurate weight result of checkweighers.

1.1 Background

Unilever Sri Lanka is a leading FMCG company which produces more than 200 different personal products in a single plant with 9 nos. of automatic production lines. All the finished goods are packed in corrugated boxes automatically and sent through traffic conveyors to automatic palletizing station. As a quality control mechanism, before palletizing, weights of all the corrugated boxes are measured while in motion to identify underweight or overweight products or to detect any short packs inside corrugated boxes. This machine is called a checkweigher which does the dynamic weighing which is different from static weighing. In static weighing, Weight is measured while the product is stationary on conveyor belt whereas dynamic weighing, it weighs the products while they are moving.

1.2 Dynamic Weighing by checkweigher

Dynamic weighing refers to a system that weight of the product is measured while the product is moving on a conveyor belt. Conveyor belt is mounted on a loadcell. An industrial type checkweigher machine consists of a series of conveyor belts called as infeed conveyor, Weighing conveyor and rejection conveyor.

- **Infeed Conveyor**: An infeed conveyor sets the gap between products to an optimal distance for weighing. Also, industrial type Barcode scanner is mounted on infeed conveyor to identify the product and so that controller can load its related settings for further processing while that product is moving in weighing conveyor.

- **Weighing conveyor**: This conveyor is mounted on a loadcell which is typically a strain-gauge load cell. Weight values are sent to programmable logic controller (PLC) while is motion.

- **Rejection conveyor:** This conveyor facilitates the removal of out of tolerance boxes from the conveyor line.

The following figure shows typical product flow diagram of industrial type checkweigher machine. Products are fed to the infeed conveyor one by one and barcode scanner reads the barcode value of the box and sends the signal to the PLC. Then PLC recognizes the box type and automatically loads the pre-defined parameters, entered via HMI by the operation team to compare the actual weight value vs target weight. Also based on the length of the box speed of the weighing conveyor is adjusted automatically to get the required amount of sample data to PLC to estimate the weight of the box.

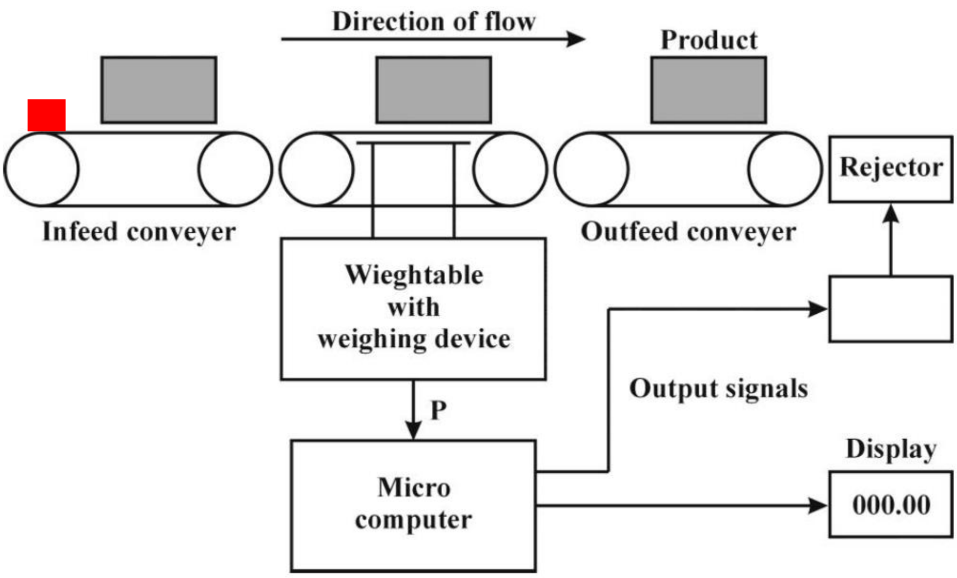


Figure 1 : Product Flow of Checkweigher **[1]**

Product is fed through the infeed conveyor to weighing conveyor from where weight is measured. Outfeed conveyor is used to reject any underweight or overweight products. There is an HMI from which operator or technician can alter parameters and visualize machine values and status.

1.3 The need of Dynamic Weighing

Dynamic weighing system has become an important part of modern manufacturing factories to use as quality control purposes. This is very popular because it is not stopping the product and measures the weight. While in motion it measures the weight. This is very important to achieve the target UPM of the production lines. Manufacturers should ensure that their products meet minimum specification either by law or by contract. Also, it should not exceed the specifications that the consumers pay for. With the current developments in the market, production rates are increased, so that there is increasing demand for high-speed check weigher machines with greater measurement accuracy. In this case static weighing is not an option at all.

1.4 Weighing Technology and current developments in industry

There are different types of weighing technologies developed over last decades in order to cater the diverse requirements of check weighing in modern factories. There are two major types of loadcell technologies used for checkweighers such as principle of wire strain gauge technology and electromagnetic force restoration (EMFR technology). A strain gauge loadcell converts displacement of loadcell into an electrical signal whereas EMFR technology converts a force to balance the load into an electrical signal. In practical applications Electromagnetic balance is used for high accurate measuring before packaging whereas strain gauge loadcell which is less accurate and less costly is used for finding out missing packages after boxing. [2]

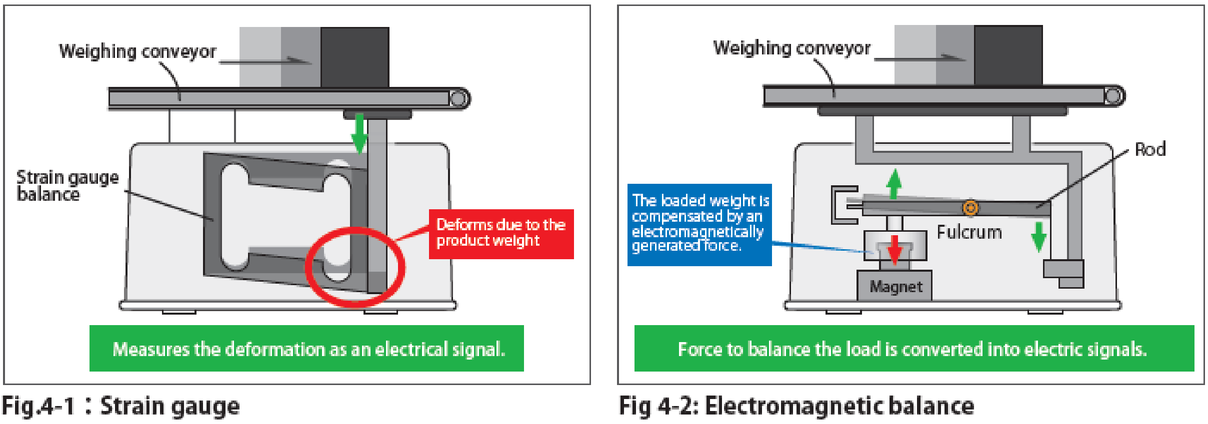


Figure 2 : Strain gauge and Electromagnetic balance weighing **[3]**

As shown in figure 02, load on the weighing conveyor deforms the strain gauge balance and that deformation converts into an electrical signal. In electromagnetic balance, the loaded weight is compensated by an electromagnetically generated force. Both of the technologies are used in industrial type check weigher machines. For very high-speed applications, Electromagnetic balance type loadcells are used whereas for general industrial applications, strain gauge type loadcells are used.

1.5 Project background

In Unilever Horana factory in Sri Lanka, there is a checkweigher machine installed in common conveyor from which all the products are flowing through before palletizing station. it measures the weight of all corrugated boxes including personal products such as signal toothpastes and shampoo bottles. When all the lines are running at 100 % efficiency, there are 30 corrugated boxes per minute flowing through the common conveyor system. Existing checkweigher machine has an error of more than ± 100 g. Due to this amount of error, there are customer complaints of short packs. Hence Unilever management wanted to do the improvements to the exiting roller type conveyor checkweigher machine to improve the accuracy. But due to the huge vibrations of roller conveyors, implementing software filtering methods did not work at all. Before implementing a filtering method, there should be improvements in mechanical setup of the machine. Hence it was decided to design and build new checkweigher machine doing changes such as using belt type conveyors instead of roller type conveyors and use of drum motors instead of conventional type induction motors. With these modifications vibrations can be minimized. Electrical system such as PLC unit, HMI and loadcell system would be remained same and existing filtering algorithm would be used for the newly designed machine as well. After observing the accuracy level of new machine with same filtering algorithm, further actions would be taken to achieve the ultimate target of ± 2 g. The new checkweigher machine has achieved accuracy up to ± 20g with 30 units per minute and belt speed is 575 mm/s. when the belt speed is increased more than 575 mm/s, accuracy further drops due to disturbances generated by the vibrating parts of the checkweigher system which may be reflected in the loadcell weight signal which is coming the PLC. The conventional way of suppressing disturbances is by low-pass filtering. OEM inbuilt Filtering inside the load cell transmitter does not work due to high settling time which means when speed of the conveyor belt is high, the response of the applied filter does not settle fast enough to enable accurate weighing of objects in motion before it leaves the conveyor. Hence the requirement is to improve the accuracy up to ± 2 g so that underweight packages or short packs or missing products (single item in a box flowing through the production line has a minimum weight of 5 g) can be detected and rejected as a quality control mechanism in the production line with required belt speed which caters the production line speed of 36 units per minute. The figure 03 shows the technical specification of proposed checkweigher machine of accuracy of ± 20 g at 575 mm/sec conveyor belt speed. This machine does not detect the single unit weight products less than 20 g due to error of ± 20 g.

Distance	Description	Equation	Actual Values	Unit
A	Conv Length		1000	mm
B	Box Length		540	mm
C	One Box Alone Length	A-B	460	mm
D	Conveyor end to next box		125	mm
E	Pitch between boxes	A+D	1125	mm
F	Total Length		1400	mm
T	Loadcell settling time		0.8	s
V	Belt Speed	C/T	575	mm/s
T'	Time between boxes	E/V	2.0	s
	UPM	60/T'	30.7	UPM

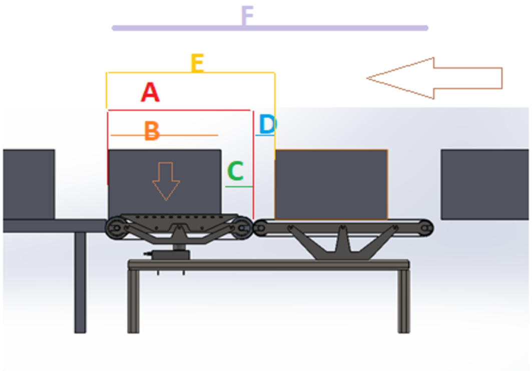


Figure 3: Technical specification of existing checkweigher

Weighing conveyor length is 1000 mm and maximum box length is 540 mm. Hence as per the above figure 03 calculation, maximum belt speed is achieved is 575 mm /sec with ± 20 g accuracy. When the speed of conveyor belt is increased, accuracy level further drops. hence the proposed machine can only handle up to 30 boxes per minute. But when all the lines are running at 100 % efficiency, expected line speed is 36 boxes per minute. Hence proposed checkweigher machine cannot handle the boxes at 100 % efficiency of lines. Hence speed of the belt should also be increased without compromising the accuracy of machine.

Figure 04 & 05 shows the customer complaints due to the quality related issues. Out of all the quality defects, pack shortage is the top-quality issue. Pack shortage means missing products inside the corrugated boxes. For example, 40 g signal tube corrugated box consists of 144 numbers of 40 g signal tubes. If one tube is missing, it should be detected by the checkweigher machine and should automatically rejected since this machine is the last quality control point before the market.

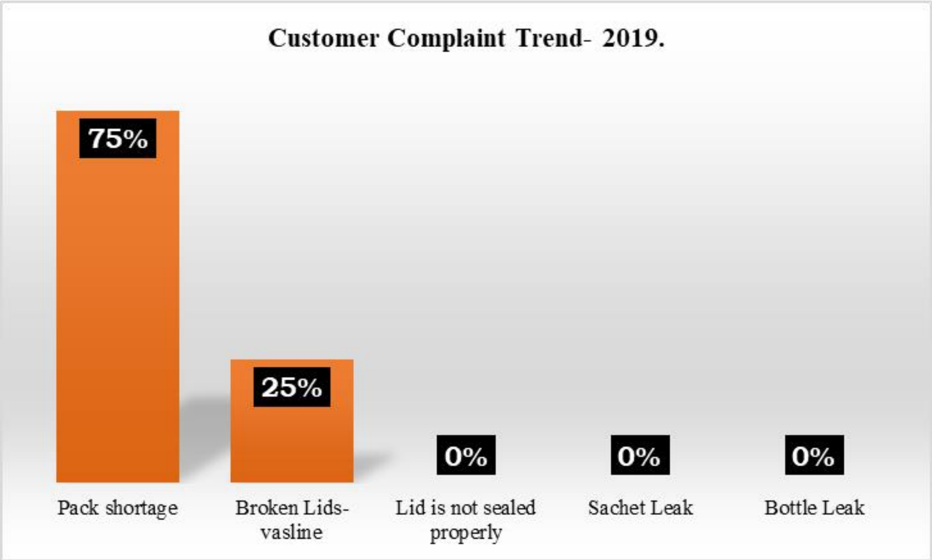


Figure 4 : Customer Complaints trend 2019 **[4]**

As per the figure 04 and 05, it shows that highest customer complaints in 2019 and 2020 are short packs. In 2019, pack shortage is 75 % and in 2020 it is 45 %. This is the top-quality issue that Unilever has faced during last couple of years when past data is analyzed. Hence there is a requirement of improving the accuracy of existing machine up to ± 2 g, so that missing single units of all the product variants are detected. With this Unilever is expecting to eliminate underweight products or missing products, flowing the to the market and 100 % compliance on not receiving of customer complaints on short packs or underweight products in year 2022.

Currently there are around more than 500 complaints on short packs annually from the market. Hence Unilever needs to improve the weighing accuracy of machine, so that short packs complaints can be eliminated.

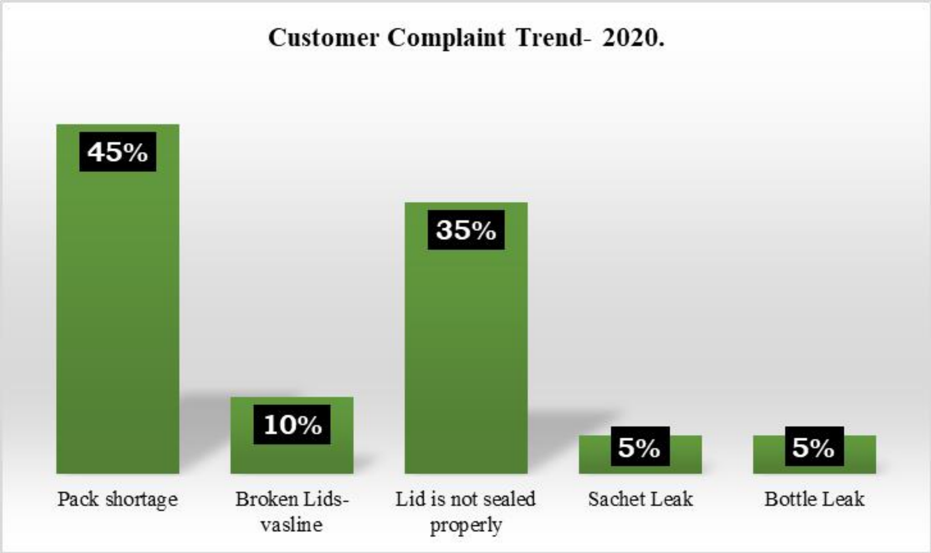


Figure 5 : Customer Complaints trend 2020 **[4]**

1.6 Research Aims and Objectives

The overall objective of the study is to design, simulate and implement a strain gauge type load cell based checkweigher system with improved speed of operation and accuracy. The focus of this research is to develop a better signal processing method that improves the accuracy of measurements by using the following methodology.

1. Dynamic weighing machine weight signal profile study in frequency domain and find out the main factors such as noise frequencies that affect the accuracy of the dynamic weighing system
2. Based on the signal profile analysis, applying different digital filtering methods such as Notch filter, low pass FIR, and low pass IIR filters to suppress the noise.
3. Derive and present the exact model of the load cell based dynamic weighing system
4. Model based approach to improve weight accuracy such as Kalman filtering method to achieve further accuracy improvement.
5. Finally implementing the best selected approach in the real system and present simulation and experimental results.

1.7 Thesis Overview

This thesis consists of eight chapters and content is briefly explained.

Chapter 1: In this chapter it introduces the thesis and discusses the project background and the problem statement which inspired the research component. Then, the main objectives of the thesis and the methodology of achieving the objectives are discussed in detailed.

Chapter 2: In this chapter modern trends of dynamic weighing technology and new innovations, challenges are discussed. Also, the influencing factors for the accuracy of the machine such as temperature, vibrations, air flows and electronic interferences are also discussed. Finally, methods explained in recently published research paper on improving accuracy of dynamic weighing machines are discussed in detail.

Chapter 3: In this chapter exiting checkweigher machine construction and related issues of the machine and existing control logic of filtering methods are discussed.

Chapter 4: In this chapter, new design of proposed checkweigher machine is discussed. Machine construction, pull load calculation of conveyor belts, drum motor selection, electrical system and experimental weighing results of applying the old machine weighing algorithm is discussed.

Chapter 5: In this chapter weight signal profile is analyzed using fast Fourier transform to identify the highest noise components at the different status of the check weigher machine.

Chapter 6: In this chapter, based on the analysis in chapter 05, different types of digital filters such as notch filter, FIR low pass filter and IIR low pass filters are tried out for better accuracy and simulation results are discussed in detail.

Chapter 7: In this chapter, model-based approach of improving accuracy up to ± 2g is discussed. Two models of checkweigher machine are discussed and finally the best model is used to apply the Kalman filtering method.

Chapter 8: In this chapter, simulation results of Kalman filtering and digital filters are discussed and comparison is done using key factors such as settling time, standard deviation and mean of filtered data set. Experimental results of applying Kalman algorithm to the real system is also discussed in detail.

2. LITERATURE REVIEW

2.1 overview

During past years, much research is done, and papers are published on dynamic weighing systems. In these papers, they have introduced in many ways to extract noise components from weight signal using different filtering methods such as LQG filters, fuzzy logic filters, Kalman Filters and Artificial Neural networks. The rest of this chapter discusses the various solutions proposed in previous years.

2.1 Challenges and Innovations of dynamic weighing systems

The primary objective of dynamic weighing is to measure the weights of a lot of products quickly and accurately. This depends on three factors namely production throughout, the product length, and the standard deviation. These factors connect as a triangle which when we alter one parameter, it affects rest of the two parameters. Production throughput means how many products per given time in production line. For example, Units per minute. When product throughput is higher, conveyor speed increases and it becomes dynamic weighing conveyor to deliver precision weight results. Also, standard deviation become higher when production output increases. When products are flowing closer together, UPM is higher, since a lot of products could flow on conveyor the line at the same conveyor speed. When distance in between products is reduced it gives more stress to loadcell system and allow less time and samples to weigh each product which reduces the precision of weighing system. When precision is less, standard deviation becomes higher. The standard deviation is a measure of number of variations of weights with repeated measurements of the same product. In order to reduce the standard deviation two options are available. They are either by increasing the distance between products or slowing down conveyor speeds. Finding the balance of these three factors would be challenge for any checkweigher machine developer. [3]

2.3 Methods of Dynamic Weighing

Strain gauge and Electromagnetic Force Restoration are the two load cell designs which are commonly used in modern dynamic weighing (Specially in checkweighers). In addition, there is x-ray weighing which is commonly used. A strain gauge load cell uses 4 strain gauges which would deflect proportional to the force placed upon it This also includes sensors to determine the changes in shape due to the spring deflection. Voltage signal will be generated proportional to the load on it. The figure 06 show how a strain gauge loadcell determine the weight of load upon it due to the deflection of loadcell strain gauges.

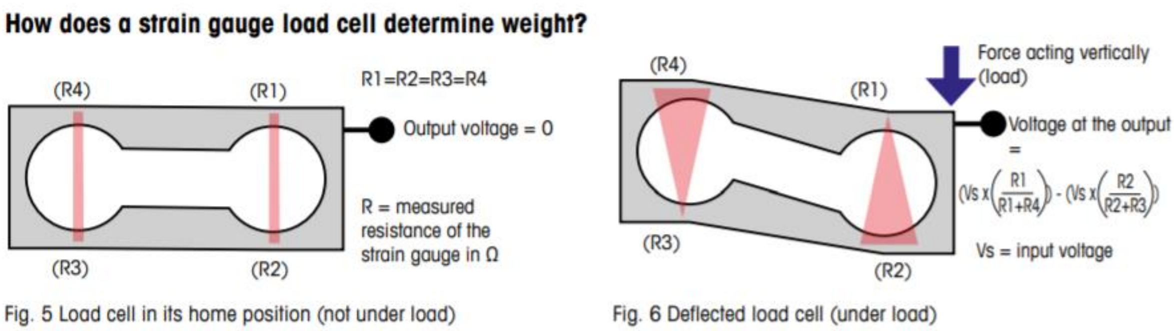


Figure 6 : Strain gauge loadcell construction **[3]**

An EMFR load cell utilizes the force generated by a current going through a coil placed upon a magnetic field. There is a displacement sensor which measures the actual displacement and loadcell controller injects the current to get the coil into its original position. The amount of current is proportional to the force required to get the coil back to its original position and with current measurement, weight of the product is estimated.

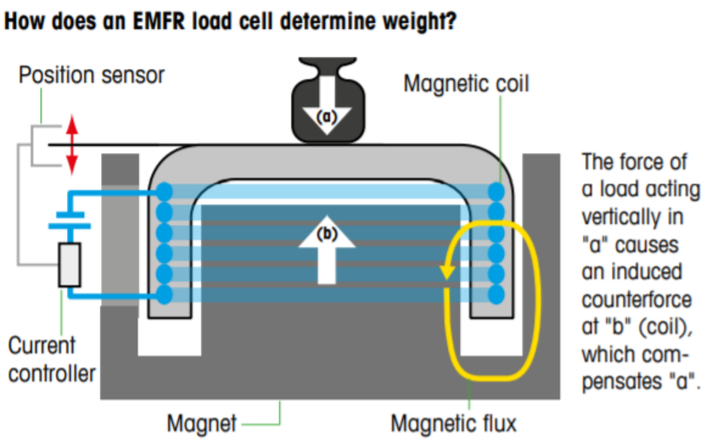


Figure 7 : Deflected Electromagnetic force restoration load cell **[3]**

strain gauge loadcells are best applicable for low-speed conveyor speeds for end-of-line applications such as completeness checks, detecting short packs whereas EMFR load cells are well suited for checkweigher applications where weighing measuring accuracy is more important. [3]

2.4 influencing factors for dynamic weighing's effectiveness

There are many root causes of weighing errors in check weighers. The accuracy level of a dynamic weighing machine is affected by the industrial environment and different characteristics of the product. The factors such as temperature, corrosive environments, ground vibrations, air flows and electromagnetic interfaces affect the weighing accuracy. Varying temperatures can show inaccurate. Any foreign matters such as oil, acid or perfume can damage the load cell. Also welding jobs cause loadcell damages. Dust particles which can lead to deposit on weighing conveyor may cause inaccurate measurements. Hence frequent cleaning or auto zero initialization should be done in defined intervals in the checkweigher. Mechanical Vibrations or ground vibrations can cause

inaccurate results.

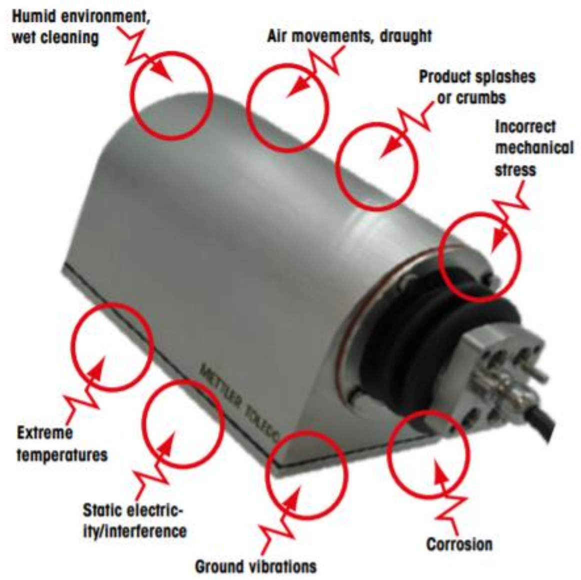


Figure 8 : Factors affecting loadcell Accuracy

Also, air streams towards the weighing conveyors may cause fluctuations in weighing results. Hence conveyor system should be covered to minimize the effects from air streams. Electrical noise or electromagnetic interferences can distort the weighing signal from loadcell to the transmitter and from transmitter to the intelligent controller. Hence proper grounding system with Screening/shielding cables should be used. There is a risk of damaging loadcells in corrosive environments. Hence special care should be taken when checkweigher is installed in corrosive or hazardous environments.

2.5 previous research done on improving accuracy of dynamic weighing

M. Halimic and W. Balachandran presented [5] a solution to filter the signal from load cell based checkweigher system by Kalman filter. In this paper it is discussed developments in filtering increases the speed of weighing and improves the measurement accuracy and a Kalman filter is proposed to suppress noise component of the dynamic weighing system. Also, the paper describes mathematical models of dynamic weighing system with forcing functions. For one particular weight of product, the parameters of the model need to be changed which means parameters are time-varying due to the product length and time of measuring in weighing belt. Hence the system becomes non-linear due to each product filter and model parameters should be changed. Hence an adaptive filtering approach has been considered in this paper. The simulation and experimental results are presented and compared. However, this kind of method can be successfully implemented on a specific system setup. but this adaptive Kalman filtering method is not suitable for general industrial type checkweigher systems. It requires repeated tuning the entire system and find out best fitting parameters for the model. Also, this paper it does not explain how to integrate the measured signal into the system controller.

M. Halimic, W. Balachandran, M. Hodzic, and F. Cecelja [6] has presented a paper on Performance improvement of dynamic weighing systems using linear quadratic Gaussian controller. The paper has presented two main objectives. They are to improve the weighing process by increasing the speed of weighing process and achieving good measurement accuracy. They used an integrated control and filtering approach. The Linear Quadratic Gaussian method was utilized to integrate the control design and noise filtering of the dynamic weighing process. Finally, the system designed was simulated and simulation results were shown. However, in this paper, it is not clearly mentioned how to integrate desired control method to practical dynamic weighing system.

M. Halimic, W. Balachandran, and Y. Enab [7] has presented Fuzzy logic estimator for check weigher system to filter the weight signal. The concept used in this paper is fuzzy space clustering which is the structure of a fuzzy estimator. This means that the input-output space of the fuzzy space is clustered. By applying this type of filter has increased the accuracy and precision of weighing system thereby, improving the results for repeated measurements. But the granularity of the filter affects the measurement accuracy. This fuzzy logic method has heavily depended on the physical parameters of product and the initial conditions of checkweigher system. For each product these settings should be altered which is challenging in practical implementation.

Maciej Nied ́zwiecki and Przemysław Pietrzak [8] has presented a paper on high precision FIR-Model-Based dynamic Weighing System. The approach proposed in this paper can be characterized as a filtering scheme based on the finite impulse response model of the weighing system response. The proposed approach was developed for a conveyor belt checkweigher. FIR filter parameters such as degree of freedom, order and cut off frequency are adaptive based on the characteristics of the product. FIR filter is applied to the model derived for the dynamic weighing system. However, this method is tested for only the weights less than 800 g.

R. Tasaki, T. Yamazaki, H. Ohnishi, M. Kobayashi, S. Kurosu [9] has presented a paper on Continuous weighing on a multi-stage conveyor belt with FIR filter. In this paper, it is explained how the continuous mass measurement is done using the multi-stage conveyor belt type weighing conveyors and main objective is to improve the measurement precision. The system is modelled as a dynamic model and simulation results are shown. The simulation results give satisfactory measuring accuracy. Also, experiments are carried out Using an actual multi-stage conveyor belt scale. But experimental results are not satisfactory as simulation results. This has complicated mechanical setup with three weighing conveyors. The measurement method is established for the multi-stage conveyor belt scale by filtering the weight signal via a FIR digital filter. There should be not any level difference between the back-and-forth conveyors. Thus, these geometric deviations do not make the weight distribute uniformly. Hence there are issues when practical implementation of this kind of complex mechanical setup.

Yasin & White [10] has presented a paper on a technique based on artificial neural network. The loadcell based dynamic system has been modelled as a non-linear system. The unknown load is the input to the dynamic model and loadcell generated voltage signal is the output of the non-linear system. Using known weights neural network algorithm has been trained. Weights used for training the neural networks are 150 g, 350 g, 550 g, 750 g and 950 g. It is observed that there is a error of ±1.5%. These results were then practically verified by repeated experiments carried out on the prototype dynamic weighing machine and observed that a maximum error of ±1.5% is there with different conditions of the weighing system. But in this paper speed of weighing system is not mentioned.

2.3 Summary

The different authors have presented a new method for dynamic weighing systems. However very little information is available on speed of the weighing conveyor and its relationship with weighing accuracy. There are many methods can be found to improve the weighing accuracy as per the literature. Some methods are model-based, and some use a model-free approach. In the model-based approach, the strain gauge load cell system has been modelled as spring -mass system and derive differential equations with respect to the time variable. differential equation with respect to the time variable.

The methods proposed can be classified as follows

- Model based approach method.
- Neural network method.
- Fuzzy logic estimator.

Advantages and disadvantages of each method were discussed under each method.

3. EXISTING DYNAMIC WEIGHING SYSTEM

3.1 Existing Checkweigher machine construction

The existing weighing system consisted of an in-feed roller conveyor, weighing roller conveyor and out-feed roller conveyor as per the following figure. Finished products are transported over the end of line conveyor system and roller conveyor type check weigher machine check weigher machine was located at the end of conveyor system before the cobot palletization area. Single strain gauge type loadcell was mounted on the weighing roller conveyor and barcode reader was mounted in infeed roller conveyor.

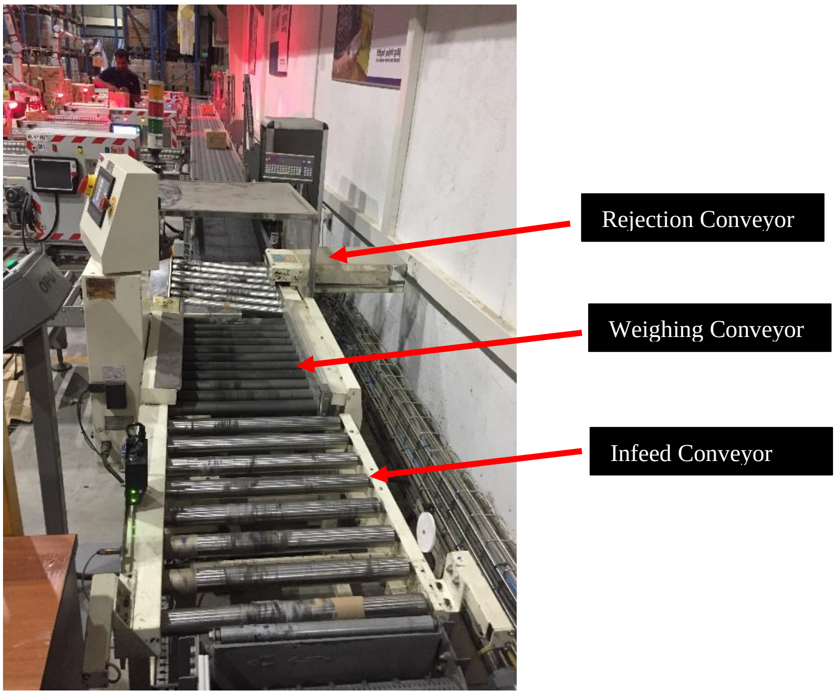


Figure 9 : Existing Roller type Checkweigher Machine

Infeed Conveyor is used as an indexer to create gap in between products allowing each product to pass weighing conveyor without entering the next box until previous box is fully exited the weighing conveyor. Weighing roller conveyor is mounted a strain-gauge load cell and data is transmitted to PLC via serial data cable.

