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Methods for measurement of Package Stability

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Abstract

This thesis has been conducted at Tetra Pak in Lund, a company active in the packaging industry. The department of downstream equipment was interested in measurements of Package Stability, a concept describing the stability of a package. The thesis was concentrated on measurements of accelerations and tip angles. A theoretical formula describing the connection between the maximum acceleration a package manages to handle and the package's tip angle was derived. This formula was tested in practice using a linear rig and an inclined plane for measurement of tip angles. The linear rig was used to create different accelerations that the packages were to be exposed to. Two different kinds of motion profiles were used, Trapezoidal profile and S-curve profile. Three types of packages were investigated and in total 240 measurements were made.

The outcome of the measurements was good, the theoretical max acceleration cohered well with their corresponding measured max accelerations which is why the formula is considered to be correct and applicable. For all measurements, the S-curve ended up right above the curve representing the theoretical formula while the Trapezoidal curve ended up below the theoretical curve. Which profile that gave the most accurate answer could not be decided.

During the thesis work two concepts of measurement stations performing measurements of packages' tip angles were developed, concept A and concept B. The formula can be applicable on the stations although it is hard to perform measurement of every package's tip angle in a continuous flow, it would require a much slower flow which is not desired in a production line. In case of an implementation of the formula it is recommended to use applications using S-curves due to the fact that there is an upper margin compared to the theoretical curve. The measurement stations are also considered to be usable for keeping statistics and detect greater deviations. Concept A is preferred to concept B because of its lesser complexity.

Keywords

Package Stability, measurements, motion profiles, accelerations, tip angles, measurement stations.

Sammanfattning

Detta examensarbete är utfört hos Tetra Pak i Lund, ett företag verksamt inom förpackningsindustrin. Avdelningen för distributionsutrustning var intresserad av att undersöka hur man kan mäta Package Stability, ett begrepp som beskriver en förpacknings stabilitet. Arbetet var inriktat mot accelerationer och fallvinklar. Ett teoretisk samband mellan den maximala accelerationen en förpackning klarar av att utsättas för och förpackningens fallvinkel togs fram i form av en formel. Denna formel testades sedan i praktiken genom användning av en linjär rigg och ett lutande plan som undersökte förpackningarnas fallvinkel. Den linjära riggen användes för att skapa olika accelerationer som förpackningarna skulle utsättas för. Två olika sorters rörelseprofiler användes, trapetsoid rörelseprofil och S-formad rörelseprofil. Tre typer av förpackningar undersöktes och totalt genomfördes 240 mätningar.

Resultaten var mycket goda. Den teoretiska maxaccelerationen hos förpackningarna stämde väl överens med deras uppmätta maxaccelerationer och därför anses formeln stämma och vara applicerbar. För alla mätningar hamnade S-formade kurvan lite ovanför kurvan som representerar den teoretiska formeln medan trapetsoidkurvan hamnade under den teoretiska kurvan. Vilken profil som gav det mest nogranna resultatet kunde inte avgöras.

Under examensarbetet utvecklades två koncept för mätstationer som utför mätningar av förpackningarnas fallvinklar, koncept A och koncept B. Formeln är applicerbar på mätstationerna men det kan vara svårt att i ett kontinuerligt flöde mäta alla förpackningars fallvinkel. Det skulle kräva ett betydligt långsammare flöde vilket inte är önskvärt i en produktionslinje. Vid implementering av formeln rekommenderas den för applikationer som använder sig av S-kurvor eftersom det finns en övre marginal jämfört med teoretiska kurvan. Mätstationerna anses även kunna användas till att föra statistik och upptäcka större avvikelser hos förpackningarna. Koncept A rekommenderas framför koncept B på grund av dess mindre komplexitet.

Nyckelord

Paketstabilitet, mätningar, rörelseprofiler, accelerationer, fallvinklar, mätstationer.

Preface

We want to start with thanking Robert Hansson for the possibility to conduct our thesis at Tetra Pak. It has been a rewarding experience to work at a big international company and getting an insight into engineering.

