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Design of a dynamic weigh system for conveyors

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Internship report

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Preface

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Contents

Abstract

Miedema and Dewulf are merged companies in the field of providing agricultural machines, especially for potato growers. They both attach great importance to innovation. A current field of research is about dynamic belt weighing systems. Miedema would like to have such a system on their conveyors and Dewulf would like to have one on their harvesters. The basic idea is similar for both applications: they have to weigh the product dynamically as accurate as possible and cope with all the present factors. The most important factors are the belt tension, sticking soil, angles, belt velocity, vibrations, non-uniform loading and environmental conditions. For carrying out measurements there are also some parameters that have to be determined like filtering, resolution and calibration. For the Miedema conveyor the goal was set to get a maximum error of 1%. The goal for these dynamic weigh systems is to optimize the process for the used machine parameters. It makes it easy to see if the belt is over loaded. An even more important goal is to get information of the yield per hectare or per hour. For the harvester this information can be coupled to the GPS signal in order to get yield maps of every field and the conveyor can load trucks exactly to the maximum allowed weight. For both applications it is chosen to use a strain gauge load cell. When this cell is loaded the strain causes a difference in resistance and this can be coupled to a mass. Some initial tests and a set-up was already made for the harvester and the goal was to gain more knowledge about the weigh principle and test some of mentioned factors. Before the actual testing a lot of literature and theory was covered to understand the test results. The same was done for the conveyor. Miedema already designed a weigh frame and the goal was to test this principle and give recommendations regarding further improvements.

From the literature it was clear that the weigh system should be close to the tail, the velocity measurement should be done at the tail pulley, the frame should be long and stiff, the belt tension must be constant, there should be uniform contact pressure with the idlers and sticking soil should be minimised. From a theoretical approximation it became clear that a correction factor is needed to get to the correct value. For the harvester this value is **3.4665** and for the conveyor it is **1.3127**. This factor comes from the configuration of the idlers which are connected to the load cells. The theory also shows the great influence of the belt tension and the angles. From testing it appears that the calculated correction factor is very close to the real life situation. For the harvester to real factor is **3.5060** and for the conveyor it is **1.3408**. For the harvester the belt shows very large vibrations so a double notch filter and a low pass filter is designed which is velocity dependent. For the conveyor only a low pass filter was necessary to get rid of most of the noise. It is chosen to measure at specific length steps so the velocity has no influence on the measurement. Tests show that a zero calibration is highly desirable so a function is made which measures the value during two belt lengths and then subtracts the mean of this zero calibration from every new measurement. All tests with the conveyor in a real life application resulted in an error lower than 1%.

Recommendations towards further research for the Dewulf harvester are to test the influence of the angle which the machine can make, the influence of the belt tension, the influence of measuring with time steps, how to reset the factor when the belt is installed in the machine and a redesign for the steel connection of the belt. For the Miedema conveyor testing should be done over a large time period, a function has to be implemented to change the factor, place the weigh frame more to the tail and rotate it 180°, do not measure if the machine operates at more than 5° in length direction and enclose the gap between the weigh frame and the total frame.

1. Introduction

1.1 About Miedema

Miedema has been providing effective solutions for potato growers throughout the world since 1940. The core business is delivering agricultural machines in the field of potatoes. Think of machines for soil cultivation, planting, grading and storage. Figure 1.1(a) shows a storage assembly.

Since about one year Miedema merged with Dewulf. The merged company is now the world's second largest in potato and vegetable machines. Dewulf's core business is producing potato harvesters like in figure 1.1(b). Together they can be provide the full range of machines needed by potato growers.

(a) Machines used for storage [1]

(b) Harvester [2]

Figure 1.1

Both companies attach great importance regarding optimization. They both are interested in a dynamic weigh system to implement in their machines. Therefore there are in fact two assignments: one for a Dewulf harvester and one for a Miedema conveyor. In the next two sections both will be elaborated.

1.2 Dewulf R3060 sorting table

In the world of technology it is all about optimizing in order to reduce costs and to be ahead of the competition. For optimal use of the machines for the used parameters there is a lot of feed back necessary. In the agriculture optimization also plays an more and more important role. Farmers want to get the most out of their fields. A way of getting the feed back in the machine and information for farmers is to weigh the product that is harvested on a specific place with specific machine parameters. Therefore Dewulf started a research in the field of weighing the potatoes in a harvester.

On the current potato harvesters it is not possible to monitor the amount of potatoes going out of the ground real time. If this is possible one can couple this information to the GPS signal. With this information the user can conclude if the process is optimal for the used parameters and there would be a map of the yield at every specific place. This result can be used for manuring, so that at every spot the desired amount of manure is provided. It is also possible to monitor the amount harvested per field or per hour. This can give great insight in the health of the soil.

The difficulty is to weigh the product dynamically with high accuracy. If it is a wet day, soil can stick to the potatoes which makes them heavier and there is always a certain amount of foliage present. Also vibrations and movement of the harvester itself will influence the weighing.

Dewulf wants to implement such a weigh system on the R3060 potato harvester, see figure 1.2. Behind the cabin there is a bunker where the potatoes are collected during harvesting. The belt/ conveyor that moves the potatoes towards the bunker is called the sorting table. Along this table people can stand and pick the last soil and foliage from the product. The end piece of the table can make an angle if the bunker is getting full. On this belt Dewulf has planned to place a weighing system, because here the product is the cleanest in the machine.

Figure 1.2: Potato harvester R3060 [2]

The goal is to design a reliable weighing system which can cope with all the present factors during harvesting.

Factors during harvesting are:

- Belt tension,
- belt velocity,
- sticking soil to the belt,
- angles of the machine,
- vibrations of the machine,
- angle of the end piece,
- non-uniform loading, and
- environmental conditions.

Besides the factors during harvesting, factors regarding the measurements also have to be taken into account:

- Design weigh system,
- measurement method,
- resolution,
- filtering, and
- calibration.

1.3 Miedema Conveyor 65

The Miedema Conveyor 65 (MC 65) is a conveyor belt used for transportation of products for storage, see figure 1.3. The 65 indicates the length in dm, so the total length is 6.5 m. During the storage it is desired to check the total amount of product stored and the current flow rate to see if the belt is not overloaded. The total mass that has travelled over the conveyor also gives insight in the yield per hectare. With this knowledge the user can adapt the storage facility and transportation planning if the yield is different than expected.

Besides the storage this belt can also be used to load trucks. The trucks cannot be too heavy, because then they will not be accepted at the factory. On the other hand it is best to get the truck as full as possible to reduce transportation costs.

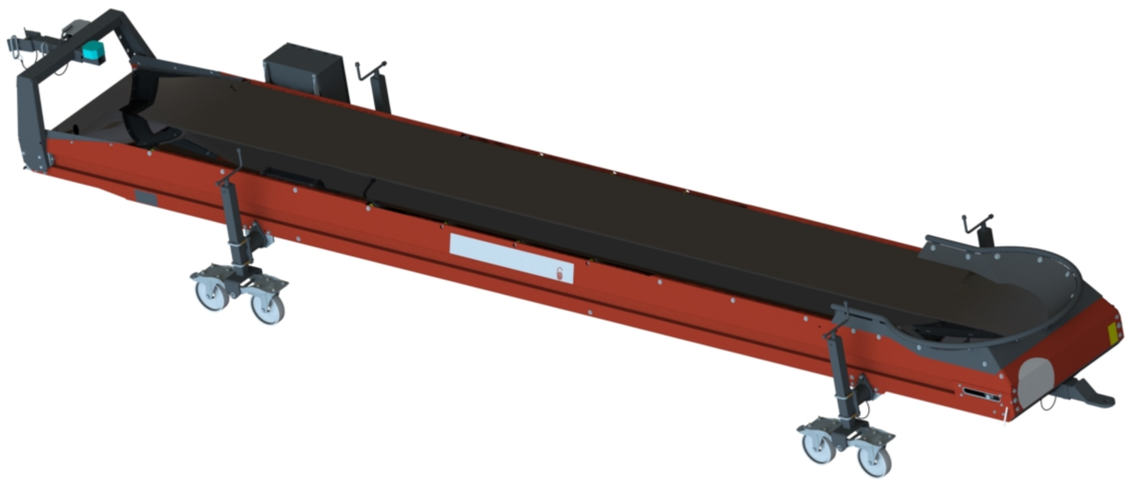


Figure 1.3: MC 65

The goal is to design a weighing system including the measurement method to measure the mass with an maximum error of 1%.

The conditions the MC 65 has to cope with are practically similar to the factors mentioned in section 1.2. Since this machine operates at stationary conditions, unexpected vibrations and movements will not be as a big issue as for the harvester.

1.4 Structure of this report

The first part of this report will cover the background information retrieved from literature and conversations with concerned persons. After this a calculation method is proposed to simulate to weighing process and get insight in various influences. Then the report is split into two parts, one concerning only about the sorting table and one about the conveyor. In these parts the theoretical approximation, the test results and the recommendations are given.

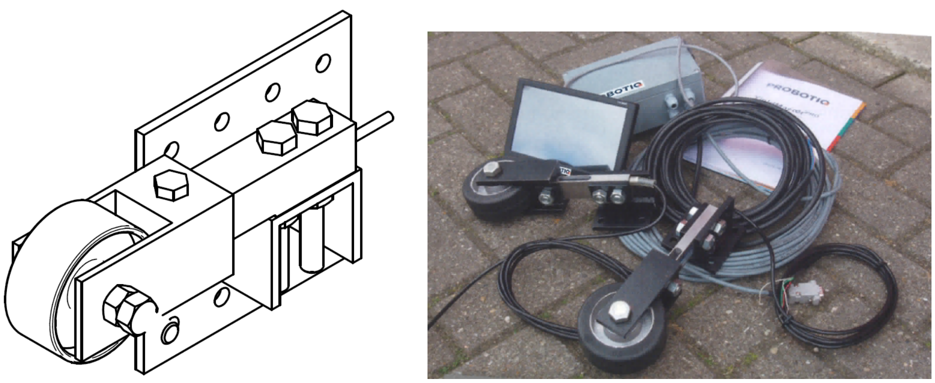
2. Background information

Before this research was started it was decided to use strain gauge load cells on both the harvester and the conveyor. Also visual systems are investigated, but not chosen because of their complexity and high costs. Consulting several sources it becomes clear this choice is confirmed to be the best option available. In the next sections the already available information and some literature study will be explained briefly.

2.1 Initial information Dewulf sorting table

Some investigation is already done by Dewulf in association with a student from the KU Leuven, Belgium. The progress of this investigation is exchanged via a visit to the Dewulf factory in Roeselare, Belgium, at the beginning of this internship. By chance there was also a exhibition called Potato Europe near the factory where the rest of the day is spent. At this exhibition the machine on which the weigh system is desired gave a demonstration of the harvesting process. This was a great opportunity the see and feel how the machine moves during operations.

The test set-up is transported to Miedema with the goal of gaining further improvements. The configuration of the weigh cells is already determined and well underpinned. The cells are directly connected to two idlers (one on each side in width direction), see figure 2.1(a). The plate with the holes is connected via bolts to the frame of the sorting table. Some research is done about the velocity of the belt, angle and belt tension, which is great background information.



(a) Configuration load cell by Dewulf

(b) Load cell connected to the idlers [3]

Figure 2.1

2.2 Existing systems on harvesters

There already are weigh systems available on the market for harvesters. Probotiq has developed such a system based on the idea of Jacob van den Borne [3]. They also managed to couple the measurement to the GPS position. The placement and configuration of the weigh cells is the same as proposed by Dewulf, see figure 2.1(b). The idlers with the connected load cell are also placed in the belt that moves the product into the bunker, because most of the tare is gone here.

The purpose according to Probotiq is the possibility to lay the yield maps on top of each other. This gives great insight where the differences may come from. One can determine if for instance the soil has problems or it is has to do with cultivation measures like manuring. A lot of variables can be monitored this way and so targeted solutions can be carried out. The yield maps are shown in figure 2.2.

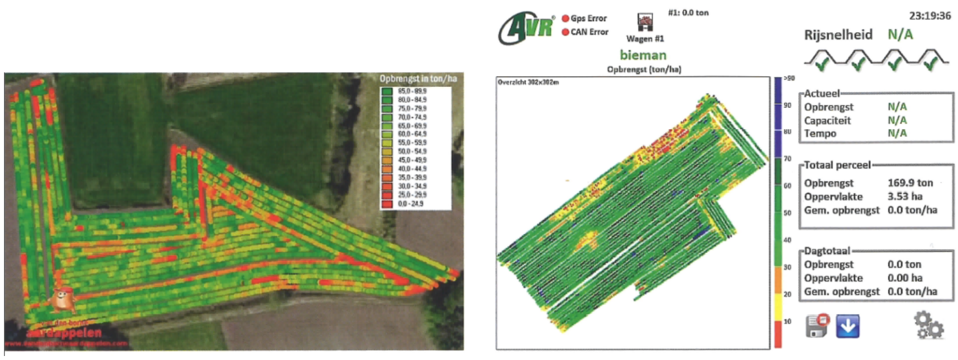


Figure 2.2: Yield maps [3]

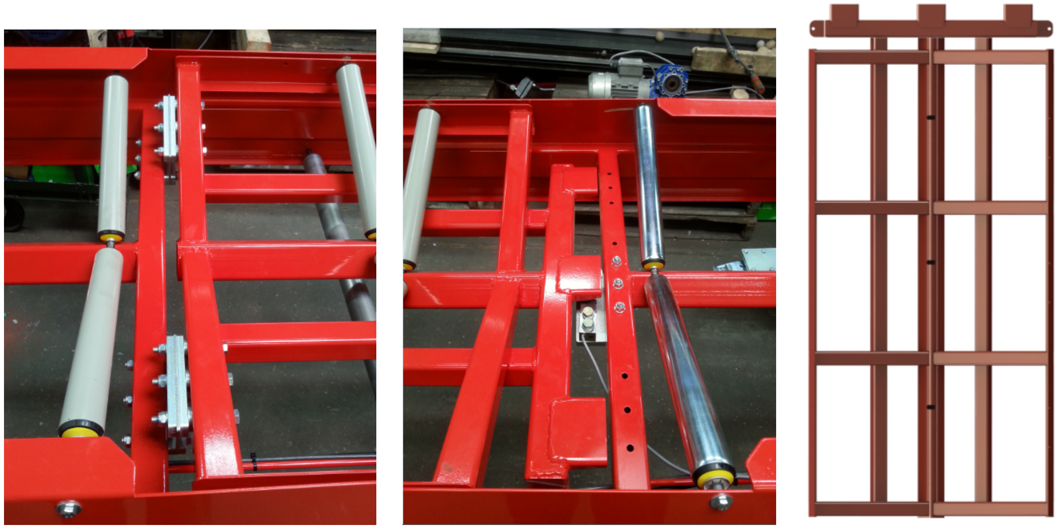
This season two companies started with an yield measurement in the field of sugar beets [4]. The new Vervaet Beet Eater 625 “Light” from the company Houbraken B.V. has load cells for continuous place specific yield measurements. Vervaet designed the weigh system in corporation with Probotiq. It has the same configuration as in the previous mentioned article, see figure 2.3. To avoid the influence of the belt tension the cells are not placed on the first or last idlers. They claim an accuracy of 2%. The weigh system is nowadays on the option list for €8,500. The downside of the system is that is will not work properly on heavy soil. More cleaning units are needed for these soils.

Figure 2.3: Load cell connected to the idlers [4]

2.3 Initial information MC 65

Before this investigation is started Miedema already made the MC 65 including the design for the weigh frame, see figure 2.4. They based their design on recommendations gathered from visiting companies that have experience in the field of weigh systems.

The initial weigh frame consists of a pivot point at one end (figure 2.4(a)) and a free end which is support by a weigh cell (figure 2.4(b)). The weigh frame can pivot due to the deflection of 4 mm thick sheet metal acting as a flexure. The use of bearings for realizing a hinge point is deliberately avoided, because of the present backlash and torsional loading effects. Furthermore, using a flexure



(a) Pivot point (b) Supported by a weigh cell (c) 3D CAD model

Figure 2.4: Designed weigh frame

eliminates moving parts and is virtually maintenance free. For the other end it is determined that one weigh cell in the middle should do the job. If it is necessary more cells can easily be added, see the prepared operations in figure 2.4(b). The first idea was to use two cells, but in this case the system is over-constrained and a close bond between the frame and the cell cannot be guaranteed. This could cause undesirable vibrations which lead to measurement errors. The total length of the frame is 1.75 m and it supports three idlers. The placement of the weigh frame inside the total frame is shown in the red box in figure 2.5.

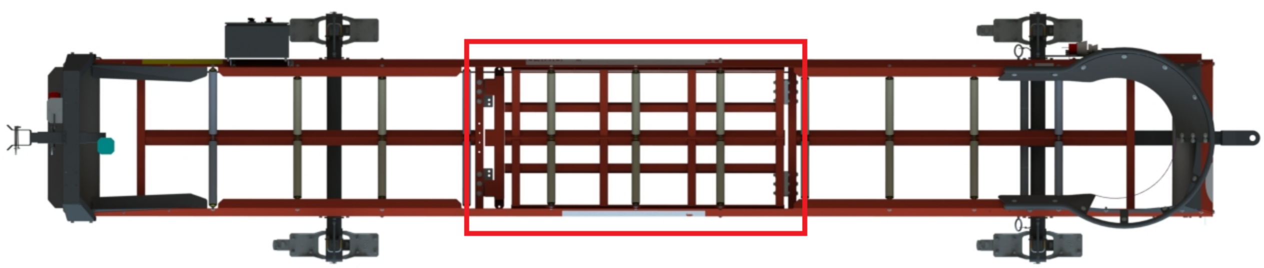
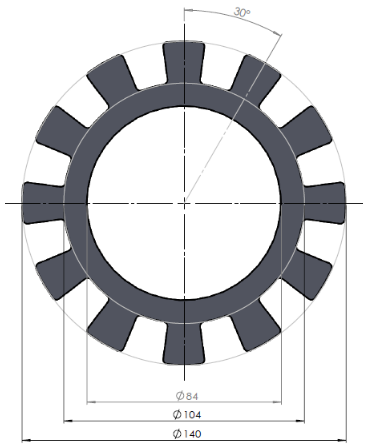


Figure 2.5: Placement weigh frame in red box

For measuring the velocity and for triggering a weight measurement request a device has to be installed. In the initial design this is done by adding a plate with flanks which rotates with the tail pulley. A fixed sensor looks at the tail pulley and every time a flank comes in sight of the sensor an event is created. The plate with flanks is constructed as in figure 2.6(a) and placed as in figure 2.6(b). Every 30° there is an event, so there are 12 events every rotation if the resolution is set to one. Using the radius of the pulley and halve the belt thickness the step length is calculated: $dl = 4.29\ cm$.



(a) Plate for the sensor

(b) Placement sensor and plate

Figure 2.6

The velocity can be adapted via a frequency controller. The mains electricity has a frequency of 50 Hz, but the controller can modify this signal. This gives a change in torque and so a change in velocity, the higher the frequency the higher the torque.