A Rejecting conveyor rejects whatever the short, packed products detected by the system.

3.1 Issues with exiting checkweigher machine

When the same product corrugated box was sent through the existing checkweigher arrangement, significant different in the weight of the same corrugated box is observed. Example is shown as below figure 10. In this case barcode no. 195, which is Fair & Lovely men 25 g face wash tube is selected. There are 172 units per one pack and total target weight of the corrugated box is 6900 g as per the calculation sheet shown in table 01.

Barcode Number	Discription	Pack Size	Units per case	Empty Corr:Box Weight	Shrink Film Weight (g)	Product Weight min	Product Weight target	Product Weight max	Empty Tube	Empty Carton	Min weight (1 Unit)	Target weight (1 Unit)	Max weight (1 Unit)	Coru: Box Min Weight	Coru: Box Target weight (kg)	Coru: Box Max Weight
195	Fair & Lovely Men	25g	172	370	0	25.2	25.5	25.8	6.2	6.2	37.6	37.9	38.2	6837	**6889**	6940

Table 1 : Target Weight Estimation of Corrugated Box

As per below two readings, signal 40 g same corrugated box (total weight of 6900 g were sent twice through the checkweigher system and two different readings were observed.

Figure 10 : Machine HMI readings for Same Weight Box of 6900 g

First reading was 6915 g with 15 g error and second reading was 7044 g with 144 g error. There is 129 g difference between the two readings. This means that with second weight reading, error is more than weight of 4 nos. of 25 g Fair & Lovely facewash tube pack. The purpose of this machine is to detect short packed corrugated box, but with this much of error, it cannot detect even 4 packs are missing. This kind error is not acceptable. Load cell calibration was done and but there is no improvement in readings. At the same time there was no better repeatability in the system. Also, the load cell is mounted on a roller conveyor. There are lots of vibrations while the product is passing through the weighing conveyor. This would badly affect the accuracy of the weight reading. At the same time, it seems the checkweigher influences by many factors such as sensitivity to temperature, noise contributed by systems and measurements which causes error readings. The noise comes from mechanical and electrical part of weighing system and from the type of the product. Significant contribution to the noise comes from the speed of the conveyer belt. It is very difficult to eliminate these factors using various inbuilt OEM filtering methods in loadcell transmitter. Hence the speed of the weighing belt cannot increase further to cater the line speed which is currently about 30 units per minute.

This causes lots of jamming in the infeed conveyor which leads to damages of corrugated boxes. In conclusion there are two issues with machine. First one is that the accuracy is very low. Second issue is that checkweigher conveyor speed cannot be increased further to cater the line of speed of 30 units per minute.

Another issue with machine is frequent zero calibration is required this machine. This is due to the sealing tapes of the corrugated boxes are entangled with rollers and tape is pasted on the conveyor rollers. This would affect the initial zero calibration. After removal of tapes, again zero calibration should be performed. This has to be done frequently since machine is running continuously. This is a operator dependent task and any ignorance form operator can lead to wrong weight readings.

3.3 Existing Control Logic

There is a stopper before infeed conveyor which is used to feed one box at a time to the infeed conveyor. This is controlled by PLC, based on the sensor input near the stopper. When sensor triggers (rising edge) stopper goes down and let the box comes inside the infeed conveyor and at the falling edge, stopper goes up to stop next box entering the infeed conveyor simultaneously. This stopper creates a gap between two boxes, so that only one box will be there in weighing conveyor at a time. Barcode scanner which is installed in infeed conveyor detects the barcode value and sends that value to PLC via serial port. Then the PLC program loads pre-entered settings for that particular box such as length of the box, target weight, upper weight limit and lower weight limit, so that measured weight value can compare with target box weight and if it is not within the limits, box can be rejected in rejection conveyor. When box is entered from infeed conveyor to weighing conveyor, loadcell transmitter starts sending data to PLC at a speed of 200 measurements per seconds. Box will travel through weighing conveyor for 2 seconds; hence 400 samples of weights are sent to PLC. PLC is using a passive algorithm to determine the weight of the box. It does not use any noise filtering algorithm due to setting time. When loadcell transmitter OEM inbuilt lowpass filters are used, filter is not settled before exit of box and next box is already entered before settling the previous weight signal. The figure 07 shows how OEM inbuilt filter behaves with cut off frequency. When we use the low cut off frequency (LPF1), filter response exceeds the length of weigh period (tw). When we use high cutoff frequency (LPF2), there are more ripples in filter response. Hence conventional low pass filtering method is not working for high-speed conveyor belt type check weighers.

Hence currently the following internally developed passive algorithm is used inside the PLC to estimate the weight of the box.The table 12 shows the sample calculation of the passive filter algorithm. Below it is explained how filter works. In column A it shows the raw data coming from loadcell transmitter to PLC. Inside PLC above calculation is done. Stage 1 filter shows in column B which is the addition of 80 % value of previous estimated value and 20% of present raw data value. Then stage 2 value is calculated from stage 1 value and present value. In stage 2 filter it compares present value and estimated value, if the difference is greater than 200 g, it keeps the present value as weight value or else stage 2 filter value is stored.

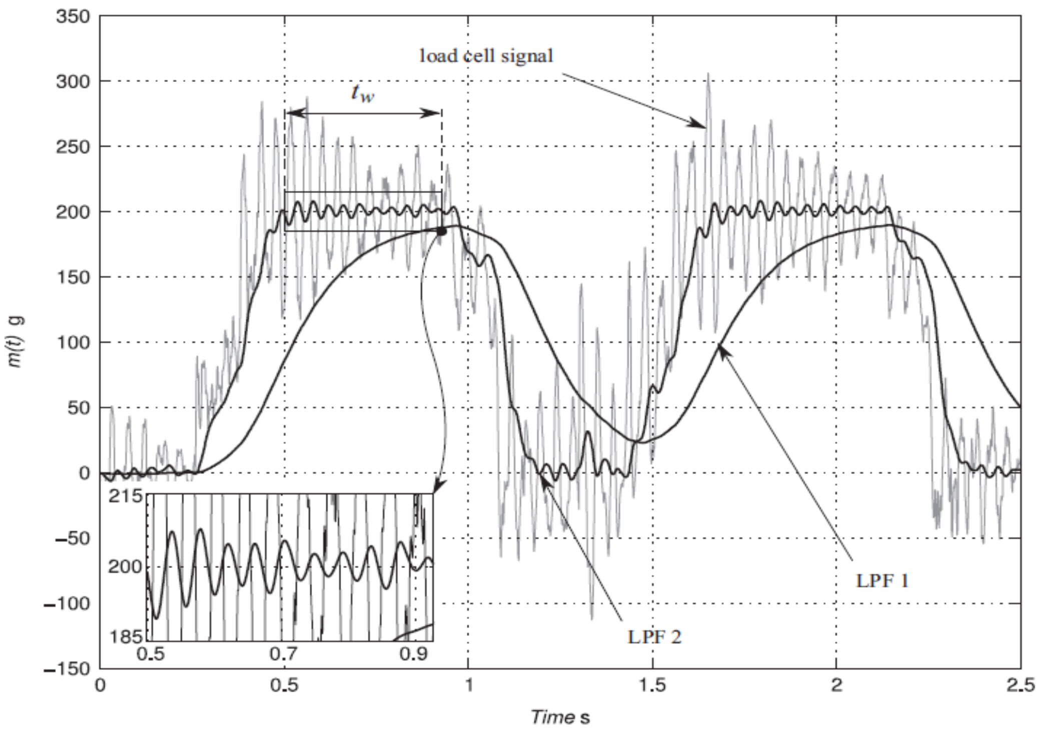


Figure 11: Conventional Low Pass Filtering by inbuilt OEM software

With this kind of algorithm, high variations of actual signals are removed. When 2nd stage filter value gives continuously same value for certain amounts time, PLC decides, that value as the weight of the box. This is passive filtering methods and figure 9 shows graphically how filter works in stage 1 and stage 2. Although this filtering method is very logical theoretically, required accuracy level has not reached due to the huge mechanical vibrations of the exiting mechanical setup.

	Raw Weight Data	Stage 1 Filter	Difference	Absolute Difference	Stage 2 Filter
	100	80%			200
1	15.49	3.10	12.39	12.39	3.10
2	35.05	9.49	25.56	25.56	9.49
3	95.58	26.71	68.87	68.87	26.71
4	88.80	39.13	49.67	49.67	39.13
5	92.78	49.86	42.93	42.93	49.86
6	80.59	56.00	24.58	24.58	56.00
7	53.69	55.54	-1.85	1.85	55.54
8	48.18	54.07	-5.89	5.89	54.07
9	31.59	49.57	-17.99	17.99	49.57
10	66.06	52.87	13.19	13.19	52.87
11	100.08	62.31	37.77	37.77	62.31
12	179.24	85.70	93.54	93.54	85.70
13	290.02	126.56	163.46	163.46	126.56
14	319.76	165.20	154.56	154.56	165.20
15	389.18	210.00	179.18	179.18	210.00
16	372.89	242.58	130.31	130.31	242.58
17	451.99	284.46	167.53	167.53	284.46
18	468.74	321.32	147.42	147.42	321.32
19	502.52	357.56	144.96	144.96	357.56
20	530.38	392.12	138.26	138.26	392.12

Figure 12: Calculation method of Passive Filter

Figure 13 shows the graphical representation of how passive filter works. Blue color plot shows the raw data received from loadcell transmitter. Orange color plot shows the stage 1 filtered data set. Yellow color plot depicts the stage 2 filter which the outcome of the algorithm. This logic is implemented inside the PLC and in the flat region, one value is taken as the weight of the box which is used for the comparison with target weight of the box.

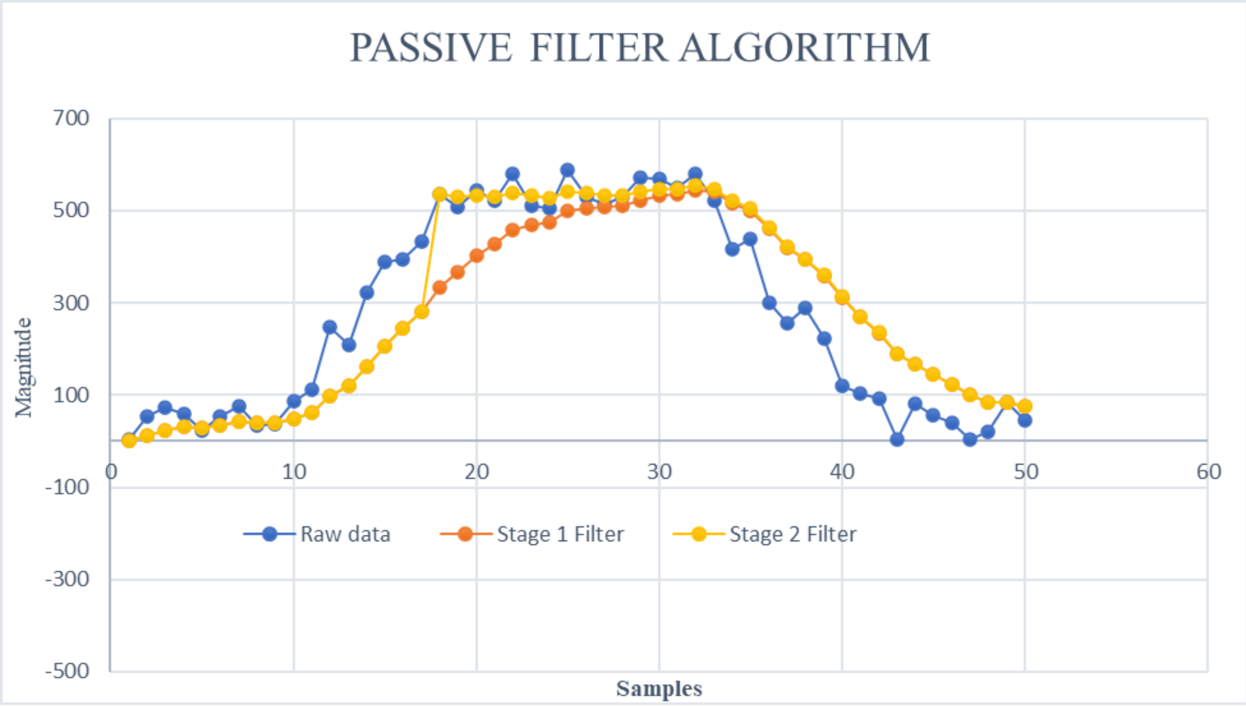


Figure 13: Passive Filter Algorithm in Existing system

3.5 Summary

Existing dynamic weighing system is a roller conveyor type weighing system with lots of mechanical vibrations. By applying software filters in the PLC logic, it is very difficult to suppress the noises, arising from the roller vibrations. This vibration noise is embedded in the weight signal and weight signal is heavily distorted. Hence there is no valid point of studying the existing system and do software algorithm to suppress noise and improve the system. Best option is to improve the mechanical set up of the system first and then apply the exiting weighing algorithm, based on the accuracy level of improved mechanical system, further study can be done to improve the accuracy level up to ± 2g. It is suggested to design and build conveyor belt type checkweigher machine using the exiting electrical hardware setup such as electrical panel, PLC, HMI and loadcell system.

4. PROPOSED DYNAMIC WEIGHING SYSTEM

4.1 New design concept of dynamic weighing system

The new design was targeted to achieve weighing accuracy of ±20 g without any new weighing algorithm and utilizing the same electrical system. System was designed in a such a way that maximum weight can be measured by the new mechanical setup is 20 kg, maximum length of the Box is 540 mm, width of the belt is 500 mm, and the speed of the machine is 30 UPM. With the new design Inlet & Weighing conveyors are replaced with belt type and exit conveyor & rejection mechanism is kept as the same. Also, Existing pre inlet conveyor stopper mechanism integration would be the same as well. Rest of system functions such as Integrating with Barcode reader & Printer would be the same. One major change done with the new design was using drum motors instead of conventional conveyor motors such as geared induction motors. This is stabilizing the weighing conveyor uniquely without giving extra weight to one side of weighing conveyor. In addition, features such as conveyor tables tilting for easy & safe belt changing, quick motor replacement in case of failure, sheet metal-based welding free structure for easy modification in future and variable belt speed for different products identified by barcode to improve accuracy are added. The figure 14 shows the conceptual design of checkweigher machine modelled using solid works software. It also shows new added features such as tilting mechanism for easy belt replacement. Also, the new design includes adjusting screws which can be used to adjust the belt tension whenever required. Both infeed and weighing conveyor system is mounted on the same structure which is fabricated using laser cutting.

Figure 14 : New Concept Design of Checkweigher modelled by solid works

4.2 New checkweigher design calculations

Unilever requirement is to design, installing and commissioning of 30 units per minute speed and ± 2g accuracy level 20 kg loadcell based check weigher machine. Based on these requirement and space availability of production line to determine the length and speed of the weighing conveyor. There will be no sagging of weighing belt since belt is driven on a flat surface.

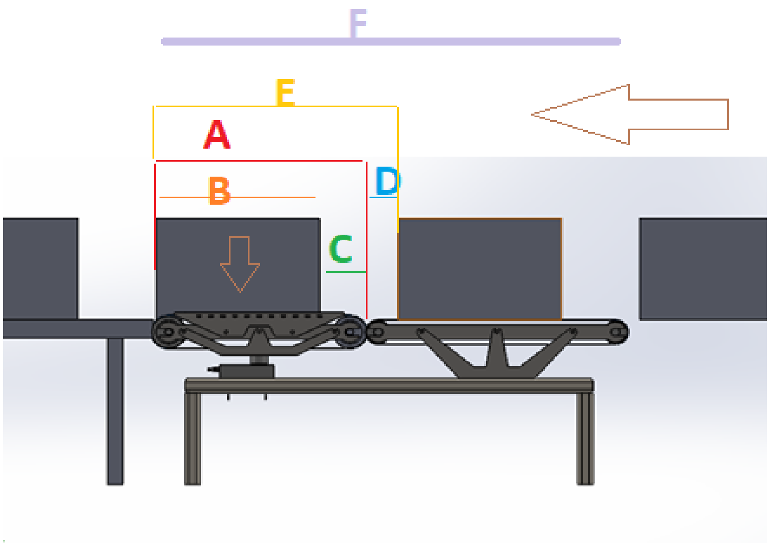


Figure 15 : Design Parameters of conveyor system

Where.

A = Weighing conveyor length

B = Maximum Box Length

C = One box alone length (C= A- B)

D = Conveyor end to next box

E = Pitch between boxes

F = Total length

T = Loadcell setting time

V = Required belt speed

T' = Time between boxes

UPM = Units per minute (speed of the check weigher)

The following table shows the sequence of back calculation done to determine the conveyor length and speed of weighing machine.

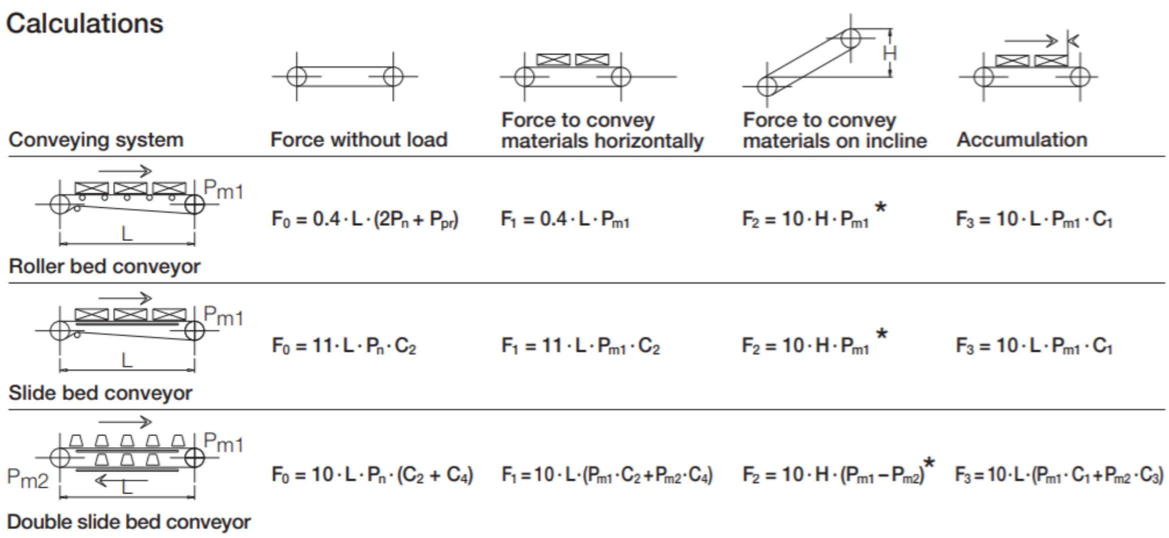
Distance	Description	Equation	Actual Values	Unit	Remarks
A	**Conveyor Length**		**800**	**mm**	**Designed parameter**
B	Box Length		540	mm	Maximum box length
C	One Box alone length	C= A-B	260	mm	
D	Conveyor end to next box		125	mm	Selected based on space availability
E	Pitch between boxes	E= A+D	1125	mm	
F	Total Length		1400	mm	Selected based on space availability
T	Loadcell settling time		0.8	sec	By loadcell data sheet
V	**Belt Speed**	**V= C/T**	**600**	**mm/s**	**Designed parameter**
T'	Time between boxes	T= E/V	2.0	s	
UPM	Units per minute	UPM =60/T'	30.7	UPM	

Table 2 : Sequence of calculation to determine weighing conveyor length and speed

4.3 Belt pull load calculation and drum motor selection

The following equations are used to calculate the belt pull load. Based on the calculation results, drum motor is selected using the manufacturer’s data sheet. The figure 16 shows the list of equations for conveyor belt pull load calculation.

F = Belt pull (N): $F = F_0 + F_1 + F_2 + F_3$



Belt pull calculation

F	= Belt pull [N]. $F = F_0 + F_1 + F_2 + F_3$ The belt pull [N] for the drum motors is shown in the respective tables	
P_n	= Belt weight per linear meter	[kg/m]
P_{pr}	= Weight of rotating parts of the belt conveyor (carrying and return section) per meter length	[kg/m]
P_{m1}	= Weight of the conveyed product on the load section, for each meter of length of the belt conveyor	[kg/m]
P_{m2}	= Weight of the conveyed product on the return section, for each meter of length of the belt conveyor	[kg/m]
C_1	= Coefficient of friction between product and belt carrying side	
C_2	= Coefficient of friction between belt carrying side and slider bed	
C_3	= Coefficient of friction between return belt and product	
C_4	= Coefficient of friction between return belt side and slider bed	
L	= Centre-to-centre length	[m]
H	= Height difference in conveyor	[m]
F_0–F_3	= Force components for shown operating conditions	[N]

Figure 16 : Equations for Belt Pull load calculation

P_n = 1.1 kg /m ; Belt weight per linear meter

C_2 = 0.5 ; co-efficient of friction between belt carrying side and slider bed

L = 0.6 ; Centre to Centre length

$F_0 = 11 * P_n * C_2 * L$

$F_0 = 11 * 1.1 * 0.5 * 0.6$

= 3.63 N

F_0 is the free run load

P_{m1} = 41.7 kg /m ; Weight of conveyed product on the load section for each meter of length

$F_1 = 11 * P_{m1} * C_2 * L$

$F_1 = 11 * 41.7 * 0.5 * 0.6$

= 137.5 N ; Load with product

$F_2 = 0$; Load on inclined

$F_3 = 10 * P_{m1} * C_2 * L$

$F_3 = 10 * 41.7 * 0.5 * 0.6$

$F_3 = 175$ N ; When products are blocked on the conveyor

Hence belt pull load (F) would be as the follows.

$F = F_0 + F_1 + F_2 + F_3$

F = 3.63 + 137.5 + 0 + 175

F = 316. 1 N

Drum motor power requirement can be calculated considering the belt speed as V = 700 mm / sec using below equation

P = F*V

P = ($F_0 + F_1 + F_2$) * V

P = 143.13 * 0.7

P = 98.8 Watts : Without slipping or blocking of boxes

P = ($F_0 + F_1 + F_2 + F_3$) * V

P = 221.3 Watts : With slipping or blocking of boxes.

In summary pull load is calculated as 316.1 N and motor power is calculated as 221.3 W.

INTERROLL
DRUM MOTOR 113i

Product Range

The following tables give an overview of the possible motor versions. When ordering, please specify the version in accordance with the configurator at the end of the catalogue.

All data and values in this catalogue refer to 50 Hz operation.

Motor versions

Mechanical data for 3-phase motors (Standard motors)

P_N kW	np	gs	i	v m/s	n_A min^{-1}	M_A Nm	F_N N	SL_{min} mm
0.070	12*	3	43.49	0.048	8.1	77.4	1,363	300
			37.05	0.057	9.5	65.9	1,161	300
			31.96	0.066	11.0	56.9	1,002	300
0.080	8	3	43.49	0.093	15.6	45.8	808	250
			37.05	0.109	18.4	39.1	688	250
0.100	6	3	43.49	0.118	19.9	45.0	793	250
			37.05	0.139	23.3	38.4	676	250
0.150	8	3	37.05	0.109	18.3	73.6	1,296	300
	4	3	43.49	0.184	31.0	43.4	764	250
			31.96	0.251	42.2	31.9	562	250
			28.17	0.285	47.9	28.1	495	250
			24.00	0.334	56.2	23.9	422	250
			20.71	0.387	65.2	20.7	364	250
		2	15.17	0.529	89.0	15.4	272	250
			12.92	0.621	104.5	13.2	232	250
			11.15	0.720	121.1	11.4	200	250
0.180	6	3	43.49	0.125	21.0	76.9	1,356	300
			37.05	0.147	24.7	65.6	1,155	300
		2	11.15	0.488	82.1	20.1	355	300
0.225	2	3	43.49	0.386	64.9	31.1	548	250
			31.96	0.525	88.3	22.9	403	250
			28.17	0.595	100.1	20.2	355	250
			24.00	0.699	117.5	17.2	303	250
			20.71	0.810	136.2	14.8	261	250
		2	15.17	1.105	186.0	11.1	195	250
			12.92	1.297	218.3	9.4	166	250
			11.15	1.504	253.0	8.1	143	250
0.300	4	3	43.49	0.188	31.6	85.1	1,500	300
			31.96	0.256	43.1	62.6	1,103	300
			28.17	0.290	48.8	55.2	972	300
			24.00	0.341	57.3	47.0	828	300
			20.71	0.395	66.5	40.5	714	300
		2	15.17	0.539	90.7	30.3	534	300
			12.92	0.633	106.5	25.8	455	300
			11.15	0.733	123.4	22.3	392	300
0.370	4	3	24.00	0.322	54.2	61.4	1,083	300
			20.71	0.373	62.8	53.0	934	300
		2	12.92	0.598	100.7	33.8	595	300
			11.15	0.693	116.7	29.1	513	300
	2	3	43.49	0.387	65.2	51.2	901	300
			31.96	0.527	88.7	37.6	663	300
			28.17	0.598	100.6	33.1	584	300
			24.00	0.702	118.1	28.2	498	300
			20.71	0.814	136.9	24.4	429	300
		2	15.17	1.111	186.9	18.2	321	300
			12.92	1.304	219.4	15.5	273	300
			11.15	1.511	254.3	13.4	236	300

Note: *Not suitable for all applications. Please contact your Interroll customer consultant.

Figure 17 : Drum motor manufacturer Data Sheet

Then using the manufacturer data sheet, commercially available drum motor was selected with the above highlighted parameters in figure 17.

Figure 18 shows the dimensions of newly designed check weigher machine as per the above calculations.

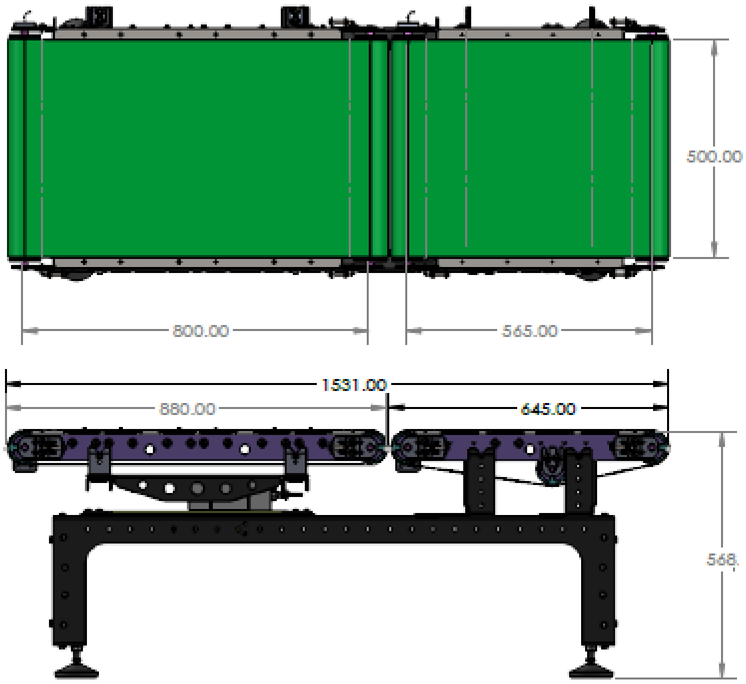


Figure 18: Checkweigher Construction

The specifications of new checkweigher machine which is built can be summarized as below.

Weighing Conveyor

- Length : 800 mm
- Width : 500 mm
- Speed : 700 mm/s
- Belt : PVC 2mm thick, Green Color
- Total weight on load cell : 28 kg
- Drum Motor : 225 W, induction 3 Phase 230V AC and 303 N load.
- VFD : Allen Bradley 525, 0.75kW 3 Phase 400V input
- Load Cell : Flintec 100 kg, Single Point
- Weight Transmitter : Flintec DAD 141.1 ASCII TCP used

Infeed Conveyor

- Length : 565 mm
- Width : 500 mm
- Speed : 700 mm/s
- Belt : PVC 2mm thick, Green Color
- Motor : 225 W, induction 3 Phase 230V AC and 303 N load
- VFD : Allen Bradley 525, 0.75kW 3 Phase 400V input

Figure 19: Newly designed and Built checkweigher Machine Unilever Horana Factory

The above figure shows the actual installation in factory and the detailed analysis, and the study were done in this checkweigher system. All finished products from all the production lines go through this machine before palletizing, so that underweight or short packs packages are detected and rejected online. This is used as a critical quality control point in factory.

4.4 Machine Architecture

The following figure 20 shows the system architecture of checkweigher machine.

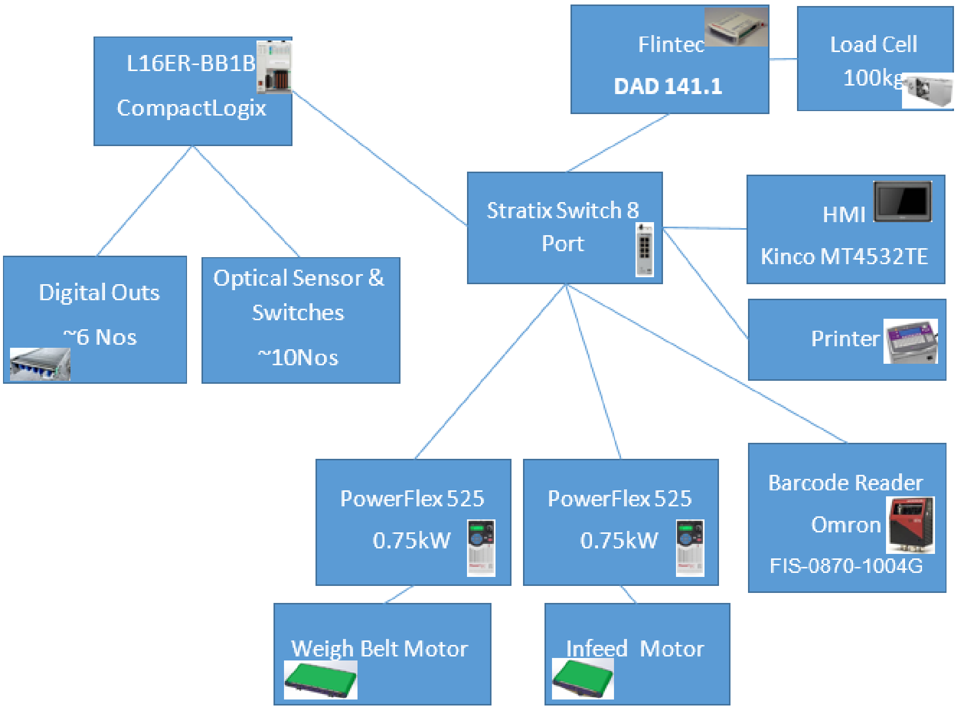


Figure 20: Checkweigher Machine system Architecture

In new machine PLC is used as the main controller. PLC used is Allen Bradley CompactLogix 5370 L1 controller with 2 Ethernet/IP, 384kb internal memory and 16 inbuilt Inputs/Outputs. 6 digital outputs and 10 digital inputs are utilized for this machine. 225 W, 3 Phase, 400 V drum motors which are used to drive weighing conveyor and infeed conveyor are, driven through PowerFlex 525 Ethernet/IP VFD drives. Flintec brand PCB-100 KG-M-C3 Y strain gauge type loadcell is connected to DAD141.1 Flintec loadcell transmitter and weight data is sent through ethernet/IP protocol around 200 measurements/sec speed to the PLC unit. Also, ethernet/IP communicated Omron FIS-0870-1004G Barcode scanner which is used to detect barcode value of the corrugated boxes is connected through ethernet/IP protocol to the PLC unit. In addition, Printer is connected via Ethernet to print the weight to the box and HMI is also connected through ethernet for operator assistance. All the major devices such as Loadcell transmitter, Barcode scanner, Printer, HMI and two VFD drives are ethernet devices and are connected via ethernet switch inside the panel. The figure 21 shows the physical arrangement of checkweigher machine control panel.