We also want to thank our supervisors, Martin Pettersson at Tetra Pak and Bengt Simonsson at LTH for their guidance and support.

Finally, a big thanks to the employees of Tetra Pak who helped in many different ways. A special thanks to Ulf Mossberg for his work with the drawing of the concepts.

Johan Carlsson and Mattias Klasson

August 2020

Contents

1 Introduction

This chapter is an overview of the thesis. It presents Tetra Pak, the company where the work has been conducted. This chapter also describes the background and goals of the thesis along with its resources, motivations, and delimitations.

1.1 Background

Tetra Pak is a global company founded in Lund, Sweden in 1951. They are a world leading company in developing solutions for processing and packaging, mainly for liquid food. Today the company has around 25 000 employees operating in over 160 countries. The head office is located in Switzerland.

When a certain type of package is to be produced, all packages go through the same manufacturing processes so they can be identical. But in reality, every package is unique. It is practically impossible to produce all packages with the same accuracy giving them the same characteristics. The outcome of this could be different behaviors when being handled by different machine functions.

The department of downstream equipment works with processes that occur after the packages have been produced. The department wants help with investigating how package deviations can be measured in a production flow. The measurement data can be used to keep statistics and possibly regulate machine functions and adapt them to the deviations.

Package Stability is a term used to describe how stable a package is when it is exposed to dynamic forces. This thesis intends to investigate Package Stability by conducting measurements on relevant parameters. Another task is creating a measurement station that can be used in a production line and apply the measurement method on the station.

1.2 Purpose

The purpose of this thesis is to get an understanding of how to measure different parameters, related to Package Stability, that are affecting the packages of Tetra Pak. At the end of the thesis the goal is to have developed a method for conducting measurements of Package Stability.

1.3 Goals

One goal is to find out what parameters affect the packages and how they can be measured. Another goal is to define a method for conducting measurements of the above-mentioned parameters. The final goal is to present a concept for a measurement station which can be used in production.

1.4 Problem formulation

By the end of this project, the following questions were answered.

- What measurable properties of a package can be connected to Package Stability? Are there any dependencies between these?

- What methods can be used to perform the measurements?

- How can Package Stability be measured in a production line?

1.5 Motivation

We chose to work on this thesis since it felt both interesting and relevant to what we have learned in school. We have been working with measurements, PLC programming and concept creation. This characterizes a working day for an automation engineer which gave us the opportunity to practice what we have learned during our education and what we furthermore will do for a living.

1.6 Delimitations

In consultation with the supervisor at Tetra Pak it was decided to concentrate on accelerations and tip angles, which are parameters considered to be a part of Package Stability.

Because of time limits, a real station was not designed and manufactured. That said, a concept was created for a measurement station that can be used in a production line.

1.7 Resources

Tetra Pak provides computers and software programs. Access was given to the Tetra Pak site in Lund. To complete the project, it was vital to be able to work with the thesis on location. Laboratory and measurement tools were also available at the site.

For consulting and guidance, Tetra Pak provided a supervisor who was available during office hours. A supervisor was also provided by the school.

2 Technical Background

This chapter describes the technologies used throughout the work with the thesis. A linear rig located in Tetra Pak's automation laboratory was used for producing different accelerations through a servo motor. The rig with its associated components is further explained in section 2.1. The software used for programming and reading data was RS Logix5000. The PLC languages used for programming were ladder diagram and structured text and is further explained in section 2.1.3. Both languages are part of the IEC 61131 standard for programmable logic controllers [1].

When working with measuring accelerations it is of interest to try different motion profiles, such as Trapezoidal profile and S-curve profile. Those motion profiles were considered to have a great importance for the outcome of the measurements in this thesis, which is why they are to be explained. The reader of this report should have a basic knowledge of their characteristics and differences to comprehend the results explained in a later chapter.