2.4 Existing systems on conveyors

Nowadays belt scales on conveyors are frequently used in the mining industry. The knowledge from these systems can be very useful for designing a weigh system for the MC 65. On the internet a lot of guidelines/ handbooks for designing an accurate weigh frame can be found [5]–[8]. The literature concludes:

- The weigh system should be close to the tail, because the tension variation is the lowest in this area. On the other hand the system should be at enough distance from the input of the product, because the product can still move when entering the conveyor (depending on the velocity).
- The velocity measurement should preferably not be done at the drive pulley, because it can slip.
- The weigh frame should be as long as possible to get rid of the effect of non-uniform distributed loads. On the other hand the frame should be very stiff to transfer all the energy directly to the cell in stead of deformation of the frame.
- The belt tension plays a very important role. A long frame should minimize this influence. Another solution is to use a gravity take-up or a spring system which takes away the backlash and ensures a more or less constant belt tension, see figure 2.7.

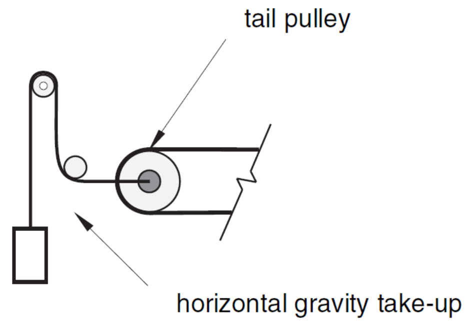


Figure 2.7: Horizontal gravity take-up [5]

- An uniform contact pressure on the idlers is desired. Therefore the alignment of the idlers is very important.
- The length of the cables of the cells must have the same length if multiple cells are used. Otherwise the electrical resistance will change and one cell will measure a different value than another for the same mass.
- A close bond should be realised between the weigh frame and the cell.
- Material roll back should be avoided. Especially potatoes tend to roll back if there is only a small angle. The roll back is highly undesirable. One can image that if a potato keeps rolling on the weigh frame the total mass will keep adding up. So, ideally the conveyor should be kept horizontal.
- Basically there are two types of weigh frames: a pivoted and a floating frame. The advantage of the floating frame is that it is more sensitive than the pivoted one. The advantage of a pivoted frame is a relative better stability. Within the two types of frames the choice has to be made on the number of supported idlers. The more supported idlers the higher the accuracy.
- All possible vibrations should be avoided. The conveyor is operating close to other machines which vibrate and the input of product also causes vibrations.
- To minimize the effect of sticking soil to the belt a properly working scraping device should be installed. Sticking soil causes a change in the dead weight and the velocity changes, because of the increase of diameter of the pulleys. Also vibrating cleaners are often used on conveyors, but these are of course not desirable.

2.5 Basic information belt scales

A belt scale consists of three elements [9]:

- The weigh frame,
- device which measures the belt velocity, and
- electronics which combines the inputs and deliver the outputs.

So, with these elements one can see how much material has travelled on a day, a shift, a plant or real time. The conveyor belt loading is measured by the weigh frame and measures the mass per metre. The conveyor belt travel is measured by a tachometer and measures the velocity. If those two measurements are multiplied the mass flow rate is gained: $[\frac{kg}{m}] \cdot [\frac{m}{s}] = [\frac{kg}{s}]$. Belt weighing systems can achieve relative high accuracies, typically between 0.25% and 1% [9].

2.6 Strain gauges

Before the modern strain gauges were invented mechanical devices were used for strain measurements [10]. These devices have several disadvantages w.r.t. the modern electrical measurement techniques:

- Only suitable for static processes,
- restrictions for measuring small test samples (or even impossible),
- only accurate results for uniform conditions, and
- automatic recording is not possible.

Electrical measurements should cover the previous mentioned shortcomings. For this research the fact that electrical measurements can cope with dynamic processes is of most importance. Furthermore, there are several advantages [11]:

- Low mass and small dimensions,
- vast frequency range,
- excellent linearity over a vast strain range,
- low and predictable temperature effects, and
- good stability.

2.6.1 Operating principle

The main goal of the gauge is to transmit information to the user from the applied strain on the cell. The gauge used in this research is an electrically resistive strain gauge where the strain causes a change in its electrical resistance [10]. The change in resistance comes partially from the deformation of the conductor and partially from the change in resistivity of the material in the conductor as a result of micro structural changes. A schematic view of this principle can been seen in figure 2.8.

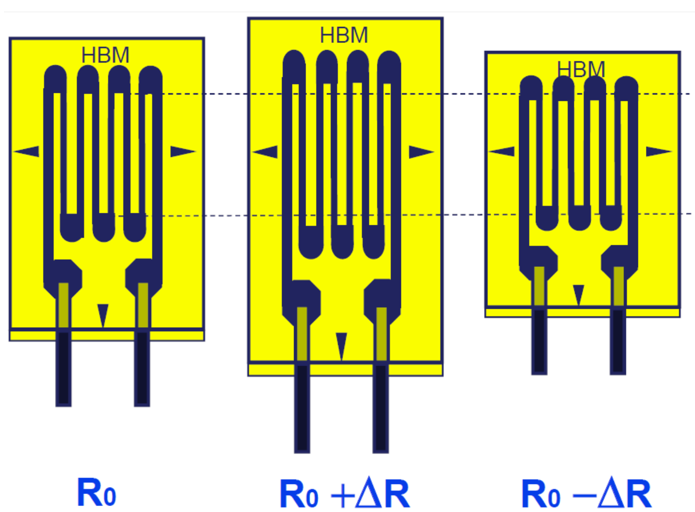


Figure 2.8: Schematic view of the operating principle of a strain gauge [11]

Definition of strain A relative change in length is the most regular strain definition (for the linear case). This looks like $\varepsilon = \frac{\Delta l}{l_0}$ and usually has the dimension $[\frac{\mu m}{m}]$, because the change in length is most of the time very small for strain gauges. For correct measurements a close bond between the strain gauge and the object is required so there is no loss in the transformation of strain.

2.6.2 Wheatstone bridge

The relative changes of resistance in a strain gauge are usually around the order of 10^{-4} to 10^{-2} [10]. To be able to transform these small changes into measurable voltages, the Wheatstone bridge circuit is used in strain gauge techniques, see figure 2.9.

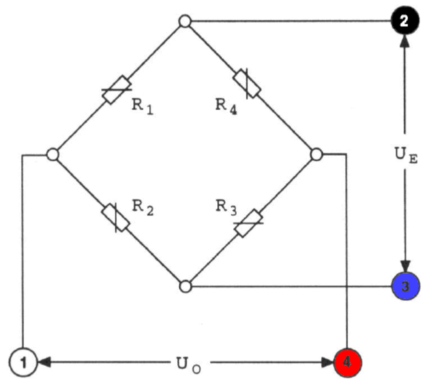


Figure 2.9: Representation of the Wheatstone bridge circuit [10]

In figure 2.9 R_1 to R_4 are called bridge arms and points 1 tot 4 (colour coded) are the bridge points. If there is a voltage between bridge points 2 and 3 (U_E) then there is a output voltage between 1 and 4 (U_0). The relative output voltage can now be calculated with the following equation:

$$\frac{U_0}{U_E} = \frac{k}{4}(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4) \tag{2.1}$$

This equation holds for the fact that the two halves of the bridge should have the same value: $R_1 = R_2$ and $R_3 = R_4$. The factor k is also known as the gauge factor which represents the sensitivity. This factor should be determined with experiments.

There are different versions of the circuit. In the so called “Quarter bridge” only one resistance is changing, in the “Halve bridge” two resistances and in the “Full bridge” all four resistances change their values. A representation of a “Full bridge” circuit can be seen in figure 2.10. The yellow rectangular planes represent a single strain gauge as shown in figure 2.8. The load F causes a positive strain in strain gauge 1 and 3, and a negative strain in gauge 2 and 4, see also equation (2.1).

2.6.3 Compensation for disturbances

The effect of temperature is one of the most problematic disturbance [11]. Due to temperature difference materials expand or shrink and the resistance can change. This means that every strain gauge gives out a value when the temperature varies. In the Wheatstone bridge circuit the temperature can be compensated. In a “Quarter bridge” a strain gauge which is not used for measuring strain can be used for compensation. There are some restrictions for this compensating gauge:

- It must be applied in a place where it will be subjected to the same interference effect as the active gauge,

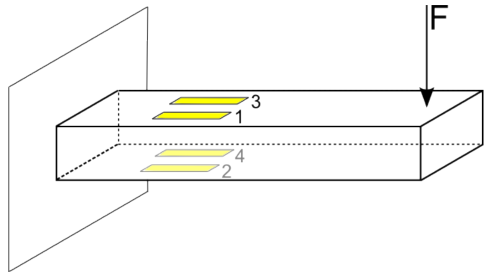


Figure 2.10: Representation of a measurement on a bending beam using a 'Full bridge' circuit [11]

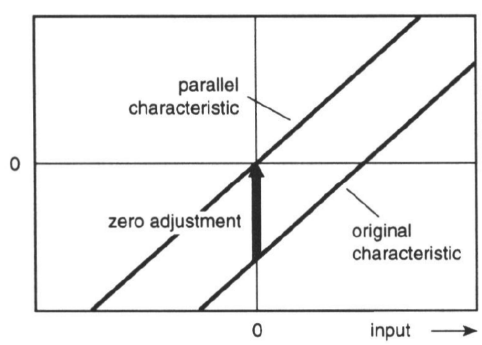
- it must have the same physical properties, and
- it must be applied at the same material.

Using this compensation has the advantage that no temperature has to be measured during the measurement. In the "Full bridge" version changes of the resistance of the same sign appearing in neighbouring arms will be subtracted w.r.t. the bridge output signal.

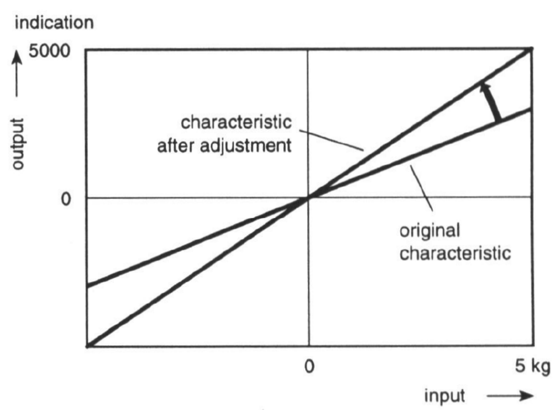
Additional disturbances can be: bridge misalignment, additional strain and the dependent k factor. The bridge misalignment is not present when the cable lengths are identical. Additional strain is not present with identical twisted supply lines and the k factor should come out experiments (calibration).

2.6.4 Calibration and adjustments

The total weigh system contains of the weigh cell, signal conditioning unit and a display/ evaluation device. To work with this system first calibration and adjustments are necessary. Calibration means that the measuring amplifier must be changed in such a way the display shows the correct physical quantity. In practice, two adjustments have to be carried out: the zero adjustment and the full range adjustment, see figure 2.11. Since the relation is linear this should be the correct way for calibration. This can easily be checked to use masses which are in this range, the value should be on the line.



(a) Zero adjustment



(b) Full range adjustment

Figure 2.11: Adjustments [10]

There are three possibilities to carry out the calibration:

- Simulating a signal,
- loading with real mass,
- using intelligent instruments and auto-calibration.

It is recommended, especially for this research, to calibrate with real mass [10].

3. Theoretical approximation

Now all the background information is known it is time to simulate the process of the moving mass over the belt and how this can be felt by the load cell. In this chapter a general calculation method is proposed. Also the influences of non uniform loading, angles and belt tension are covered.

3.1 Measurement method

The software must send a request for a measurement and the software of the weigh cell (HBM) must send back the measured value. This request can be send at specific time or length steps. It is chosen to measure at specific length steps based on the fact that otherwise the measurement output has to be multiplied with the velocity. The velocity must also be measured. In every measurement errors occur, so if the velocity measurement is not used these errors cancel out. Besides, measuring every specific time can lead to missing data at high velocities if the step time is set to long. The last reason to use step lengths is that it will not continue measuring when the belt slips (if the measurement is done on the not driven pulley). The rest of this report is based on measuring at specific length steps.

3.2 Calculation method

In order to get an idea of how the mass on the belt is transferred to the weigh cell a theoretical approximation is necessary. The cell will give the mass per unit length, but it is the question if the actual mass per unit length equals the output of the cell.

In this approximation the applied forces/ masses are indicated in blue, the reaction forces/ masses in red and the internal forces/ moments in green. In figure 3.1 the free body diagram of the (partially) loaded belt is shown.

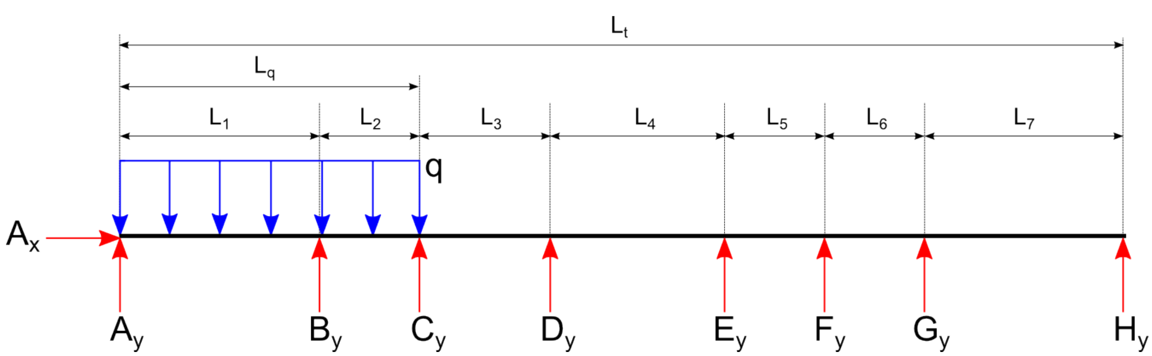


Figure 3.1: Free body diagrams of the load in general case

In this figure L_q is the length of the load, L_t is the total length, q is the distributed load and A_x, A_y to H_y are the reactions from the idlers. The load cell can be connected to one or more idlers. It is assumed that before point A and after point H the load has no influence on the cell. In fact there are three load cases. The first one is when the load enters the belt and moves towards point H ($L_q = 0 : L_t$). The second one is when the belt is fully loaded ($L_q = L_t$) and the last one is when the load is leaving the belt ($L_q = L_t : 0$).

To calculate all the reactions simple statics cannot be applied, because the number of unknown reactions (9) exceeds the available number of equilibrium equations (3). This means that $9-3=6$ reactions are not necessary to keep it in stable equilibrium, the system is statically indeterminate. The equilibrium equations are as follows:

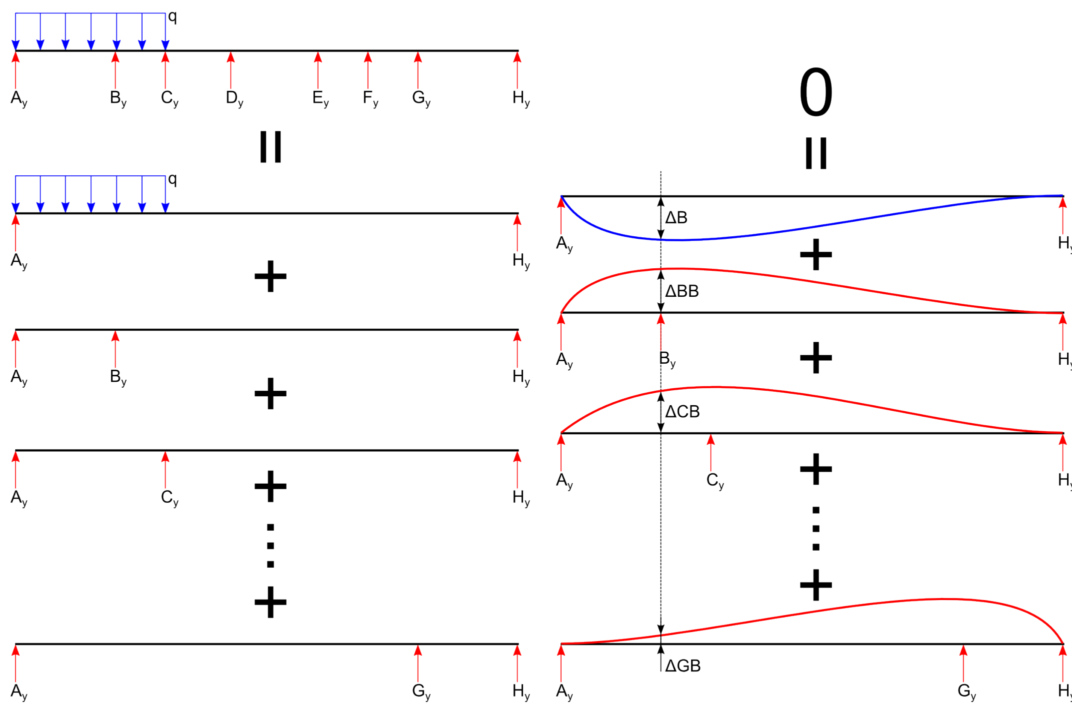
$$\sum F_x = A_x = 0 \tag{3.1}$$

$$\sum F_y = A_y + B_y + C_y + D_y + E_y + F_y + G_y + H_y - qL_q = 0 \tag{3.2}$$

$$\begin{aligned}\sum M_A = L_1 B_y + (L_1+L_2)C_y + (L_1+L_2+L_3)D_y + (L_1+L_2+L_3+L_4)E_y \\ + (L_t - L_6 - L_7)F_y + (L_t - L_7)G_y + L_t H_y - \frac{1}{2}qL_q^2 = 0\end{aligned} \tag{3.3}$$

Besides the force and moment equilibrium equations there are 6 additional equations needed. The unnecessary reactions (redundants) can be determined from conditions of geometry, also called compatibility conditions [12]. Once determined these conditions the remaining reactions can be calculated with the equilibrium equations. In this report the method of superposition is used.

Method of superposition [12]: First the redundant reactions are removed to obtain a system which is statically determinate and is exposed to external loads. Then the similar system can be used in which the external loads are replaced by a separate redundant reaction, see figure 3.2(a).



(a) The sum of every load case equals the total load case (b) The sum of the deflections equals zero at point B

Figure 3.2: Method of superposition

The first additional equation is the deflection due to the distributed load at point B minus the deflection (in the other direction) caused by all separate reaction forces at point B must equal zero. This is true, because there is no deflection possible at point B, see figure 3.2(b). This results into equation (3.4). The same procedure can be done for every reaction which leads to the desired 6 equations. Note that a minus sign is used between the deflections, because all deflections are considered as positive.

$$\Delta B - \Delta BB - \Delta CB - \Delta DB - \Delta EB - \Delta FB - \Delta GB = 0 \tag{3.4}$$

The next job is to find all the deflection equations and solve for every reaction. Since the deflection equations are involved the distributed load cannot be seen as a point load as in statics. The proof is relatively simple: consider a full load case. The total distributed load is than qL_t. Substituting this in both the deflection equations for a point load and distributed load at $\frac{L_t}{2}$ gives [12]:

$$\frac{5qL_t^4}{384EI} \neq \frac{qL_t^4}{48EI} \rightarrow \frac{5}{384} < \frac{1}{48} \tag{3.5}$$

Also without the proof it is relatively easy to imagine that a concentrated force in the middle between the supports causes a larger deflection.