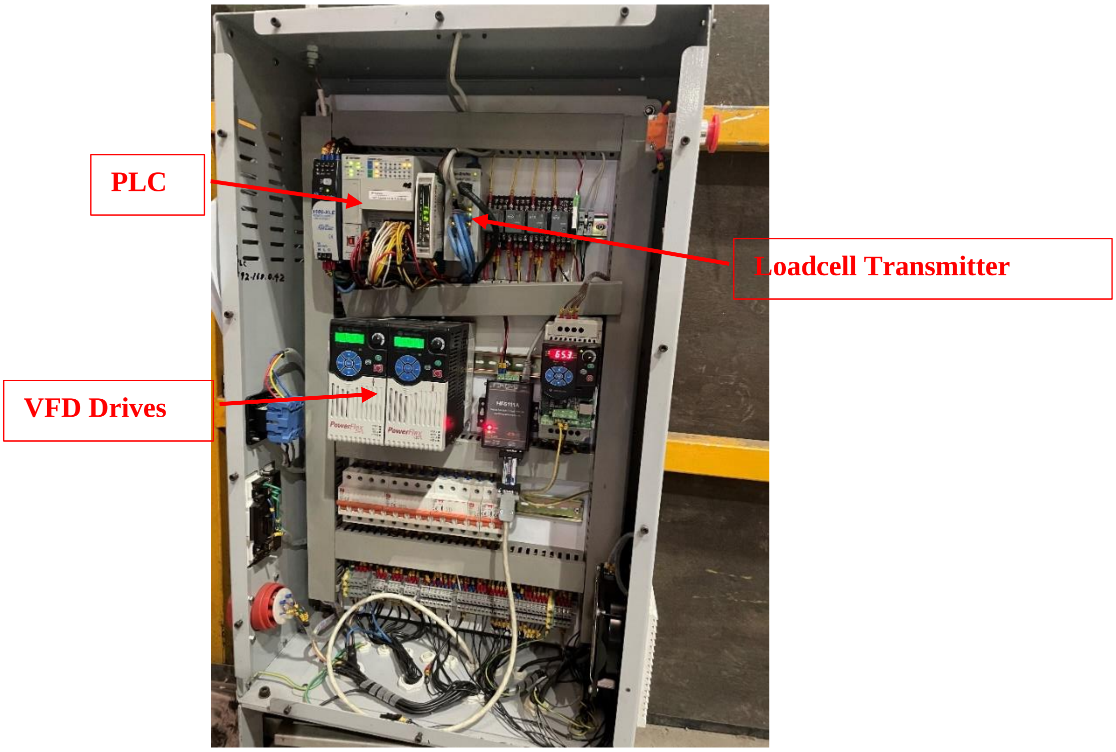


Figure 21 : Check weigher control panel

4.5 Control logic of the new system

The same control logic used for the previous dynamic weighing system which was described in section 3.3 was implemented in the improved system and accuracy was observed. With this filtering method, accuracy of weight value of any box is achieved up to ±20 g. With improved belt type conveyor system, mechanical vibrations are minimum. Hence with the exiting control logic, accuracy has achieved up to ±20 g with tests conducted with different types of weighed boxes.

4.6 Summary

After the site implementation of improved version of checkweigher machine with belt type conveyors and drum motors has achieved up to the accuracy level of ±20 g with the existing control algorithm inside the programmable logic controller. This is due to the minimization of mechanical vibrations aroused by roller conveyors in the previous system. But the target accuracy which is ±2 g is not achieved yet to eliminate the quality issue (short packs) of the Unilever products which is coming back from the market. Hence further study was conducted of the newly developed machine to achieve final target of ±2 g accuracy. In chapter 05 onwards, systematic approach of achieving of target accuracy is described in detail

5. WEIGHT DATA ANALYSIS FOR NOISE IDENTIFICATION

In this chapter loadcell signal profile is analyzed using fast Fourier transform considering all possible scenarios or status of the machine

5.1 Identifying Different Noise types that can affect the accuracy

There are different types of noises which are added in weight signal that is transmitted from loadcell transmitter to PLC. These noises may include noises due to motor vibration, electronic noises, belt transfer noises and natural frequency noises. When all these noises are added, weight signal is distorted. To analysis the impact of each noise type, different status of the checkweigher machine is considered and data is collected in different scenarios covering all status of checkweigher machine as below.

1. Conveyor Belt is stopped. This to identify any electronic noises in the system.
2. Conveyor Belt is running at different belt speeds without any load on it. For example, belt Motor Frequency Drive speed at 28 Hz ,30 Hz,32 Hz, 34 Hz and 36 Hz.
3. Same weigh box running at different belt speeds. For example, belt Motor Frequency drive speed at 28 Hz ,30 Hz,32 Hz, 34 Hz and 36 Hz.
4. Two different weigh boxes running at same belt speed of 575 mm/sec.
5. Same box running at same speed several times. This test is to analysis the repeatability of the system

Collected data of each scenario is analyzed in frequency domain by doing fast Fourier transform.

5.2 Different Status of Check weigher Machine

5.2.1 Conveyor Belt is stopped

Figure 22 shows the data stream obtained when the belt is stopped. In order to get a better understanding on noise frequencies, fast Fourier transform is performed in as shown figure 23. There is wide range of frequency components up to 30 Hz. But magnitude of noise frequency component is considerably very low. Hence the effect of electronic noises is considerably low in this matter and there is no point of applying filters for suppression of electronic noises.

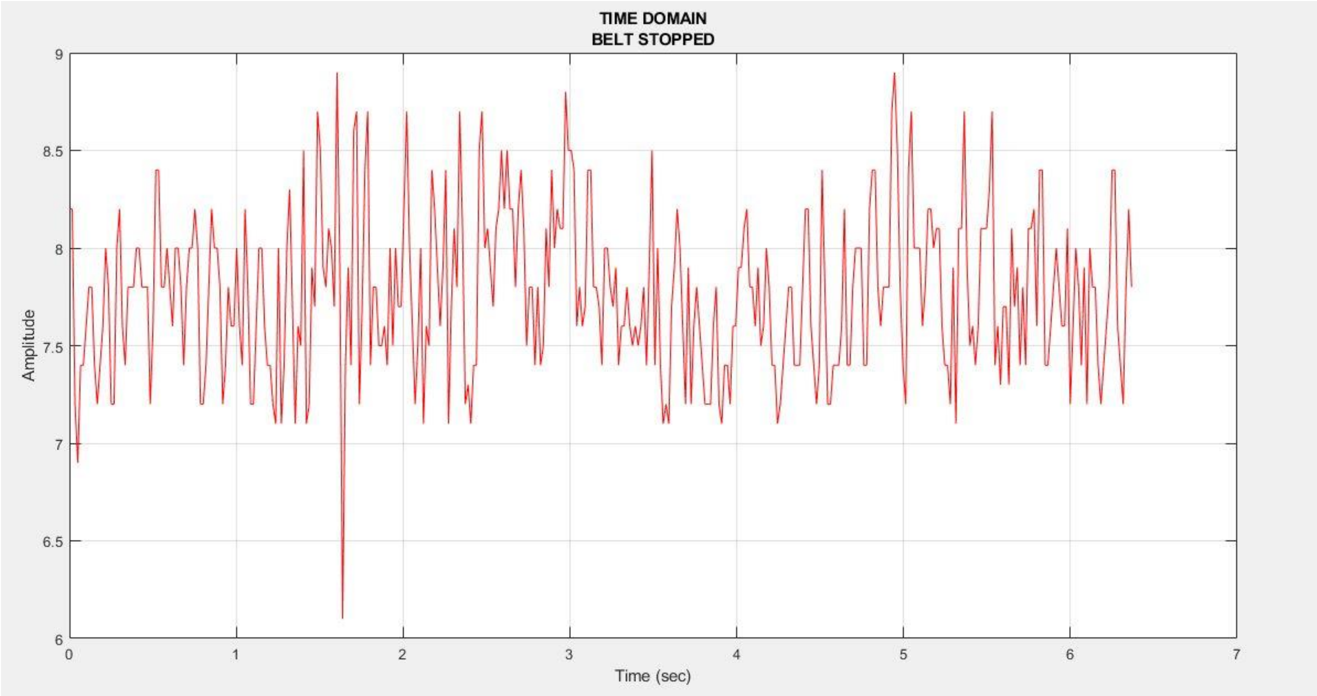


Figure 22: Weight Signal Time Domain-Belt stopped

The following figure shows the frequency spectrum of loadcell signal when conveyor belt is stationary. Since there is no movement, these noises due to electronics and environment factors such as temperature and air flows.

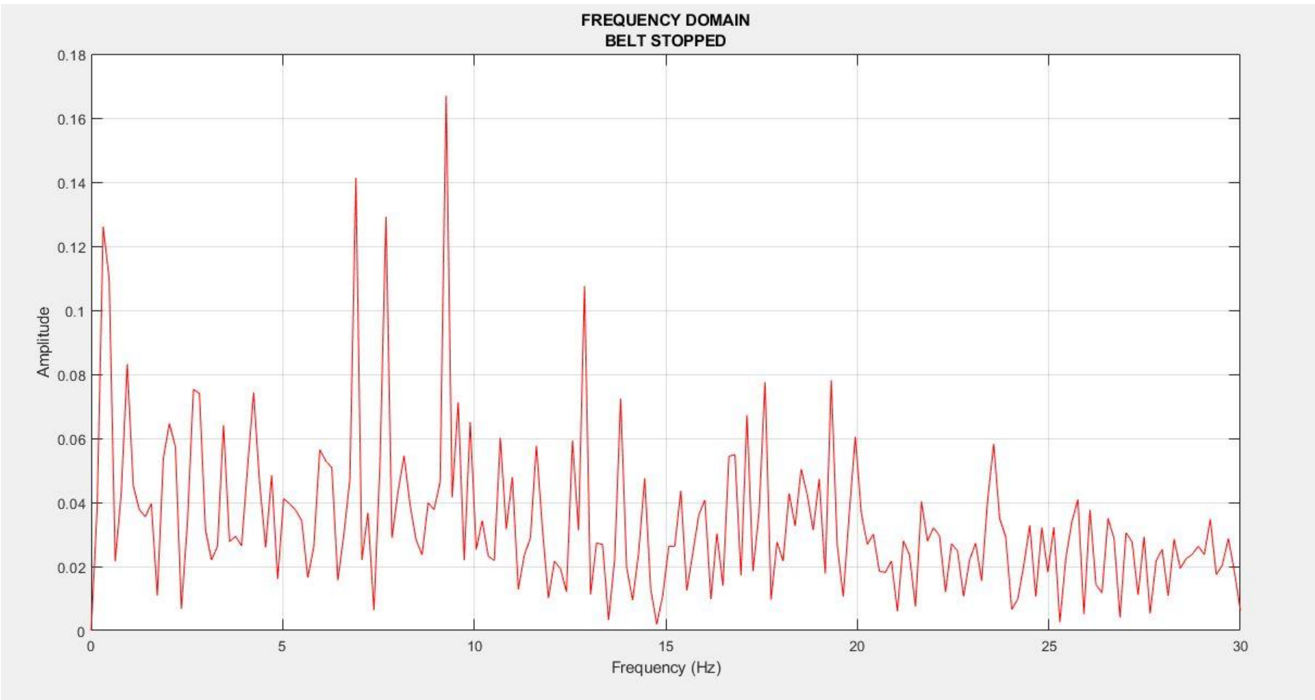


Figure 23:Weight Signal in Frequency Domain-Belt stopped

The following readings are also taken to check the accuracy level of checkweigher machine when the belt is stopped. Few standard weights were kept on the stationery belt and weight readings were taken to check the accuracy level of static weight. It is obvious that with exiting mechanical set up, accuracy level of dynamic weighing cannot go below accuracy level of static weighing.

Standard Weight (g)	Static Weight of Check Weigher (g)
1000	999.80
2000	1999.70
3000	2999.40
4000	3999.70
5000	4999.40
10000	9999.60
15000	14999.50
20000	19999.40

Table 3 : Static Weight Readings of Standard Weight Sets

5.2.2 Conveyor Belt is running at different belt speeds without any load

Weighing conveyor speed can be adjusted through VFD drive. At different speeds of weigh conveyor, loadcell weight data stream is analyzed both with time and frequency domain. This is to identify the motor vibration impact on weight signal and identify any relationship between conveyor belt speed and motor vibration noises.

- Conveyor belt is running at 28 Hz VFD drive Speed.

Conveyor belt drum motor is driven by a VFD. Speed of the conveyor belt can be adjusted by adjusting the output frequency of VFD drive. Here setting of the VFD drive frequency is kept as 28 Hz.

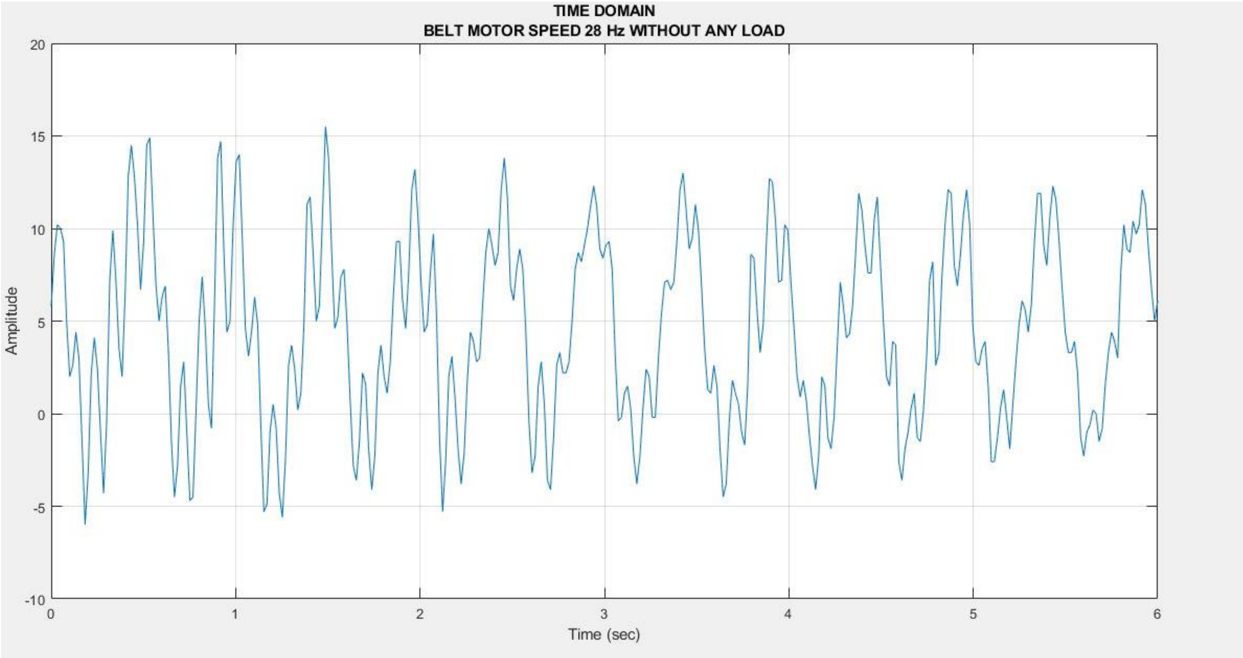


Figure 24: Weight Signal at 28Hz Belt Speed

Figure 24 shows weight data graph at time domain at the VFD drive speed of 28 Hz. To analyze the frequency components, Fourier transformation is performed as per figure 25.

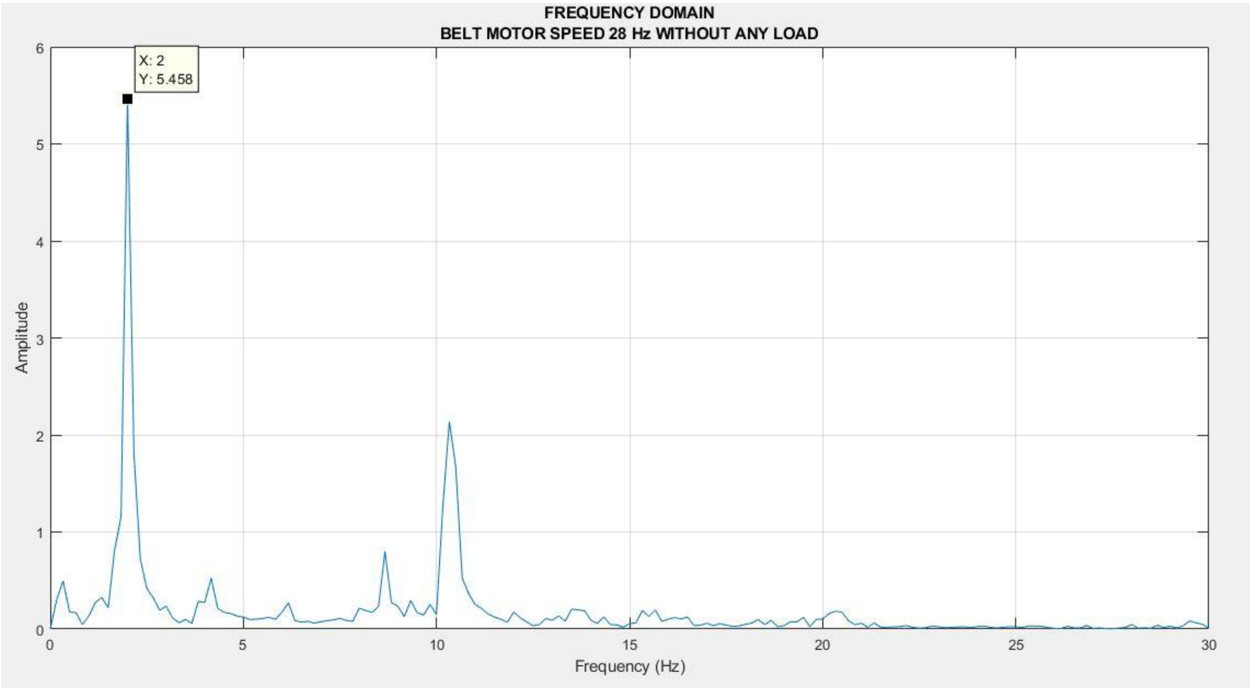


Figure 25: Weight Signal at 28Hz Belt Speed-Frequency domain

As per figure 25, highest noise frequency magnitude of 5.4 is at 2 Hz frequency component.

- Conveyor belt is running at 30 Hz VFD drive Speed

Conveyor belt drum motor is driven by a VFD. Speed of the conveyor belt can be adjusted by adjusting the output frequency of VFD drive. Here setting of the VFD drive frequency is kept as 28 Hz

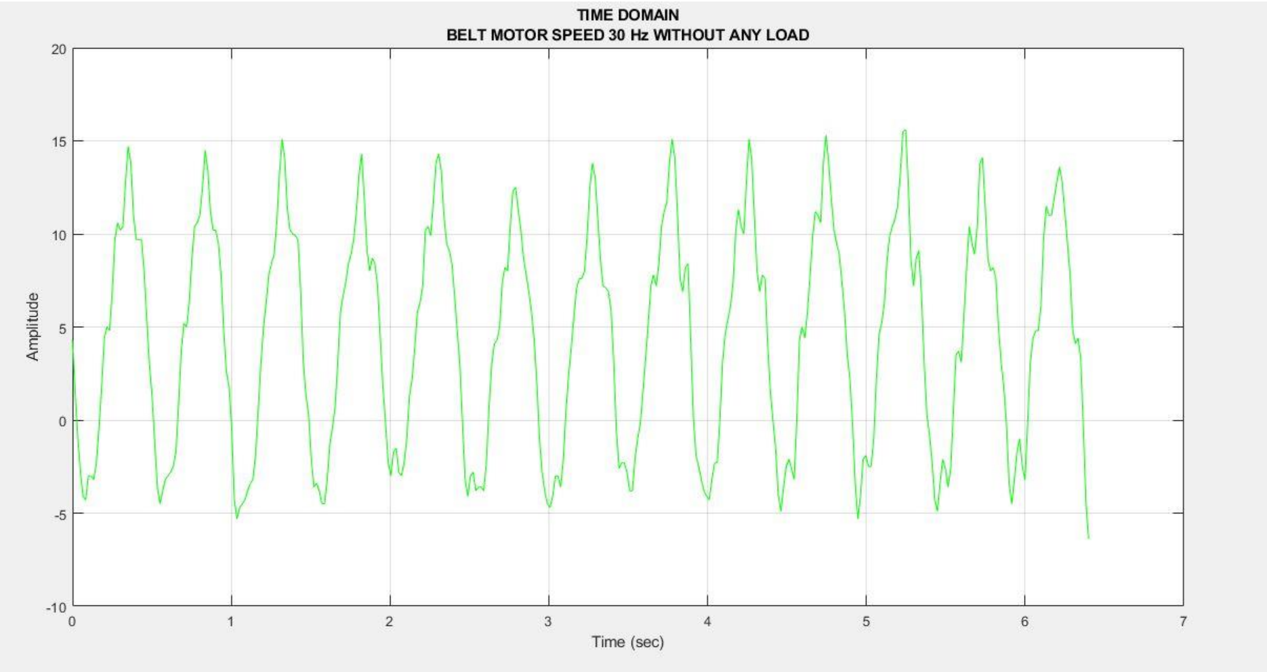


Figure 26:Weight Signal at 30 Hz Belt Speed-Time domains.

Figure 26 shows weight data graph at time domain at the VFD drive speed of 30 Hz. To analyze the frequency components, Fourier transformation is performed as per figure 27. By observing the frequency domain plot, it is clearly seen that all major frequency components are less than 5 Hz range. It seems that it is challenging to separate required frequency components and noise frequency components since all frequencies are within the range of 5 Hz.

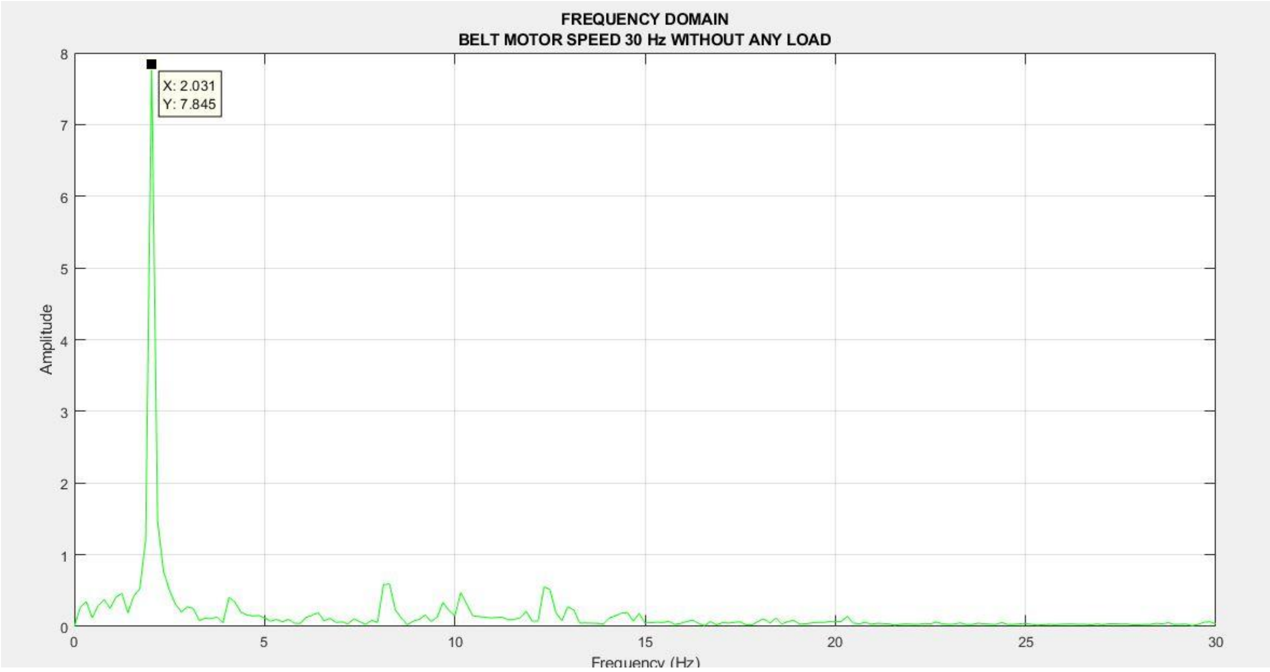


Figure 27:Weight Signal at 30 Hz Belt Speed-Frequency domains

As per figure 27, highest noise frequency magnitude of 7.845 is at 2.031 Hz frequency component

- Conveyor belt is running at 32 Hz VFD drive Speed.

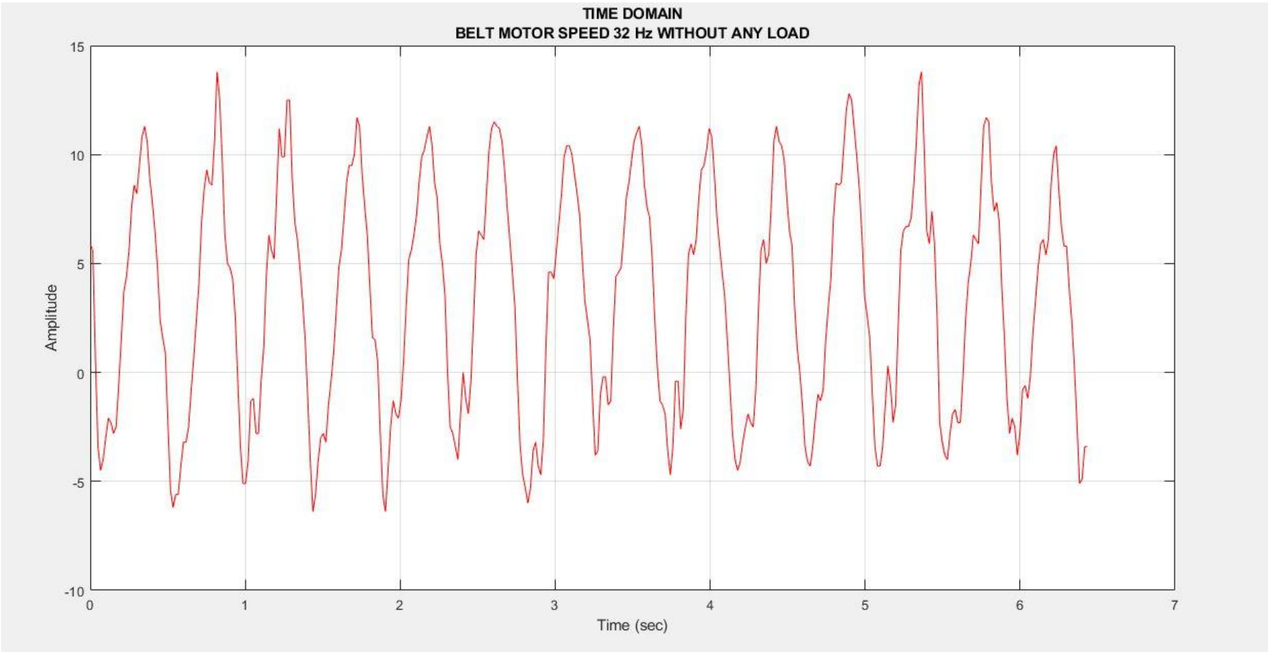


Figure 28:Weight Signal at 32 Hz Belt Speed-Time domains.

Figure 28 shows weight data graph at time domain at the VFD drive speed of 32 Hz. To analyze the frequency components, Fourier transformation is performed as per figure 29.

- Conveyor belt is running at 34 Hz VFD drive Speed.

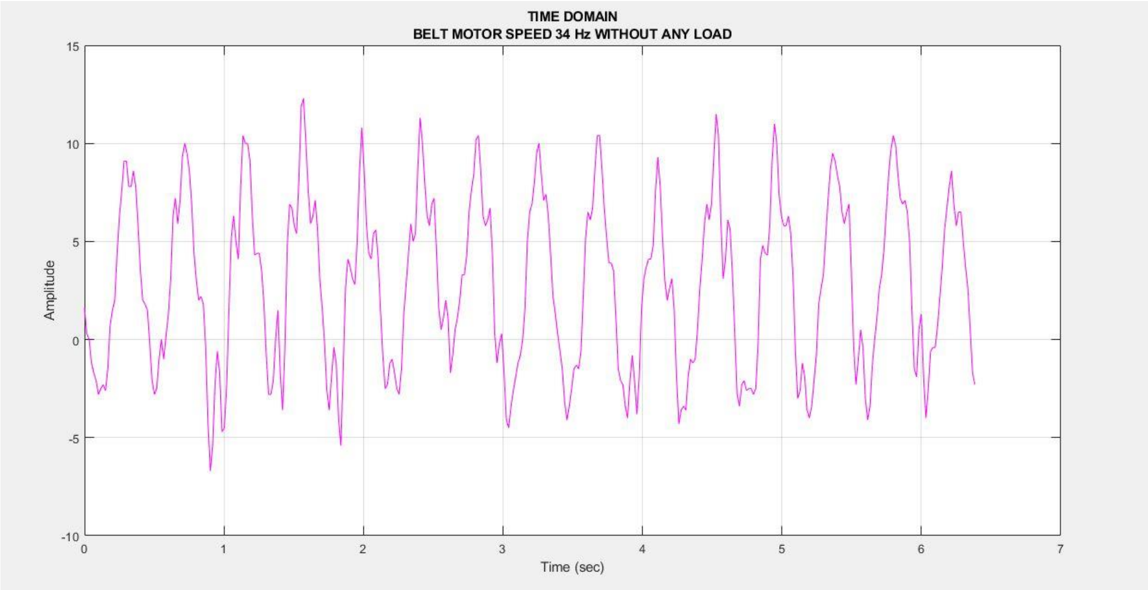


Figure 29:Weight Signal at 34 Hz Belt Speed-Time domains.