2.1 Linear rig

The linear rig shown in Figure 1 consists mainly of three components:

- Linear unit
- Servo motor
- PLC

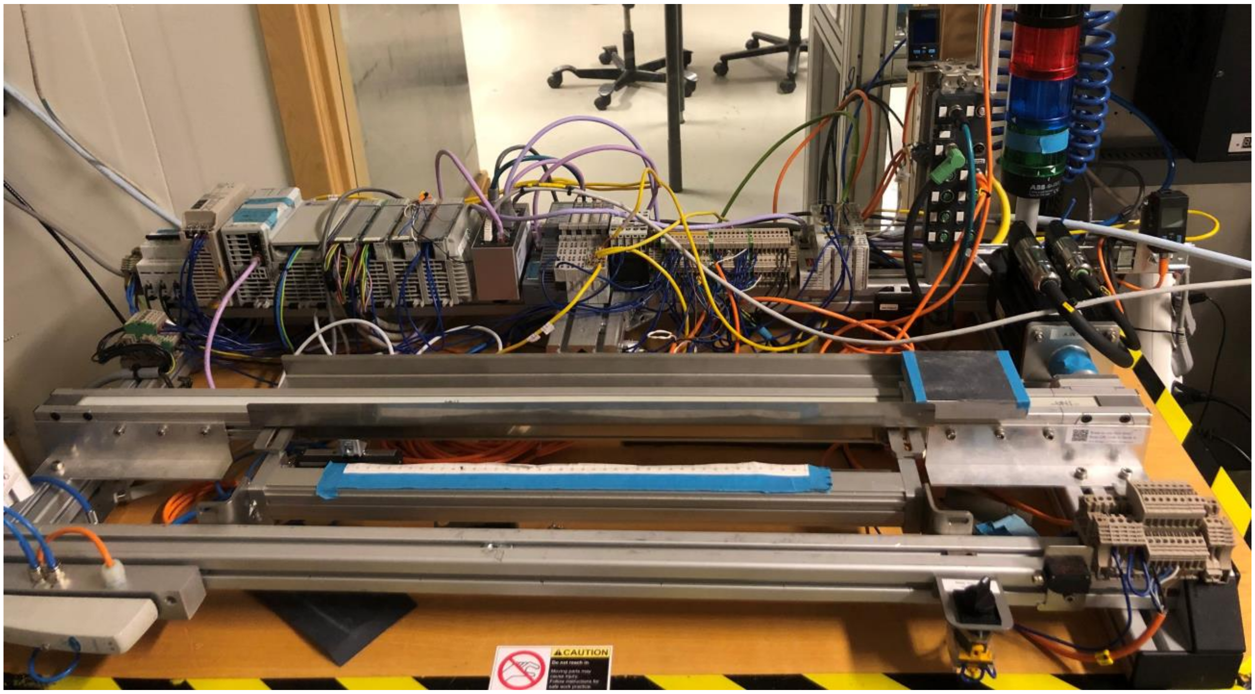

Figure 1. The Linear rig.

2.1.1 Linear Unit

The linear unit is a mechanical component that possess the ability to execute motion in a straight line by means of a belt drive, moving forward and backwards. First, a rotary motion is produced by the servo motor which the linear unit converts to a linear motion. The servo is coupled to the belt drive through a transition unit. A metal platform is mounted on the linear unit.

2.1.2 Servo motor

A servo motor is a motor that is part of a closed-loop system. The motor can provide feedback to a control unit. The desired feedback is often number of revolutions per minute, position or angle. To enable feedback the motor is coupled to a sensing unit, either a resolver or an encoder [2]. Servos are frequently used in industrial applications to move parts of machines with high precision and efficiency. The servo motor is controlled by an electrical signal from a controller. The ability to move to a certain position with this high accuracy is a feature a regular motor does not have.

2.1.3 PLC

The PLC or Programmable Logic Controller is a special computer used for control of a function or machine. PLCs are very popular within industrial automation where they control and monitor different processes. What differentiates the PLC from a normal computer is that the PLC is more optimized for industrial environments and control tasks.