Since most of the time the entering (and leaving) load is not a nice symmetric continues load case the standard deflection formula's cannot be applied. "Cuts" have to be made at the sections where the load case is changing. Taking the moment balance and integrating twice give the deflection equation with two integration constants. This can take a lot of work, but there is a way that makes life relatively easy. Using Macaulay's method it is possible to write a single equation for the bending moment of the entire "beam" (it is still beam theory).

Macaulay's method [13]: The starting point is the relation between bending moment and curvature from Euler-Bernoulli beam theory, see equation (3.6). In this equation M is the internal moment, y is the deflection, x is the distance along the beam and EI is the bending stiffness. Using this method only two integration constants have to be calculated instead of four. This is done by the Macaulay bracket, $[\cdot]$, which is zero when the term inside is negative and equal to the term when it is positive, see equation (3.7).

$$M(x) = \frac{d^2y}{dx^2} EI \rightarrow y = \iint \frac{M(x)}{EI} dx \tag{3.6}$$

$$F_n(x) = [x-a]^n = \begin{cases} 0 & \text{when } x \leq a \\ (x-a)^n & \text{when } x > a \end{cases} \quad \text{with } n = 0, 1, 2, ... \tag{3.7}$$

This report only deals with uniformly distributed loads. These loads (q) can be represented as a step function (taking $n = 0$ in equation (3.7)). This gives the following expression for the bending moment:

$$M(x) = \iint q[x-a]^0 dx = \frac{q}{2}[x-a]^2 \tag{3.8}$$

Now all six deflection equations can be calculated and the reactions can be solved. Further in this report for both the sorting table as for the conveyor this method is used to get a theoretical approximation of the felt mass per length.

3.3 Total measured mass

The goal is not only measuring the mass per unit length every dl, but one especially interested in the total mass. The unit of the value coming out the weigh cell is $[\frac{kg}{m}]$. So if all those values are known one can integrate over the length to get the actual measured mass.

Since an integration can only be done on a smooth, known function and not real time on a discrete signal a summation method is desired, see figure 3.3. This summation method is called the middle Riemann sum, also known as the trapezoidal rule.

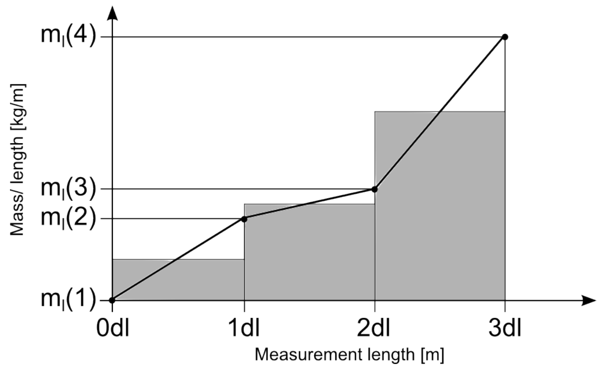


Figure 3.3: Summation method for getting the total mass

At the beginning there is $m_l(1) = 0$ and after the first step dl $m_l(2)$ is measured. The mass gained during this step can be calculated by taking the average value and multiply by the step length, see the grey area in figure 3.3. This can be done for every step and if the previous solution is added to current one the total mass is yield, see equation (3.9). Note that the total mass is always one step behind the measured mass/ length. Also note that the summation method is normally an approximation of the exact result, but since the step length is used as summation interval this is an exact method. Between the step lengths there are no measurements so a straight line is drawn between the points.

$$m(i-1) = m(i-2) + \frac{m_l(i-1) + m_l(i)}{2} dl \tag{3.9}$$

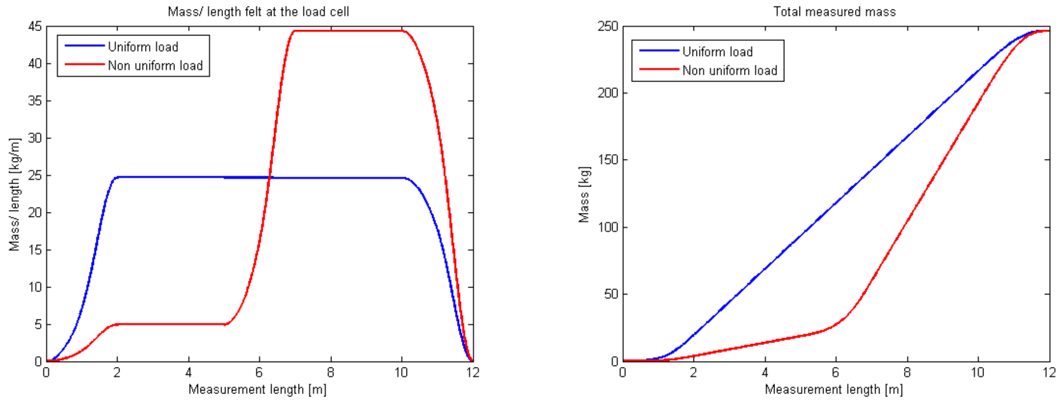
3.4 Non uniform loading

In the previous sections the calculation method is explained for uniform loading conditions. In practice it is very plausible that the mass per length can change during the weigh measurement. Using the same principle as in the previous sections results in figure 3.4:

The first halve of the load is 5 $\frac{kg}{m}$ and the second halve is 45 $\frac{kg}{m}$. Apparently it does not matter for the total measured mass if there is a non uniform load. Possible differences could have come from the fact that relative heavier parts of the belt lift the less heavy parts.

3.5 Angles

The influence of the angle on the weigh system is a relative easy relation. Since the load cell always measures the vertical component of the force, the force has to be multiplied with the cosine of the angle theta: $F_y = F \cos\theta$, see figure 3.5. This relation is valid for the angles in every direction. This means that the measured mass is less when the weigh system is at an angle relative to horizontal in both length and width direction.



(a) (b)

Figure 3.4: Non uniform versus uniform load

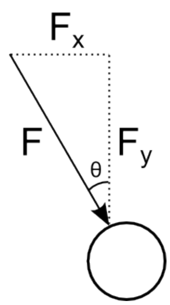


Figure 3.5: Influence force at an angle

3.6 Belt tension

Intuitive the load cell will be weighing more when the tension becomes less. In this case there is slightly more belt length between the idlers and the belt will have a larger deflection. Both phenomena mean that more mass is felt at the idler and when the tension becomes higher the opposite will happen. Great care has to be given to make sure all the idlers are still in contact with the belt, which is crucial for gaining accurate measurements.

A relative lower and higher belt tension are shown graphically in figure 3.6, T_{low} and T_{high} respectively. This shows that if a relative higher tension is present the vertical component will be larger which will lift the belt and therefore less mass is weighted. This can also be proven with some formula's [14]:

$$\sigma_b = E\varepsilon \tag{3.10}$$

$$\sigma_t = \frac{F}{t \cdot w} \tag{3.11}$$

In equation (3.10) ε is the strain, σ_b the bending stress and E the Young's modulus. In equation (3.11) σ_t is the tensile stress, F the tensile force, t the belt thickness and w the belt width. So, if the belt tension gets lower the strain and tensile force will also be lower. Using the formula's this result in both a lower bending and tensile stress (material properties and belt dimensions do not change), so more mass will be felt. The exact influence should be tested in real life.

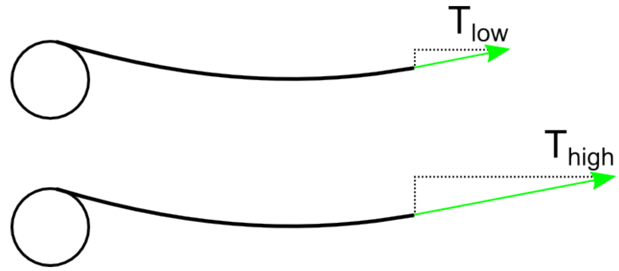


Figure 3.6: Influence belt tension shown graphically

The tension during operation is different along the length of the conveyor as mentioned in the literature in section 2.4. Catalogues for calculating and designing conveyors also confirm this [15]. The tension schematically looks like the red area in figure 3.7. The tension variation is the least at the tail pulley. The tension becomes higher at the drive pulley, because a slip front is created with micro slip. The slip front is opposed to the direction of rotation [14].

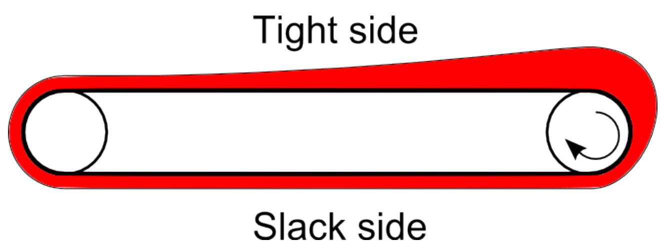


Figure 3.7: Belt tension along the length

The relation between the tensile forces and the location of the slip front is as follows [14]:

$$\frac{N^+}{N^-} = e^{\mu\alpha} \tag{3.12}$$

In this relation N^- is the pre stress, N^+ is the stress to get movement, μ is the friction coefficient and α the slip front angle. If α is equal to the angle of contact, in this case 180°, there is complete slip. It is obvious that complete slip should be avoided completely. Therefore it is advised to put the measurement device on the tail pulley, so that it will stop measuring when the belt slips. And because of the tension variation it is also advised to put the weigh frame as close to the tail pulley as possible.

Besides the influence of micro slip leading to the tension variation, the alignment of the idlers is also of great importance. This is true, because the system is over constrained as mentioned in section 3.2. In figure 3.8 two idlers are shown in which the degree of freedom is θ. The alignment ϕ is not a very big issue, because the belt is relative easy to twist small angles. However, alignment ξ can cause serious problems. In case of misalignment the line of action of the tensile force is not centric. If the misalignment is only $\frac{1}{6}$ of the belt width this has already major consequences [14]. The maximum stress doubles and the complete belt width is no longer under tensile stress. This can cause local buckling.

The last factor that will influence the belt tension is the velocity. During operation the belt velocity can vary from 0.4 $\frac{m}{s}$ up to 1.4 $\frac{m}{s}$. Change in velocity is made possible by a change in torque. A change in torque means a change in the tension in the belt, because the frictional forces will remain

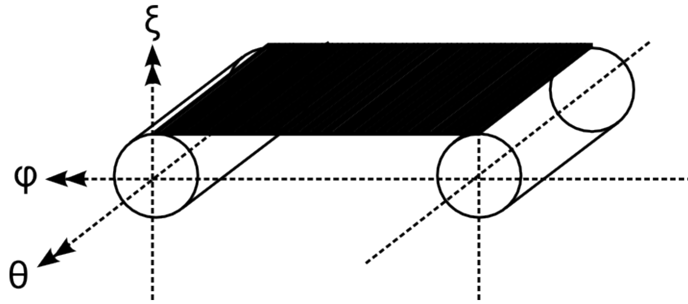


Figure 3.8: Influence idler alignment

more or less the same. More torque will create a larger slip front. So, close to the tail pulley not much of this phenomenon will be felt.

3.7 Conclusion

To this end it can be stated that there are a lot of factors that can seriously influence the weigh process. Main focus must be set to belt tension. From now on the report is split into two parts, one about the Dewulf sorting table and one about the Miedema conveyor. In these parts attention will be given to the theoretical approximation and the test results.

Part I

Dewulf R3060 Sorting table

4. Theoretical approximation

A section view of the the total sorting table is shown in figure 4.1. On the part between idler 1 and 7 the weigh cell is mounted, see figure 4.2. The load moves from the left to the right. The weigh cell is connected to the idler indicated in red.

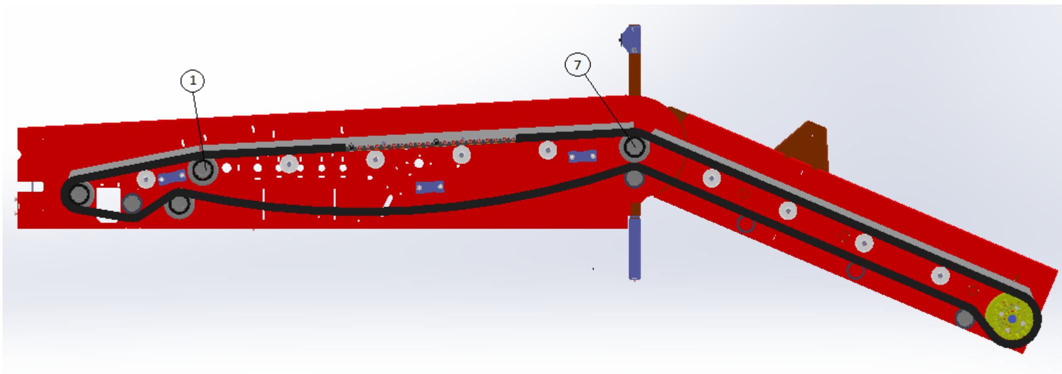


Figure 4.1: Section view of the sorting table

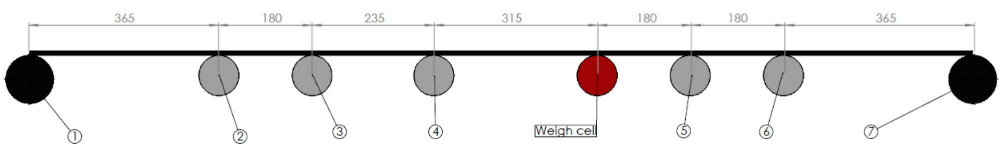


Figure 4.2: Position of the idlers in the horizontal part

Recall the free body diagram from figure 3.1 used in section 3.2 for the theoretical approximation. In this figure reaction E_y refers to the weigh cell. The calculation is done for every load case in the next sections.

4.1 Entering load

Before the belt is fully loaded the load enters the belt and every step (dl) the mass is read. Starting point is the expression for the bending moment using Macaulay's method. Reaction A_x is from now on omitted, because it equals zero, recall equation (3.1) in section 3.2.

The moment balance retrieved from the lower free body diagram in figure 4.3 and integrating twice gives:

$$M(x) = H_y x - \frac{q}{2}[x - (L_t - L_q)]^2 = EI\frac{d^2y}{dx^2} \tag{4.1a}$$

$$EI\frac{dy}{dx} = \frac{1}{2}H_y x^2 - \frac{q}{6}[x - (L_t - L_q)]^3 + C_\theta \tag{4.1b}$$

$$EIy = \frac{1}{6}H_y x^3 - \frac{q}{24}[x - (L_t - L_q)]^4 + C_\theta x + C_\delta \tag{4.1c}$$

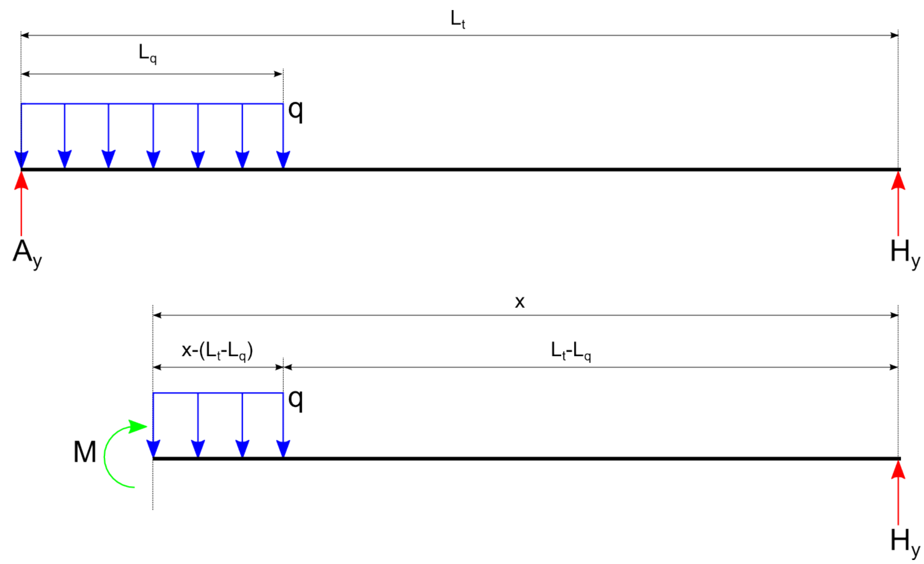


Figure 4.3: Free body diagrams of the entering load

Note there is also an internal vertical force, but the force is omitted, because the moment balance is taken around the point at the cut. Also note that the square brackets are Macaulay's brackets. In order to find the integration constants C_θ and C_δ the following boundary conditions must be applied: $y = 0$ at $x = 0$ and $x = L_t$. From the boundary condition at $x = 0$ follows $C_\delta = 0$ and from the other condition follows:

$$C_\theta = \frac{-\frac{1}{6}H_y L_t^3 + \frac{q}{24}L_q^4}{L_t} \tag{4.2}$$

Reaction H_y can be retrieved by taken the moment balance around point A using the upper free body diagram in figure 4.3.

$$H_y = \frac{\frac{1}{2}qL_q^2}{L_t} \tag{4.3}$$

This leads to the total deflection equation:

$$y(x) = \frac{\frac{1}{6}H_y x^3 - \frac{q}{24}[x - (L_t - L_q)]^4 + C_\theta x}{EI} \tag{4.4}$$

Filling in the x-coordinate along the beam of point B, C, ..., G gives the displacements ΔB, ΔC, ..., ΔG respectively.

To find the displacements caused by the reactions a standard deflection formula can be used [12]:

$$y(x) = \begin{cases} \frac{Pbx}{6EIL_t}\left(L_t^2 - x^2 - b^2\right) & \text{for } 0 < x \leq a \\ \frac{Pb}{6EIL_t}\left(\frac{L_t}{b}(x-a)^3 + (L_t^2 - b^2)x - x^3\right) & \text{for } a < x < L_t \end{cases} \tag{4.5}$$

In this equation P is the reaction, a is the length from point A to the coordinate of the reaction and $b = L_t - a$. Hence this equation is true for every load case, because they are only caused by reactions who do not move with dl.

4.2 Full load

The deflection equation for the full load case is much easier than the previous one. Now there is a nice symmetric continues load, so a standard deflection formula can be used, see equation (4.6).

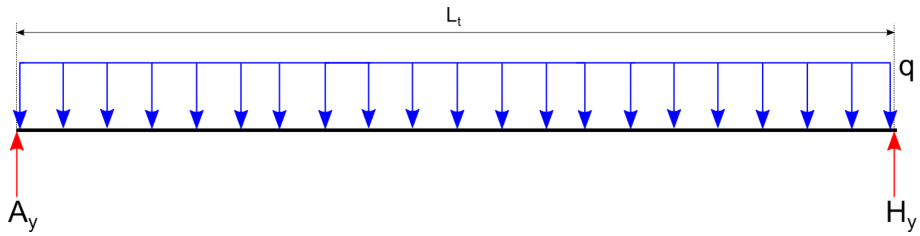


Figure 4.4: Free body diagram of the full load

$$y(x) = \frac{qx}{24EI}\left(L_t^3 - 2L_t x^2 + x^3\right) \tag{4.6}$$

Filling in the x-coordinate along the beam of point B, C, ..., G gives the displacements ΔB, ΔC, ..., ΔG respectively. Recall equation (4.5) to find the displacements caused by the reactions.