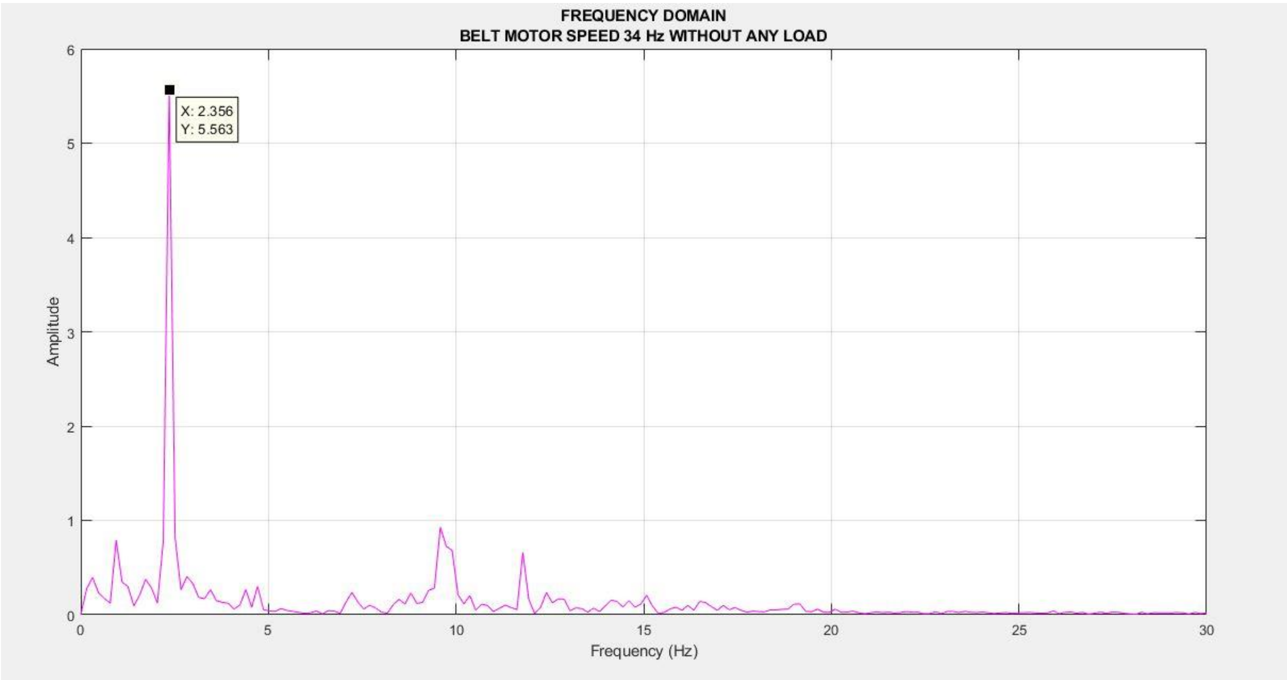


Figure 30:Weight Signal at 34 Hz Belt Speed-Frequency domains

As per figure 30, highest noise frequency magnitude of 5.563 is at 2.356 Hz frequency component.

When a graph is plotted highest noise frequency Vs belt Speed, there is a linear relationship identified between highest noise frequency Vs belt Speed.

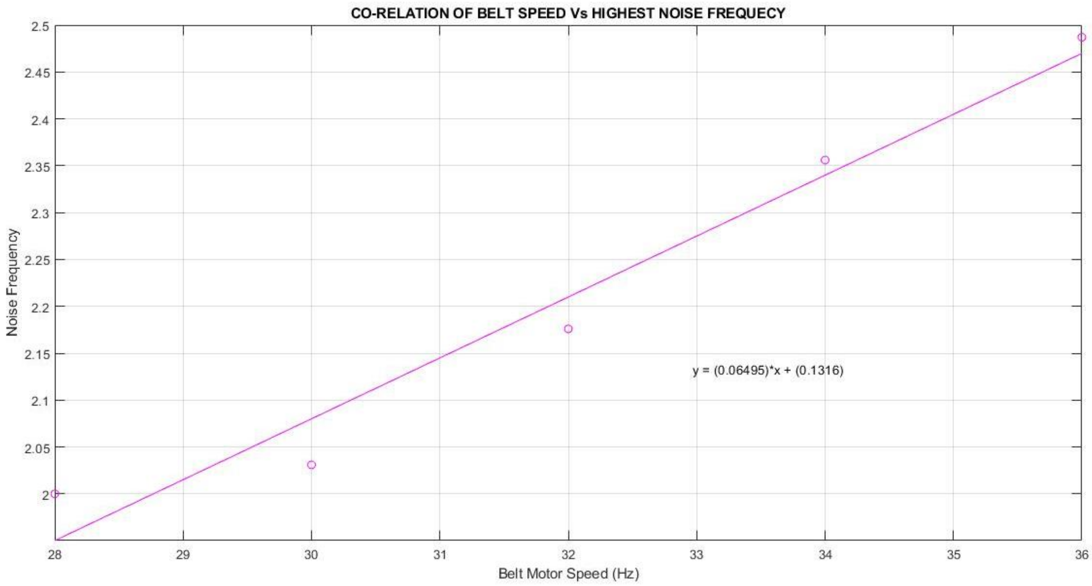


Figure 31:Co-relation between Highest Noise Frequency Vs Belt Speed

5.2.3 Same weighed box running at different belt speeds

9130 g weigh box has been sent in three different speeds and weight data has been collected at 200 Hz sampling frequency. Then frequency domain analysis is done after performing Fourier transform. The figure 20 shows the weight signal profile of 9130 g box at 200 Hz sampling frequency.

- Conveyor belt is running at 28 Hz VFD drive Speed with 9130 g weight

Conveyor belt drum motor is driven by a VFD. Speed of the conveyor belt can be adjusted by adjusting the output frequency of VFD drive. Here setting of the VFD drive frequency is kept as 28 Hz. VFD drive control is set as vector control inside the VFD, so that conveyor belt is not become slow due to load on it and VFD drive will automatically control the torque to keep the same speed irrespective of the load on it.

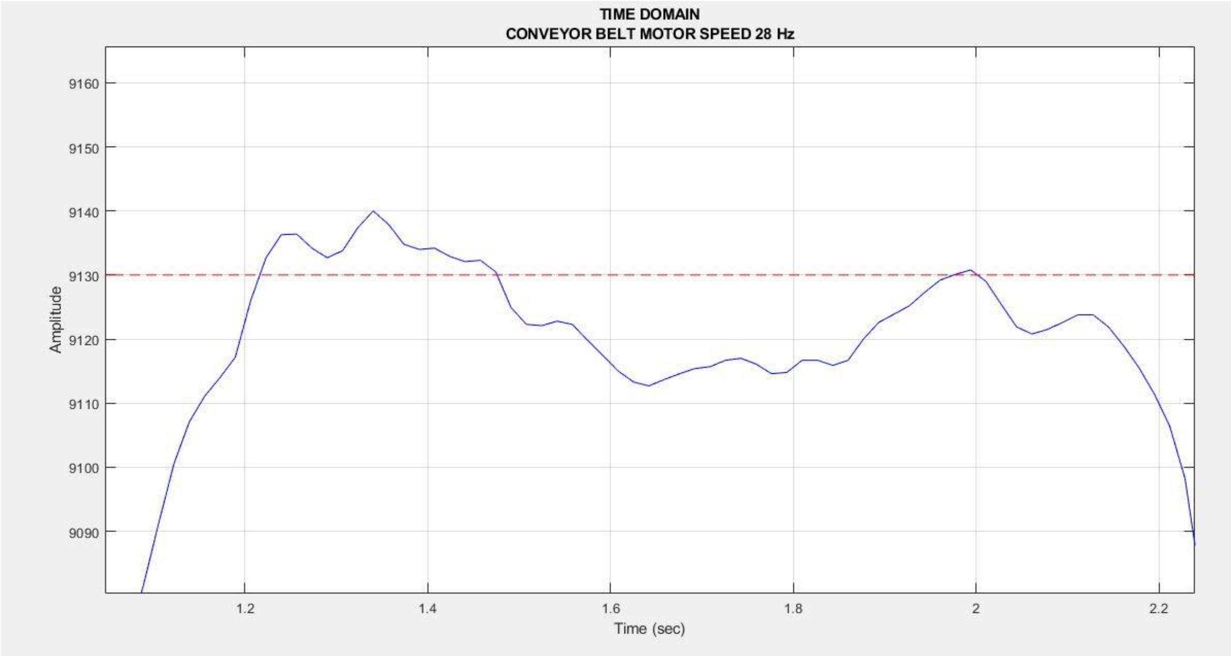


Figure 32: 9130g Weight at 28 Hz VFD drive Speed

Figure 33 shows the FFT of figure 20 weight signal profile.

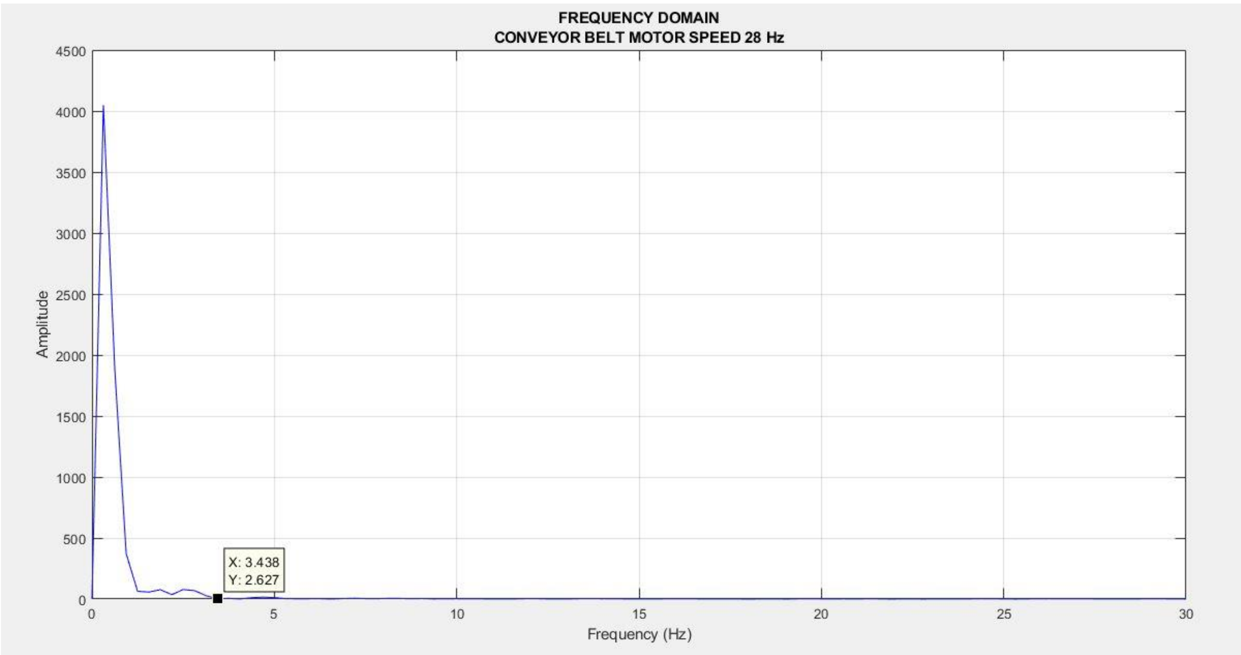


Figure 33: FFT of 9130g weight signal at 28 Hz VFD Drive Speed

As per figure 21, it is clear that all the frequency components are less than 5 Hz range.

- Conveyor belt is running at 30 Hz VFD drive Speed with 9130 g weight

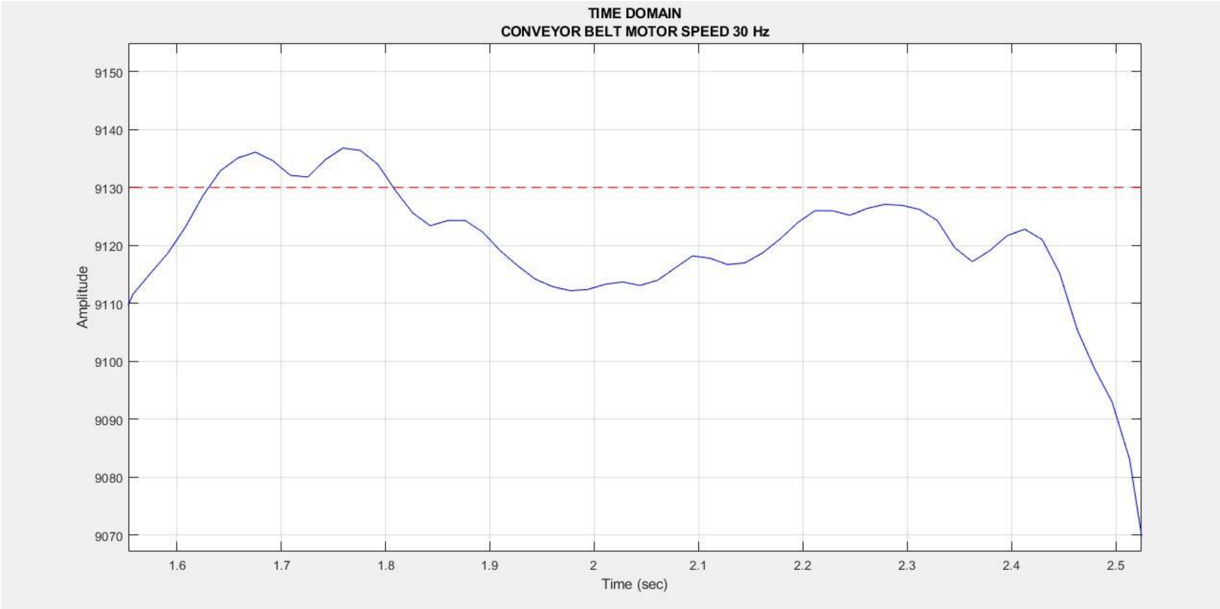


Figure 34: 9130g Weight at 30 Hz VFD drive Speed

The figure 34 shows the weight signal profile of 9130 g box at 200 Hz sampling frequency at conveyor belt VFD drive speed of 30 Hz. And Figure 35 shows the FFT of this.

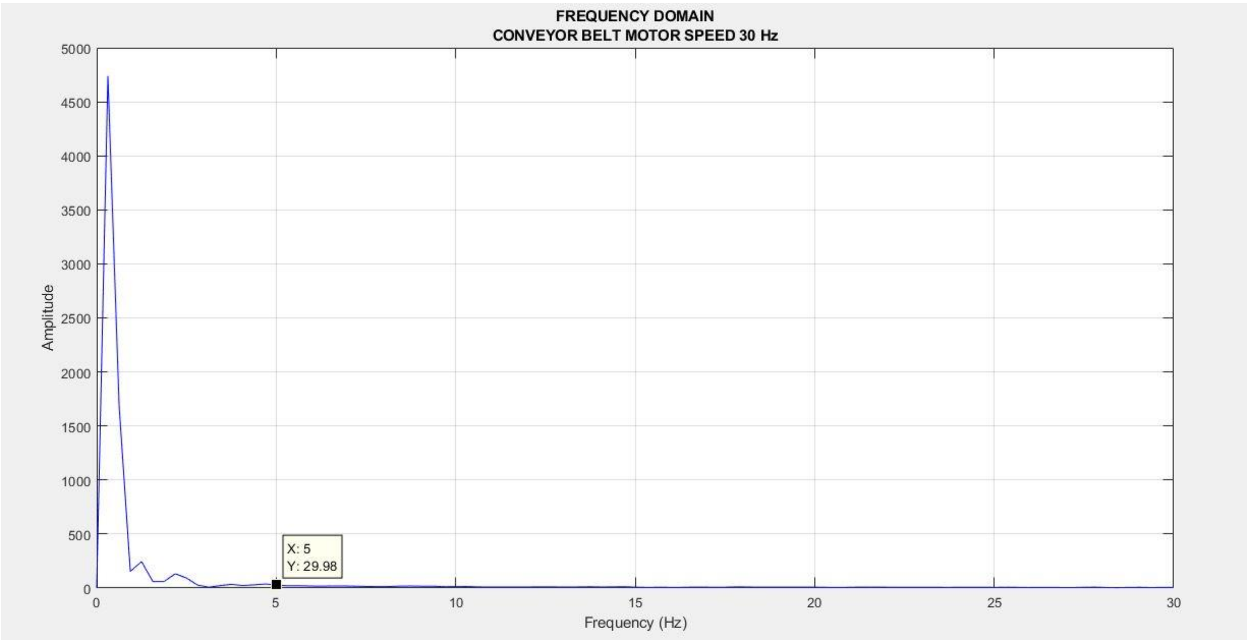


Figure 35:FFT of 9130g weight signal at 30 Hz VFD Drive Speed

- Conveyor belt is running at 32 Hz VFD drive Speed with 9130 g weight

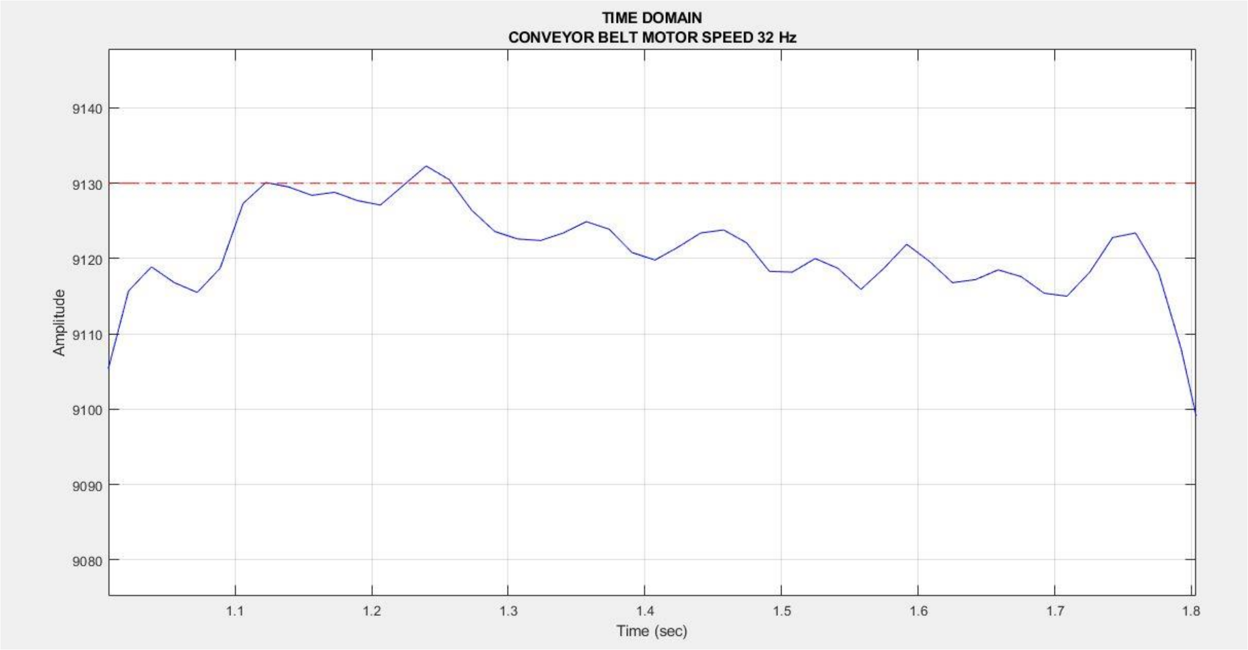


Figure 36: 9130g Weight at 32 Hz VFD drive Speed

The figure 36 shows the weight signal profile of 9130 g box at 200 Hz sampling frequency at conveyor belt VFD drive speed of 32 Hz. And Figure 37 shows the FFT of this.

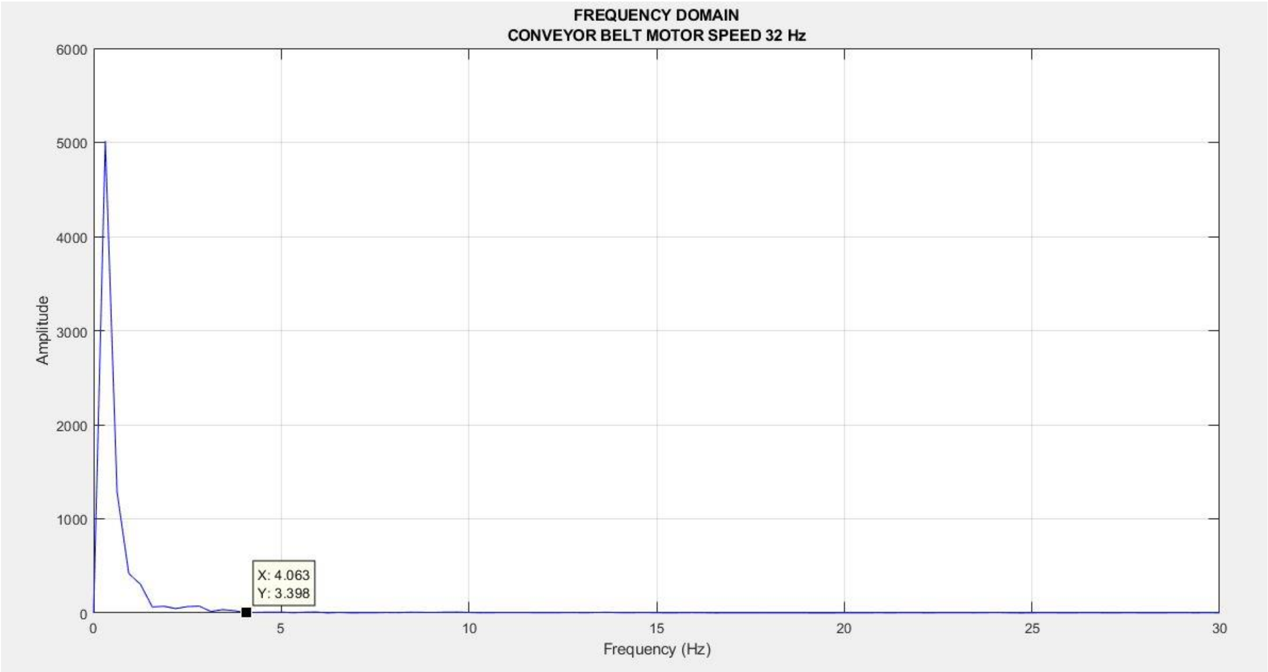


Figure 37:FFT of 9130g weight signal at 32 Hz VFD Drive Speed

As per figure 37, it is clear that all the frequency components are less than 5 Hz range. Also, it is clear that highest frequency component magnitude is increasing with belt speed proportionally. Higher the belt speed higher the magnitude of highest frequency.

5.2.4 Two weigh boxes running at same belt speed

Two weigh boxes are selected as 9130 g and 6930 g. Weight data was collected for the two boxes at 32 Hz VFD drive speed at the rate of 200 measurements per second.

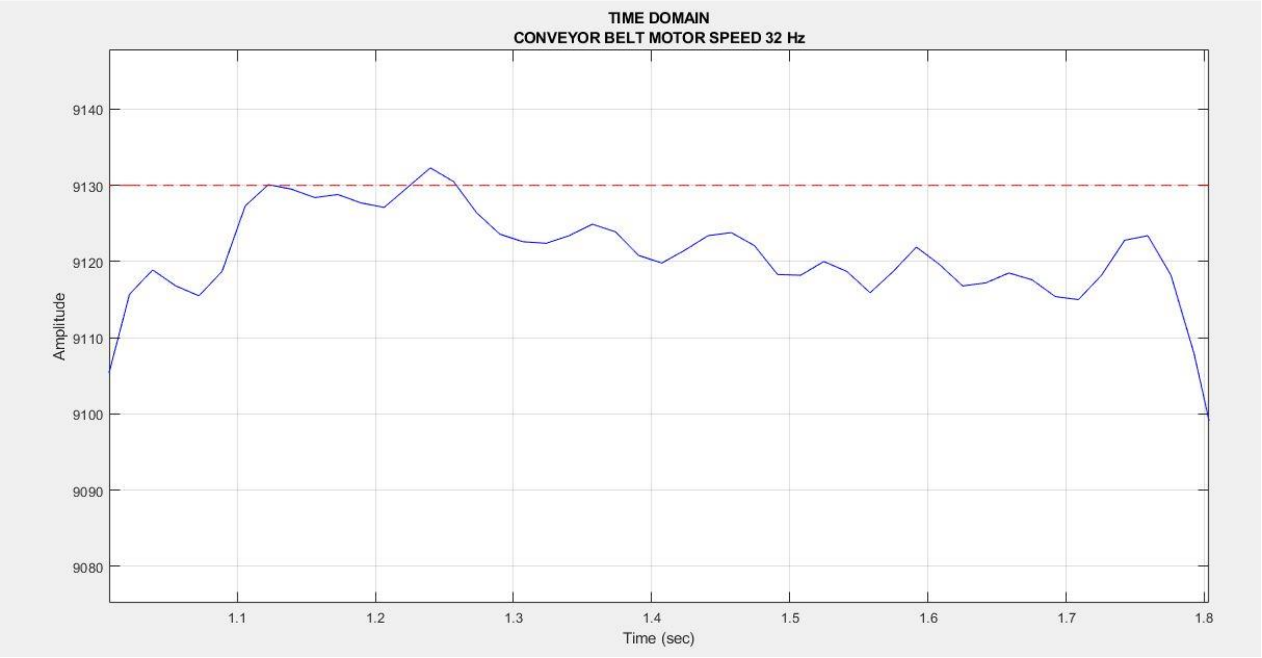


Figure 38 : 9130 g Weight at 32 Hz VFD Drive Speed Weight Profile

This test is important to identify effects due to the product characteristics such as weight and length of the box. In this case check weigher machine conditions are maintained same and different weight boxes are sent through the machine to observe the weight signal profile.

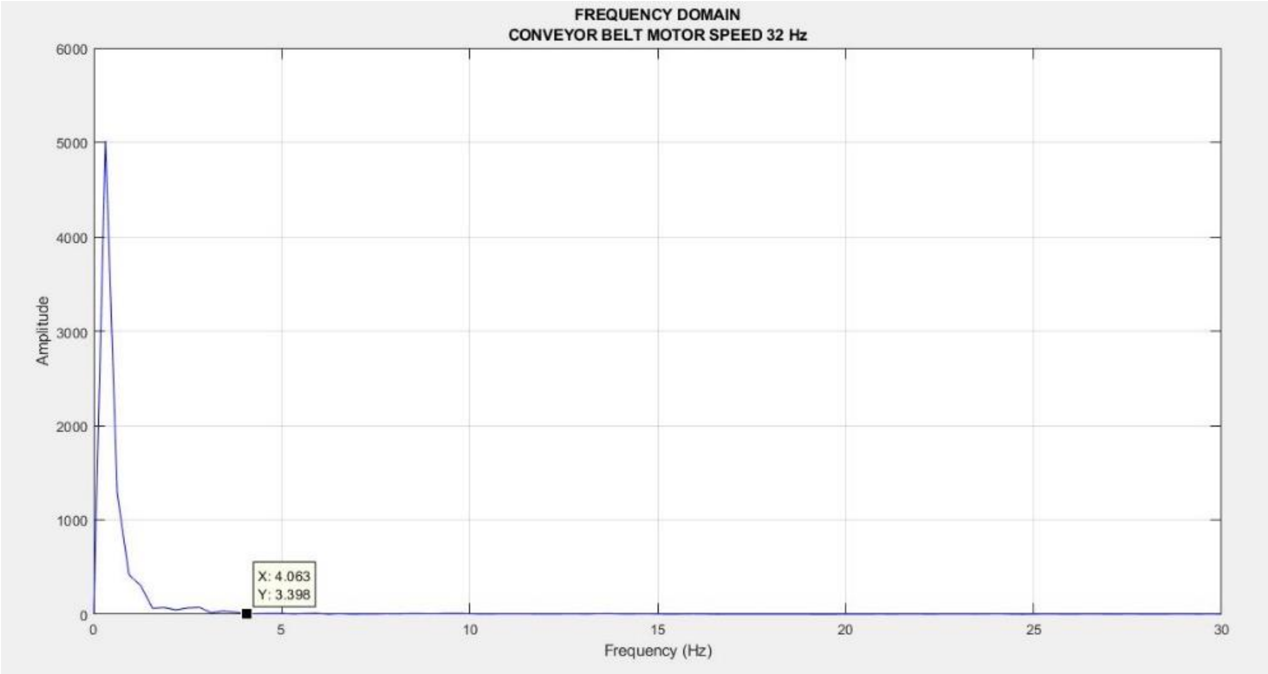


Figure 39: FFT of 9130 g Weight 32Hz VFD speed Weight Profile

Figure 38 shows the time domain weight profile of 9130 g Weight whereas Figure 37 shows frequency response of the same weight profile.