For control of the linear rig servo motor, a 1769-L36ERM CompactLogix Controller, manufactured by Allen-Bradley, is utilized. Allen-Bradley is today a brand owned by Rockwell Automation. The 1769-L36ERM uses RS Logix5000 software [3].

A standard PLC system is composed of the following components [4]:

- **Input/Output modules.** The input module consists of devices like switches and sensors. The output is an entity whose function is controlled by the input signals. It could for example be a motor.
- **CPU.** The Central Processing Unit is the brain of the PLC system, processing the program that is sent to the PLC from the programming device.
- **Programming device.** The programming device is the platform where control logic is written.
- **Power supply.** The power supply provides power for all the PLC system by converting the AC wall power to DC power and regulating a safe voltage for the other PLC components.
- **Memory unit.** Input and output data are stored in the memory unit. It also stores the program containing the logic that is to be executed by the PLC.

- **Communication interface.** The communication interface enables the PLC to transmit and receive data from other remote PLCs.

PLCs work in cycles: every PLC has a scan cycle and a scan time. The scan time is the amount of time it takes the PLC to execute one scan cycle. The working principle or the scan cycle of a PLC can be described by the following three steps:

1. Read data from the input section.
2. Calculate output signals based on the program downloaded from the programming device.
3. Update the output section.

There are five standardized PLC programming languages according to the IEC 61131 standard:

- Ladder diagram
- Instruction list
- Structured text
- Function block diagram
- Sequential function chart

Ladder diagram and Structured text have been used during the work with this thesis.

2.1.3.1 Ladder diagram

Ladder diagram is a graphical PLC programming language. It is the most common language used to program PLCs due to its simplicity and the fact that it looks very similar to electrical relay circuits. The term “ladder” is used because the ladder diagram programs resemble ladders. The code has two vertical rails that corresponds to electrical plus and electrical minus. A series of horizontal rungs are placed between the vertical rails. In the rungs, the user places the ladder logic symbols to create the desired logic. Each rung begins with one or more inputs and ends with at least one output. One rung can be defined as one operation in a control process.

2.1.3.2 Structured text

Structured text is a text-based PLC language looking very similar to high level programming languages, such as Pascal and C. Just like the high-level languages, structured text consists of a series of instructions separated by semicolons. Loops, variables, operators and conditions are functions also utilized by Structured Text. Just like the ladder diagram, structured text is one of the more commonly used languages for PLC programming.

2.2 RS Logix5000

RS Logix5000 is a software tool offering programming, configuring, and maintaining of Allen-Bradley controllers with related devices. RS Logix5000 is part of the Studio 5000 Automation Engineering & Design Environment developed by Rockwell Automation [5].

Two of many instructions that RS Logix5000 offers for motion control are the Motion Axis Move (MAM) instruction and the Motion Axis Time Cam (MATC) instruction, both available in Ladder diagram. They are both used to produce different type of moves [6].

For this thesis, the MAM instruction was used for creating the Trapezoidal profile. The instruction includes parameters like acceleration and velocity that could be configured.

The MATC instruction was used instead of MAM for creating the S-curve profile. It is possible to use s-curve with MAM although the options for the curve is limited. Using the MATC-instruction, the user can adjust the S-curve as desired. This was useful since a longer constant acceleration was needed to gather a readable value.

2.3 Motion profiles

Motion profile is a method frequently used to depict how a servo motor should behave during a movement, principally in terms of position, velocity and acceleration. For instance, with a motion profile, an engineer working with motion control can describe graphically and/or mathematically how the motion changes during a specific time interval by creating a profile. The controller reads the profile and controls the motor.

In the industry, two common types of motion profiles used are the Trapezoidal and the S-curve profiles, named by the shape they render when plotting velocity profile as a function of time. What sets these two profiles apart is the acceleration and jerk behavior. Jerk is the change of rate of acceleration per time unit, that is the derivate of acceleration.