4.3 Leaving load

The deflection equation for the leaving load follows from the same procedure as done for the entering load in section 4.1. Now the situation is as in figure 4.5.

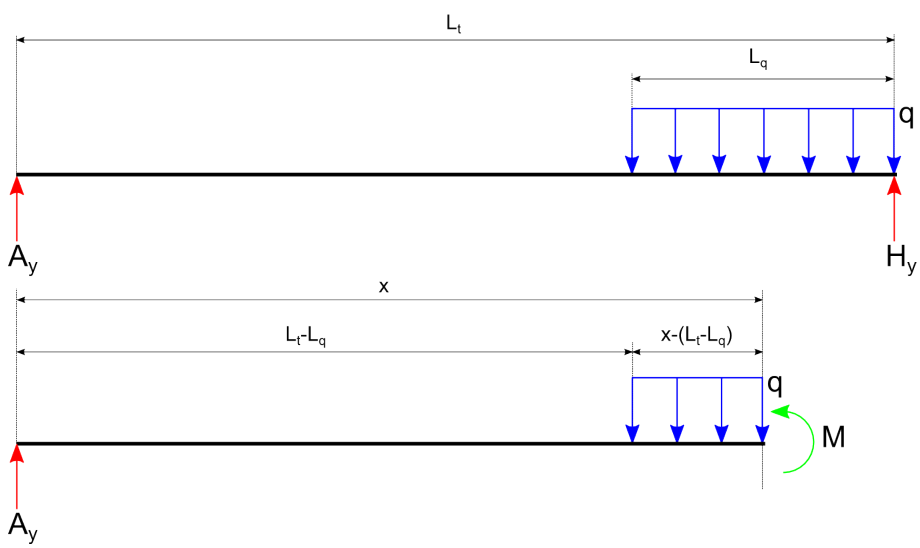


Figure 4.5: Free body diagram of the leaving load

In this case the integration constant becomes:

$$C_\theta = \frac{-\frac{1}{6}A_y L_t^3 + \frac{q}{24}L_q^4}{L_t} \tag{4.7}$$

In which A_y equals:

$$A_y = \frac{\frac{1}{2}qL_q^2}{L_t} \tag{4.8}$$

This leads again to the total deflection equation:

$$y(x) = \frac{\frac{1}{6}A_y x^3 - \frac{q}{24}[x-(L_t-L_q)]^4 + C_\theta x}{EI} \tag{4.9}$$

Filling in the x-coordinate along the beam of point B, C, ..., G gives the displacements ΔB, ΔC, ..., ΔG respectively. Recall equation (4.5) to find the displacements caused by the reactions.

4.4 Result

The calculation is done with `MatLab`, see Appendix A.1 for the script. Note that for the Macaulay bracket the function max is used, $[x-a] = \max(x-a, 0)$, and the step length is chosen to be 5 mm, $dl = 0.005$, because the distances between the idlers are rounded to 5 mm. Also note that the bending stiffness EI is omitted for a better calculation speed, because it cancels out anyway by solving the equations. The total load length L_q is chosen to be 5 m. Running the script takes several minutes, because at every length step six equations with six unknowns have to be solved.

Figure 4.6 shows the reaction of every idler, except for idler A and H. The x-axis represents the measurement length. Before the first dashed line the load is entering the belt, between the two dashed lines there is full load and after the second dashed line the load is leaving the belt.

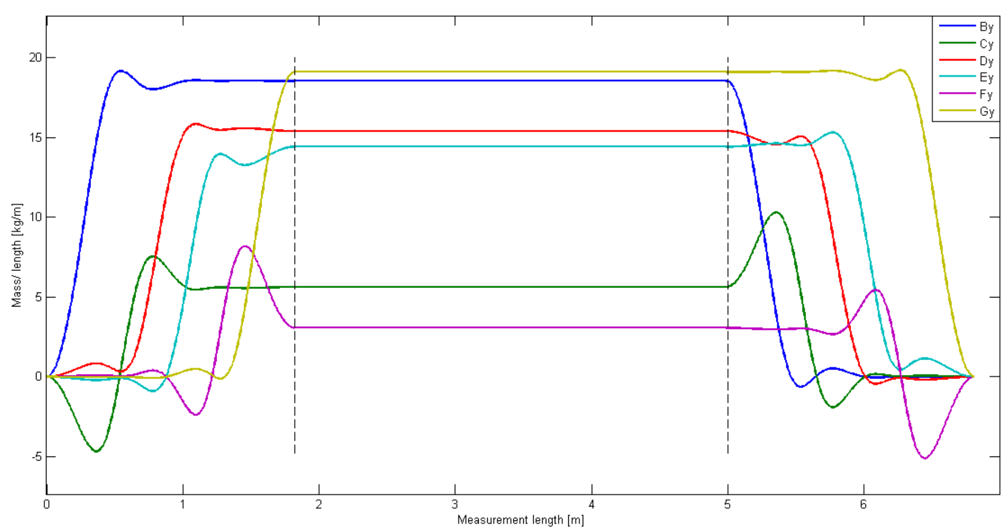
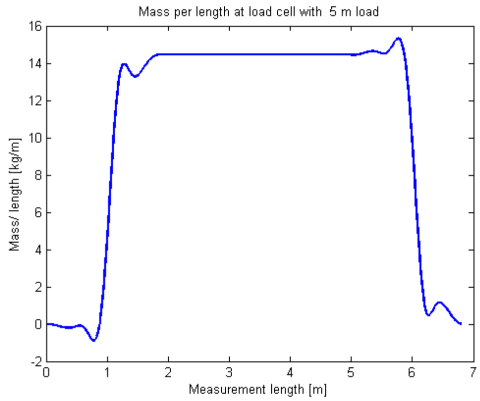


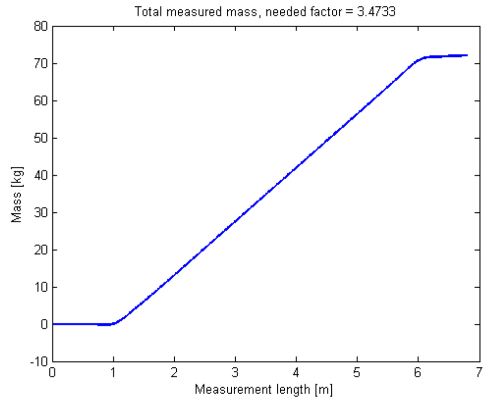
Figure 4.6: Reactions of the idlers

Since the weigh cell is only connected to idler at point E this is the reaction of interest and it is plotted again in figure 4.7(a) with the corresponding cumulative mass in figure 4.7(b).

The total measured mass should equal qL_q, for which q can be chosen arbitrary (here $q = 50\ \frac{kg}{m}$). It seems that this total mass is not as it should be, so a certain factor is needed to get to correct mass.



(a) Mass/ length at the load cell



(b) Cumulative mass

Figure 4.7: Results of the simulation

The needed factor is shown in the title of figure 4.7(b). The factor comes from the configuration of the idler with the weigh cell. The mass is already felt when it is at the beginning of the belt and this all contributes to the total mass. In table 4.1 the factors are shown for different lengths of load. The factor is getting smaller when the load length is bigger, because the influence of the entering and leaving load becomes smaller. Changing the step length dl will not result in significant changes.

Table 4.1: Length of the load and the corresponding correction factor

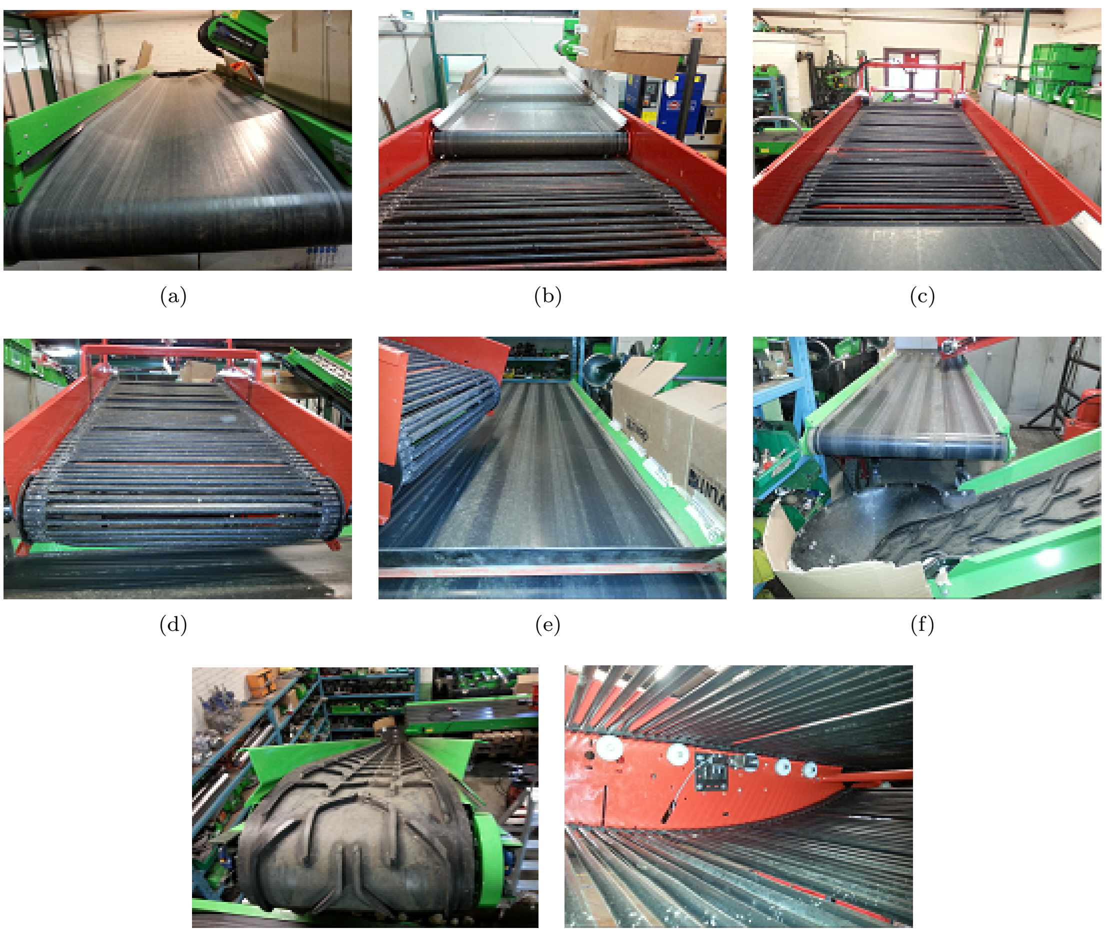
L_q	5	10	20	50	100	200
factor	3.4733	3.4698	3.4681	3.4670	3.4667	3.4665

5. Testing

Now all theoretical aspects are covered in the previous chapters it is time to test in real life. First the system has to be identified and then all sorts of tests are carried out.

5.1 Test set-up

Fortunately Dewulf already made a frame for the sorting table. The whole frame is again used at Miedema. Furthermore four conveyors are added by Jan de Groot with the purpose to do measurements with real potatoes that travel in a cycle. This way multiple measurements can be done without interruption. The test set-up is shown in figure 5.1(a) to 5.1(g) and the idler connect to the load cell is shown in figure 5.1(h).



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 5.1

5.2 System identification

Before testing with load it is necessary to get insight in the system and to examine the responses. The HBM software also delivers an AED Panel on which one can do the calibration, setting filters and logging of measurement values. A great advantage is that the filters can be added afterwards so that the effect is very clear. The calibration is very straightforward, but choosing the right filters is a more extensive job.

To calibrate the cell first the calibration mass has to be filled in. It has to be between 20% and 120% of the nominal value of the load cell. For this test two cells with a nominal value of 110 kg where used. Then the dead weight is measured and after this the calibration masses are added and measured.

To identify the system first raw data is logged at two different velocities, see figures 5.2 and 5.3.

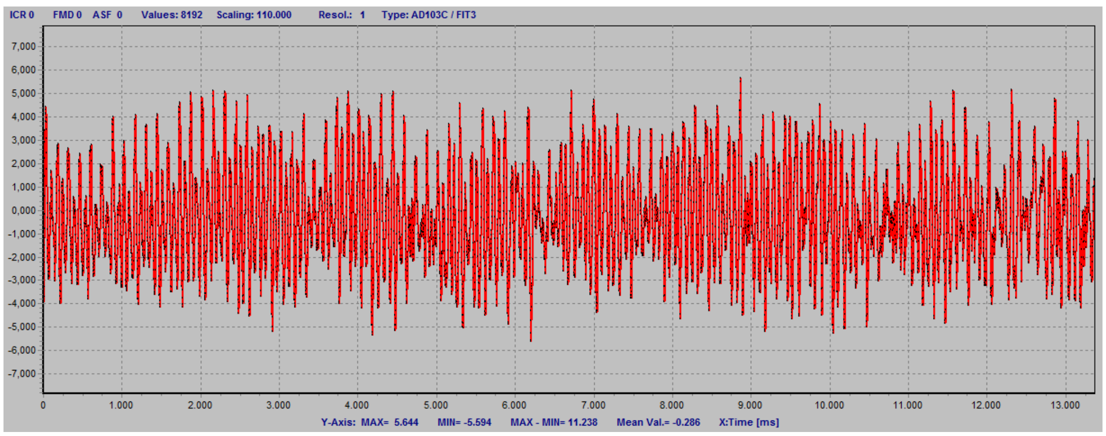


Figure 5.2: Raw data at 0.26 $\frac{m}{s}$ with 600 $\frac{\text{values}}{s}$

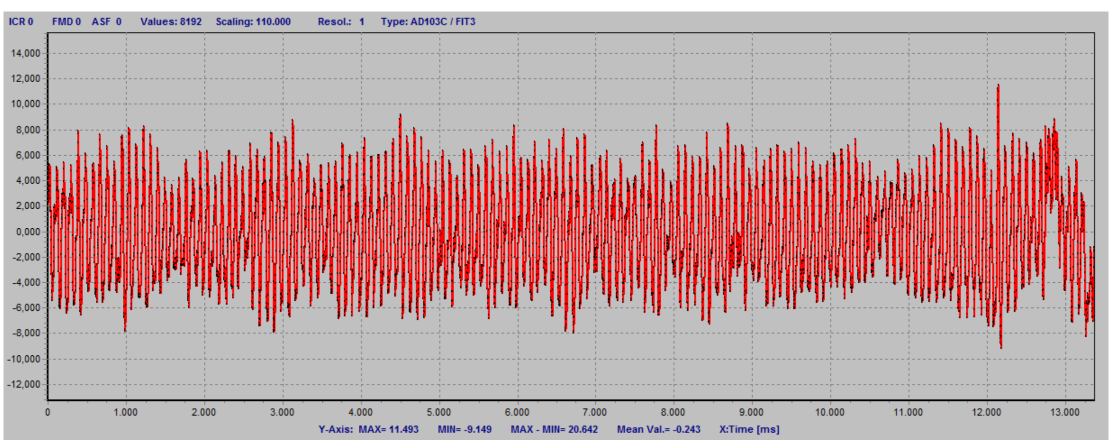
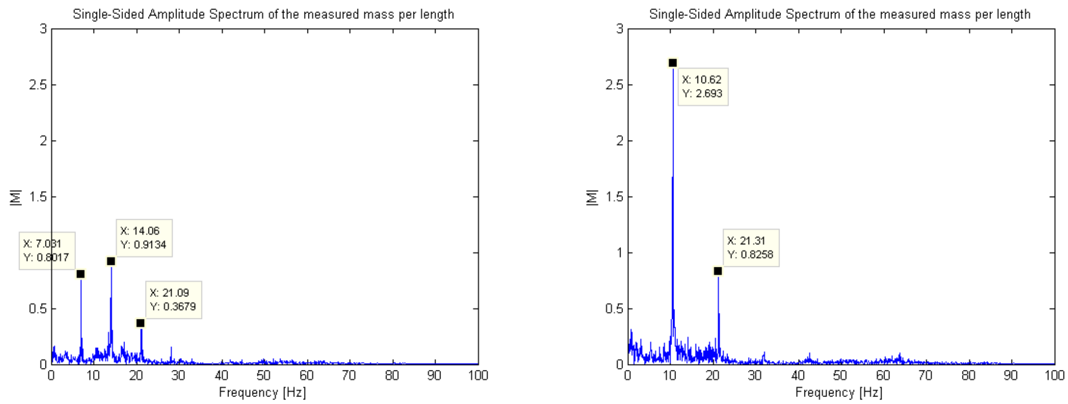


Figure 5.3: Raw data at 0.40 $\frac{m}{s}$ with 600 $\frac{\text{values}}{s}$

On the y-axis the measured mass per length is shown. It is clear that the amplitudes are way to high (order of ± 8 $\frac{kg}{m}$), so filtering is highly desired. In order to choose the right filters the present frequencies have to be read. This is done with a Fast Fourier Transform (FFT) analysis in `MatLab` by using the log file from the AED Panel. At both velocities three measurements were done. For each velocity the three measurements result in the same frequencies. The result is shown in figure

5.4. At $v = 0.26\ \frac{m}{s}$ there are three frequencies present: 7.03 Hz, 14.06 Hz and 21.09 Hz. At $v = 0.40\ \frac{m}{s}$ there are two frequencies present: 10.62 Hz and 21.31 Hz. The same test is also done for different angles of the tip, resulting in the same frequencies.

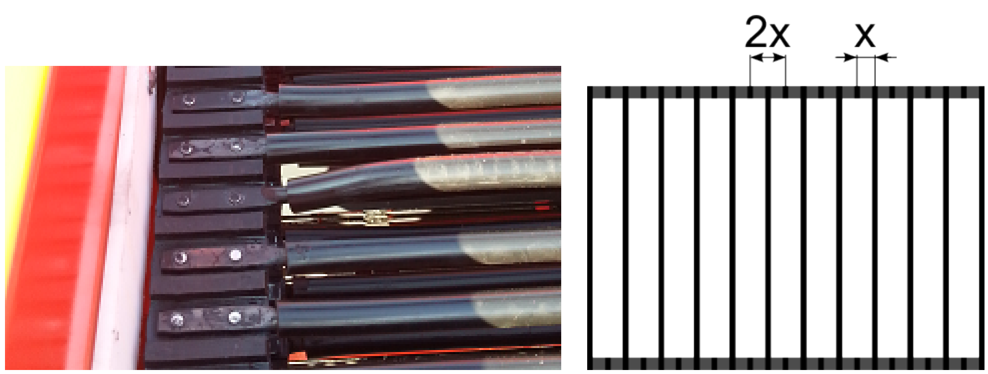


(a) FFT of the raw signal at 0.26 $\frac{m}{s}$

(b) FFT of the raw signal at 0.40 $\frac{m}{s}$

Figure 5.4

Apparently the frequencies change with the same order as the velocity. Closer looking at the belt it consists of rods and they are connected to a rubber strip on each side along the whole belt length, see figure 5.5(a). Between the connection points there are rubber blocks to protect the connection points and prevent the potatoes coming into to contact with the hard metal, see figures 5.5(a) and 5.5(b). The distance between a rubber block and a connection point is x and between two connection points is $2x$ with $2x = 37\ mm$.