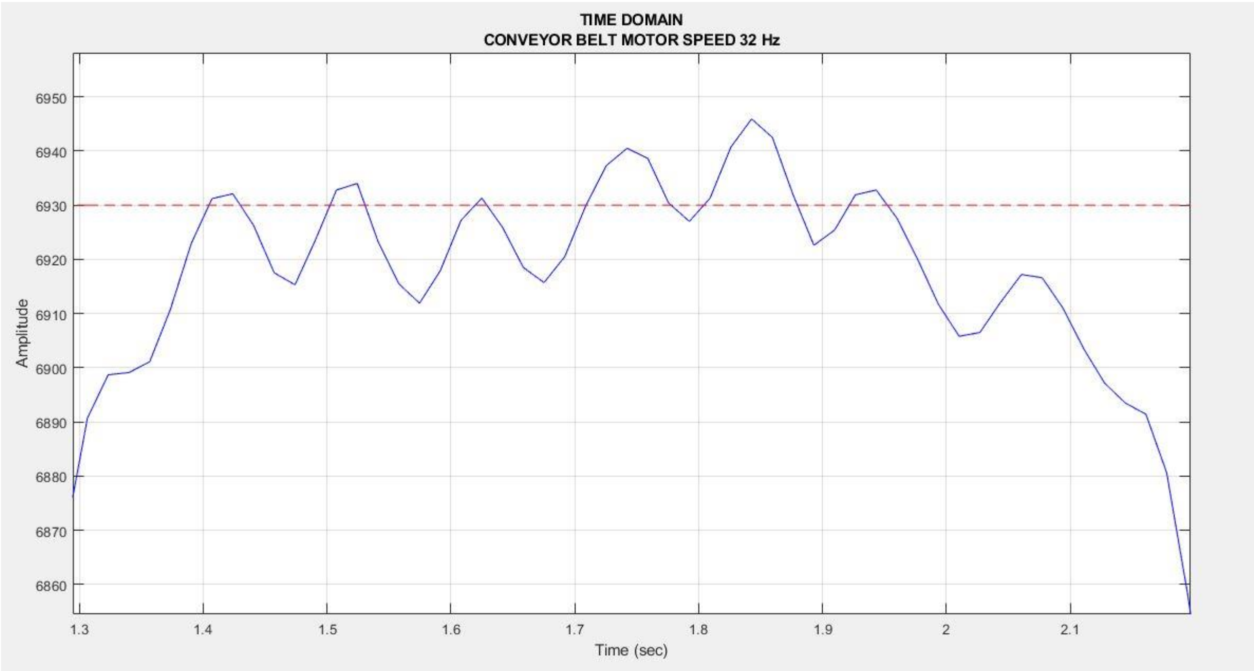


Figure 40: 6930 g Weight at 32 Hz VFD Drive Speed Weight Profile

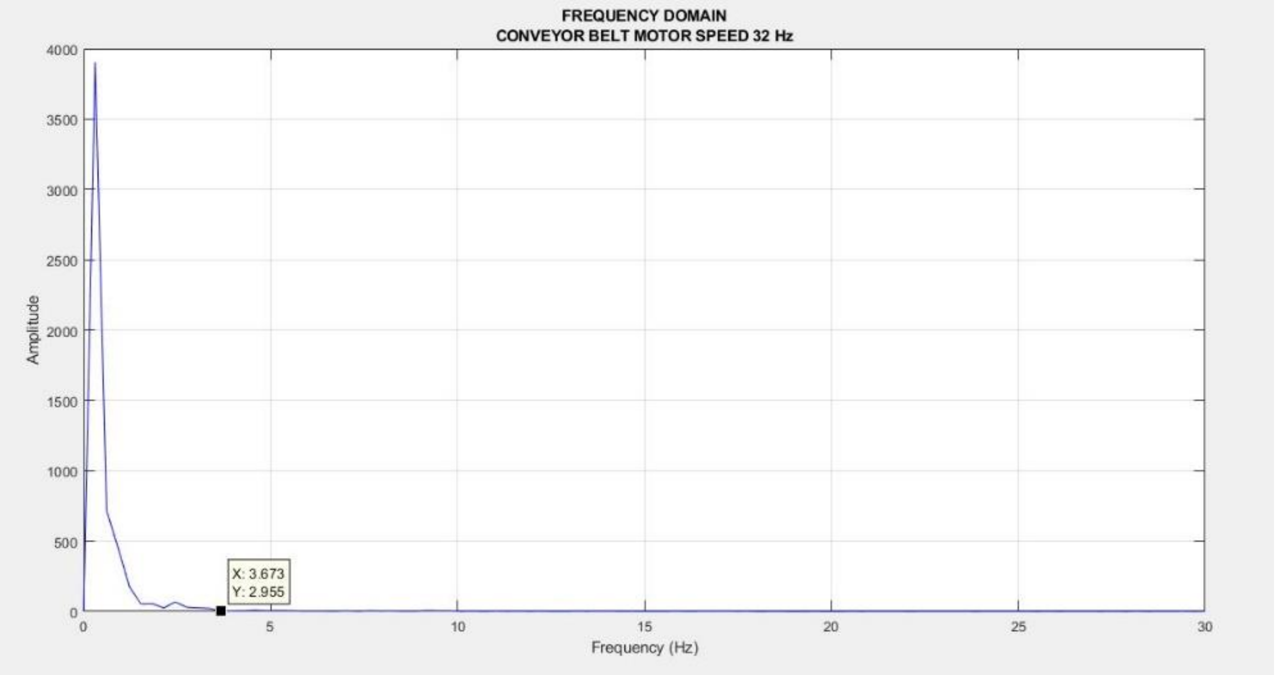


Figure 41: FFT of 6930 g Weight 32Hz VFD speed Weight Profile

With the frequency response graphs in figure 39 & Figure 41, It is clear that all frequency components are within 5 Hz range and frequency band expands when weight of the box is increasing.

5.2.5 Same box running at same speed several times

6930 g weigh box is sent through several times through the weighing conveyor at the same speed and analyzed time domain and frequency domain response. System repeatability is important to identify the variations in consecutive measurements of the same weight taken under the same conditions of the check weigher machine. Repeatability is an indicator of accuracy of the machine, and it determines the calibration frequency and requirement of the machine. Figure 42 shows that weight profiles are plotted in the same graph. It is clearly seen that there is a minimum variation between each weight profiles which means system repeatability is in satisfactory level.

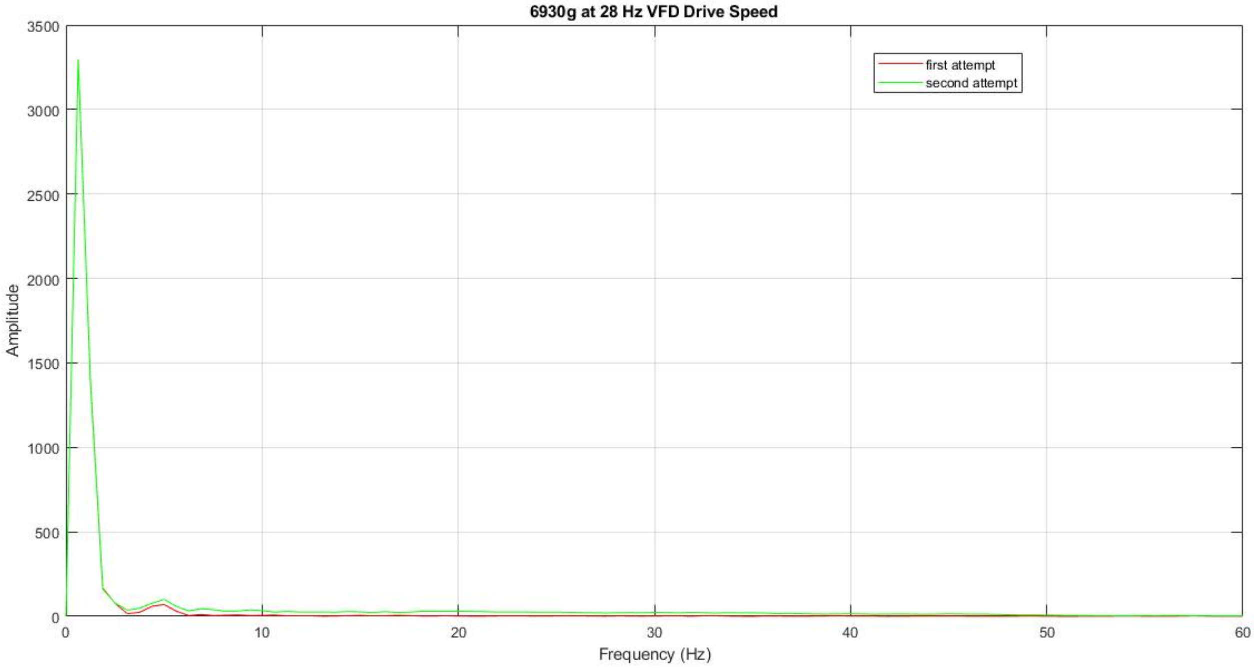


Figure 42: 6930 g Weight Repeatability -Frequency response

With above graph it is clear that frequency response of each attempt is almost same. Hence system repeatability is good.

5.3 Summary of Frequency Response Analysis and Data Analysis.

When conveyor belt is run at different speeds without any load on it, with the frequency response graph, it shows that there is linear relationship between highest noise frequency of weight signal vs Belt speed. When Belt speed is increased, noise frequency component is also increased proportionally. Hence highest noise frequency component in related conveyor speed is suggested to be suppressed by a Notch Filter. Also, original weight signal frequency components are less than 5 Hz range. Hence low pass digital filters can be tested for noise suppression of the system. Since digital filters are implemented in two ways namely FIR (Finite Impulse Response) and IIR (Infinite Impulse Response), both FIR LP filter and IIR LP Filter can be tested for the system initially. If the above three digital filters do not satisfy the required accuracy at required speed, it is suggested to go for model-based filtering technique for better results. When frequency response of stationary belt data (without any load on it) is analyzed noise components magnitude is considerably low compared to motor vibration noises. Hence noises generated due to electronics can be ignored for the study. Exiting system has an error of **± 20 g.** System repeatability is very good. Also, it is clear that Accuracy cannot go beyond ± 1 g with exiting mechanical set up of the machine. The following figure shows error of static weights against standard weights.

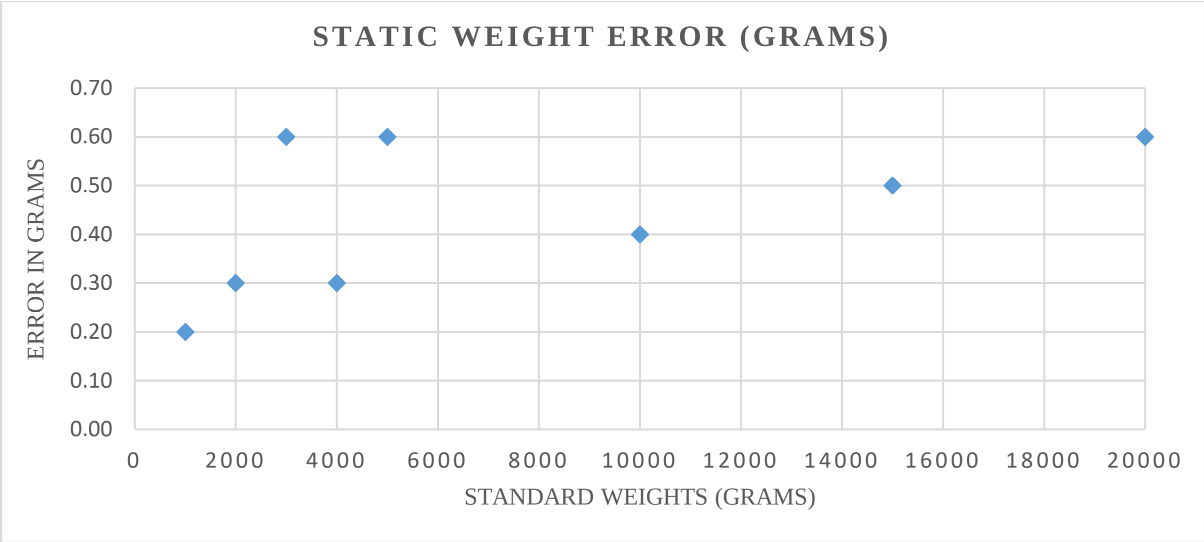


Figure 43 : Static Weight Error

6. APPLYING DIGITAL FILTERS TO WEIGHT SIGNAL

6.1 Introduction

As per the frequency analysis of the signal in chapter 05, it is identified that there is a linear relationship between the highest noise frequency of signal and its belt speed. Hence the best approach is to implement a notch filter to suppress the highest noise frequency and analyze the output. Also, it is clearly seen that signal frequencies are less 5 Hz range. Therefore, low pass filtering is the method of suppressing noise frequencies. Two main classifications of digital filters which are used for signal filtration are FIR and IIR filters. The FIR filter generates impulse response of a finite period where as IIR filter provides impulse response of infinite duration for a dynamic system. In this study FIR low pass filter and IIR low pass filter are used to filter the noise components from the weight signal.

6.2 Notch Filter

As discussed in chapter 5.2.2 there is a linear relationship with highest noise frequency vs belt speed. Hence it is suggested to suppress highest noise frequency by a notch filter. By definition of notch filter, notch filter allows the frequency components below and above the notch frequency. Notch filters are also utilized to eliminate the resonance frequency components from the systems.

In this case Notch filter is designed with notch width of 0.1 to suppress 2.176 Hz frequency component from the frequency spectrum shown in figure 43. Figure 32 shows the frequency domain plot of belt speed of 32 Hz VFD drive speed before applying the notch filter.

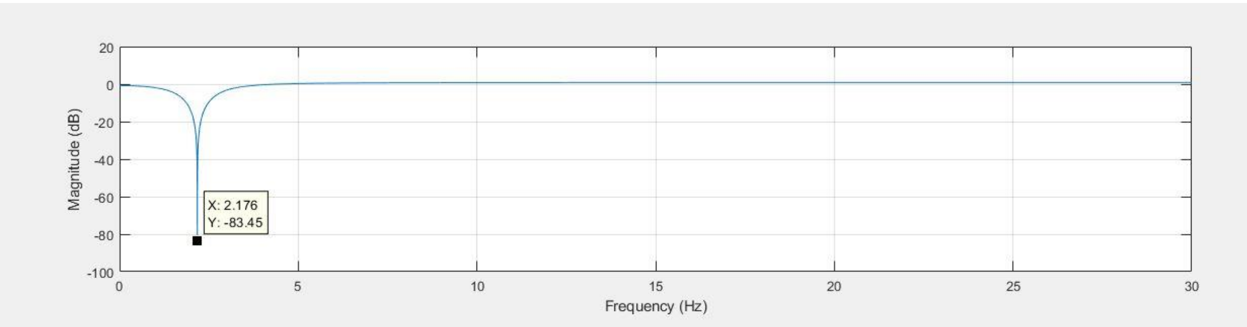


Figure 44: Notch Filter Design at 2.176 Hz with notch width 0.1

Above notch filter is applied to figure 32 frequency spectrum which is the weight signal profile of belt running without any load on it at VFD drive speed of 32 Hz.

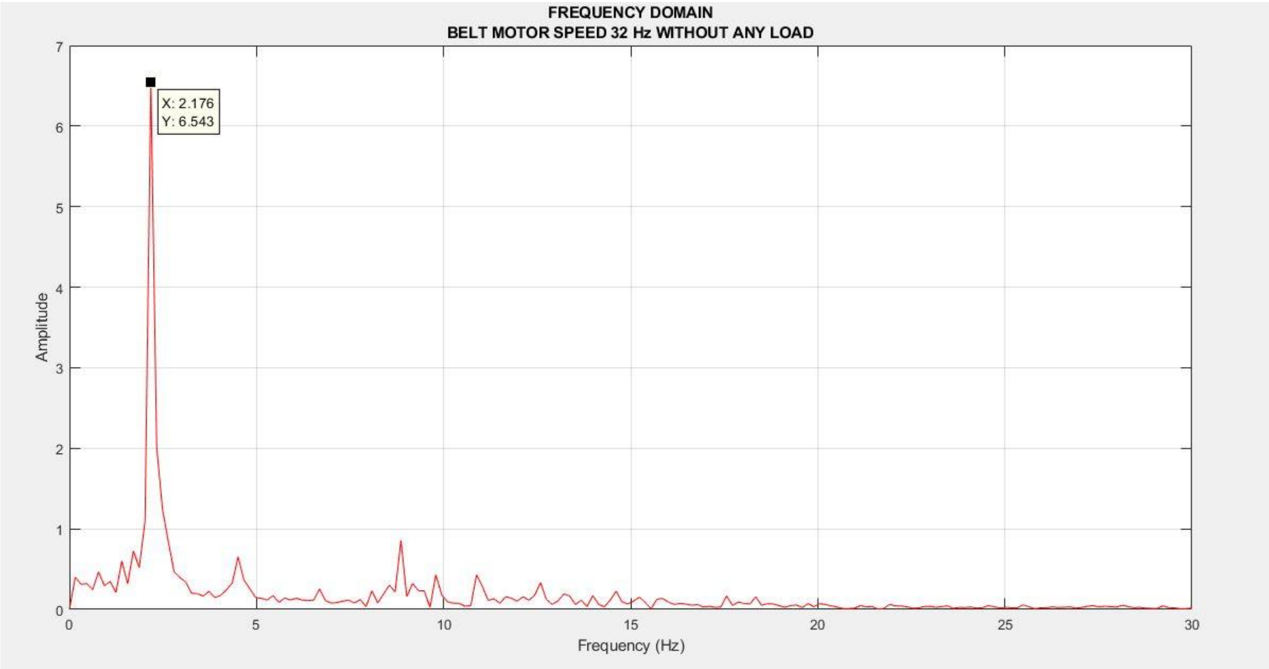


Figure 45: Before applying Notch Filter

Figure 45 shows the Notch filter output frequency spectrum. Noise magnitude has become significantly low after applying notch filter.

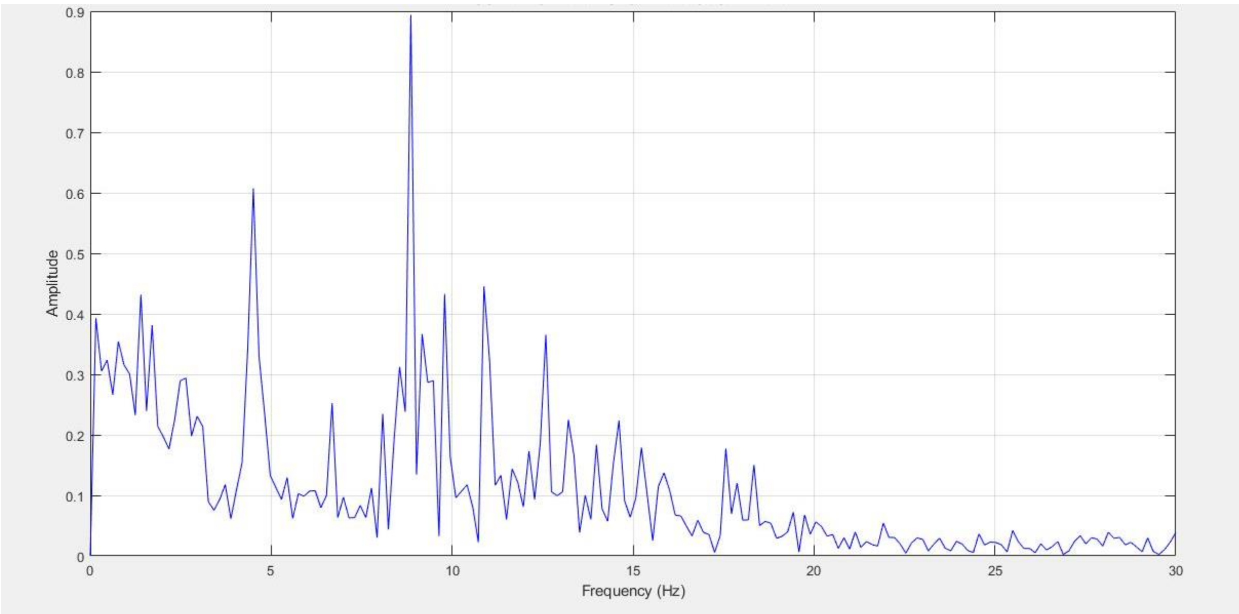


Figure 46: After applying Notch Filter

Then same notch filter is applied to 6930 g weight signal profile. Then the results are shown is figure 34 & 35. ‘

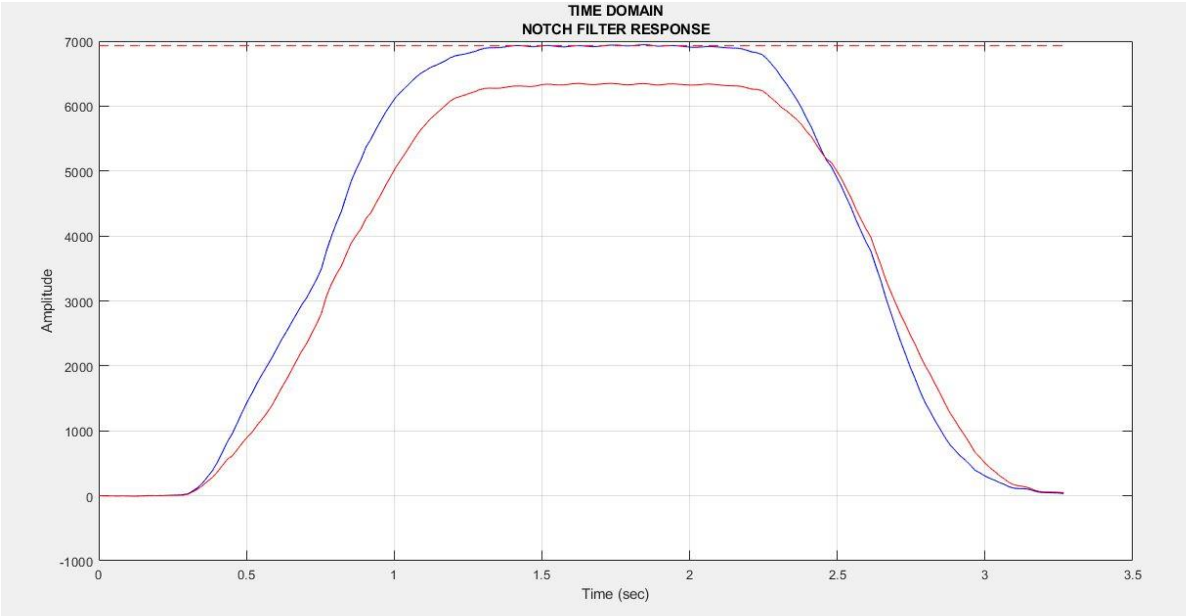


Figure 47: Notch Filter applied 6930 g weight Profile

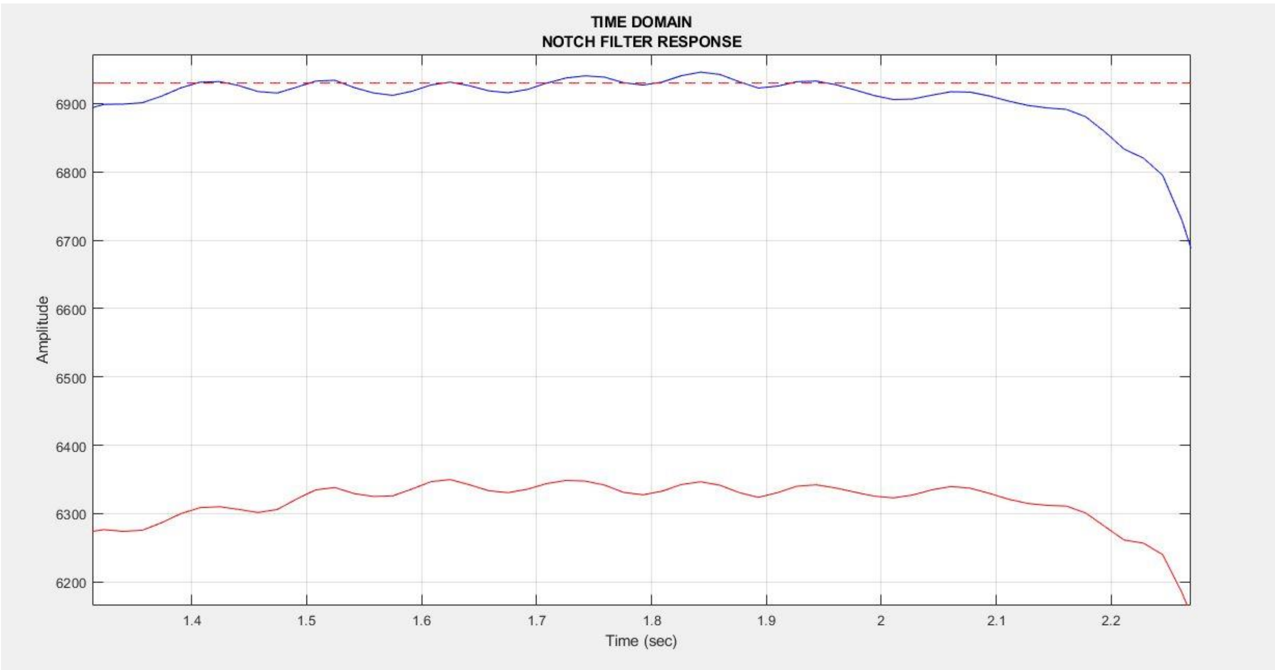


Figure 48: Notch Filter applied 6930 g weight Profile-Flat Region

Filtered signal has not even reached the weight value of 6930 g. there is a huge error. This is due to the original signal frequencies also within noise frequency range. When filter is applied, some good signal frequency components are also cut off. Hence further notch width is reduced to see any improvement. Notch filter is designed at 2.176 Hz with notch width 0.01.

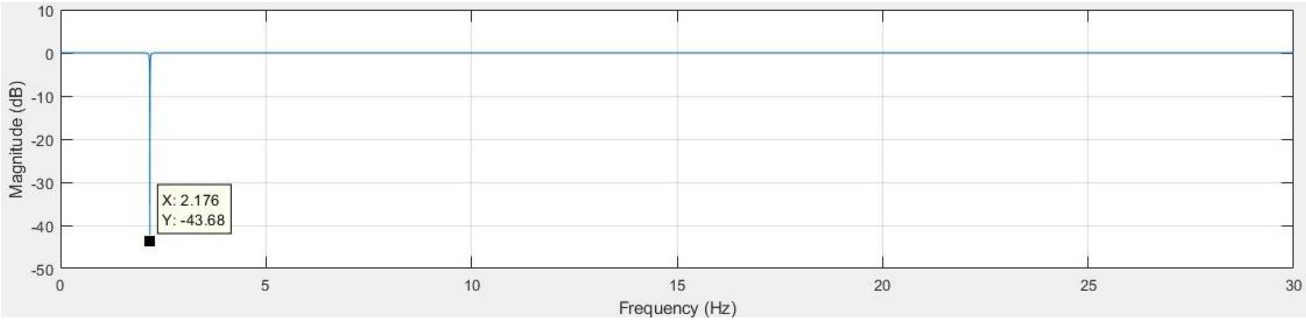


Figure 49:Notch Filter Design at 2.176 Hz with notch width 0.01

When modified notch filter is applied, resulted filtered output is shown in Figure 49.

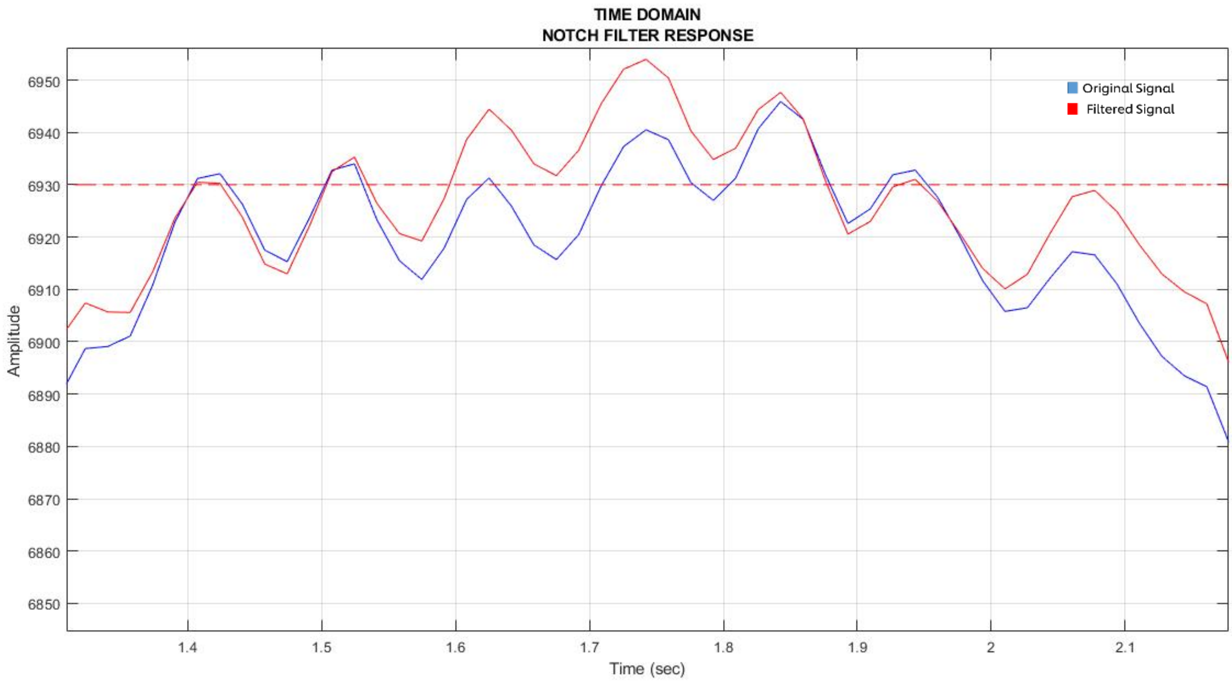


Figure 50:Notch Filter output with notch width 0.01

As per figure 49, Filtered signal has reached the weight value 6930 g. but following actual weight signal. This is due to the exact frequency component cannot be cut off. When filter is applied, some required signal frequency components are also cut off. Hence applying notch filter is not practically possible and make no difference compared to actual signal.

6.3 Finite Impulse Response (FIR) Low Pass Filter

In FIR filters the response gets fixed to zero in a finite period of time. In FIR filters, feedback is not available thus these work on only present and past input values. Hence the output is the summation of a finite quantity of finite samples of input values. The following figure shows the discrete form of FIR filter. [11] . It shows how the filter works shows inside. b_0 , b_1 , … b_n should be selected by tuning the system.

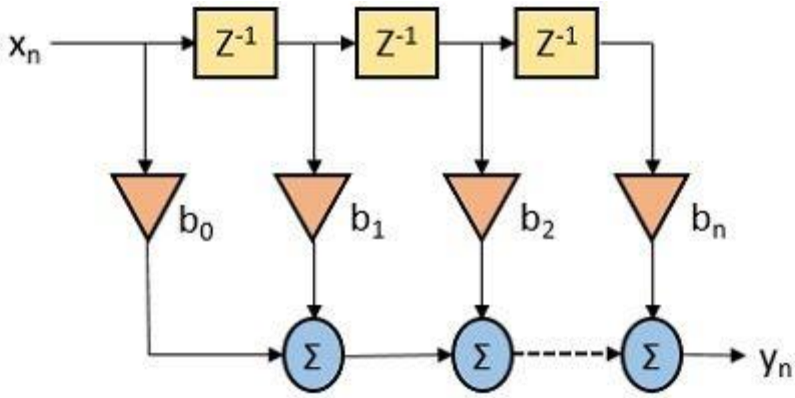


Figure 51: Discrete form of FIR Filter

In order to implement FIR low pass filter in MATLAB, two critical parameters should be selected. These are filter cutoff frequency (Hz) and filter order. In order to select the cutoff frequency, frequency response of weight signal should be considered. As per the figure 39, the highest noise frequency component starts at 0.3 Hz. Hence cutoff frequency is selected as 0.3 Hz. Also, the effect of increasing the cutoff frequency is also studied.

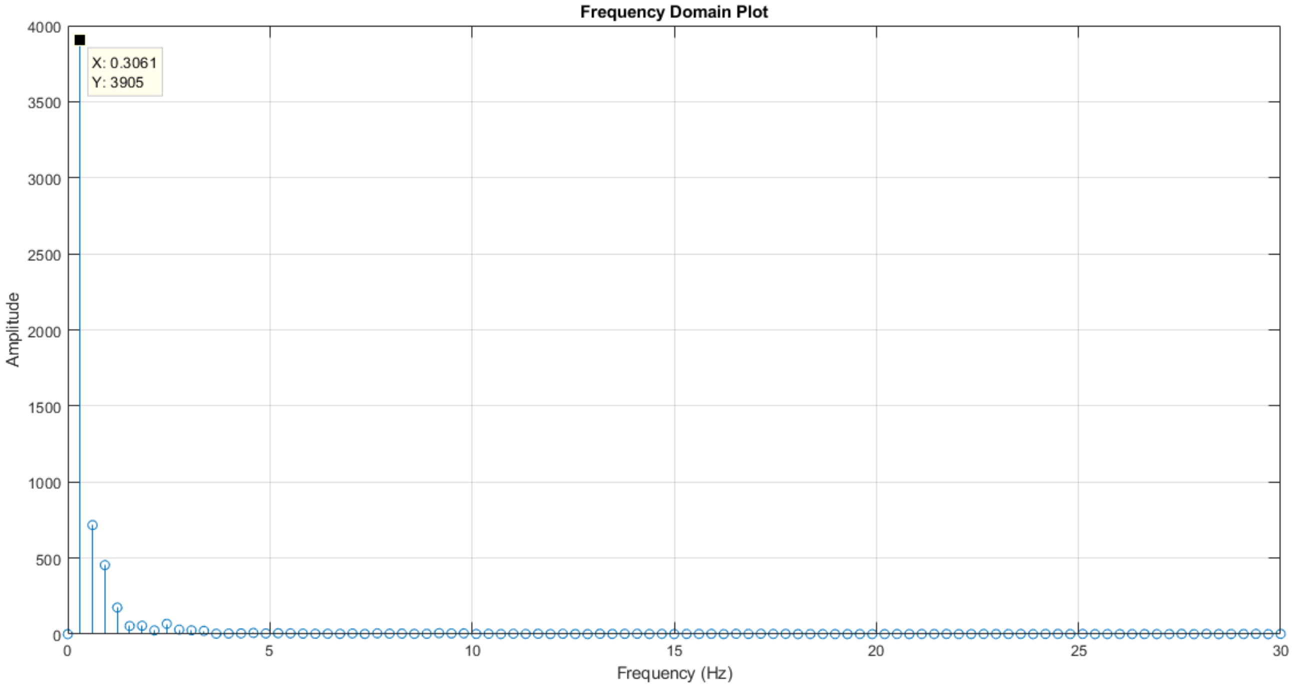


Figure 52: Frequency Domain Plot of 6930 g Weight Profile

Next step is selecting the filter order. Best fitting polynomial degree is considered as Filter order. If degree is increased further from 30, best fit will become smoother. When the filter order is further increased, there is a delay in filter response. Hence optimum filter order should be selected without compromising the accuracy & response time.