The trapezoidal velocity profile has three phases of motion. This profile gives a constant velocity in the second phase of motion, resulting in zero acceleration. Acceleration is constant in the first and in the third phase of motion. The transition of acceleration between the phases occur instantly. It leads to oscillations, decreased accuracy, and increased settling time [7]. Figure 2 describes a trapezoidal profile and how the acceleration is changed.

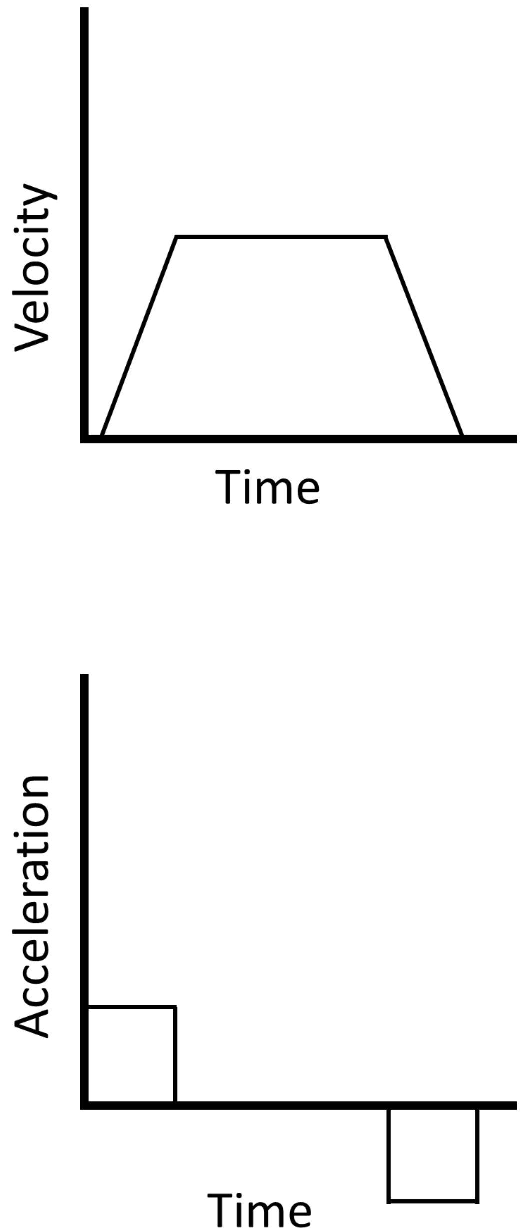

Figure 2. Trapezoidal velocity profile with associated acceleration profile.

The S-curve velocity profile is used more often than the Trapezoidal profile to reduce the jerk by smoothing the beginning and the end of the acceleration phase. Unlike the trapezoidal profile, S-curve profiles usually consist of seven phases of motion. This creates a smoother movement than the trapezoidal profile, but it results in a slower motion. Figure 3 shows a S-curve velocity profile and the associated acceleration.