(a) Close up picture of the sorting table

(b) Schematic view of the sorting table

Figure 5.5

Doing the math gives the following frequencies at 0.26 $\frac{m}{s}$:

$$f_1 = \frac{v}{2x} = \frac{0.26}{0.037} = 7.03 \text{ Hz} \tag{5.1}$$

$$f_2 = \frac{v}{x} = \frac{0.26}{0.0185} = 14.05 \text{ Hz} \tag{5.2}$$

And for the frequencies at 0.40 $\frac{m}{s}$:

$$f_1 = \frac{v}{2x} = \frac{0.40}{0.037} = 10.81 \text{ Hz} \tag{5.3}$$

$$f_2 = \frac{v}{x} = \frac{0.40}{0.0185} = 21.62 \text{ Hz} \tag{5.4}$$

The calculated frequencies are very close to the ones found with FFT analysis. This means that the frequencies will always be present in the system. A way of filtering out specific frequencies is to make use of notch filters. In the AED panel there are four filters available with notch filters. One of them is not applicable for dynamic weighing, so there are three left. The filters are low pass filters and they are called `IIR4FT`, `FIR64` and `FIR64+MA`. The first one is a fast settling filter with a settling time lower than 260 ms, the second one is also a fast settling filter, but with a settling time lower than 100 ms. The last one is the same as the second one, but also a moving average filter can be connected. This information comes from the help function in the AED Panel. This report restricts to the filters available in the software, because it is very simple to apply different settings. A filter can be rebuilt in `MatLab` to filter afterwards, but it is verified that this gives the same result as the filters in the software. Applying such a notch filter at the data in figure 5.2 gives figure 5.6. This is a `IIR4FT` with two notch filters at the previous mentioned frequencies with a low pass frequency of 6 Hz. The low pass frequency is chosen such that the delay is as low as possible, but the signal is still rather smooth. Applying one of the other filters will not result in big differences. The filter has to be chosen when testing with a load.

Once in a while there was also a short, relative high fluctuation visible in the measurements. Regarding the distance between two consecutive fluctuations it seems to be the connection of the belt. This connection is made from steel and when it is at the underside it has to move around relative tight angles. This causes high friction and therefore a vibration in the system.

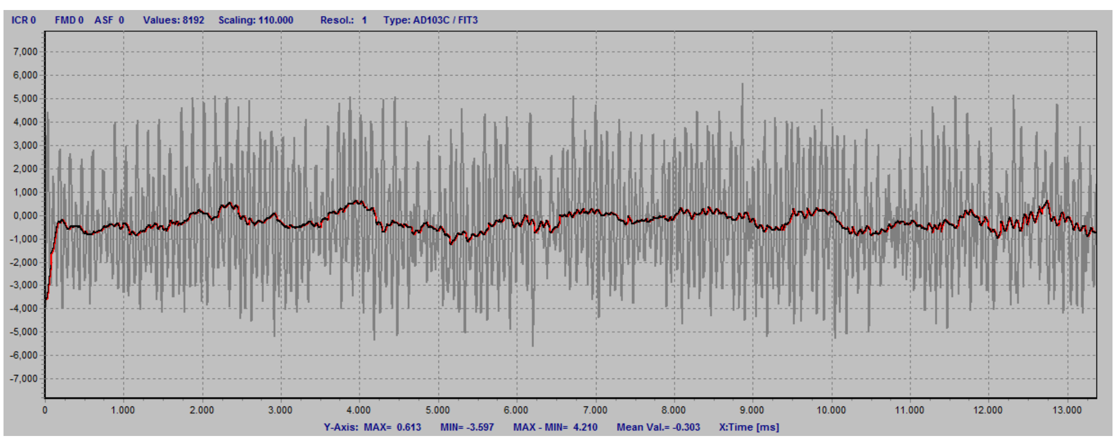


Figure 5.6: Raw (grey) and filtered (red) data at 0.26 $\frac{m}{s}$

As mentioned before there are two frequencies which are velocity dependent. So these frequencies have to be set before the measurement is done. For this test a plastic bag filled with golf balls with a mass of 21.76 kg is used. The result with different filters can be seen in figure 5.7. Approximately the same result is gained at the lower velocity. Note that these measurements are done separately. The moving average filter is tested with 10 and 90 values. As expected the raw data shows the most fluctuations. The filtered data is rather close, but the moving average filters cause a slight delay. This is not very clear from this figure, but examination of the data in the AED Panel shows this effect very clearly, see figure 5.8.

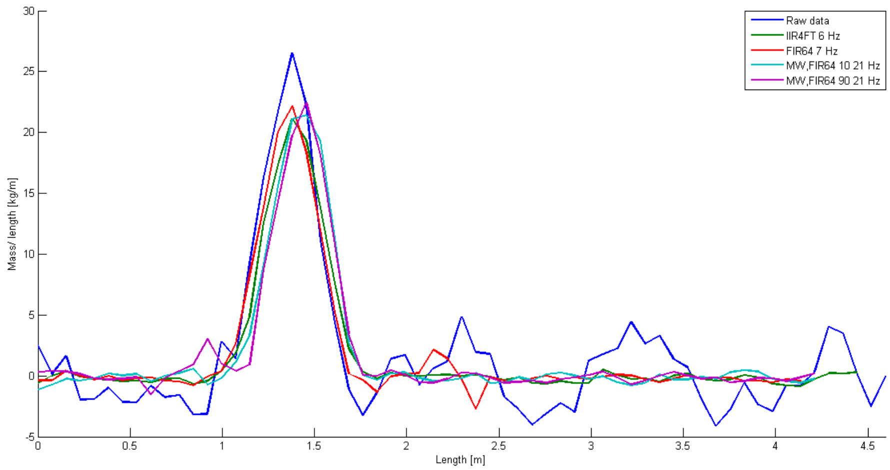


Figure 5.7: Different filters for the same kind of measurement at 0.40 $\frac{m}{s}$

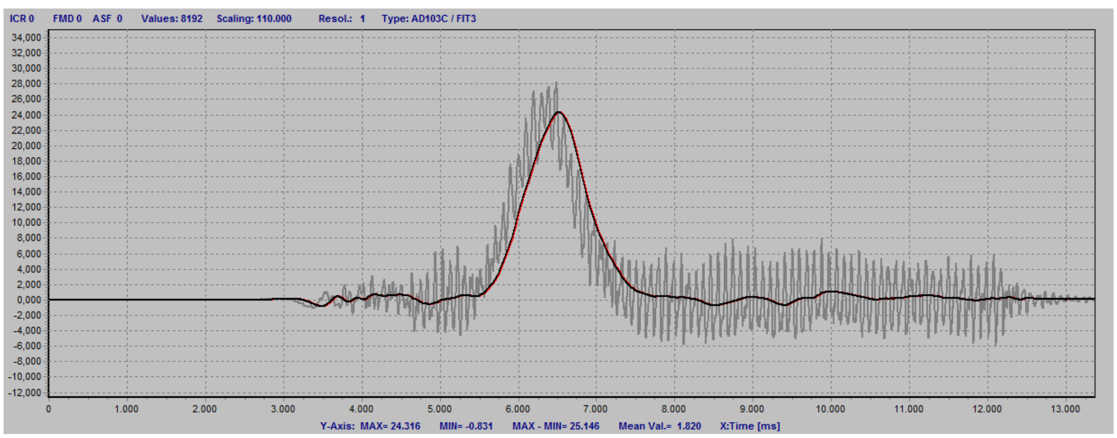


Figure 5.8: Raw (grey) and MW,FIR64 filter with 90 moving average values (red) at 0.40 $\frac{m}{s}$

Using the `MW,FIR64` with 10 moving average values results in more vibrations in comparison with the `FIR` and the `IIR` filter. To choose between these two filters the belt is driven without load. The filter where the difference between the maximum and minimum mass per length is minimal is the chosen filter, in this case the `IIR` filter.

5.3 Measurement method

The measurements in the AED Panel can only be done for a limit amount of values, maximum 8192 values. To measure constantly some software has to be written.

For measuring length steps a pulse bearing is used. This bearing rotates on the axle of the drive pulley. In this bearing 80 flanks are available, the maximum resolution is 320 events per revolution. With the radius of the pulley and halve the belt thickness the travelled distance per pulse can easily be calculated.

The log file looks as follows:

```
(989456550.053196) can0 63F#4000200100000000
(989456550.054566) can0 5BF#43002001D0FFFFFF
(989456550.056031) can0 002#FFFFFFD000000008
```

The big number between brackets is a time signal, message `63F#` is the request, message `5BF#` is the response and message `002#` contains the information. In message `002#` the first 8 digits represents the measured weight per length and the last digit is the used resolution, where 8 means that there are $\frac{320}{8} = 40$ events per revolution (= 1.53 cm belt length). To read this log file a `MatLab` function is made which reads the correct row and translates the hexadecimal number to a decimal number, see Appendix A.3. From the time signal it follows that the response time is 1.4 ms for a weigh measurement and 1.5 ms for writing the message with information.

5.4 Resolution

It is important to select the correct resolution, so no important data is lost and there is enough time to handle the requests. If there are vibrations in the system such as a sine function and there are not enough data points it can be the case that there is a data point at the peak of the positive side and near the peak at the negative side. The average is then greater than zero, but in fact this is not true. The desired resolution is tested by looking at the shape of the vibrations. When the shape is not changing a higher resolution is not necessary. When the shape is very pointy it obvious that the resolution is too low. The outcome is a resolution of 40 measurements per revolution which is 1.53 cm belt length.

5.5 Different loads

This test is done with real potatoes and in different amounts. Also two different velocities where used to see if this has any influence. The tests were done with 53.48 kg, 70.64 kg, 92.80 kg and 142.62 kg. The potatoes are weighted afterwards to get to these masses. The average factor at the velocity of 0.26 $\frac{m}{s}$ is **3.4197** and for 0.40 $\frac{m}{s}$ the factor is **3.5923**. The difference in velocity can be explained by the fact that different torques are generated at the drive pulley which differences in belt tension. The higher the velocity the higher the tension and the less mass will be weighted, see section 3.6. The tests are done with the filter chosen in section 5.2. Every test is done three times to simultaneously test the consequence of the measurements and it turns out that this is quite accurate.

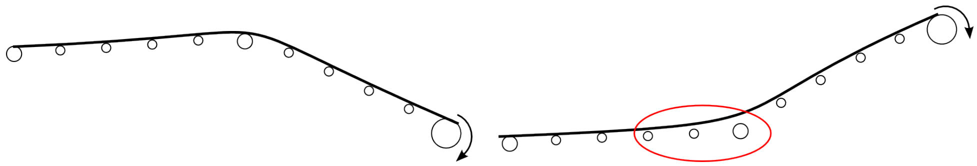
The factor from the theoretical approximation is **3.4686** which is between the two factors found by testing, see section 4.4. This means that the system is rather predictable and there are no uncertainties left. If the belt tension is kept constant one factor can be used for all velocities. This should result in the errors given in table 5.1, because the factor is used which corresponds with the velocity. Besides the belt tension the calibration of the cells is very important. The theoretical factor is only true when the cell output is exact.

Table 5.1: Errors at different loads and velocities

	53.48 kg	70.64 kg	92.80 kg	142.62 kg
0.26 $\frac{m}{s}$	1.02 %	0.94 %	0.63 %	0.15 %
0.40 $\frac{m}{s}$	0.60 %	0.95 %	1.65 %	0.54 %

5.6 Angle of the tip

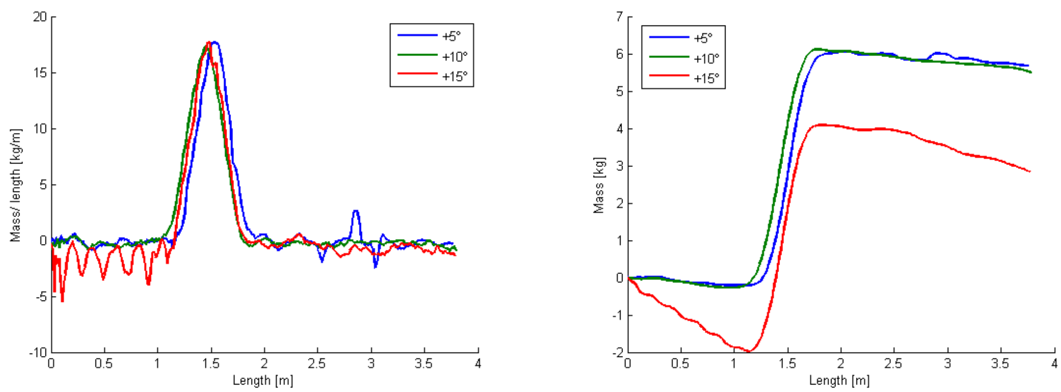
The tip of the belt must make an angle when the bunker is getting full. This angle has a great influence on the mass, see the schematic view in figures 5.9(a) and 5.9(b). Statically more mass will be weighted when the tip is at the maximum height. Dynamically the opposite will happen, because the belt is pulled by the drive pulley. This causes the belt to lose contact with the idler, see figure 5.9(b).



(a) Configuration when the tip is down (b) Configuration when the tip is up

Figure 5.9

Until the tip is in line with the rest of the belt (approximately horizontal) there is no influence measured. Further increasing the angle will result is large differences, see figure 5.10. The tests are again done with the bag of golf balls. The red line shows large fluctuations, because the belt is fully loose from one or two idlers, see figure 5.11.



(a) Measured mass per length at different tip angles (b) Cumulative mass at different tip angles

Figure 5.10

Figure 5.11: Picture where is it obvious that the belt is loose from the idler

5.7 Testing with Marijn Ooghe

Since the sorting table is for a potato harvester from Dewulf this project is of their interest. Marijn Ooghe from Dewulf was two days at Miedema to see the improvements and test results. After the exchange of information and a lot of testing the belt goes back to the site of Dewulf where Marijn will continue the project.

During the two days there were a lot of improvements:

- The biggest improvement was that filtering is made velocity dependent like explained in section 5.2. The frequency of the notch filters have to be adapted to the velocity.
- In order to compensate for the belt lifting when the tip angle is increasing two idlers at the upper side of the belt are installed, see figure 5.12. This ensures that the belt stays nicely on the idlers under the belt. The downside is that the potatoes have to be guided along these extra idlers.

Figure 5.12: Adding extra idlers on the top side of the belt

- At Dewulf they already made a function which is used for zeroing. If this is done every time the belt is empty, one can compensate for sticking soil to the belt. This function is also used during the tests.
- The load cell was placed relatively far to the pivot point, which made it very sensitive for the belt tension. So, the cell was moved closer to the tail pulley.

At the end of the second day several tests where done with approximately 120 kg potatoes. The result was an error of about 1%. The mass decreased during the tests, because the potatoes started to fall apart and pieces slipped trough the belt. Therefore the error is even lower than 1%.

6. Recommendations

There are still some parameters left for investigation. Some recommendations towards further refinement are:

- Test the influence of the angle of the total system in both length and width direction to simulate movement of the machine.
- Test the influence of the belt tension. Place the load cell even further to the tail if necessary.
- Test the influence of measuring with time or length steps.
- Investigate how to reset the needed factor when it is installed in the machine. On the test set-up it easy to adjust the factor with a known mass, but when the sorting table is inside the machine this becomes difficult.
- Redesign the connection of the belt. The steel connection causes a large undesired vibration.

Part II

Miedema Conveyor 65

7. Theoretical approximation

The theoretical approximation procedure for the MC 65 is exactly the same as for the sorting table. The difference is that there is a larger number of idlers and that the weigh cell is connected to a weigh frame, see figure 7.1. The weigh frame is connected to three idlers and is pivoted at one side (point P). So, after the reactions are calculated the weigh frame has to be investigated separately in which reactions E_y, F_y and G_y can be regarded as external forces. Reaction Q_y is the weigh cell, so this is the reaction of interest. This reaction can be calculated with the moment balance around point P, see equation (7.1) and (7.2).

$$\sum M_P = L_a E_y + (L_a + L)F_y + (L_a + 2L)G_y - L_w Q_y = 0 \tag{7.1}$$

$$Q_y = \frac{L_a E_y + (L_a + L)F_y + (L_a + 2L)G_y}{L_w} \tag{7.2}$$

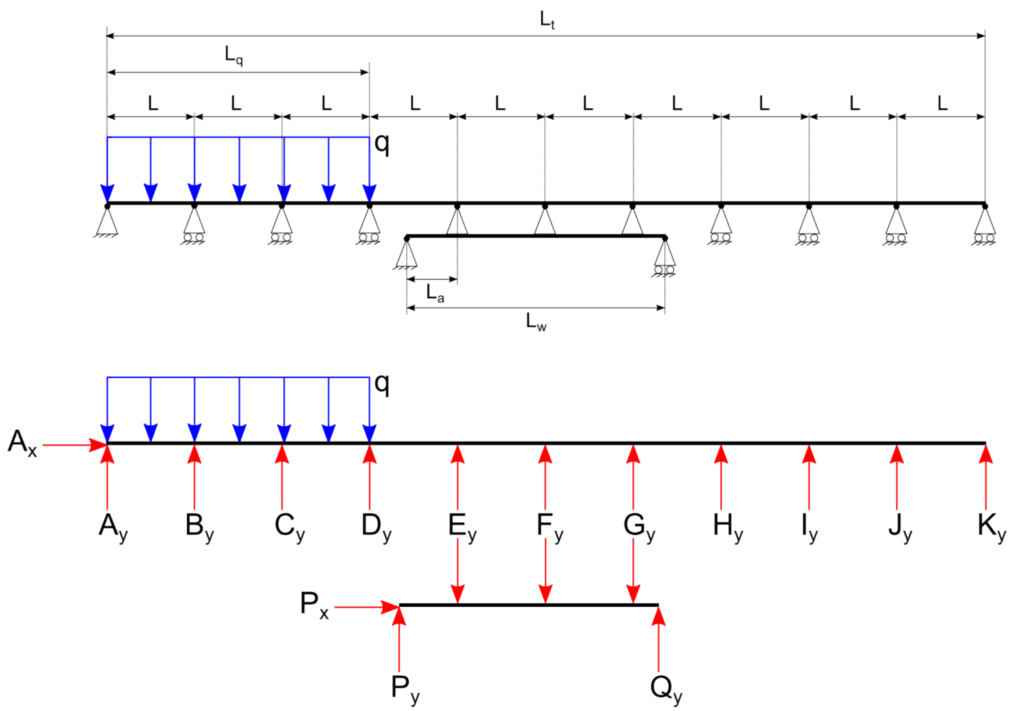
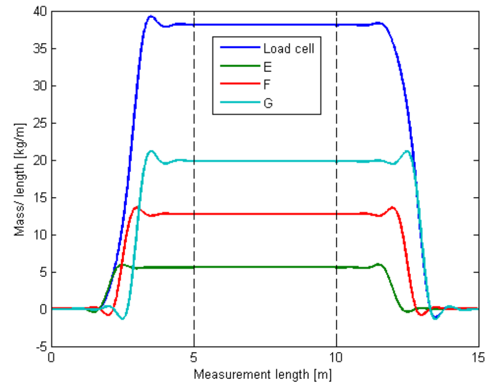
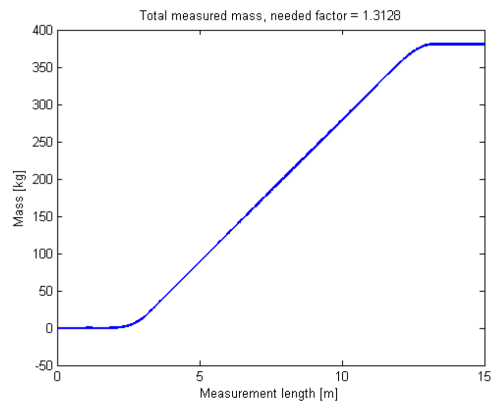


Figure 7.1: Free body diagrams

The script used in `MatLab` can be seen in Appendix A.2. The step length is chosen to be 1 cm, $dl = 0.01$, because the lengths are rounded to centimetres. The total load length is 10 m and the distributed load is 50 $\frac{kg}{m}$. Figure 7.2(a) shows the individual felt reactions of E_y, F_y and G_y at the location of the load cell and the total felt reaction. The total measured mass with the corresponding factor is shown in figure 7.2(b). The factors for other load lengths are shown in table 7.1. Running this script takes even more time than the one for sorting table, because at every length step eleven equations with eleven unknowns have to be solved. Changing the step length dl will not result in significant changes.