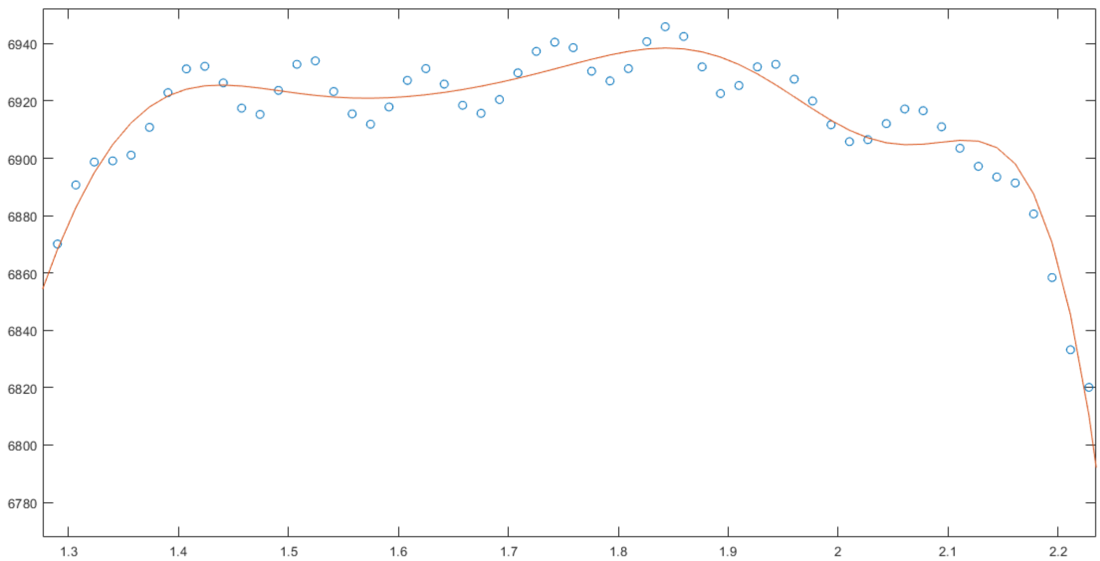


Figure 53: polynomial p(x) of degree 30 that is a best fit (in a least-squares sense) for the data

Then FIR low pass filter is designed using the following filter parameters for 6930 g weight box running at belt VFD speed of 32 Hz.

FIR filter parameters

Sampling Frequency	200 Hz
Nyquist Frequency	100 Hz
Sampling interval	0.005 sec
Cut off Frequency	0.3 Hz
Filter Order	30

Table 4: FIR Filter Parameters

Design filter as per above parameters shows in figure 53.

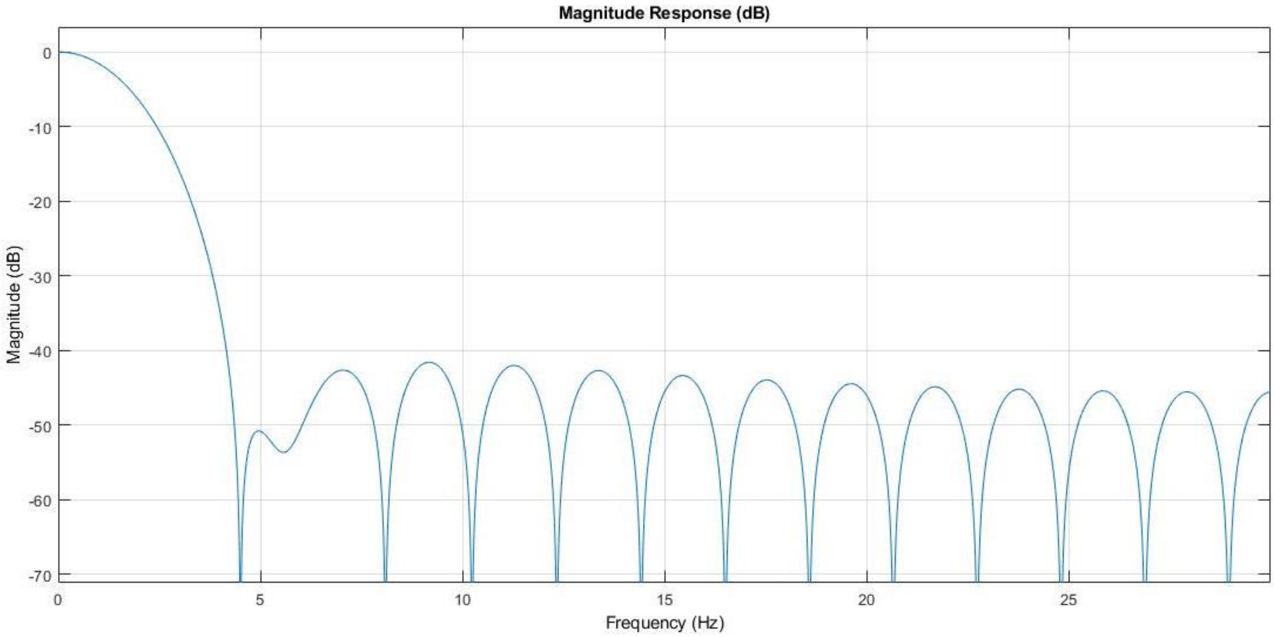


Figure 54: FIR filter of cutoff frequency at 0.3 Hz and order of 30

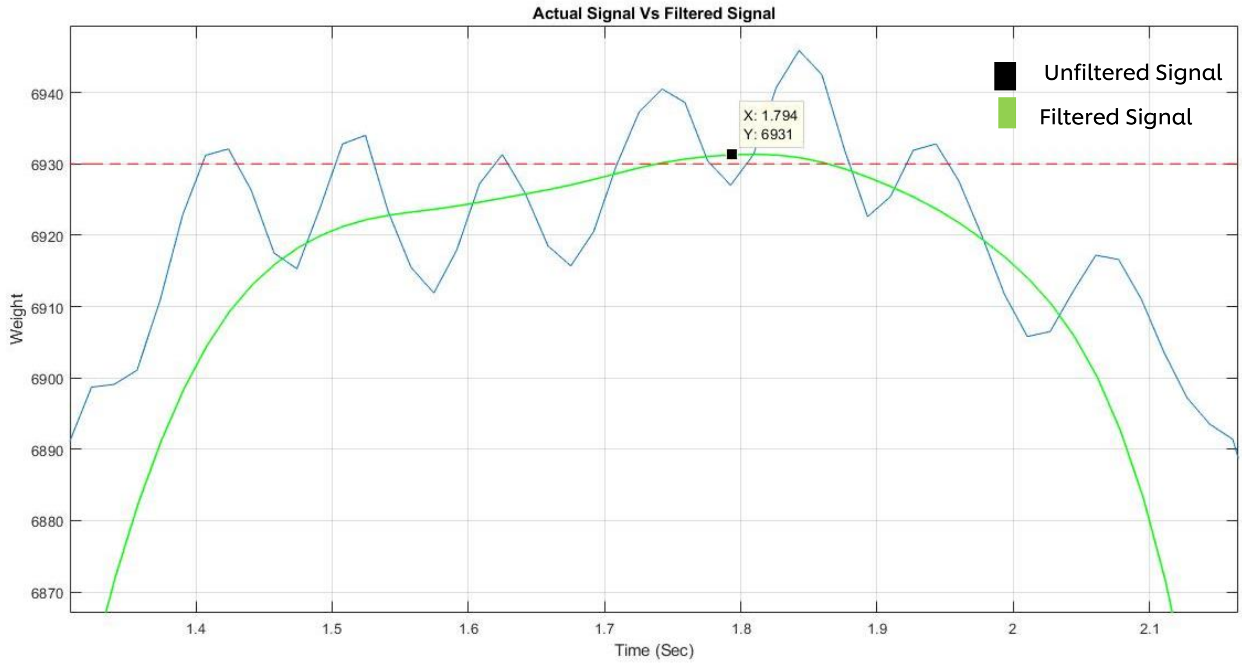


Figure 55 : FIR Filtered Signal for 6930 g weight

Then above designed filter is applied to the weight profile of 6930 g at belt speed of 32Hz VFD speed and results are shown in figure 54. Green color plot shows the filtered signal whereas blue color plot is the unfiltered weight profile. Maximum value of the filtered signal would be a good estimate for the final weight value.

It is clearly seen that most of noise components are cutoff and filtered signal is smooth. It is important to decide the final weight value of the box, before the box exits the weighing conveyor. As per filtered graph, there is a delay in filtered output. Easiest way to reduce the filter response time, is to slow the speed of conveyor. But it is not practical to implement at actual site due to speed of the line should be maintained. Best solution is to use DSP in between loadcell transmitter and PLC, so that all the filtering and computation are done inside DSP and final weight value is sent to PLC. This is because of computation time of DSP unit is considerably low. Maximum value in flat region of filtered signal can be considered as good estimate for weight value of box. Data should be considered between Falling Edge of Entry sensor & Rising Edge of exit sensor. Considering Computation time in DSP is insignificant, weight estimate can be obtained, before box fully exit from weighing conveyor. Belt speed also can be reduced without affecting the line speed. This should be considered in practical implementation at site. The figure 43 shows the weight estimating algorithm of maximum value of filtered signal. With this algorithm it shows that accuracy of the weight of box has reached up to ± 5 g.

In this case weight data is considered in the flat region only. It is identified by inlet and exist sensors. All the calculations and filtering algorithm will be performed inside the DSP and final weight value is sent to PLC to do the comparison against the target weight pre-programmed inside the PLC ladder logic to do the automatic rejection of out of tolerance boxes.

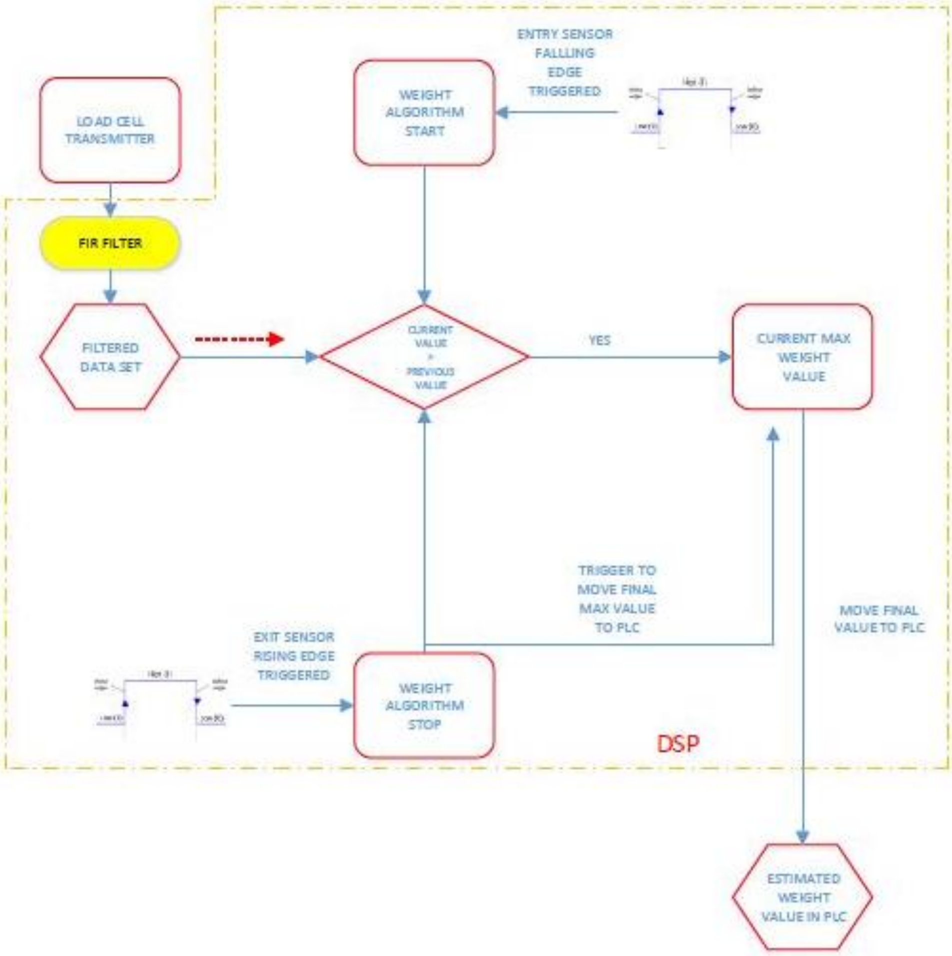


Figure 56: Weight Estimating Algorithm of FIR Filtered signal

The same FIR filter designed as per the parameters in table 01 is applied to a differed weight profile and analyzed the results. In this case 9130 g weight profile is considered. The filtered and Unfiltered signal is shown in figure 44. Hence it can be concluded that filter parameters need not to be changes for each box weight profile and can be set as fixed inside the filter algorithm. For 9130 g signal profile also weight accuracy is ± 5 g when maximum value of filtered signal is considered. Hence above explained weight algorithm can be used for the system irrespective of the weight of the box.

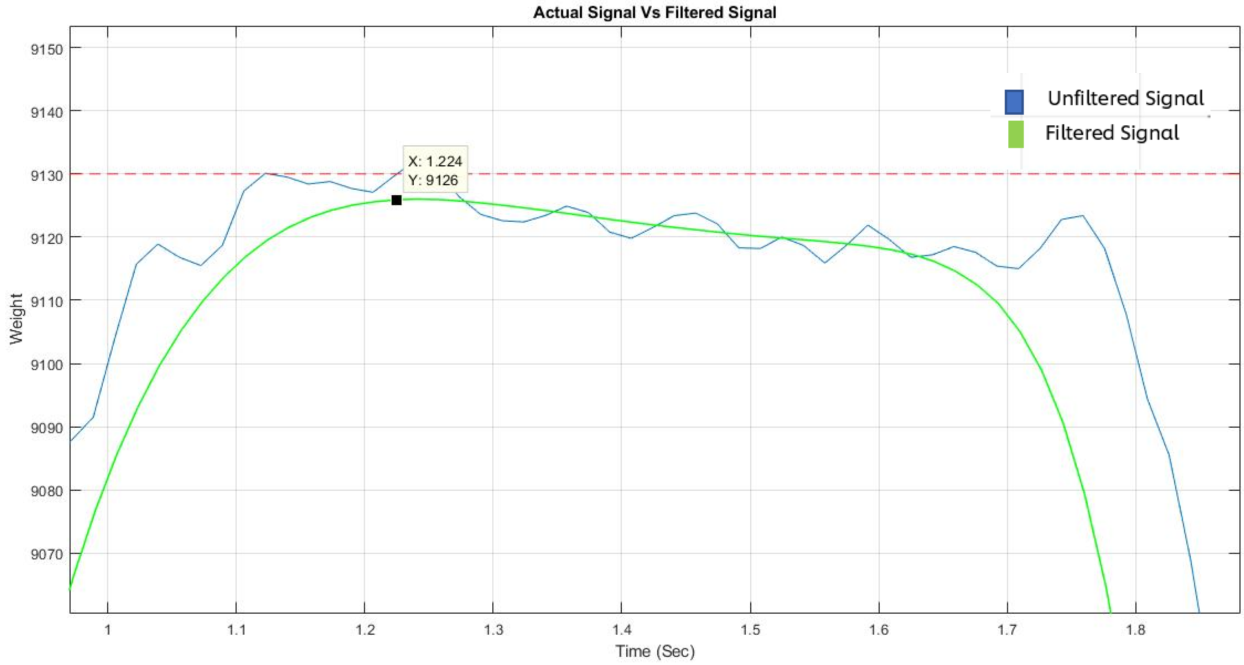


Figure 57: FIR Filtered signal of 9130g Weight profile

6.4 Infinite Impulse Response (IIR) Low Pass Filter

IIR filter generates infinite impulse response of a dynamic system. Since there is internal feedback mechanism, the filter operates for an indefinite period of time. IIR filter operates in a way that not only the present and past inputs, but the past output sample is also taken into consideration. The structure of the IIR filter is shown in figure 45. [11]

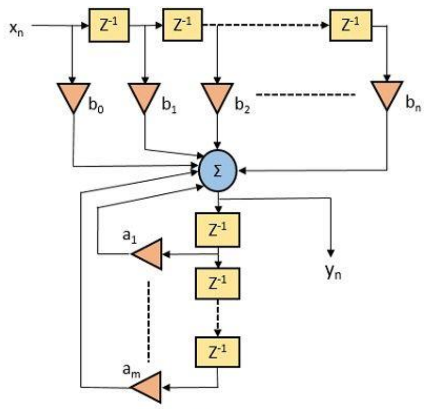


Figure 58: Structure of IIR Filter

There are few design filter parameters for IIR low pass filter as per the followings. Figure 46 shows the definition of each parameter. Hence these parameters are selected carefully by simulating in MATLAB to get the required accuracy level by trial & error method.

1. Passband frequency (ωp)
2. Stop band frequency (ωs)
3. Pass band attenuation (δ p)
4. Stop band attenuation (δ s)
5. Transition band

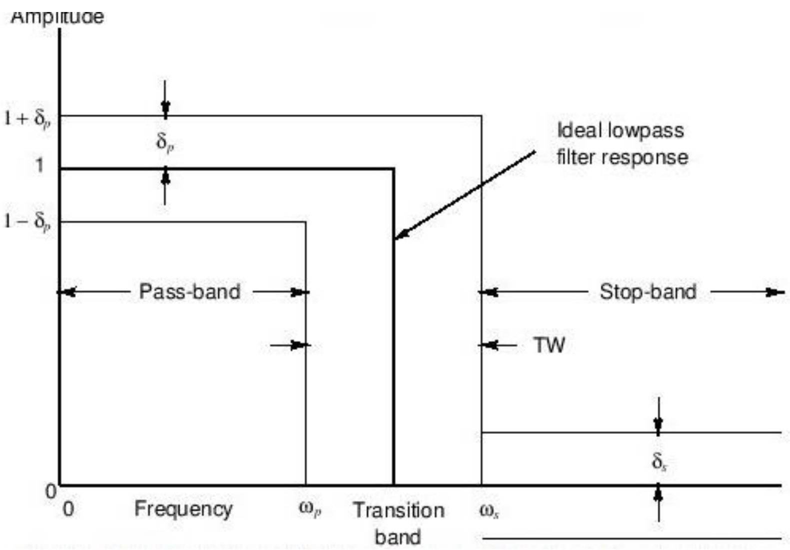


Figure 59: Definitions of IIR Low Filter Parameters

1. Passband frequency (ωp)	0.1 Hz
2. Stop band frequency (ωs)	1 Hz
3. Pass band attenuation (δ p)	0.1 dB
4. Stop band attenuation (δ s)	0.7 dB
5. Sampling Frequency	200 Hz

Table 5: IIR Low Pass Filter Design Parameters

Selected parameters by trial & error method are shown in table 02. Designed filter with table 02. parameters show in figure 59.

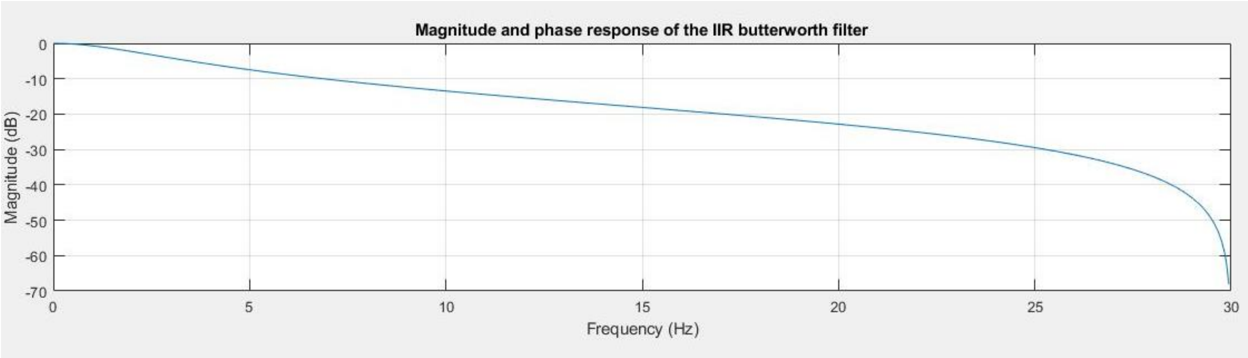


Figure 60: Magnitude & Phase Response of IIR low pass filter

Then filter is applied to the weight signal of 6930 g box and output of the filter is shown in figure 48..The weight estimating Algorithm explained in figure 43 , can be used to decide the weight of the box after applying IIR low pass filter. Accuracy can be achieved up to ± 5g.

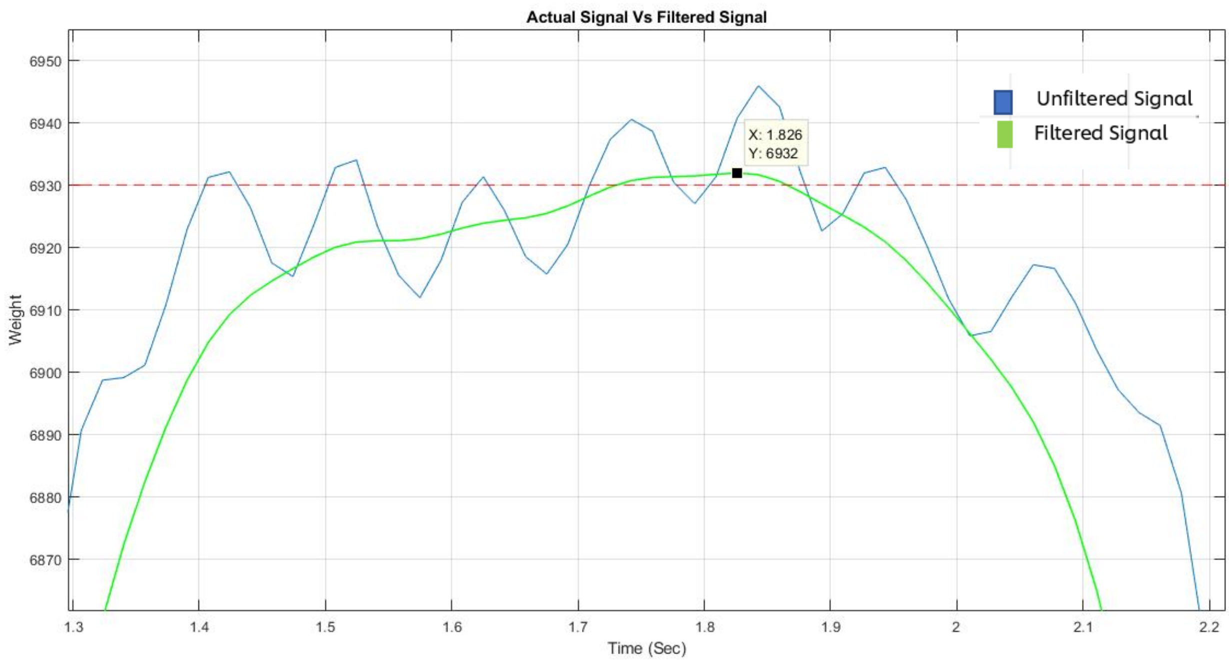


Figure 61: IIR Filtered Signal for 6930 g weight

Same filter with designed parameters as per table 02, is applied to a different weight box and analyzed the weight profile. Figure 49 shows the weight profile of 9130g with filtered signal. The same accuracy of ± 5g is achieved.

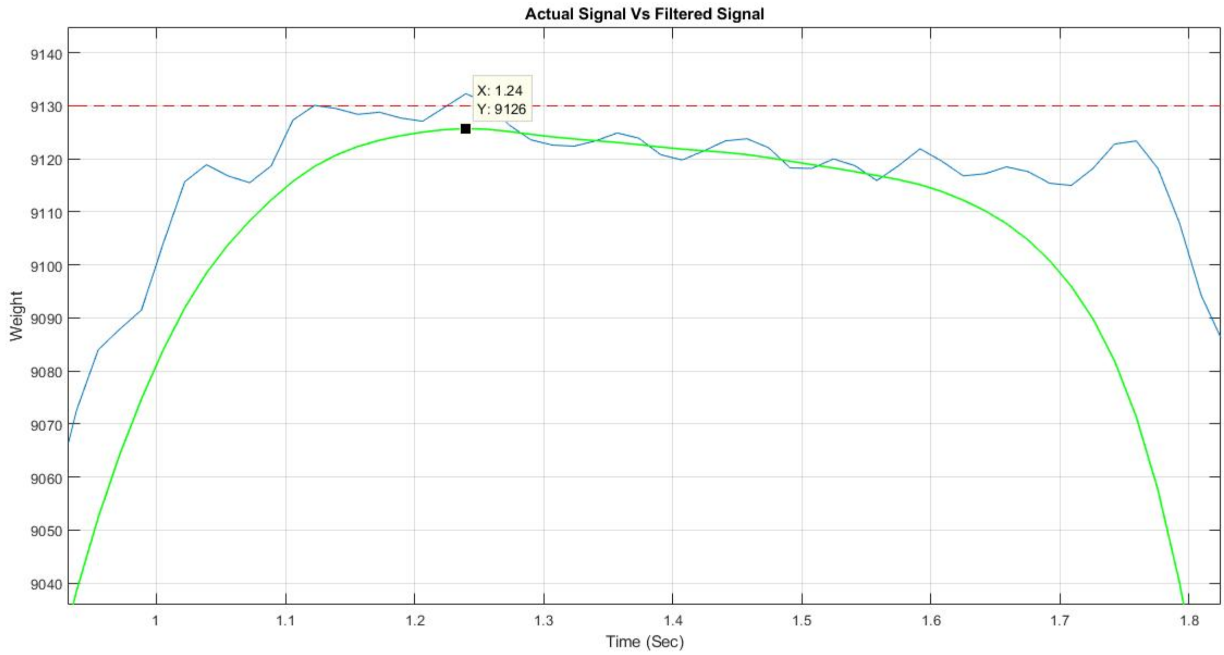


Figure 62:IIR Filtered signal of 9130g Weight profile

6.5 Summary

As per the literature review, considering the controllability & stability, FIR Low pass filter would be more practical for implementation. At the same time FIR filters are more powerful than IIR filters, but also require more processing power and more work to set up the filters. With FIR low pass filter ± 5 g accuracy level is achieved. In order to analyze and improve the dynamic system further model-based approach is suggested. In chapter 06 different types of mathematical models are considered for the dynamic system and best selected model is used to apply Kalman filter to the dynamic weighing system.

7. KALMAN FILTERING APPROACH

7.1 Introduction to Kalman Filter

The Kalman filter is an optimal estimation algorithm developed by the Rudolf E. Kalman (Kalman, 1960). [12] The different states of a dynamic system are not directly measurable but can be estimated on indirect measurements. The measurements are then translated into a state using known relationship between the measurements and the state. The measurements taken using the sensors contain measurement noise and other uncertainties and it is a challenging task to estimate states precisely and accurately. With use of the laws of physics, system dynamics may be included in the state estimation process. However, the system dynamics are not completely known and often associated with deviations and errors. In the Kalman filter approach, partial uncertainty in both measurement and system dynamics are expressed in terms of probability. The information from both measurements and system dynamics are then assimilated in a statistical way to 'filter out' the noise and obtain the best estimate of the system state. It is an efficient recursive filter that minimizes the mean square error between the estimated state and the expected state based on a state space model of the system.

7.2 Kalman Filter Theory

In order to implement Kalman filter, there should be a model that fits to the actual system. There are two methods of estimating system models namely first principle-based modelling and data driven modelling. Hence first step Kalman filtering is estimating system model. There are two equations of Kalman filter as follows. [13]

$x_k = Ax_{k-1} + Bu_k + w_{k-1}$ -------------- Equation 01

$z_k = Hx_k + v_k$------------------------------ Equation 02

x_k which are signal values may be evaluated by using a linear stochastic equation (First Equation). Any x_k is a linear combination of its previous value plus a control signal u_k and a process noise w_{k-1} .The second equation explains that any measurement value z_k (with measurement errors) is a linear combination of the signal value x_k and the measurement noise v_k. Both process noise and measurement noise are considered to be Gaussian. The process noise and measurement noise are statistically independent. The entities A, B and H are in general form matrices which are estimated through the system model. Most of the numerical models, these matrices become numerical constants.

When the estimated Model fits into Kalman Filter, then the next step is to determine the necessary parameters and initial values. There are two distinct set of equations such as Time Update (prediction) and Measurement Update (correction). Both equation sets are applied at each k^{th} state.

Time Update *(prediction)*	Measurement Update *(correction)*
$\hat{x}_k^- = A\hat{x}_{k-1} + Bu_k$	$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1}$
$P_k^- = AP_{k-1}A^T + Q$	$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H\hat{x}_k^-)$
	$P_k = (I - K_k H)P_k^-$

Figure 63: Time Update & Measurement Update Equations of Kalman Filter

$\hat{x}_k^-$ is the prior estimate which in a way, means the rough estimate before the measurement update correction.

P_k^- is the prior error covariance. We use these prior values in our Measurement Update equations.

The Kalman Gain (K_k) is evaluated during measurement update. Q is the process noise co-variance whereas R is measurement noise co-variance.

This is an iterative process with all gathered keeping in mind that the previous estimates will be the input for the current state as shown in figure 63.