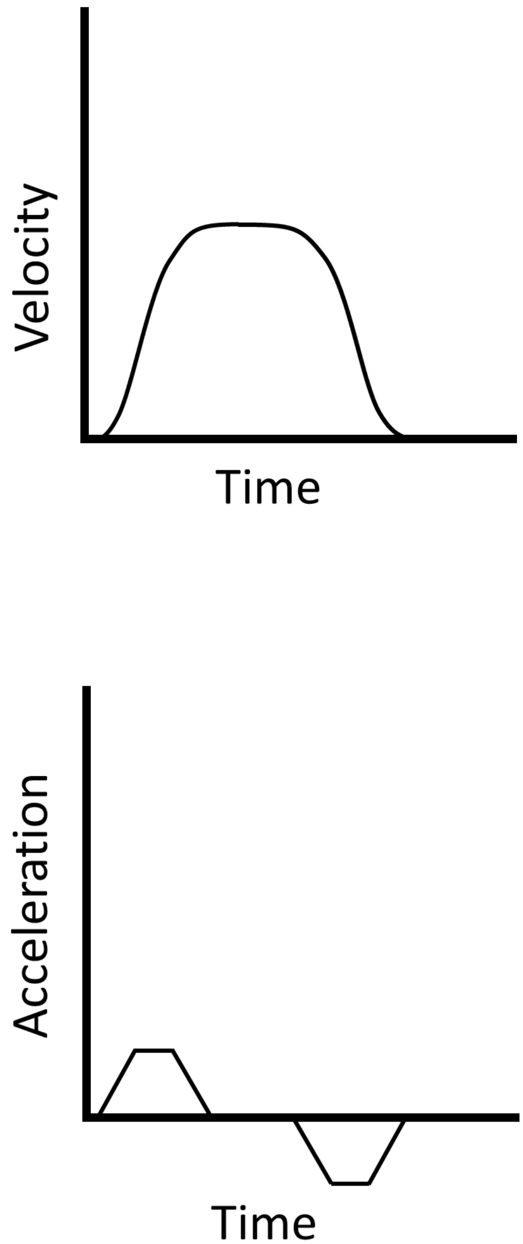

Figure 3. S-curve velocity profile with associated acceleration profile.

3 Physical Background

This chapter explains the connection between the tip angle of a package and its maximum acceleration: the acceleration a package can handle before it tips over. The upcoming sections describe and prove the formulas that the thesis is based on.

3.1 Tip angle

In the picture below a package stands at the critical tip angle α degrees: the angle where the package is about to fall. The package has an arbitrary center of gravity: x.

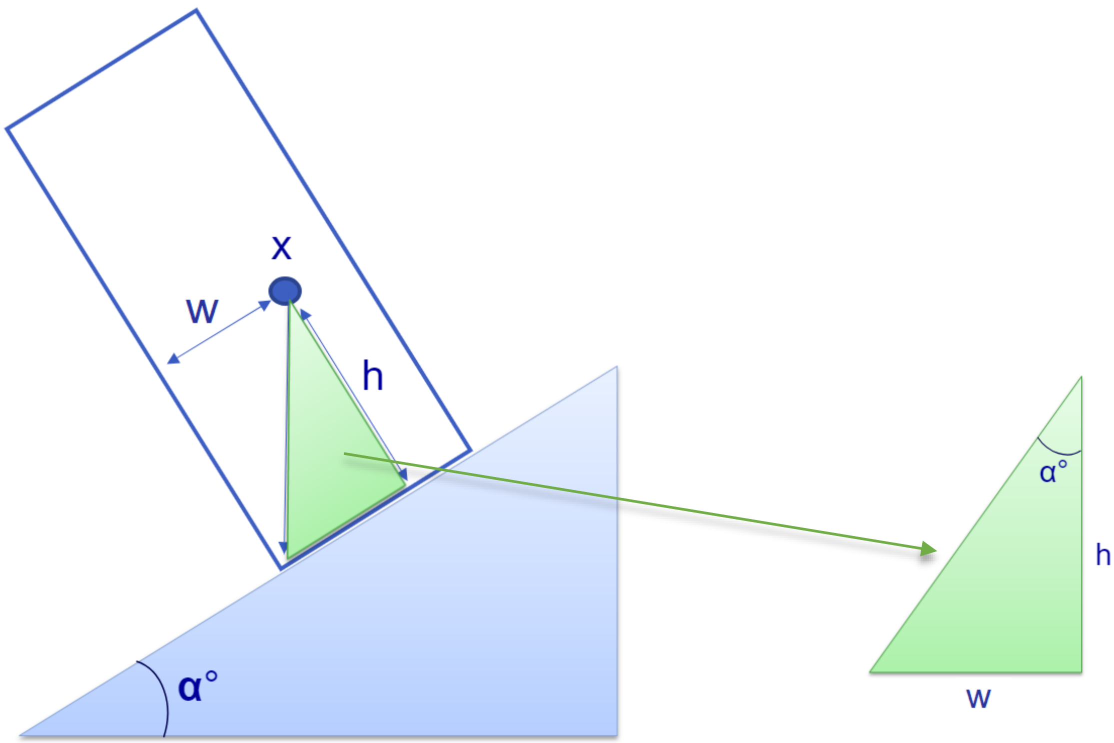

Figure 4. Package on an inclined plane.