(a) Felt reactions by load cell and total felt reaction (blue)



(b) Cumulative mass

Figure 7.2: Results of the simulation

Table 7.1: Length of the load and the corresponding correction factor

L_q	5	10	20	50	100	200
factor	1.3130	1.3128	1.3127	1.3127	1.3127	1.3127

8. Testing

Approximately the same test procedure is done for the MC 65 as for the sorting table. There was more time available for the MC 65 so the testing was done more extensively. It was even possible to test the conveyor in a real life application at a company.

8.1 Test set-up

Testing the MC is done in the same room as the sorting table. Some conveyors where modified and one is removed to get the same sort of testing set-up. Also a HMI screen is added to print results real time with the purpose that logging is not always necessary, see figure 8.1. The values at the top represents the current belt load in $[\frac{kg}{m}]$, note that the screen shows $[kg]$. The two values under the current load represent the cumulative mass. For both the belt load and cumulative mass the left value is the raw signal and the right one is the value multiplied with the empirical factor. The value after "Tarra" is the zero calibration value, which is explained further in this report. Next to the zero value there is the amount of steps the calibration has to fulfil. On the left and right of the screen there are yellow buttons. The second button from above on the left side sets the cumulative mass to zero and the button below this one starts the zero calibration. There is also a rotary knob (not on the picture) to adjust the number calibration steps. The other buttons are disabled.

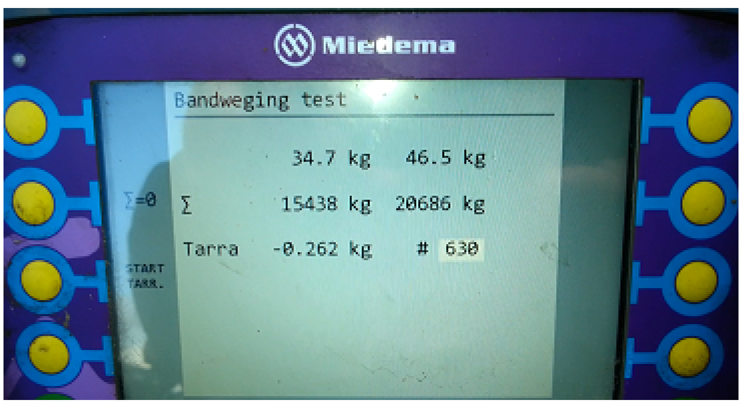


Figure 8.1: HMI screen

8.2 System identification

For this application one load cell with a nominal value of 220 kg is used. In fact a weigh cell with halve the nominal value could also do the job, but if a person stands on the belt it still has to function. The calibration procedure is the same as for the sorting table.

To identify the system a Fast Fourier Transform (FFT) is performed on the output signal. It is expected to have not as big amplitudes as for the sorting table, because the belt is totally flat and smooth. First the raw signal is investigated at different velocities. A very small peak appears which shifts with the velocity. This peak is so small and is not even visible at a certain velocity range. It seems not necessary to design a notch filter for this conveyor. The cause for the small peak is also uncertain, so it is not recommended to use a notch filter in the first place. It can be the case that it comes from one the idlers which is different for every machine.

The maximum amplitudes are around $\pm$ 0.4 $\frac{kg}{m}$. Further tests are done with the same two filters that performed best for the sorting table, because they can handle dynamic signals in the best way. To get an idea of the needed low pass frequency a low pass filter is build in `MatLab`. After determining the frequency range measurements with several frequencies are tested. Again a comprise has to be made between the delay and a smooth signal. It turns out that the `IIR4FT` with a low pass frequency of 6 Hz is again the best filter, but now without notch filters.

8.3 Calibration function

After the first couple of tests it already turns out that the zero of the belt shifts significantly. This has great influence on the results of the measurements, because the mass of the product is relatively low. In order to solve this problem a zero calibration function is developed in the software. It measures a certain range of values and calculates the mean value. This mean value is subtracted from every new measurement. To make it useful for every machine the amount of measurements for this function must be adjustable. In formula form this looks like:

$$\text{Zero} = \frac{m_l(1)}{n} + \frac{m_l(2)}{n} + ... + \frac{m_l(n)}{n} \qquad \text{with } n = 0, 1, 2, ... \tag{8.1}$$

In this equation n is the number of measurements and $m_l(n)$ is the mass per length at step n. For the MC 65 this number is chosen to be the number of steps that is necessary to complete two complete belt lengths. This way it is sure that it has seen every fluctuation in the belt. Another important aspect is to always measure full belt lengths, because if the measurement is cancelled at a peak value this will give an inaccurate result. Fluctuations can come from the weld and local deformations. The result for a raw signal is clearly shown in figure 8.2 where the blue line represents the initial (bruto) measurement and the green line represents the net measurement.

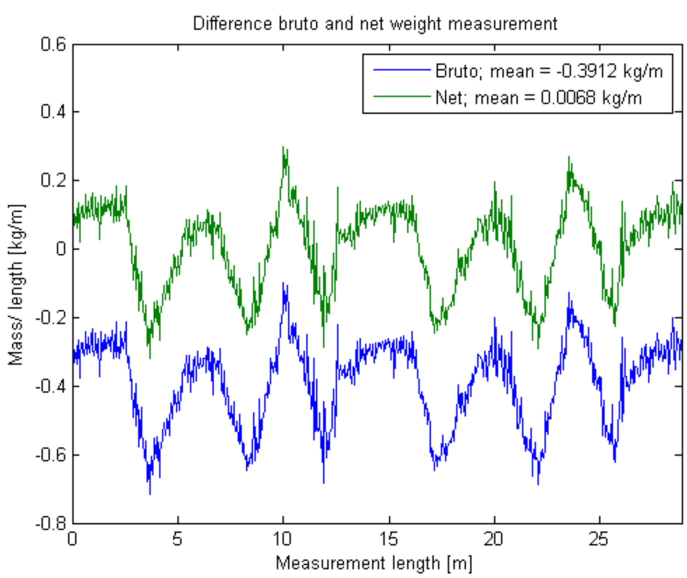


Figure 8.2: Influence calibration function on raw data

8.4 Angles

In the theoretical approximation in section 3.5 the influence of the angles is predicted. It is very important that before a measurement is done with the machine at an angle the zero calibration is performed to compensate for the mass change of the weigh frame. Tests showed that the zero calibration value indeed gets smaller for larger angles. At 1.2° the value is -0.3840 $\frac{kg}{m}$, at 5.5° the value is -0.5670 $\frac{kg}{m}$ and at 8.1° the value is -0.8720 $\frac{kg}{m}$.

Doing three tests at horizontal position results in a factor of 1.3408. Changing the angle to 1.8° gives a factor 1.3415 and for 8° the factor equals 1.3552. According to the theory the factor changes in the same way. Doing the reverse calculation to calculate the angle from the difference in factor using the cosine as in the theory gives 1.85° and 8.36°. This result is very close to the empirical values.

Also tests are done for different angles in width direction. It appears that this has hardly any influence on the measured mass. It is still recommended to set the width direction horizontal, because the product will easily move if the belt is fully loaded.

8.5 Belt tension

Initial tension is created by stretching the belt a distance of 5 mm on one metre. Tests are done for lower and higher tension situations. Practically the tension will get lower over time since the belt material can creep.

Tests were done with 123 kg potatoes and compared to the situation with initial tension. Moving the tail pulley 1.5 cm closer to the drive pulley and doing the zero calibration results in a positive value, which corresponds with the theory. The error becomes **1.18%**, which is over the desired 1%. Increasing the distance to 2.5 cm and without a new zero calibration leads to an error of **5.71%**, which is way off. Doing the same test with a new calibration leads obviously to a larger zero value, and the error is reduced to **1.59%**. Moving the tail pulley 1 cm from the initial point in the other direction results in a negative zero value and an error of **1.58%**.

From this it can be concluded that the belt tension is of big importance for getting accurate measurements. Once in a while the tension should be checked and adjusted if necessary.

8.6 Other factors

- Measurement method: The same principle is used to trigger measurements as for the sorting table, see section 5.3. The maximum resolution is 12 events per rotation, see section 2.3. This translates to a measurement every 4.29 cm belt length. During testing this seems enough to get accurate results.
- Velocity: There is no influence of the velocity on the results.
- Environmental conditions: An experiment is done to look at the influence of temperature. The cell is locally heated with a hair dryer up to about 40°C measured with an infrared thermometer. The measured value starts to increase almost immediately and drops when the hair dryer is removed. This means the cell is sensitive for changing temperatures. In reality there are not sudden temperature differences and the zero calibration should take away this effect. Furthermore the supplier claims that the cells can withstand all environments [8].
- Sticking soil: Sticking soil means that the dead weight will increase. One could do the zero calibration several times, but another way to prevent this is to use a scraper, which was already installed, see figure 8.3(a).

- Roll back of product: Setting the conveyor under a small angle (about 3°) already causes to product to roll back if there is not enough flow. Because of the roll back the product can be weighted twice or even more or not at all. Therefore the machine must set as horizontal as possible.

- Non uniform loading: Tests show non uniform loading conditions do not influence the accuracy.

- Fabrication errors: If the MC is in production there is always a change that there are fabrication errors. To simulate this some bolts of the connection at the pivot point of the weigh frame, see figure 8.3(b), are loosened or removed. It appears that this has no influence on the results.

(a) Scraper

(b) Mounting pivot joint

Figure 8.3

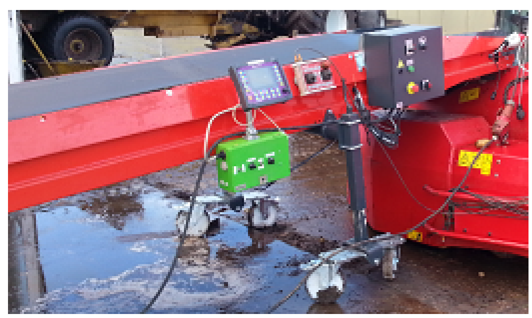
- Empirical factor: Having done all the tests the empirical factor lies between **1.33** and **1.34**. This factor is close to the theoretical factor of **1.3127**. The difference can be explained from the fact that the theoretical factor is based on a free moving pivot point, but in reality this is a flexure which cannot rotate completely free. Another reason could be that the calibration of the weigh cell is not done 100% correct. Using one factor during similar tests results in a maximum error of 0.5%. Testing with the same amount of potatoes multiple times there was always a loss of mass after testing. So this 0.5% is a very conservative error, it is definitely lower.

8.7 Field test

The previous tests were done in order to get insight in all the factors that can have an influence on the weighing. The real test is to set the machine at a production company to see if the theory still holds for large amounts of potatoes and different environments. Pieter Evenhuis offered an opportunity for this test. They have large storage facilities in which they store potatoes, beets and grains. At their site they clean the products and pick out the imperfect ones. Then the product is collected in a large bunker and when the bunker is full the product will be transported to a truck via conveyors. Between these conveyors the MC 65 is put, so that it is sure that all the potatoes in the truck have been over the weigh frame, see figure 8.4. The truck delivers the potatoes to a factory. At this factory the truck load is weighted, so this would be the reference mass. During the tests the empirical factor of 1.34 is implemented in the HMI screen.

(a)

(b)



(c)

Figure 8.4: Set-up field test at Evenhuis

Tests are done with and without logging. For logging it is necessary to connect the laptop and give the logging command to the HMI which write the text file on a usb stick. Tests without logging are done by the employees from Evenhuis. They write down the total mass from the MC and collect the weigh receipt from the factory. The advantage of logging is that all the information during the measurement is available. Note that the mean belt filling and mean tonnage is measured of a period where the flow is constant, so the effect of starting and stopping is not in this value. See table 8.1 and 8.2 for the results. From figure 8.4 it is clear that the conveyor operates under an angle (within the range of 5°). According to the theory the measured mass should be lower, but in fact the measured mass is a bit higher than the mass weighted on the weigh bridge. This could mean that the current factor of 1.34 is too high. Nevertheless all tests are within the desired error of 1%!

Table 8.1: Results of measurements with logging

		Test 1	**Test 2**
Mass measured	$[kg]$	35324	36844
Mass weigh bridge	$[kg]$	35080	36820
Mean belt speed	$[\frac{m}{s}]$	0.85	0.71
Mean belt filling	$[\frac{kg}{m}]$	33.64	39.15
Max belt filling	$[\frac{kg}{m}]$	37.96	51.86
Mean tonnage	$[\frac{tonne}{hour}]$	99.7	102.4
Zero mass	$[kg]$	-0.3780	-0.3060
Elapsed time	$[min]$	23.46	24.15
Error	[%]	0.69	0.07

Table 8.2: Results of measurements without logging

MC 65 $[kg]$	**Weigh bridge** $[kg]$	**Error** [%]
33230	33400	0.51
34886	34640	0.71
35515	35440	0.21
34208	34180	0.08

9. Recommendations

In this research most of the topics are covered. There are some recommendations and research topics for further investigation:

- Test over large time period and check if the factor changes. The user must be able to reset the factor if it changes over time. Resetting the factor should be the following procedure: Set the total weight to zero, run an amount of product over the belt (the amount must be as large as possible) and fill in the amount which is weighted afterwards. The factor will be changed by filling in this mass and the measured mass from the MC.
- Implement a velocity measurement in the software with an accurate timer. Currently the time between weight requests is used to calculate the velocity, but this is not very accurate. With the velocity also the number of tonnes per hour can be shown on the HMI screen.
- Mind that the thickness of the flexure is 4 mm, changing the thickness will lead to a change in the factor. A thicker flexure will result in a higher factor and a thinner flexure in a lower one.
- Possible solution to lower the influence of the belt tension: placing the weigh frame more to the tail. The potatoes are already steady after about 1.5 m. Another solution is to turn the frame 180° to have the most sensitive part of the frame close to the tail. In the theory it is proven that the least tension variation is at the tail, see section 3.6.
- Install an other type of sensor that can fit within the frame, see figure 9.1. The current sensor is sensible for impacts, if it fits inside the frame it is more protected. Those sensors are already available within Miedema.

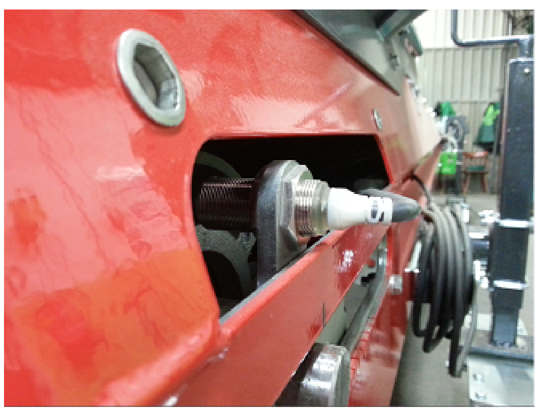


Figure 9.1: Placement sensor on frame

- Angles: The maximum error is 0.5 % between the measurements with equal parameters, see section 8.6. In order to stay within the desired 1% there is 0.5% left for compensation of the angle. In theory this is a maximum angle of: $\cos^{-1}\left(\frac{1}{1.005}\right) = 5.72°$. To be on the save side it is recommended to operate within a range of ±5°.
- Enclose the gap between the weigh frame and the total frame. Pieces of potatoes or tare can fit inside this gap, see figure 9.2. This will influence the measurement.

Figure 9.2: Gap between weigh frame and total frame

- On the weigh frame there are mountings made on which calibration weights can be mounted, see figure 9.3. As mentioned before the calibration must be performed very precisely. It makes the calibration easier if the mountings are perfectly aligned with the weigh cell ($d = 0$). Then the calibration weight can directly filled in. In the current configuration the distance between the mounting and the weigh cell (d) must be compensated via simple force equilibrium.

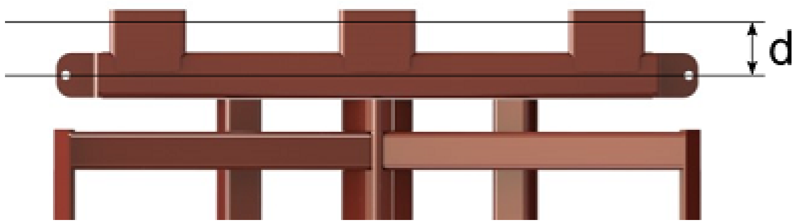


Figure 9.3: Alignment calibration mountings w.r.t. placement load cell

- There was always a slight difference in the result on the HMI screen and using the log files in `MatLab`. This difference comes from the rounding of the step length. In the software the step length is 4.29 cm, but in fact it is 4.293509... cm. The difference is not significant, but it is important to know where the difference comes from.