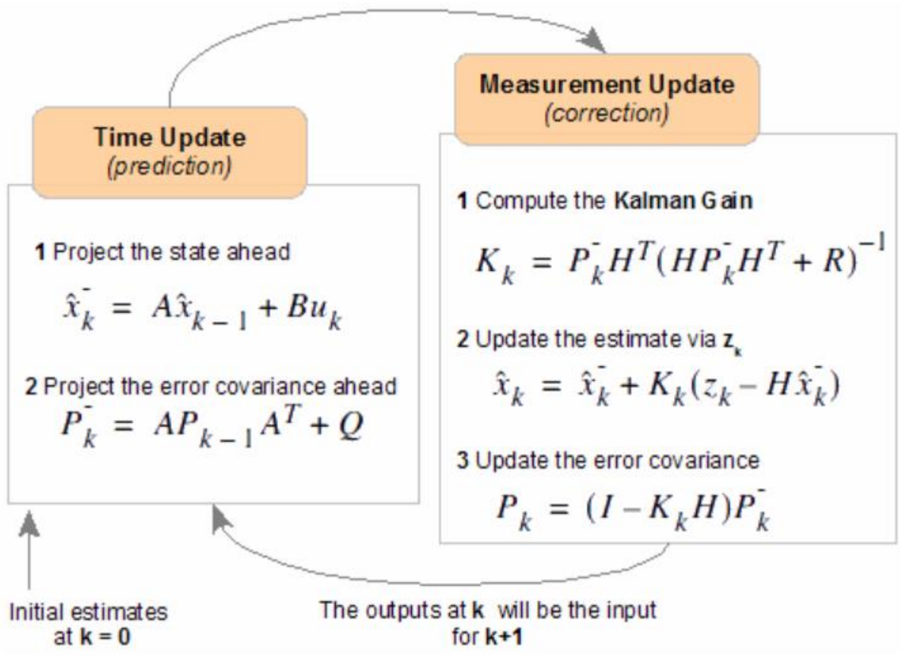


Figure 64: Kalman Filter Iterative Process

7.3 Modelling the dynamic Weighing system

There are two methods of modelling a dynamic system. They are modelling the system using physics theories which is called first principles modelling and data driven modelling which is also called as black box modelling.

7.3.1 First Principles modelling

Check weigher machine can be considered as spring-mass system and mathematical model can be derived accordingly. The second order differential equation has been used to represent the system dynamics. The state equation was derived from the second order differential equation. When a product comes onto the weighing belt, it causes the weighable to move, and this can be described by the following differential equation

$$w(t)g = (w(t) + m_l)\theta^{\cdot\cdot}(t) + c\theta^{\cdot}(t) + k\theta(t)$$ -------------- Equation 03

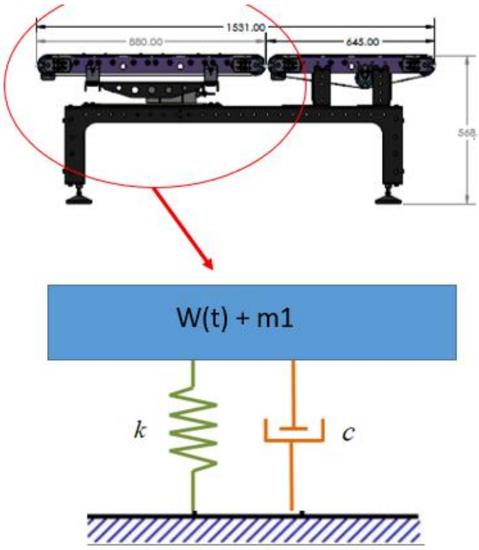


Figure 65: Check weigher as spring-mass model

Re-arranging equation 03 as the followings.

$$\theta^{\bullet\bullet}(t)+\frac{c}{w(t)+m_l}\theta^{\bullet}(t)+\frac{k}{w(t)+m_l}\theta(t)=\frac{w(t)g}{w(t)+m_l}$$ ------------- Equation 04

Where,

w(t) : Mass of the box moving on conveyor belt

m_1 : the equivalent mass of the load cell system with weighing belt

c : damping coefficient

θ : displacement of loadcell mounted under weighing conveyor

$\dot{\theta}$: velocity of displacement of loadcell

$\ddot{\theta}$: acceleration of displacement of loadcell

k : spring constant

Defining state variables as $\zeta_1(t)=\theta(t)$ and $\zeta_2(t)=\theta^{\bullet}(t)$ the differential equation becomes

$$\dot{\zeta}_2(t)+\frac{c}{w(t)+m_l}\zeta_2(t)+\frac{k}{w(t)+m_l}\zeta_1(t)=\frac{w(t)g}{w(t)+m_l}$$ ------------- Equation 05

Re-arranging equation 05 as

$$\dot{\varsigma}_2(t) = -\frac{c}{w(t)+m_l}\varsigma_2(t) - \frac{k}{w(t)+m_l}\varsigma_1(t) + \frac{w(t)g}{w(t)+m_l}$$ ------------- Equation 06

Equation 06 can be written as a state-space model

$$\begin{bmatrix} \dot{\varsigma}_1(t) \\ \dot{\varsigma}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{k}{w(t)+m_l} & -\frac{c}{w(t)+m_l} \end{bmatrix} \begin{bmatrix} \varsigma_1(t) \\ \varsigma_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{g}{w(t)+m_l} \end{bmatrix} w(t)$$ ------------- Equation 07

Let

$$x(t) = \begin{bmatrix} \varsigma_1(t) \\ \varsigma_2(t) \end{bmatrix}, \alpha(t) = -\frac{k}{w(t)+m_l}, \beta(t) = -\frac{c}{w(t)+m_l} \qquad \gamma(t) = \frac{g}{w(t)+m_l}$$

Then equation 07 can be written as

$$\dot{x}(t) = \begin{bmatrix} 0 & 1 \\ \alpha(t) & \beta(t) \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ \gamma(t) \end{bmatrix} u(t) + z(t)$$ Where $u(t) = w(t)$

$$y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} x(t) + v(t)$$

And which can be depicted as below

$$\dot{x}(t) = A(t)x(t) + B(t)u(t) + z(t)$$
$$y(t) = Cx(t) + v(t)$$

Where :

x(t) : state space of the mechanical system

U(t) : system input (w(t) unknown mass of a product)

z(t) : stochastic disturbances (system noise with covariance Rv)

y(t) : system output (displacement of loadcell ᾱ output voltage of the loadcell) v(t) : measurement noise A(t) & B(t) time varying matrices, and C is a constant matrix

Therefore, check weigher can be modelled as state space model of second order differential equation. Finding actual values for the parameters in mathematic model is a complicated task. Hence data driven modelling is the best approach for this dynamic weighing system, since actual systems input, and output data can be gathered easily with the existing system.

7.3.2 Data driven modelling (Black box modelling)

There are 3 steps of data driven modelling. [14]

1. Gather sets of experimental data
2. Estimate the mathematical model of the system
3. Validate the mathematical model with validation data set

Data driven modelling is more practical method than the first principal modelling method.

Above 3 steps are graphically shown in figure 65.

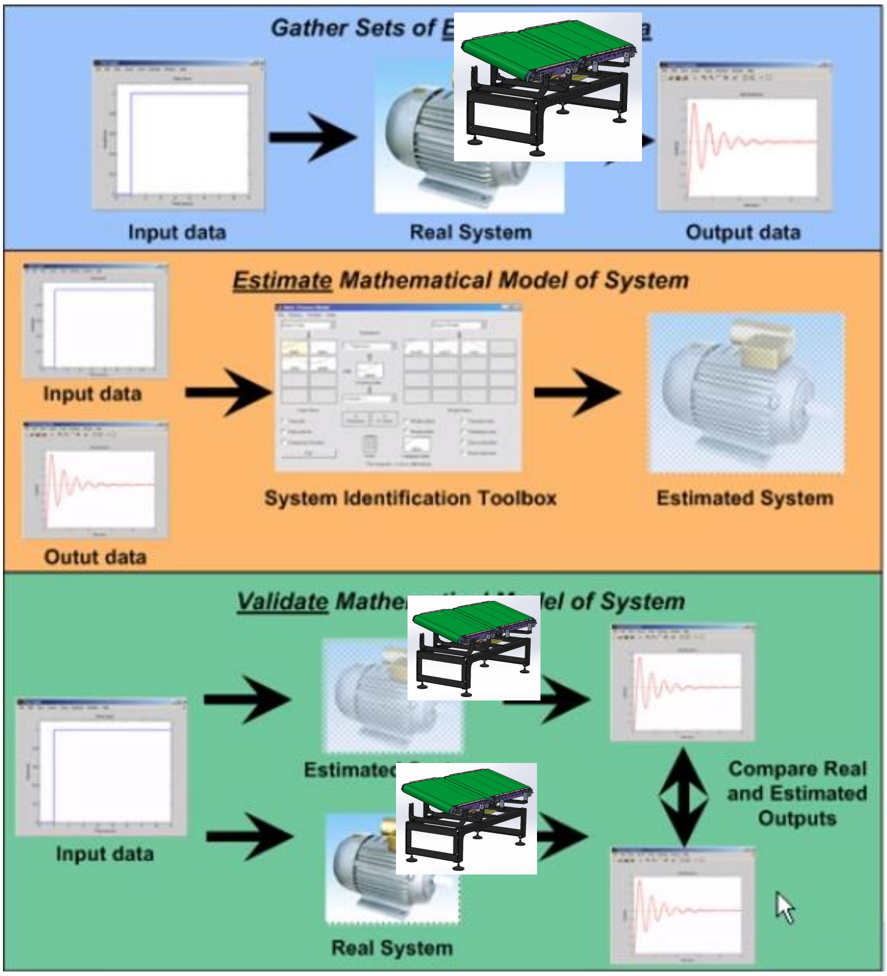


Figure 66: Method of estimating black box model

When checkweigher system is considered, known input can be fed to the system and output data profile can be collected. Then using the MATLAB system identification toolbox, system model can be estimated.
In this case, known weight of 6930 g is fed through the system and loadcell transmitter output data is collected. Then these input and output data is fed to the system identification toolbox to estimate the best fit model for the checkweigher machine. This is called black-box modelling. This is shown graphically in figure 66.

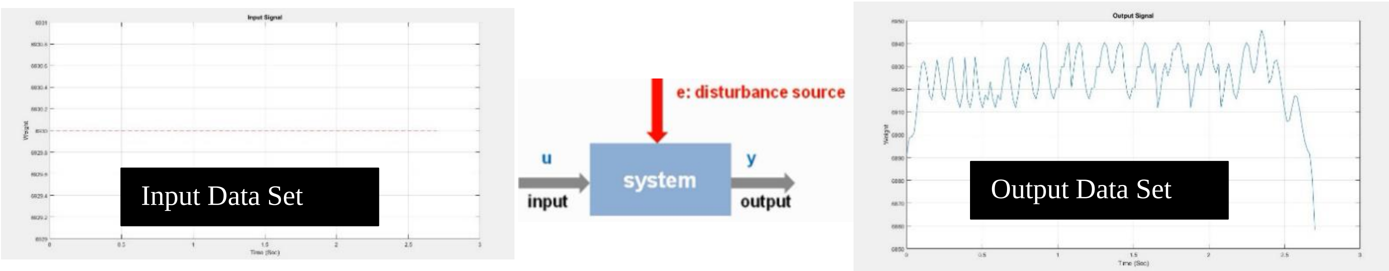


Figure 67: Checkweigher Black Box Modelling

There are three linear parametric models in System Identification toolbox as model structures as per followings

1. Input-Output Models (Transfer functions)
2. State Space Model
3. Polynomial Models

All above three models are tried out using MATLAB system identification toolbox and best fitting model is selected to implement the Kalman filter.

7.3.2.1 State space model

Figure 55 shows, the settings entered for state space model in the system identification toolbox. Model order is selected as 4 and continuous time weight profile is selected. Estimation method is selected as prediction error minimization (PEM). Rest of the settings are kept as default.

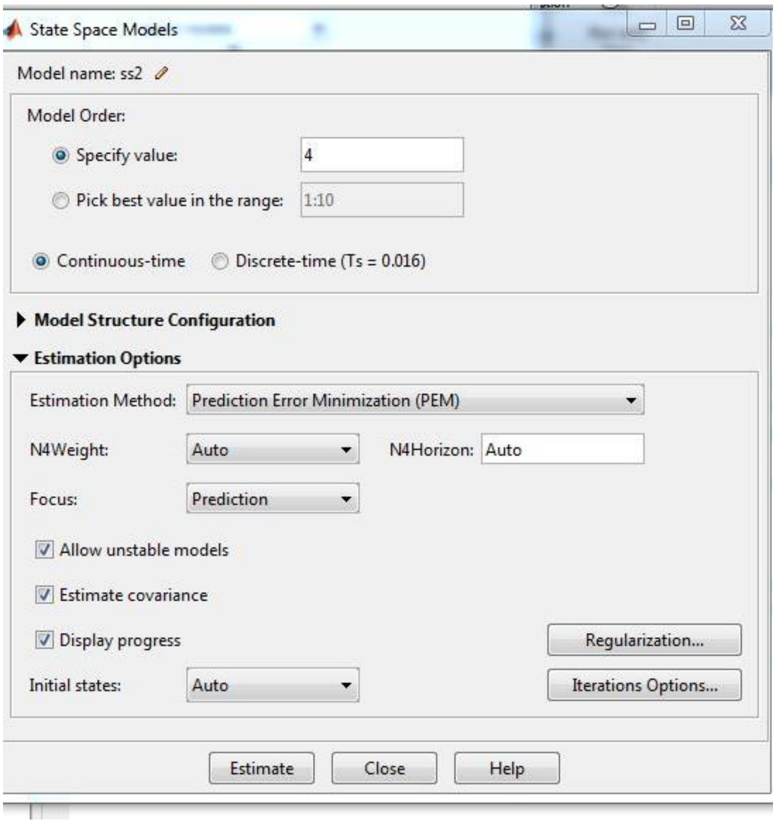


Figure 68: State Space model settings

State space model equations estimated by system identification toolbox are presented in below.

```
Continuous-time identified state-space model:
    dx/dt = A x(t) + B u(t) + K e(t)
     y(t) = C x(t) + D u(t) + e(t)
A =
          x1       x2       x3       x4
  x1  -7.506    3.274   -37.14    16.24
  x2  -1.726    9.077   -26.75   -4.407
  x3   33.52    37.59   -5.168   -28.34
```

```
B =
          u1
  x1  -0.3805
  x2  -0.1607
  x3   0.5123
  x4   0.5985
C =
          x1       x2       x3       x4
```

```
  y1    6.603   -34.86   -23.71   -0.7266
D =
      u1
  y1   0
K =
          y1
  x1   0.2199
  x2   -1.425
  x3   -1.588
  x4  -0.4816
```

```
  FREE form (all coefficients in A, B, C free).
  Feedthrough: none
  Disturbance component: estimate
  Number of free coefficients: 28
  Use "idssdata", "getpvec", "getcov" for parameters and their uncertainties.

Status:
Estimated using SSEST on time domain data "checkweigher".
Fit to estimation data: 81.56% (prediction focus)
FPE: 7.095, MSE: 3.18
```

The state space model output is shown graphically in figure 56. The model fitting to actual weight signal is around 65 %.

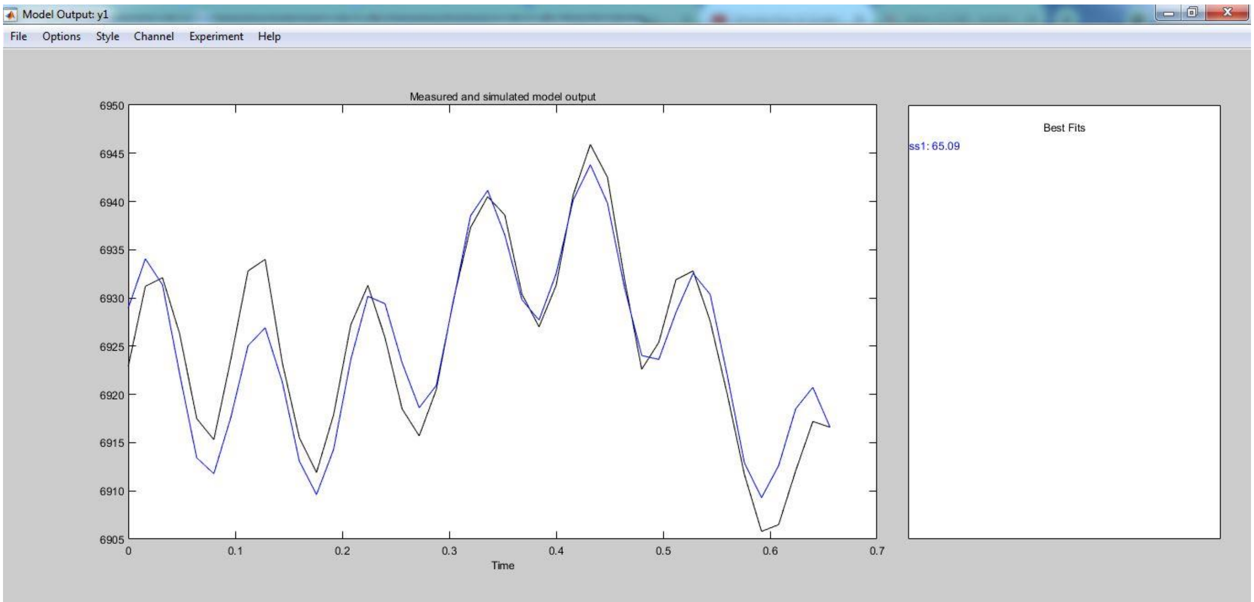


Figure 69 : Measured and simulated output of state space model

7.3.2.2 Polynomial Model

Figure 57 shows the settings of system identification toolbox of MATLAB for polynomial model. ARX model with discrete signal is considered. Rest of the settings are kept as default.

Polynomials are set of equations of a single variable with non-negative powers. MATLAB software presents polynomials with vectors including the polynomial coefficients. As shown in figure 66, MATLAB uses ARX model to determine the polynomial co-efficient.

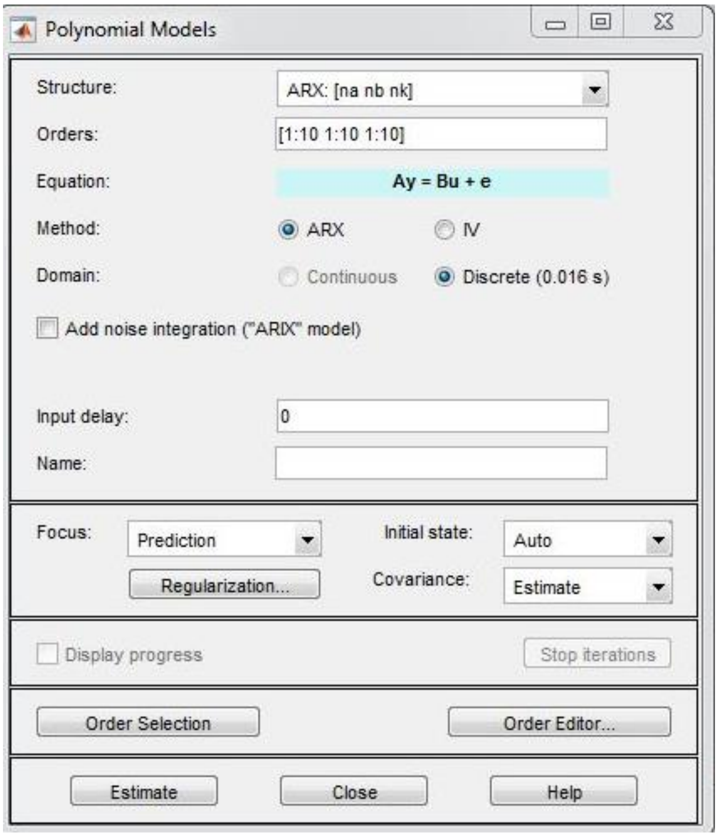


Figure 70: Settings of Polynomial Model

Polynomial equations estimated by system identification toolbox are presented in below.

```
Discrete-time ARX model:  A(z)y(t) = B(z)u(t) + e(t)

  A(z) = 1 - 1.359 z^-1 + 1.241 z^-2 - 0.7412 z^-3 + 0.04293 z^-4 - 0.08884 z^-5 - 0.08647 z^-6 - 0.114 z^-7
                                                                    + 0.4035 z^-8 - 0.3311 z^-9 + 0.5972 z^-10


  B(z) = 0.5636 z^-10 - 0.0005793 z^-11 + 0.0009835 z^-12 - 0.0001864 z^-13 - 1.259e-05 z^-14 - 0.0004287 z^-15
                             + 0.0004468 z^-16 - 0.0001007 z^-17 + 0.0005448 z^-18 - 0.0003603 z^-19

Name: arx101010
```

The polynomial model output is shown graphically in figure 70. The model fitting to actual weight signal is around 89.5 %.

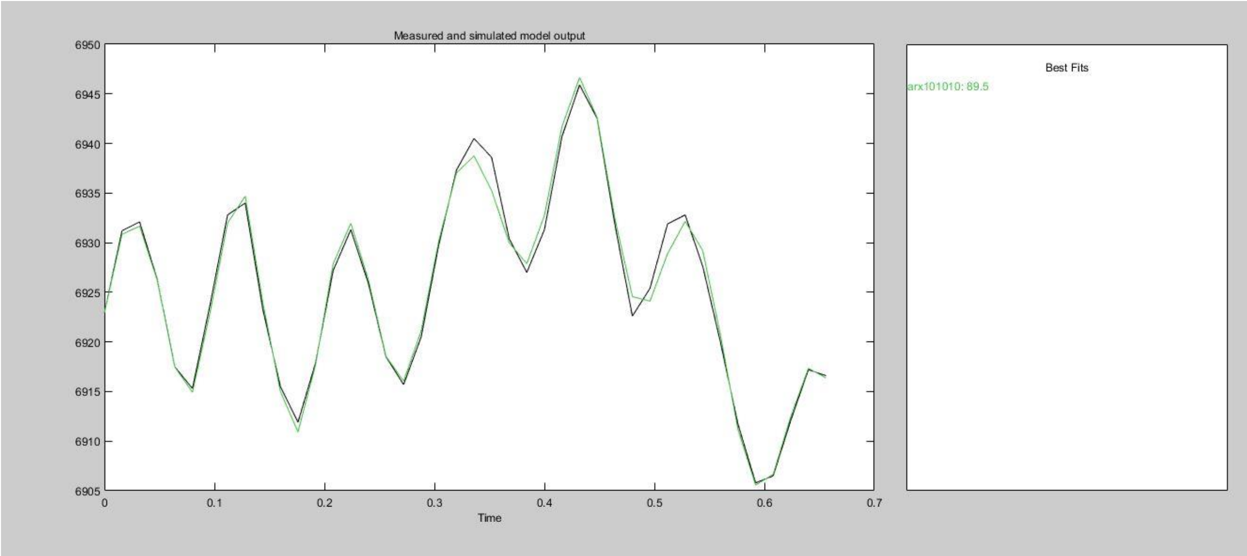


Figure 71 : Measured and simulated output of polynomial model

In figure 58, black color graph shows the actual measured output and green color graph shows the polynomial model output for 6930 g weight input. Simulated output fits to 89.5 % of actual measured output.

7.3.2.2 Transfer Function Model

Figure 59 shows the settings of transfer function model of system identification toolbox. Number of poles selected as 30 and number of zeros selected as 10. Signal is considered as continuous-time and rest of the settings are kept as default. Transfer function of the model can be got through the system identification toolbox in S-domain. The equation generated by MATLAB is presented below.

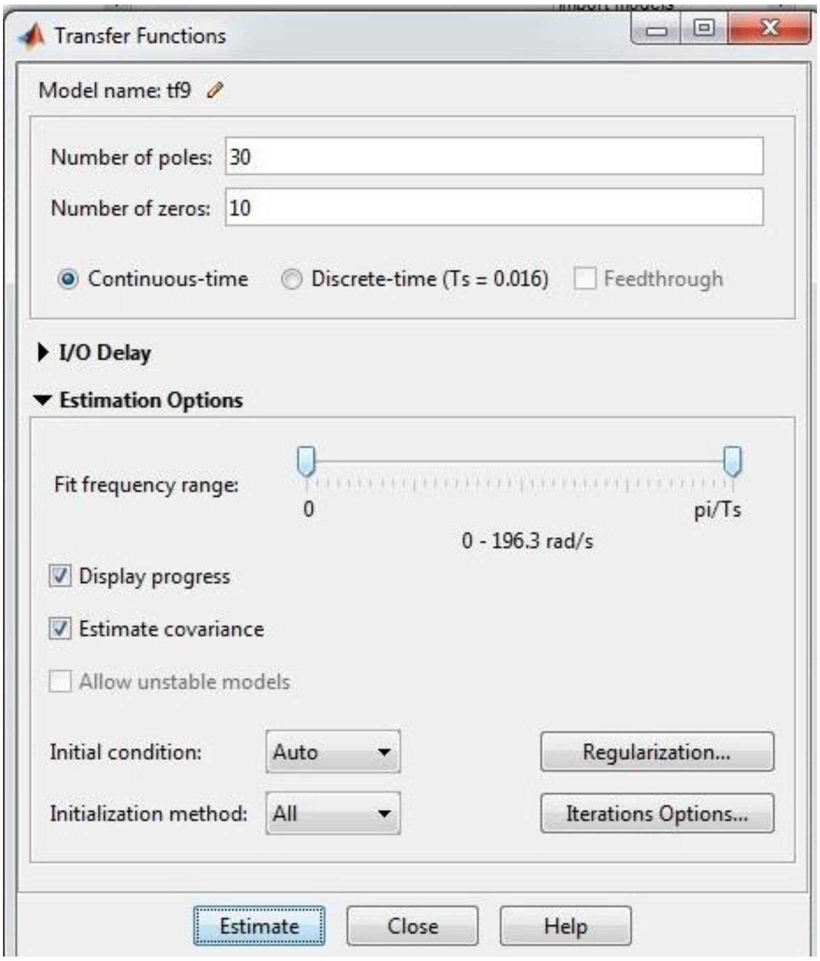


Figure 72:Settings of Transfer Function Model

Transfer function model estimated by system identification toolbox are presented in below.

```
From input "u1" to output "y1":

-1.544e42 s^10 + 1.014e43 s^9 - 3.4e46 s^8 + 9.451e46 s^7 - 1.508e50 s^6 - 2.02e51 s^5 + 2.067e53 s^4

                                                - 6.515e54 s^3 + 1.433e57 s^2 + 3.519e57 s + 3.268e59

----------------------------------------------------------------------------------------------------

s^30 + 1627 s^29 + 1.13e06 s^28 + 6.119e08 s^27 + 2.538e11 s^26 + 8.865e13 s^25 + 2.631e16 s^24

       + 6.81e18 s^23 + 1.553e21 s^22 + 3.148e23 s^21 + 5.713e25 s^20 + 9.318e27 s^19 + 1.37e30 s^18

       + 1.82e32 s^17 + 2.185e34 s^16 + 2.372e36 s^15 + 2.324e38 s^14 + 2.053e40 s^13 + 1.628e42 s^12

       + 1.156e44 s^11 + 7.311e45 s^10 + 4.088e47 s^9 + 2.004e49 s^8 + 8.508e50 s^7 + 3.084e52 s^6

                     + 9.292e53 s^5 + 2.268e55 s^4 + 4.241e56 s^3 + 5.532e57 s^2 + 5.492e58 s + 3.268e59
```

The transfer function model output is shown graphically in figure 72. The model fitting to actual weight signal is around 46.7 %.

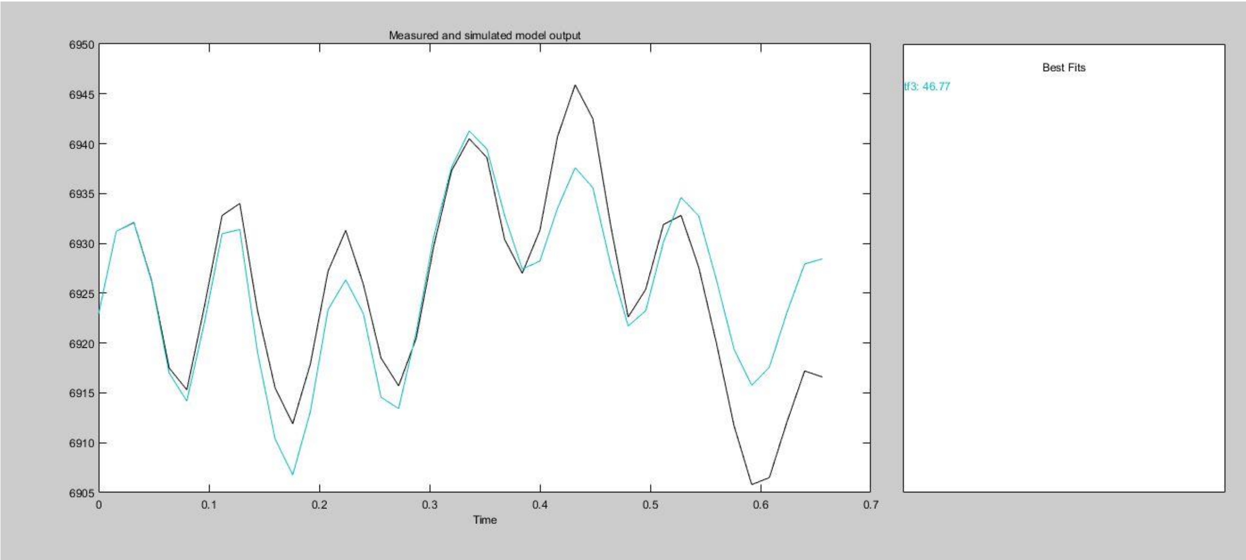


Figure 73:Measured and simulated output of Transfer Function model

Poles and zeros of the transfer function is selected by trial & error method which gives the highest best fit to actual weight signal. With this method, transfer functions poles and zeros are considered 30 and 10 respectively. In figure 60, black color graph shows the actual measured output and blue color graph shows the transfer function model output for 6930 g weight input. Simulated model output fits only to 46.7 % of actual measured output.

The figure 61 shows the comparison of the three model outputs to actual weight signal in single graph. State space model, polynomial model and transfer function model fit to original weight output by 65.9 %, 89.5 % and 46.7 % respectively. With these simulated results, it is clear that polynomial model is the best model to replicate actual dynamic weighing.