From the right triangle the following theorem can be derived:

$$\tan \alpha = \frac{w}{h}$$

Here w is the width between the side which the package will fall onto and the center of gravity, and h is the height from the bottom of the package to the center of gravity.

3.2 Max acceleration

The same package from section 3.1 stands on a horizontal surface, shown in figure 5. This section investigates how fast the surface can accelerate without the package tipping, given that the surface and the package have such high friction coefficient that the package will not slip.

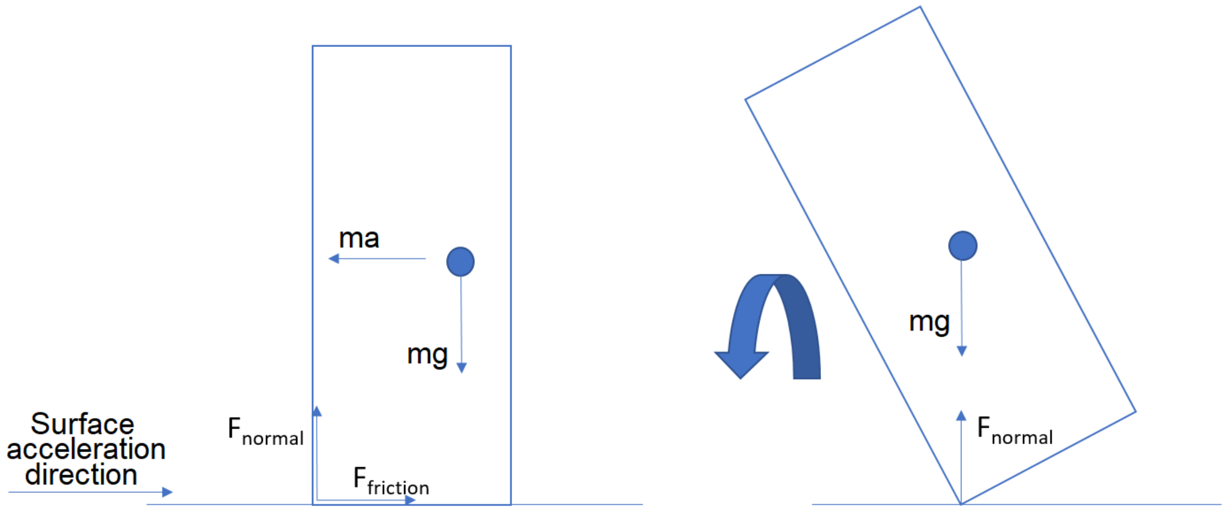

Figure 5. Package on an accelerating surface.

$$\sum F_x = 0 \Rightarrow m \cdot a = F_{friction}$$

$$\sum F_y = 0 \Rightarrow m \cdot g = F_{normal}$$

While the acceleration is too low to make the package move, the total torque will be equal to zero. There are two main torques acting on the package, τ_1 and τ_2, where τ_1 is the torque that is trying to tip the package and τ_2 counteracts this motion. The package will tip when $\tau_1 > \tau_2$.

$$\tau_1 = h \cdot F_{friction} = m \cdot a \cdot h$$

$$\tau_2 = w \cdot F_{normal} = m \cdot g \cdot w$$

$$\tau_1 - \tau_2 = 0 \Rightarrow \tau_1 = \tau_2 \Rightarrow m \cdot a \cdot h = m \cdot g \cdot w$$

$$a_{max} = g \cdot \frac{w}{h}$$

The formula shows the highest acceleration where the total torque is still equal to zero. In other words, the max acceleration the package endures without tipping.