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A. Matlab code

A.1 Theoretical approximation sorting table

```
%% Properties
dl=0.005;                   % step length [m]
L1=365e-3;                  % length [m]
L2=180e-3;                  % length [m]
L3=235e-3;                  % length [m]
L4=315e-3;                  % length [m]
L5=180e-3;                  % length [m]
L6=180e-3;                  % length [m]
L7=365e-3;                  % length [m]
Lq=200;                     % load length [m]
Lt=L1+L2+L3+L4+L5+L6+L7;    % total length [m]
q=50;                       % distributed mass [kg/m]
mtot=q*Lq;                  % total mass on weigh cell [kg]

syms By Cy Dy Ey Fy Gy
%% From By
a=L1; b=Lt-a;
dBB=(By*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);
dCB=(By*b)/(6*Lt)*(Lt/b*((L1+L2)-a)^3+(Lt^2-b^2)*(L1+L2) - (L1+L2)^3);
dDB=(By*b)/(6*Lt)*(Lt/b*(L1+L2+L3-a)^3+(Lt^2-b^2)*(L1+L2+L3) - (L1+L2+L3)^3);
dEB=(By*b)/(6*Lt)*(Lt/b*((L1+L2+L3+L4)-a)^3+(Lt^2-b^2)*(L1+L2+L3+L4) - (L1+L2+L3+L4)^3);
dFB=(By*b)/(6*Lt)*(Lt/b*((L1+L2+L3+L4+L5)-a)^3+(Lt^2-b^2)*(L1+L2+L3+L4+L5) - (L1+L2+L3+L4+L5)^3);
dGB=(By*b)/(6*Lt)*(Lt/b*((L1+L2+L3+L4+L5+L6)-a)^3+(Lt^2-b^2)*(L1+L2+L3+L4+L5+L6) - (L1+L2+L3+L4+L5+L6)^3);

%% From Cy
a=L1+L2; b=Lt-a;
dBC=(Cy*b*L1)/(6*Lt)*(Lt^2 - L1^2 - b^2);
dCC=(Cy*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);
dDC=(Cy*b)/(6*Lt)*(Lt/b*(L1+L2+L3-a)^3+(Lt^2-b^2)*(L1+L2+L3) - (L1+L2+L3)^3);
dEC=(Cy*b)/(6*Lt)*(Lt/b*((L1+L2+L3+L4)-a)^3+(Lt^2-b^2)*(L1+L2+L3+L4) - (L1+L2+L3+L4)^3);
dFC=(Cy*b)/(6*Lt)*(Lt/b*((L1+L2+L3+L4+L5)-a)^3+(Lt^2-b^2)*(L1+L2+L3+L4+L5) - (L1+L2+L3+L4+L5)^3);
dGC=(Cy*b)/(6*Lt)*(Lt/b*((L1+L2+L3+L4+L5+L6)-a)^3+(Lt^2-b^2)*(L1+L2+L3+L4+L5+L6) - (L1+L2+L3+L4+L5+L6)^3);

%% From Dy
a=L1+L2+L3; b=Lt-a;
dBD=(Dy*b*L1)/(6*Lt)*(Lt^2 - L1^2 - b^2);
dCD=(Dy*b*(L1+L2))/(6*Lt)*(Lt^2 - (L1+L2)^2 - b^2);
dDD=(Dy*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);
dED=(Dy*b)/(6*Lt)*(Lt/b*((L1+L2+L3+L4)-a)^3+(Lt^2-b^2)*(L1+L2+L3+L4) - (L1+L2+L3+L4)^3);
dFD=(Dy*b)/(6*Lt)*(Lt/b*((L1+L2+L3+L4+L5)-a)^3+(Lt^2-b^2)*(L1+L2+L3+L4+L5) - (L1+L2+L3+L4+L5)^3);
dGD=(Dy*b)/(6*Lt)*(Lt/b*((L1+L2+L3+L4+L5+L6)-a)^3+(Lt^2-b^2)*(L1+L2+L3+L4+L5+L6) - (L1+L2+L3+L4+L5+L6)^3);

%% From Ey
a=L1+L2+L3+L4; b=Lt-a;
dBE=(Ey*b*L1)/(6*Lt)*(Lt^2 - L1^2 - b^2);
dCE=(Ey*b*(L1+L2))/(6*Lt)*(Lt^2 - (L1+L2)^2 - b^2);
dDE=(Ey*b*(L1+L2+L3))/(6*Lt)*(Lt^2 - (L1+L2+L3)^2 - b^2);
dEE=(Ey*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);
dFE=(Ey*b)/(6*Lt)*(Lt/b*((L1+L2+L3+L4+L5)-a)^3+(Lt^2-b^2)*(L1+L2+L3+L4+L5) - (L1+L2+L3+L4+L5)^3);
dGE=(Ey*b)/(6*Lt)*(Lt/b*((L1+L2+L3+L4+L5+L6)-a)^3+(Lt^2-b^2)*(L1+L2+L3+L4+L5+L6) - (L1+L2+L3+L4+L5+L6)^3);

%% From Fy
a=L1+L2+L3+L4+L5; b=Lt-a;
dBF=(Fy*b*L1)/(6*Lt)*(Lt^2 - L1^2 - b^2);
dCF=(Fy*b*(L1+L2))/(6*Lt)*(Lt^2 - (L1+L2)^2 - b^2);
dDF=(Fy*b*(L1+L2+L3))/(6*Lt)*(Lt^2 - (L1+L2+L3)^2 - b^2);
dEF=(Fy*b*(L1+L2+L3+L4))/(6*Lt)*(Lt^2 - (L1+L2+L3+L4)^2 - b^2);
```

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dFF=(Fy*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);
dGF=(Fy*b)/(6*Lt)*(Lt/b*((L1+L2+L3+L4+L5+L6)-a)^3+(Lt^2-b^2)*(L1+L2+L3+L4+L5+L6) - (L1+L2+L3+L4+L5+L6)^3);

%% From Gy
a=L1+L2+L3+L4+L5+L6; b=Lt-a;
dBG=(Gy*b*L1)/(6*Lt)*(Lt^2 - L1^2 - b^2);
dCG=(Gy*b*(L1+L2))/(6*Lt)*(Lt^2 - (L1+L2)^2 - b^2);
dDG=(Gy*b*(L1+L2+L3))/(6*Lt)*(Lt^2 - (L1+L2+L3)^2 - b^2);
dEG=(Gy*b*(L1+L2+L3+L4))/(6*Lt)*(Lt^2 - (L1+L2+L3+L4)^2 - b^2);
dFG=(Gy*b*(L1+L2+L3+L4+L5))/(6*Lt)*(Lt^2 - (L1+L2+L3+L4+L5)^2 - b^2);
dGG=(Gy*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);

%% Entering load
xG=L7; xF=L7+L6; xE=L7+L6+L5; xD=L7+L6+L5+L4; xC=L7+L6+L5+L4+L3; xB=L7+L6+L5+L4+L3+L2;
for Lq_ent=0:Lt/dl-1
    Hy=(0.5*q*(Lq_ent*dl)^2)/Lt;
    C=(-Hy*Lt^3/6 + q*(Lq_ent*dl)^4/24)/Lt;

    dB=-((Hy*xB^3)/6 - q/24*(max(xB-(Lt-(Lq_ent*dl)),0))^4 + C*xB);
    dC=-((Hy*xC^3)/6 - q/24*(max(xC-(Lt-(Lq_ent*dl)),0))^4 + C*xC);
    dD=-((Hy*xD^3)/6 - q/24*(max(xD-(Lt-(Lq_ent*dl)),0))^4 + C*xD);
    dE=-((Hy*xE^3)/6 - q/24*(max(xE-(Lt-(Lq_ent*dl)),0))^4 + C*xE);
    dF=-((Hy*xF^3)/6 - q/24*(max(xF-(Lt-(Lq_ent*dl)),0))^4 + C*xF);
    dG=-((Hy*xG^3)/6 - q/24*(max(xG-(Lt-(Lq_ent*dl)),0))^4 + C*xG);

    eq1=dB-dBB-dBC-dBD-dBE-dBF-dBG;
    eq2=dC-dCB-dCC-dCD-dCE-dCF-dCG;
    eq3=dD-dDB-dDC-dDD-dDE-dDF-dDG;
    eq4=dE-dEB-dEC-dED-dEE-dEF-dEG;
    eq5=dF-dFB-dFC-dFD-dFE-dFF-dFG;
    eq6=dG-dGB-dGC-dGD-dGE-dGF-dGG;

    reactions=solve(eq1 == 0, eq2 == 0, eq3 == 0, eq4 == 0, eq5 == 0, eq6 == 0,...
        By, Cy, Dy, Ey, Fy, Gy);

    By_ans(Lq_ent+1)=double(reactions.By);
    Cy_ans(Lq_ent+1)=double(reactions.Cy);
    Dy_ans(Lq_ent+1)=double(reactions.Dy);
    Ey_ans(Lq_ent+1)=double(reactions.Ey);
    Fy_ans(Lq_ent+1)=double(reactions.Fy);
    Gy_ans(Lq_ent+1)=double(reactions.Gy);
end

%% Full load
dB=(q*L1)/24*(L1^3-2*Lt*L1^2+Lt^3);
dC=(q*(L1+L2))/24*((L1+L2)^3-2*Lt*(L1+L2)^2+Lt^3);
dD=(q*(L1+L2+L3))/24*((L1+L2+L3)^3-2*Lt*(L1+L2+L3)^2+Lt^3);
dE=(q*(L1+L2+L3+L4))/24*((L1+L2+L3+L4)^3-2*Lt*(L1+L2+L3+L4)^2+Lt^3);
dF=(q*(L1+L2+L3+L4+L5))/24*((L1+L2+L3+L4+L5)^3-2*Lt*(L1+L2+L3+L4+L5)^2+Lt^3);
dG=(q*(L1+L2+L3+L4+L5+L6))/24*((L1+L2+L3+L4+L5+L6)^3-2*Lt*(L1+L2+L3+L4+L5+L6)^2+Lt^3);

eq1=dB-dBB-dBC-dBD-dBE-dBF-dBG;
eq2=dC-dCB-dCC-dCD-dCE-dCF-dCG;
eq3=dD-dDB-dDC-dDD-dDE-dDF-dDG;
eq4=dE-dEB-dEC-dED-dEE-dEF-dEG;
eq5=dF-dFB-dFC-dFD-dFE-dFF-dFG;
eq6=dG-dGB-dGC-dGD-dGE-dGF-dGG;

reactions=solve(eq1 == 0, eq2 == 0, eq3 == 0, eq4 == 0, eq5 == 0, eq6 == 0,...
    By, Cy, Dy, Ey, Fy, Gy);

By_ans(length(By_ans)+1:length(By_ans)+(Lq-Lt)/dl)=double(reactions.By);
Cy_ans(length(Cy_ans)+1:length(Cy_ans)+(Lq-Lt)/dl)=double(reactions.Cy);
Dy_ans(length(Dy_ans)+1:length(Dy_ans)+(Lq-Lt)/dl)=double(reactions.Dy);
Ey_ans(length(Ey_ans)+1:length(Ey_ans)+(Lq-Lt)/dl)=double(reactions.Ey);
Fy_ans(length(Fy_ans)+1:length(Fy_ans)+(Lq-Lt)/dl)=double(reactions.Fy);
Gy_ans(length(Gy_ans)+1:length(Gy_ans)+(Lq-Lt)/dl)=double(reactions.Gy);
```

```
%% Leaving load
xB=L1; xC=L1+L2; xD=L1+L2+L3; xE=L1+L2+L3+L4; xF=L1+L2+L3+L4+L5; xG=L1+L2+L3+L4+L5+L6;
for x=1:Lt/dl
    Lq_leav=Lt-x*dl;
    Ay=(0.5*q*Lq_leav^2)/Lt;
    C=(-Ay*Lt^3/6 + q*(Lq_leav)^4/24)/Lt;

    dB=-((Ay*xB^3)/6 - q/24*(max(xB-(Lt-(Lq_leav)),0))^4 + C*xB);
    dC=-((Ay*xC^3)/6 - q/24*(max(xC-(Lt-(Lq_leav)),0))^4 + C*xC);
    dD=-((Ay*xD^3)/6 - q/24*(max(xD-(Lt-(Lq_leav)),0))^4 + C*xD);
    dE=-((Ay*xE^3)/6 - q/24*(max(xE-(Lt-(Lq_leav)),0))^4 + C*xE);
    dF=-((Ay*xF^3)/6 - q/24*(max(xF-(Lt-(Lq_leav)),0))^4 + C*xF);
    dG=-((Ay*xG^3)/6 - q/24*(max(xG-(Lt-(Lq_leav)),0))^4 + C*xG);

    eq1=dB-dBB-dBC-dBD-dBE-dBF-dBG;
    eq2=dC-dCB-dCC-dCD-dCE-dCF-dCG;
    eq3=dD-dDB-dDC-dDD-dDE-dDF-dDG;
    eq4=dE-dEB-dEC-dED-dEE-dEF-dEG;
    eq5=dF-dFB-dFC-dFD-dFE-dFF-dFG;
    eq6=dG-dGB-dGC-dGD-dGE-dGF-dGG;

    reactions=solve(eq1 == 0, eq2 == 0, eq3 == 0, eq4 == 0, eq5 == 0, eq6 == 0,...
        By, Cy, Dy, Ey, Fy, Gy);

    By_ans(length(By_ans)+1)=double(reactions.By);
    Cy_ans(length(Cy_ans)+1)=double(reactions.Cy);
    Dy_ans(length(Dy_ans)+1)=double(reactions.Dy);
    Ey_ans(length(Ey_ans)+1)=double(reactions.Ey);
    Fy_ans(length(Fy_ans)+1)=double(reactions.Fy);
    Gy_ans(length(Gy_ans)+1)=double(reactions.Gy);
end
```

A.2 Theoretical approximation MC

```
%% Properties
dl=0.01;             % step length [m]
Lq=200;              % load length [m]
L=0.5;               % length [m]
Lw=1750e-3;          % length weigh frame [m]
La=390e-3;           % length La on weigh frame [m]
Lt=10*L;             % total length [m]
q=50;                % distributed mass [kg/m]
mtot=q*Lq;           % total mass on weigh cell [kg]

syms By Cy Dy Ey Fy Gy Hy Iy Jy
%% From By
a=L; b=Lt-a;
dBB=(By*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);
dCB=(By*b)/(6*Lt)*(Lt/b*(2*L-a)^3+(Lt^2-b^2)*2*L - (2*L)^3);
dDB=(By*b)/(6*Lt)*(Lt/b*(3*L-a)^3+(Lt^2-b^2)*3*L - (3*L)^3);
dEB=(By*b)/(6*Lt)*(Lt/b*(4*L-a)^3+(Lt^2-b^2)*4*L - (4*L)^3);
dFB=(By*b)/(6*Lt)*(Lt/b*(5*L-a)^3+(Lt^2-b^2)*5*L - (5*L)^3);
dGB=(By*b)/(6*Lt)*(Lt/b*(6*L-a)^3+(Lt^2-b^2)*6*L - (6*L)^3);
dHB=(By*b)/(6*Lt)*(Lt/b*(7*L-a)^3+(Lt^2-b^2)*7*L - (7*L)^3);
dIB=(By*b)/(6*Lt)*(Lt/b*(8*L-a)^3+(Lt^2-b^2)*8*L - (8*L)^3);
dJB=(By*b)/(6*Lt)*(Lt/b*(9*L-a)^3+(Lt^2-b^2)*9*L - (9*L)^3);

%% From Cy
a=2*L; b=Lt-a;
dBC=(Cy*b*L)/(6*Lt)*(Lt^2 - L^2 - b^2);
dCC=(Cy*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);
dDC=(Cy*b)/(6*Lt)*(Lt/b*(3*L-a)^3+(Lt^2-b^2)*3*L - (3*L)^3);
dEC=(Cy*b)/(6*Lt)*(Lt/b*(4*L-a)^3+(Lt^2-b^2)*4*L - (4*L)^3);
dFC=(Cy*b)/(6*Lt)*(Lt/b*(5*L-a)^3+(Lt^2-b^2)*5*L - (5*L)^3);
dGC=(Cy*b)/(6*Lt)*(Lt/b*(6*L-a)^3+(Lt^2-b^2)*6*L - (6*L)^3);
```

```
dHC=(Cy*b)/(6*Lt)*(Lt/b*(7*L-a)^3+(Lt^2-b^2)*7*L - (7*L)^3);
dIC=(Cy*b)/(6*Lt)*(Lt/b*(8*L-a)^3+(Lt^2-b^2)*8*L - (8*L)^3);
dJC=(Cy*b)/(6*Lt)*(Lt/b*(9*L-a)^3+(Lt^2-b^2)*9*L - (9*L)^3);

%% From Dy
a=3*L; b=Lt-a;
dBD=(Dy*b*L)/(6*Lt)*(Lt^2 - L^2 - b^2);
dCD=(Dy*b*(2*L))/(6*Lt)*(Lt^2 - (2*L)^2 - b^2);
dDD=(Dy*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);
dED=(Dy*b)/(6*Lt)*(Lt/b*(4*L-a)^3+(Lt^2-b^2)*4*L - (4*L)^3);
dFD=(Dy*b)/(6*Lt)*(Lt/b*(5*L-a)^3+(Lt^2-b^2)*5*L - (5*L)^3);
dGD=(Dy*b)/(6*Lt)*(Lt/b*(6*L-a)^3+(Lt^2-b^2)*6*L - (6*L)^3);
dHD=(Dy*b)/(6*Lt)*(Lt/b*(7*L-a)^3+(Lt^2-b^2)*7*L - (7*L)^3);
dID=(Dy*b)/(6*Lt)*(Lt/b*(8*L-a)^3+(Lt^2-b^2)*8*L - (8*L)^3);
dJD=(Dy*b)/(6*Lt)*(Lt/b*(9*L-a)^3+(Lt^2-b^2)*9*L - (9*L)^3);

%% From Ey
a=4*L; b=Lt-a;
dBE=(Ey*b*L)/(6*Lt)*(Lt^2 - L^2 - b^2);
dCE=(Ey*b*(2*L))/(6*Lt)*(Lt^2 - (2*L)^2 - b^2);
dDE=(Ey*b*(3*L))/(6*Lt)*(Lt^2 - (3*L)^2 - b^2);
dEE=(Ey*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);
dFE=(Ey*b)/(6*Lt)*(Lt/b*(5*L-a)^3+(Lt^2-b^2)*5*L - (5*L)^3);
dGE=(Ey*b)/(6*Lt)*(Lt/b*(6*L-a)^3+(Lt^2-b^2)*6*L - (6*L)^3);
dHE=(Ey*b)/(6*Lt)*(Lt/b*(7*L-a)^3+(Lt^2-b^2)*7*L - (7*L)^3);
dIE=(Ey*b)/(6*Lt)*(Lt/b*(8*L-a)^3+(Lt^2-b^2)*8*L - (8*L)^3);
dJE=(Ey*b)/(6*Lt)*(Lt/b*(9*L-a)^3+(Lt^2-b^2)*9*L - (9*L)^3);

%% From Fy
a=5*L; b=Lt-a;
dBF=(Fy*b*L)/(6*Lt)*(Lt^2 - L^2 - b^2);
dCF=(Fy*b*(2*L))/(6*Lt)*(Lt^2 - (2*L)^2 - b^2);
dDF=(Fy*b*(3*L))/(6*Lt)*(Lt^2 - (3*L)^2 - b^2);
dEF=(Fy*b*(4*L))/(6*Lt)*(Lt^2 - (4*L)^2 - b^2);
dFF=(Fy*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);
dGF=(Fy*b)/(6*Lt)*(Lt/b*(6*L-a)^3+(Lt^2-b^2)*6*L - (6*L)^3);
dHF=(Fy*b)/(6*Lt)*(Lt/b*(7*L-a)^3+(Lt^2-b^2)*7*L - (7*L)^3);
dIF=(Fy*b)/(6*Lt)*(Lt/b*(8*L-a)^3+(Lt^2-b^2)*8*L - (8*L)^3);
dJF=(Fy*b)/(6*Lt)*(Lt/b*(9*L-a)^3+(Lt^2-b^2)*9*L - (9*L)^3);