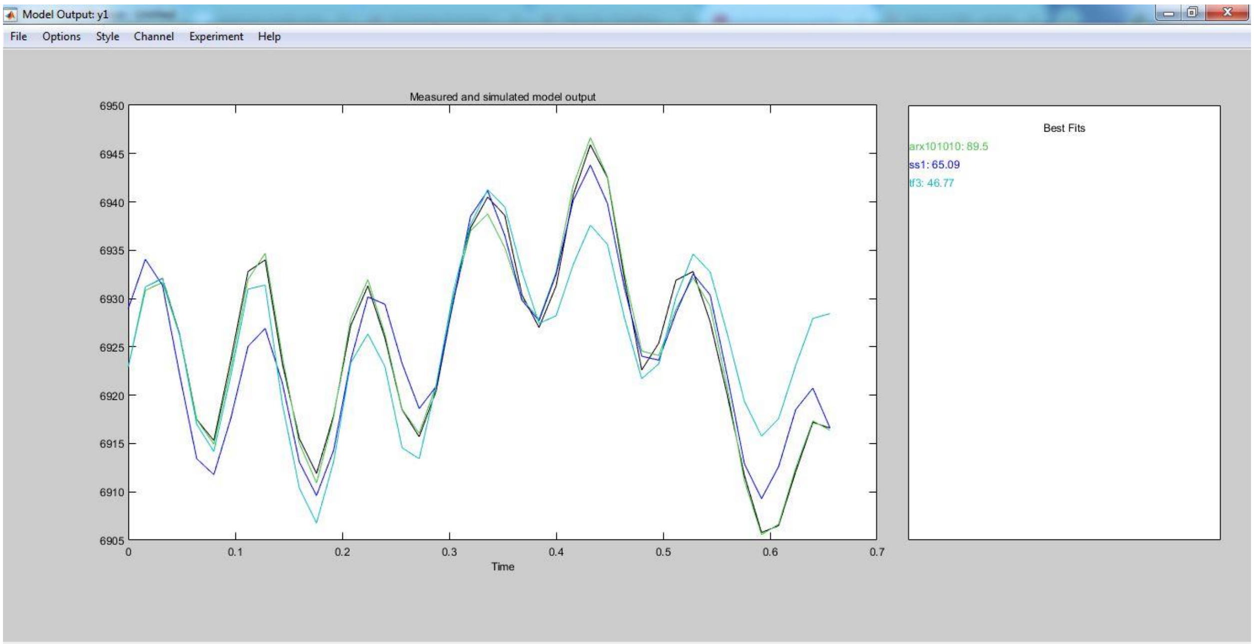


Figure 74: Comparison of model outputs

7.4 Incorporating the dynamical model into the filter

A mathematical model of a physical system is never perfect in capturing every nuance of its character. The equations formulated above utilize vectors for state variables and matrices to implement the model. The ability of MATLAB to work so seamlessly with matrices and vectors lends itself to the application of the Kalman filter. The tools present in MATLAB for the process of system identification allow effortless incorporation of the model into the code written for the Kalman filter. For these reasons, MATLAB is used to implement the filter. [15]

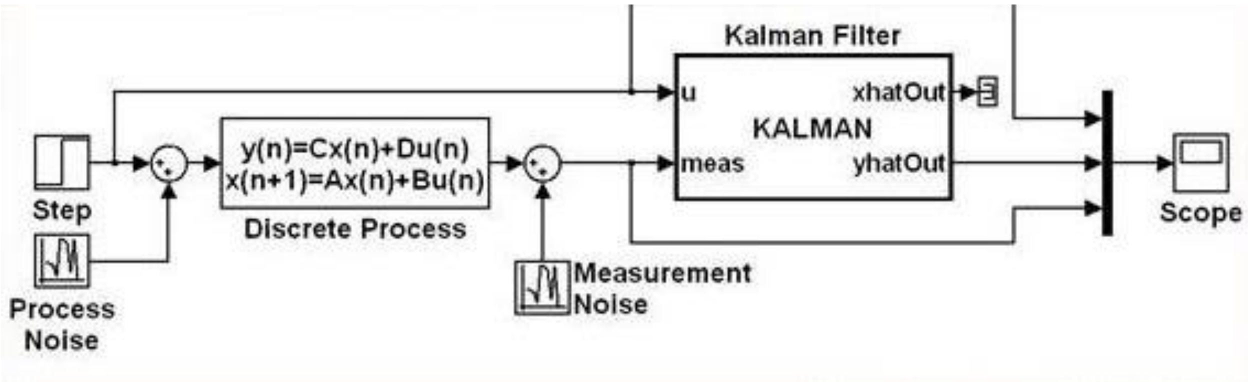


Figure 75: Kalman Filter Simulink Model

Step function is the weight signal which is coming by the loadcell transmitter. Process noise component is added to the weight signal and superimposed signal is directly fed to the model derived from section 7.3. Then measurement noise is added to the process output signal, Kalman filter is applied to the signal output of the discrete process.

7.5 Implementation of the Kalman filter algorithm

The following flowchart in figure 63 shows the implementation of the Kalman algorithm on the polynomial model derived in section 7.3.2.2. As described in the diagram, based on the initial estimates Kalman gain is calculated. By using equations explained in section 7.2 iterative process is performed.

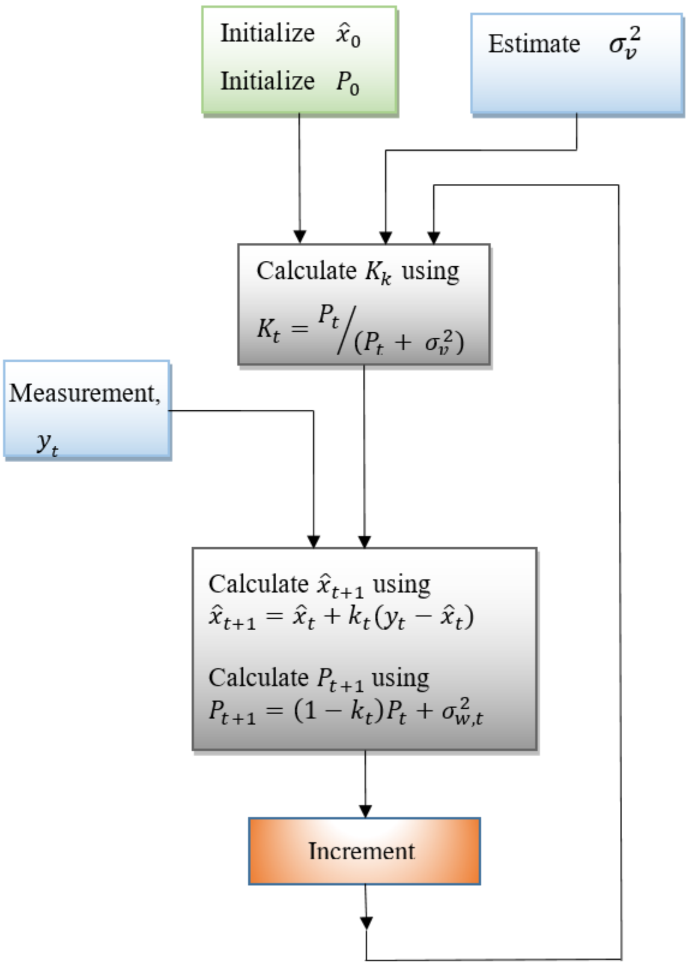


Figure 76: Kalman Algorithm Implementation

Sample calculation is shown below.

Kalman filter is applied when the weight is fully entered to the weighing conveyor. There is entry sensor and exit sensor to trigger the calculations to start and end. First weight value coming to PLC when box is fully entered is considered as initial condition. The next data value is considered as initial observation. Variance of the process noise is considered as zero. Measuring noise of the weight signal is considered as 20. (Since current system has an error of ± 20 g). Estimated weight is calculated using available data and that value is considered as initial predicted data.
Sample calculation of estimated weight is as follows.

Discription	**Pack Size**	**Unit For cs**	**Empty Corr:Box Weight (g)**	**Shrink Film Weight (g)**	**Product Weight min (g)**	**Product Weight target (g)**	**Product Weight max (g)**	**Empty Tube (g)**	**Empty Carton (g)**	Min weight (1 Unit)	**Target weight (1 Unit)**	Max weight (1 Unit)	Coru: Box Min Weight	**Coru: Box Target weight (g)**	Coru: Box Max Weight
SIGNAL HERBAL	160g	48	276	34	160.2	160.5	160.8	7	16.4	183.6	183.9	184.2	9123	**9137**	9152
Closep Redhot	120g	48	300	30	120.2	120.5	120.8	9	13	142.2	142.5	142.8	7156	**7170**	7184
Closep Redhot	40g	72	180	28	40.2	40.5	40.8	4.6	6.6	51.4	51.7	52	3909	**3930**	3952
Closep Pappermint	40g	72	180	28	40.2	40.5	40.8	4.6	6.6	51.4	51.7	52	3909	**3930**	3952
Fair & Lovely A:M:V:	50g	72	410.2	54.6	50.2	50.5	50.8	10.2	10	70.4	70.7	71	5534	**5555**	5577
Fair & Lovely A:M:V:	25g	144	370	0	25.2	25.5	25.8	6.2	6.2	37.6	37.9	38.2	5784	**5828**	5871
Fair & Lovely Men	50g	72	410.2	54.6	50.2	50.5	50.8	10.2	10	70.4	70.7	71	5534	**5555**	5577
Fair & Lovely Men	25g	144	370	0	25.2	25.5	25.8	6.2	6.2	37.6	37.9	38.2	5784	**5828**	5871

Table 6 : Estimating actual weight of Boxes

In table 3 shows weight estimation by adding up individual parts of corrugated box to sum up total weight. This weight can be used as the initial estimate for the Kalman Filter.

Let

x=6828 initial condition

z= 6825 initial observation

then $P_o = (x - z)^2 = 9$

Calculate $K_1 = \frac{P_o}{P_o + \sigma_w^2} = \frac{9}{9+20} = 0.034$

$$\hat{x}_{t+1} = \hat{x}_t + K_t(y_t - \hat{x}_t)$$

$\hat{x}_{t+1}$ = 6930 + 0.034 (6828-6930)

$\hat{x}_1$ = 6926.5

$P_1 = (1 - K_1)\, P_0 + \sigma_w^2$

P_1 = (1-0.034)9

P_1 = 8.69

P_1 is then used to calculate the next update for the Kalman gain K_2, and the calculations repeats for all the measurements. The state estimate improves through these iteration

7.6 Static weight vs dynamic weight Analysis

It is important to do an analysis of static weight readings and dynamic weight readings of the same standard weight. Ideally it is impossible to go for an accuracy less than static weight. The following table shows how standards weights of 1000 g ,2000 g ,3000 g ,4000 g ,5000 g ,10000g ,15000 g and 20000 g give readings in dynamic way and static way. For example, for 4000 standard weight, static weight reading is 3999.7 g whereas dynamic weight reading is 4995.3 g. Hence achieving ± 2g accuracy of dynamic weighing is still a possible scenario.

Standard Weight (g)	Static Weight of Check Weigher (g)	Dynamic Weight of Check Weigher (g)
1000	999.80	996.10
2000	1999.70	1997.30
3000	2999.40	2994.20
4000	3999.70	3995.30
5000	4999.40	4995.30
10000	9999.60	9996.30
15000	14999.50	14993.10
20000	19999.40	19993.30

Table 7 : Static Weight vs Dynamic Weight

As per the figure 83, it can be concluded that accuracy level cannot go below 1 g due to static weight accuracy is also within 1 g range with the existing setup.

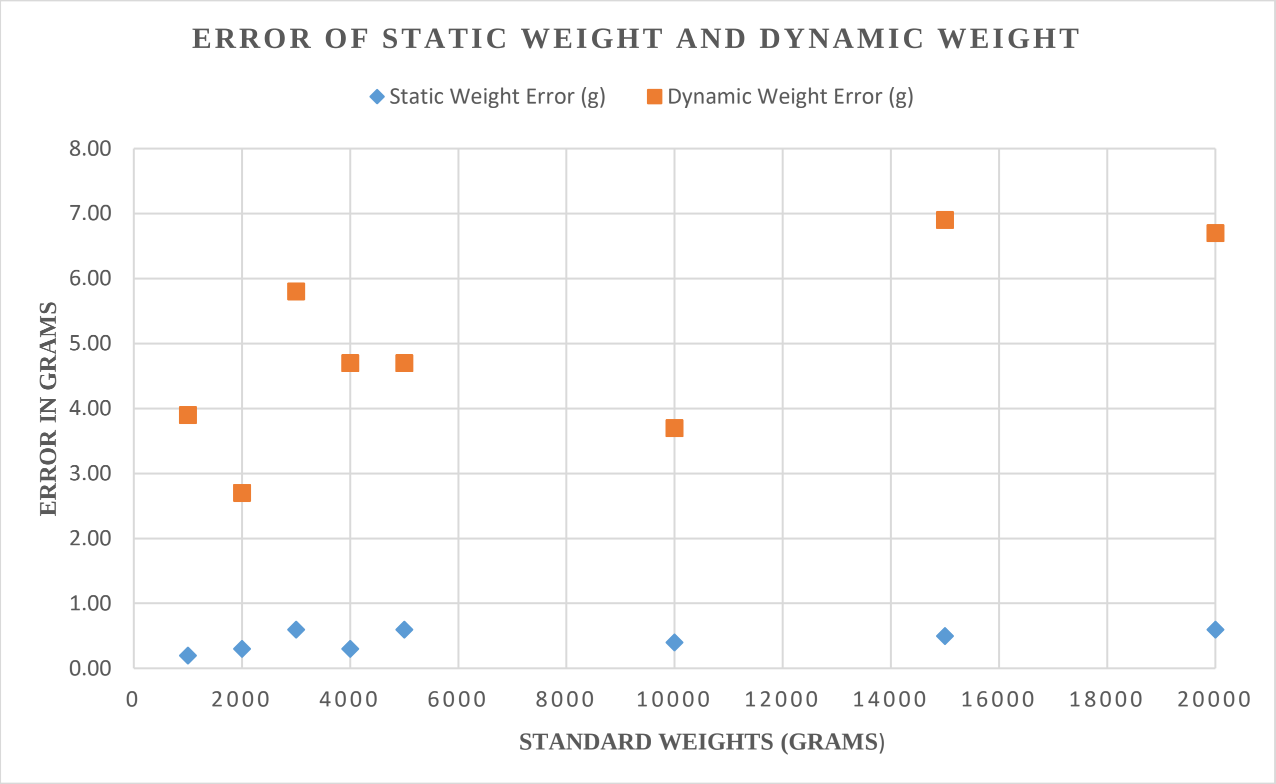


Figure 77 : Static Weight Error Vs Dynamic Weight Error

8. SIMULATIONS AND EXPERIMENTAL RESULTS

8.1 Introduction

This chapter discusses simulations and results of filtering methods. Mathematical modeling of a checkweigher was carried out based on first principles as well as using input and output data which is also called as black box modelling. In chapter 6.3 it is concluded that polynomial model is best estimated model for the checkweigher machine. Both Simulation and practical experiments were carried out to test the Kalman filtering algorithm to minimize to noise in the weight signal.

8.2 Simulation results

The simulation method allows us to test different scenarios changing filter parameters to find out the best parameters to gain the stability and performance of the model. But there can be unaccounted internal and external factors in real world testing rather than in simulations. In this case actual data received via loadcell transmitter software is fed to the Kalman MATLAB model, selected initial parameters as discussed in chapter 7 and final output is analyzed. In figure 72 black color plot is actual weight signal coming from loadcell before filtering. Green color plot is the target weight of the product. Red color plot is the Kalman filtered output of the weight signal.

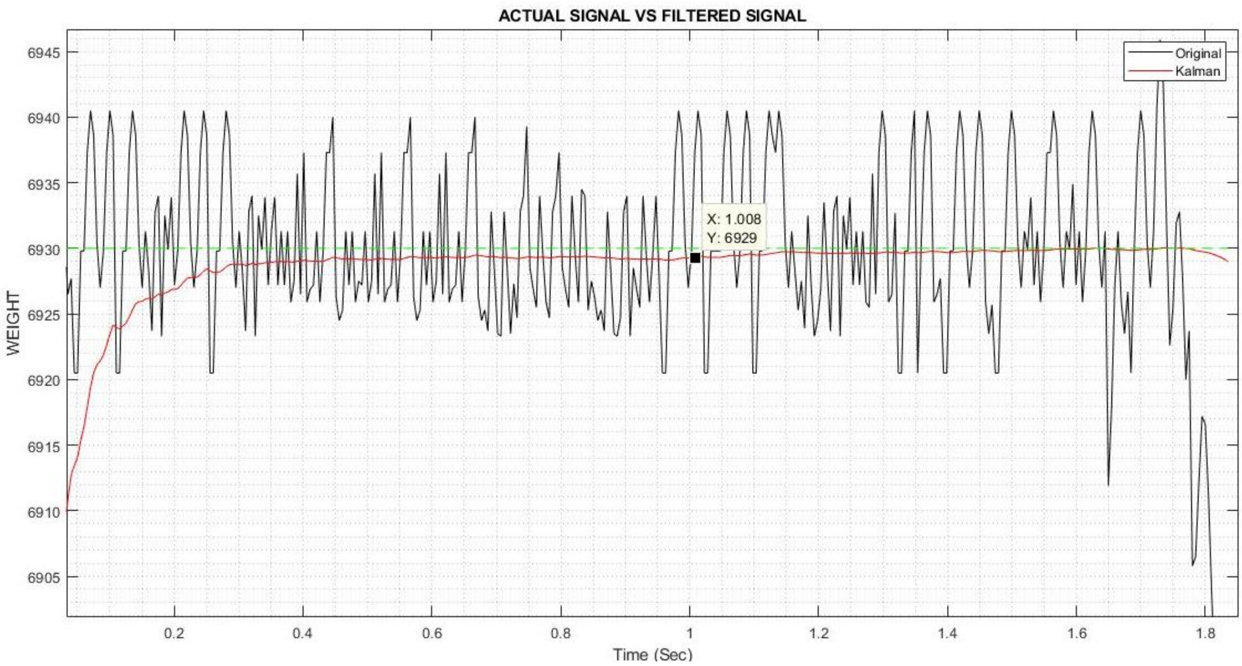


Figure 78 : Kalman Filter 6930 g Weight

The figure 76 shows the Kalman Filter output of 6930 g weight profile. Accuracy has reached up to ± 2g.

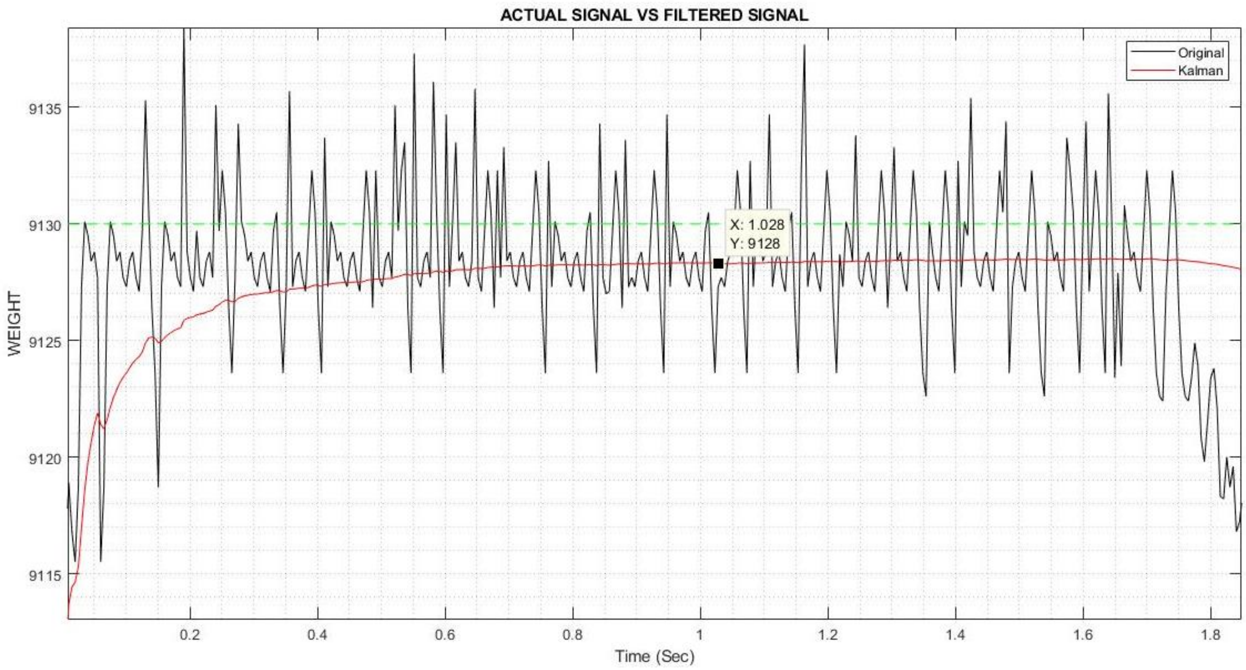


Figure 79: Kalman Filter Output 9130 g Weight

The figure 77 shows the Kalman Filter output of 9130 g weight profile. In this case also accuracy has reached up to ± 2g.
The results obtained from the filtered signal using the Kalman filter algorithm is compared with both the FIR low pass filter output and IIR low pass filter output. Then summary of the results is listed in table

Mass (g)	FIR Lowpass Filter			IIR Lowpass Filter			Kalman Filter		
	Mean	Std	Settling time (ms)	Mean	Std	Settling time (ms)	Mean	Std	Settling time (ms)
6930	6929.6	7.081	295.8	6927.8	6.2202	245.7	6928.2	4.4513	280.8
9130	9128.7	0.7734	260.9	9128.5	0.7777	255.7	9128.6	0.3619	250.7

Table 8: comparison of filters using mean, std deviation and settling time

Results in table 4 are presented at two masses running at constant speed of 0.5 m/s. The standard deviation is a measure of variation of the set of data in the filtered signal. The reduction in the standard deviation implies lower variation of data thus increases reliability of the estimate of the mean. Mean value, standard deviation & setting time are used for comparison of filtering methods. As per above results, Kalman has the least Std deviation and average minimum setting time compared to FIR lowpass & IRR lowpass filter.

Figure 78 shows, Kalman, IIR low pass filter, FIR low pass filter outputs in the same plot. In summary, the Kalman filter shows significant improvement in steady state signal and the settling time for lower speed of 0.5 m/s than other types of filtering methods tested up to now.

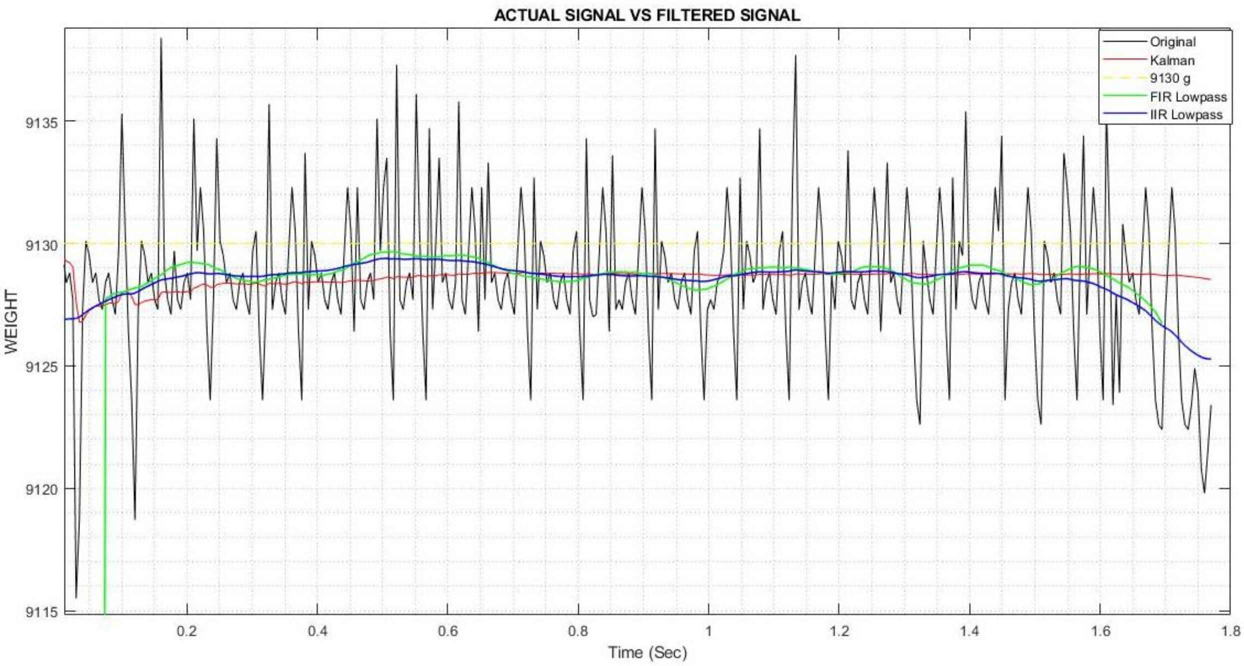


Figure 80: Filtering method comparison

8.3 Experimental results

Kalman filter algorithm was programmed inside Allen Bradley L16 compact Logix PLC using studio 5000 V32 version software as a sub program. Then tests were carried out with passive average method and Kalman filtering method. Experimental results are shown in table 5. During test, 3 different weight boxes were sent 5 times and recorded the weight value output generated from Kalman filtering method inside the PLC. PLC takes the final weight value as the last value of Kalman filter before box exits the weighing conveyor.

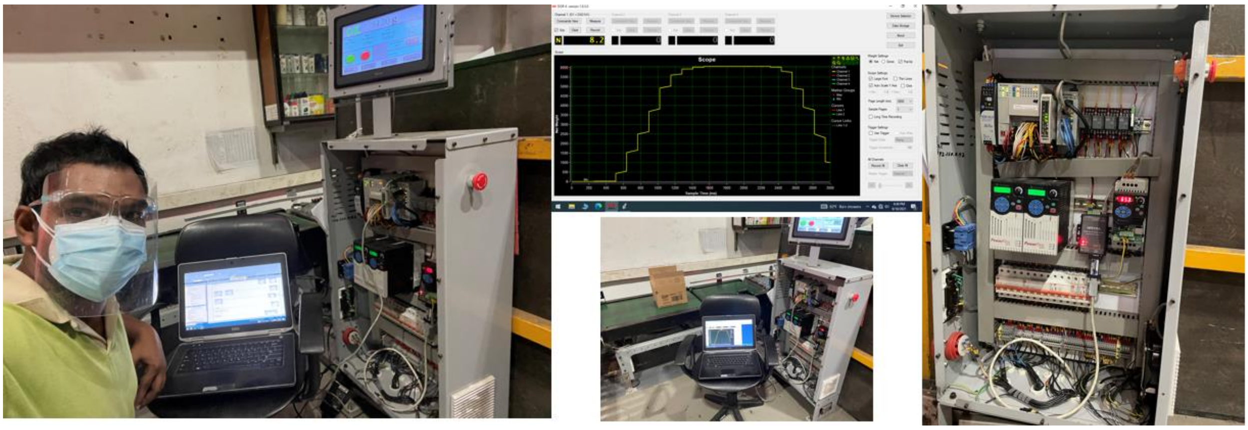


Figure 81 : Check Weigher Weight Sample Checking

	Existing Averaging Method Discussed in section 3.3 (grams)		Kalman Filtering Method	
Actual Weight	Actual reading (g)	Error %	Actual reading (g)	Error %
3946 g	3935	0.28 %	3940	0.15 %
	3940	0.15 %	3942	0.10 %
	3955	0.23 %	3948	0.05 %
	3937	0.23 %	3951	0.13 %
	3962	0.41 %	3941	0.13 %
6005 g	6015	0.17 %	5998	0.12 %
	6018	0.22 %	6001	0.07 %
	6010	0.08 %	6008	0.05 %
	6002	0.05 %	5995	0.17 %
	5990	0.25 %	6004	0.02 %
5194 g	5185	0.17 %	5192	0.04 %
	5195	0.02 %	5190	0.08 %
	5200	0.12 %	5189	0.10 %
	5180	0.27 %	5198	0.08 %
	5184	0.19 %	5193	0.02 %

Table 9 : Experimental results of Kalman filter compared with Existing Passive Filter

Based on above experimental values for each weight box, standard deviation and mean are calculated to evaluate the best option. The standard deviation of the filtered data quantifies the variation of data about its mean value. These two tools can be used to compare the outcome of the Kalman filter and the Existing Average Method.

	Existing Average Method (Passive Filter)		Kalman Method	
Actual Weight	Mean	Standard Deviation	Mean	Standard Deviation
3946 g	3946	11.99	3944	4.83
6005 g	6007	11.27	6001	5.07
5194 g	5189	8.35	5192	3.51

Table 10: Comparison Using standard deviation and Mean

A significant reduction in the standard deviation is observed of masses when using the Kalman Filter other than exiting filtering method.

The following figure shows the summary of the experimental results done at site and it is clear that using Kalman filter ± 5 g accuracy can be achieved.

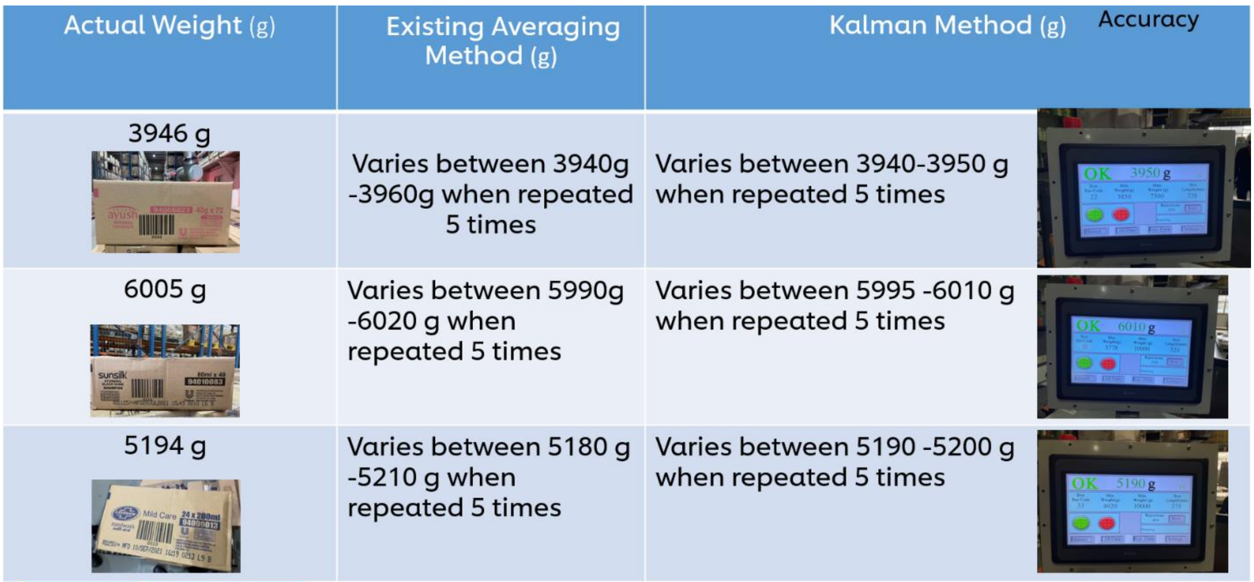


Figure 82 : Experimental results

When Kalman filter algorithm is implemented inside the PLC program, the following actual results are obtained.

- 15 g Ayush face cream one missing tube is detected 100 %.
- 10 g sachet Lifebuoy and sunsilk missing packet is detected 100 %
- 15 g Fair and Lovely face cream one missing product is detected 100 %
- Above 20 g all products (missing one unit) is detected 100 %

The following figure shows few short packs detected samples of products with implementation of Kalman filtering method. Due to this new algorithm of weight estimation, short packs complaints or short packs passing market has reduced by more than 98 %.

Figure 83: Short packs detected with Kalman Filtering Method

9. CONCLUSION

In dynamic weighing systems, there are limitations in conventional way of filtering methods in improving the accuracy and throughput rate of the system. During this study various types of filtering methods were studied, simulated, and compared the outcome using the tools such as mean, standard deviation and settling time of weight signal. With the simulation results, it is concluded that Kalman filtering gives better results. Then Kalman filter was implemented in the actual system and observed that weight can be estimated with an accuracy of ± 5 g whereas simulation results accuracy is ± 2 g.

Future work will be on gaining accuracy up to ± 2 g in the actual system. The loadcell transmitter maximum sampling rate is 600 measurements /sec. Currently with the limitation of PLC controller, 200 measurements/sec is used for the calculation due to the processing power of PLC controller. Changing existing PLC controller to an Advance version of PLC which has higher processing speed, to process 600 measurements /sec of data speed may improve the filtered signal. so that ± 2g accuracy target may be achievable. Or else it is suggested to install DSP in between Loadcell transmitter and Exiting PLC so that filter algorithm programmed inside DSP and send final weight value to PLC for next step.

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