%% From Gy
a=6*L; b=Lt-a;
dBG=(Gy*b*L)/(6*Lt)*(Lt^2 - L^2 - b^2);
dCG=(Gy*b*(2*L))/(6*Lt)*(Lt^2 - (2*L)^2 - b^2);
dDG=(Gy*b*(3*L))/(6*Lt)*(Lt^2 - (3*L)^2 - b^2);
dEG=(Gy*b*(4*L))/(6*Lt)*(Lt^2 - (4*L)^2 - b^2);
dFG=(Gy*b*(5*L))/(6*Lt)*(Lt^2 - (5*L)^2 - b^2);
dGG=(Gy*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);
dHG=(Gy*b)/(6*Lt)*(Lt/b*(7*L-a)^3+(Lt^2-b^2)*7*L - (7*L)^3);
dIG=(Gy*b)/(6*Lt)*(Lt/b*(8*L-a)^3+(Lt^2-b^2)*8*L - (8*L)^3);
dJG=(Gy*b)/(6*Lt)*(Lt/b*(9*L-a)^3+(Lt^2-b^2)*9*L - (9*L)^3);

%% From Hy
a=7*L; b=Lt-a;
dBH=(Hy*b*L)/(6*Lt)*(Lt^2 - L^2 - b^2);
dCH=(Hy*b*(2*L))/(6*Lt)*(Lt^2 - (2*L)^2 - b^2);
dDH=(Hy*b*(3*L))/(6*Lt)*(Lt^2 - (3*L)^2 - b^2);
dEH=(Hy*b*(4*L))/(6*Lt)*(Lt^2 - (4*L)^2 - b^2);
dFH=(Hy*b*(5*L))/(6*Lt)*(Lt^2 - (5*L)^2 - b^2);
dGH=(Hy*b*(6*L))/(6*Lt)*(Lt^2 - (6*L)^2 - b^2);
dHH=(Hy*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);
dIH=(Hy*b)/(6*Lt)*(Lt/b*(8*L-a)^3+(Lt^2-b^2)*8*L - (8*L)^3);
dJH=(Hy*b)/(6*Lt)*(Lt/b*(9*L-a)^3+(Lt^2-b^2)*9*L - (9*L)^3);

%% From Iy
a=8*L; b=Lt-a;
dBI=(Iy*b*L)/(6*Lt)*(Lt^2 - L^2 - b^2);
dCI=(Iy*b*(2*L))/(6*Lt)*(Lt^2 - (2*L)^2 - b^2);
```

```
dDI=(Iy*b*(3*L))/(6*Lt)*(Lt^2 - (3*L)^2 - b^2);
dEI=(Iy*b*(4*L))/(6*Lt)*(Lt^2 - (4*L)^2 - b^2);
dFI=(Iy*b*(5*L))/(6*Lt)*(Lt^2 - (5*L)^2 - b^2);
dGI=(Iy*b*(6*L))/(6*Lt)*(Lt^2 - (6*L)^2 - b^2);
dHI=(Iy*b*(7*L))/(6*Lt)*(Lt^2 - (7*L)^2 - b^2);
dII=(Iy*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);
dJI=(Iy*b)/(6*Lt)*(Lt/b*(9*L-a)^3+(Lt^2-b^2)*9*L - (9*L)^3);

%% From Jy
a=9*L; b=Lt-a;
dBJ=(Jy*b*L)/(6*Lt)*(Lt^2 - L^2 - b^2);
dCJ=(Jy*b*(2*L))/(6*Lt)*(Lt^2 - (2*L)^2 - b^2);
dDJ=(Jy*b*(3*L))/(6*Lt)*(Lt^2 - (3*L)^2 - b^2);
dEJ=(Jy*b*(4*L))/(6*Lt)*(Lt^2 - (4*L)^2 - b^2);
dFJ=(Jy*b*(5*L))/(6*Lt)*(Lt^2 - (5*L)^2 - b^2);
dGJ=(Jy*b*(6*L))/(6*Lt)*(Lt^2 - (6*L)^2 - b^2);
dHJ=(Jy*b*(7*L))/(6*Lt)*(Lt^2 - (7*L)^2 - b^2);
dIJ=(Jy*b*(8*L))/(6*Lt)*(Lt^2 - (8*L)^2 - b^2);
dJJ=(Jy*b*a)/(6*Lt)*(Lt^2 - a^2 - b^2);

%% Entering load
xJ=L; xI=2*L; xH=3*L; xG=4*L; xF=5*L; xE=6*L; xD=7*L; xC=8*L; xB=9*L;

By_ans=zeros(1,(Lt+Lq)/dl);
Cy_ans=zeros(1,(Lt+Lq)/dl);
Dy_ans=zeros(1,(Lt+Lq)/dl);
Ey_ans=zeros(1,(Lt+Lq)/dl);
Fy_ans=zeros(1,(Lt+Lq)/dl);
Gy_ans=zeros(1,(Lt+Lq)/dl);
Hy_ans=zeros(1,(Lt+Lq)/dl);
Iy_ans=zeros(1,(Lt+Lq)/dl);
Jy_ans=zeros(1,(Lt+Lq)/dl);

for Lq_ent=0:Lt/dl-1
    Ky=(0.5*q*(Lq_ent*dl)^2)/Lt;
    C=(-Ky*Lt^3/6 + q*(Lq_ent*dl)^4/24)/Lt;

    dB=-((Ky*xB^3)/6 - q/24*(max(xB-(Lt-(Lq_ent*dl)),0))^4 + C*xB);
    dC=-((Ky*xC^3)/6 - q/24*(max(xC-(Lt-(Lq_ent*dl)),0))^4 + C*xC);
    dD=-((Ky*xD^3)/6 - q/24*(max(xD-(Lt-(Lq_ent*dl)),0))^4 + C*xD);
    dE=-((Ky*xE^3)/6 - q/24*(max(xE-(Lt-(Lq_ent*dl)),0))^4 + C*xE);
    dF=-((Ky*xF^3)/6 - q/24*(max(xF-(Lt-(Lq_ent*dl)),0))^4 + C*xF);
    dG=-((Ky*xG^3)/6 - q/24*(max(xG-(Lt-(Lq_ent*dl)),0))^4 + C*xG);
    dH=-((Ky*xH^3)/6 - q/24*(max(xH-(Lt-(Lq_ent*dl)),0))^4 + C*xH);
    dI=-((Ky*xI^3)/6 - q/24*(max(xI-(Lt-(Lq_ent*dl)),0))^4 + C*xI);
    dJ=-((Ky*xJ^3)/6 - q/24*(max(xJ-(Lt-(Lq_ent*dl)),0))^4 + C*xJ);

    eq1=dB-dBB-dBC-dBD-dBE-dBF-dBG-dBH-dBI-dBJ;
    eq2=dC-dCB-dCC-dCD-dCE-dCF-dCG-dCH-dCI-dCJ;
    eq3=dD-dDB-dDC-dDD-dDE-dDF-dDG-dDH-dDI-dDJ;
    eq4=dE-dEB-dEC-dED-dEE-dEF-dEG-dEH-dEI-dEJ;
    eq5=dF-dFB-dFC-dFD-dFE-dFF-dFG-dFH-dFI-dFJ;
    eq6=dG-dGB-dGC-dGD-dGE-dGF-dGG-dGH-dGI-dGJ;
    eq7=dH-dHB-dHC-dHD-dHE-dHF-dHG-dHH-dHI-dHJ;
    eq8=dI-dIB-dIC-dID-dIE-dIF-dIG-dIH-dII-dIJ;
    eq9=dJ-dJB-dJC-dJD-dJE-dJF-dJG-dJH-dJI-dJJ;

    reactions=solve(eq1 == 0, eq2 == 0, eq3 == 0, eq4 == 0, eq5 == 0, eq6 == 0,...
        eq7 == 0, eq8 == 0, eq9 == 0, By, Cy, Dy, Ey, Fy, Gy, Hy, Iy, Jy);

    By_ans(Lq_ent+1)=double(reactions.By);
    Cy_ans(Lq_ent+1)=double(reactions.Cy);
    Dy_ans(Lq_ent+1)=double(reactions.Dy);
    Ey_ans(Lq_ent+1)=double(reactions.Ey);
    Fy_ans(Lq_ent+1)=double(reactions.Fy);
    Gy_ans(Lq_ent+1)=double(reactions.Gy);
    Hy_ans(Lq_ent+1)=double(reactions.Hy);
    Iy_ans(Lq_ent+1)=double(reactions.Iy);
```

```
    Jy_ans(Lq_ent+1)=double(reactions.Jy);
end

%% Full load
dB=(q*L)/24*(L^3-2*Lt*L^2+Lt^3);
dC=(q*2*L)/24*((2*L)^3-2*Lt*(2*L)^2+Lt^3);
dD=(q*3*L)/24*((3*L)^3-2*Lt*(3*L)^2+Lt^3);
dE=(q*4*L)/24*((4*L)^3-2*Lt*(4*L)^2+Lt^3);
dF=(q*5*L)/24*((5*L)^3-2*Lt*(5*L)^2+Lt^3);
dG=(q*6*L)/24*((6*L)^3-2*Lt*(6*L)^2+Lt^3);
dH=(q*7*L)/24*((7*L)^3-2*Lt*(7*L)^2+Lt^3);
dI=(q*8*L)/24*((8*L)^3-2*Lt*(8*L)^2+Lt^3);
dJ=(q*9*L)/24*((9*L)^3-2*Lt*(9*L)^2+Lt^3);

eq1=dB-dBB-dBC-dBD-dBE-dBF-dBG-dBH-dBI-dBJ;
eq2=dC-dCB-dCC-dCD-dCE-dCF-dCG-dCH-dCI-dCJ;
eq3=dD-dDB-dDC-dDD-dDE-dDF-dDG-dDH-dDI-dDJ;
eq4=dE-dEB-dEC-dED-dEE-dEF-dEG-dEH-dEI-dEJ;
eq5=dF-dFB-dFC-dFD-dFE-dFF-dFG-dFH-dFI-dFJ;
eq6=dG-dGB-dGC-dGD-dGE-dGF-dGG-dGH-dGI-dGJ;
eq7=dH-dHB-dHC-dHD-dHE-dHF-dHG-dHH-dHI-dHJ;
eq8=dI-dIB-dIC-dID-dIE-dIF-dIG-dIH-dII-dIJ;
eq9=dJ-dJB-dJC-dJD-dJE-dJF-dJG-dJH-dJI-dJJ;

reactions=solve(eq1 == 0, eq2 == 0, eq3 == 0, eq4 == 0, eq5 == 0, eq6 == 0,...
    eq7 == 0, eq8 == 0, eq9 == 0, By, Cy, Dy, Ey, Fy, Gy, Hy, Iy, Jy);

By_ans(Lt/dl+1:Lt/dl+(Lq-Lt)/dl)=double(reactions.By);
Cy_ans(Lt/dl+1:Lt/dl+(Lq-Lt)/dl)=double(reactions.Cy);
Dy_ans(Lt/dl+1:Lt/dl+(Lq-Lt)/dl)=double(reactions.Dy);
Ey_ans(Lt/dl+1:Lt/dl+(Lq-Lt)/dl)=double(reactions.Ey);
Fy_ans(Lt/dl+1:Lt/dl+(Lq-Lt)/dl)=double(reactions.Fy);
Gy_ans(Lt/dl+1:Lt/dl+(Lq-Lt)/dl)=double(reactions.Gy);
Hy_ans(Lt/dl+1:Lt/dl+(Lq-Lt)/dl)=double(reactions.Hy);
Iy_ans(Lt/dl+1:Lt/dl+(Lq-Lt)/dl)=double(reactions.Iy);
Jy_ans(Lt/dl+1:Lt/dl+(Lq-Lt)/dl)=double(reactions.Jy);

%% Leaving load
xB=L; xC=2*L; xD=3*L; xE=4*L; xF=5*L; xG=6*L; xH=7*L; xI=8*L; xJ=9*L;

for x=1:Lt/dl
    Lq_leav=Lt-x*dl;
    Ay=(0.5*q*Lq_leav^2)/Lt;
    C=(-Ay*Lt^3/6 + q*(Lq_leav)^4/24)/Lt;

    dB=-((Ay*xB^3)/6 - q/24*(max(xB-(Lt-(Lq_leav)),0))^4 + C*xB);
    dC=-((Ay*xC^3)/6 - q/24*(max(xC-(Lt-(Lq_leav)),0))^4 + C*xC);
    dD=-((Ay*xD^3)/6 - q/24*(max(xD-(Lt-(Lq_leav)),0))^4 + C*xD);
    dE=-((Ay*xE^3)/6 - q/24*(max(xE-(Lt-(Lq_leav)),0))^4 + C*xE);
    dF=-((Ay*xF^3)/6 - q/24*(max(xF-(Lt-(Lq_leav)),0))^4 + C*xF);
    dG=-((Ay*xG^3)/6 - q/24*(max(xG-(Lt-(Lq_leav)),0))^4 + C*xG);
    dH=-((Ay*xH^3)/6 - q/24*(max(xH-(Lt-(Lq_leav)),0))^4 + C*xH);
    dI=-((Ay*xI^3)/6 - q/24*(max(xI-(Lt-(Lq_leav)),0))^4 + C*xI);
    dJ=-((Ay*xJ^3)/6 - q/24*(max(xJ-(Lt-(Lq_leav)),0))^4 + C*xJ);

    eq1=dB-dBB-dBC-dBD-dBE-dBF-dBG-dBH-dBI-dBJ;
    eq2=dC-dCB-dCC-dCD-dCE-dCF-dCG-dCH-dCI-dCJ;
    eq3=dD-dDB-dDC-dDD-dDE-dDF-dDG-dDH-dDI-dDJ;
    eq4=dE-dEB-dEC-dED-dEE-dEF-dEG-dEH-dEI-dEJ;
    eq5=dF-dFB-dFC-dFD-dFE-dFF-dFG-dFH-dFI-dFJ;
    eq6=dG-dGB-dGC-dGD-dGE-dGF-dGG-dGH-dGI-dGJ;
    eq7=dH-dHB-dHC-dHD-dHE-dHF-dHG-dHH-dHI-dHJ;
    eq8=dI-dIB-dIC-dID-dIE-dIF-dIG-dIH-dII-dIJ;
    eq9=dJ-dJB-dJC-dJD-dJE-dJF-dJG-dJH-dJI-dJJ;

    reactions=solve(eq1 == 0, eq2 == 0, eq3 == 0, eq4 == 0, eq5 == 0, eq6 == 0,...
        eq7 == 0, eq8 == 0, eq9 == 0, By, Cy, Dy, Ey, Fy, Gy, Hy, Iy, Jy);
```

```
    By_ans(Lt/dl+(Lq-Lt)/dl+x)=double(reactions.By);
    Cy_ans(Lt/dl+(Lq-Lt)/dl+x)=double(reactions.Cy);
    Dy_ans(Lt/dl+(Lq-Lt)/dl+x)=double(reactions.Dy);
    Ey_ans(Lt/dl+(Lq-Lt)/dl+x)=double(reactions.Ey);
    Fy_ans(Lt/dl+(Lq-Lt)/dl+x)=double(reactions.Fy);
    Gy_ans(Lt/dl+(Lq-Lt)/dl+x)=double(reactions.Gy);
    Hy_ans(Lt/dl+(Lq-Lt)/dl+x)=double(reactions.Hy);
    Iy_ans(Lt/dl+(Lq-Lt)/dl+x)=double(reactions.Iy);
    Jy_ans(Lt/dl+(Lq-Lt)/dl+x)=double(reactions.Jy);
end
```

A.3 Read log files

```
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
%  Setting frequency controller --> belt velocity              %
%                          20 Hz --> 0.39 m/s                  %
%                          30 Hz --> 0.58 m/s                  %
%                          40 Hz --> 0.77 m/s                  %
%                          50 Hz --> 0.96 m/s                  %
%                          60 Hz --> 1.16 m/s                  %
%                          70 Hz --> 1.35 m/s                  %
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
% Log in HMI: root hmi8084                                     %
% Start HMI: weighing-test-hmi > /dev/null &                   %
% Logging:  candump can0 -L > /media/usb0/<filename.txt>       %
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %

%% Input
Filename='xxxxx';

mtot = 35080;           % total mass from the weigh bridge

mlengte1 = 240;         % begin measurement length for mean kg/m
mlengte2 = 1030;        % end measurement length for mean kg/m

factor = 1.33;          % empirical factor = between 1.33 and 1.34
                        % theoretical factor = 1.3127

bound = 0;              % bound (absolute)

%% Process
% Open file
fid=fopen(Filename);
x=textscan(fid,'%s %s %s');
fclose(fid); clear fid

% Filter the mass and convert to decimal number
m=x{3}; ym=strmatch('002#',m); m=m(ym); clear ym
m=cellfun(@(x)(x(5:12)), m, 'UniformOutput', false);
m=nhex2dec(m);

% Apply the absolute bound
for i=1:length(m)
    if abs(m(i)) <= bound
        m(i) = 0;
    end
end

% Zero calibration value
tar=x{3}; ytar=strmatch('007#',tar); tar=tar(ytar); clear ytar
tar=cellfun(@(x)(x(13:20)), tar, 'UniformOutput', false);
tar=nhex2dec(tar); tar=tar(1);

% Time
t=cellfun(@(x)(x(2:18)), x{1}, 'UniformOutput', false);
```

```
yt=strmatch('63F#',x{3}); t=t(yt); clear yt
t=cellfun(@str2num,t);

% Time difference
dt=zeros(1,length(t)-1);
for i=1:length(t)-1
    dt(i)=t(i+1)-t(i);
end
dt=dt.';

% Properties
R=82e-3;                            % radius drive pulley + halve belt width [m]
dl=pi*R/6;                          % travelled distance per pulse [m]
vel=dl./dt;                         % velocity drive pulley [m/s]
vel_mean=mean(vel);                 % mean velocity
dt_mean=mean(dt);                   % mean step time

dl_m=0:dl:dl*(length(m)-1);         % measurement length mass [m]
dl_vel=0:dl:dl*(length(vel)-1);     % measurement length velocity [m]

m=factor*m;
Bandvulling_max=max(m);
Bandvulling_gem=mean(m(round(mlengte1/dl):round(mlengte2/dl)));

% Tonnage
vel_hour=vel*3600;                   % m/hour
tonnage=m(1:end-1).*vel_hour/1000;   % tonnes/hour
Tonnage_gem=mean(tonnage(round(mlengte1/dl):round(mlengte2/dl)));

% Cumulative mass
m_cum=zeros(1,length(m)-1);

m_cum(1)=(dl/2)*(m(1)+m(2));
for i=2:length(m)-1
    m_cum(i)=m_cum(i-1)+(dl/2)*(m(i)+m(i+1));
end

needed_factor=mtot/max(m_cum);
error=abs(100-max(m_cum)*100/mtot);
```