3.3 Correlation between tip angle and max acceleration

From the last section these two functions were derived:

$$\tan\alpha = \frac{w}{h}$$

$$a_{max} = g \cdot \frac{w}{h}$$

Since the formulas both describe the same package it is possible to substitute the variables w and h between the two. When substituting $\frac{w}{h}$ from the second formula with $\tan\alpha$ we get the following function:

$$a_{max} = g \cdot \tan\alpha$$

With this new derived formula there is a direct connection between the maximum acceleration a package endures without tipping and its tip angle. Important to highlight is that this formula can be applied to all types of packages as long as they have a base to stand on.

3.4 Friction force

The calculations above are all based on that the package will tip and not slip. To make sure this is also the case in practice, the surface needs to have a sufficiently high friction coefficient.
The surface tested here is a 220-grit sandpaper.

According to Newton's second law, the force F is the product of an objects mass and its acceleration:

$$F = m \cdot a.$$

The formula for friction force:

$$F_{Friction} = \mu \cdot N$$

Where N is the normal force and μ is the friction coefficient.

With consideration to friction, the maximum acceleration the package can handle before it starts sliding is:

$$a_{max} = \frac{F_{max}}{m} = \frac{m \cdot g \cdot \mu}{m} = g \cdot \mu$$

From this, μ can be solved as:

$$\mu = \frac{F}{m \cdot g}$$

$$\mu_{lowest\ required} = \frac{a_{max}}{g}$$

All three packages will have different friction forces. This is due to the different base sizes and various weights. Therefore, all three packages must be calculated.

The TBA 200SL package manages a max acceleration of about 2.0 m/s² according to the theoretical calculations before they tip. It exerts 2 newtons of force. If we do not want the package to slide on the surface it is required to have a friction coefficient greater than: $\frac{a_{max}}{g} = \frac{2.0}{9.82} = 0.21$.
The real friction coefficient is: $\mu = \frac{1.4}{2.0} = 0.7$, where 1.4 is the friction force on the sandpaper and 2.0 is the normal force of the package. Since 0.7 > 0.21 this result means that the TBA 200SL package will not slide.

Table 1 presents the results from the measurements and calculations of the lowest friction coefficient required for the packages. It proves that when accelerating on the 220-grit sandpaper the packages will not slide.

Table 1. Calculations of friction coefficients.

	TBA 1000E	**TT 1000B**	**TBA 200SL**
Normal force (N)	10.4	10.2	2.0
Friction force on sandpaper (N)	5.8	5.2	1.4
Highest theoretical acceleration (m/s²)	2.8	2.5	2.0
Friction coefficient, μ	0.56	0.51	0.7
Lowest μ required	0.29	0.25	0.21

4 Methods

This chapter explains how the thesis was conducted. The procedure can be divided into three main parts: preliminary studies (where all the theory is gathered), measurements (where the theory is tested), and design of a concept (where the theory is implemented on a machine).

4.1 Theory

As mentioned before, the thesis concerns Package Stability in form of accelerations and tip angles. There was a need for a physical background to be able to predict how a package would behave under those conditions. It was possible to find a connection between different parameters regarding Package Stability with the help of some calculations based on elemental formulas, such as Newton's second law.

4.2 Measurements

When the mathematical connection was derived it was time to test it in practice. For this, a linear rig and an inclined plane was used. The rig was provided by Tetra Pak while the inclined plane was constructed. The plane was built using an aluminum piece with a threaded hole on one side. Through this hole a long screw was inserted with a wingnut head. Turning the wingnut compels the plane to go up and down making the plane adjustable. The inclined plane can be seen in figure 8.

Three types of packages were to be tested: TBA 1000E, TBA 200SL and TT 1000B. For each of these types 20 packages were used and every package contained water. After observing the machines and having a dialog with engineers in Tetra Pak it became clear that the package mostly is exposed to external forces in two directions. Therefore, the measurement was only conducted on these two opposite sides. The sides are in this report named A and B.

Figure 6. TBA 200SL, TT 1000B and TBA 1000E, side A.

Figure 7. TBA 200SL, TT 1000B and TBA 1000E, side B.

4.2.1 Measurements of friction

The calculations in this report are based on the fact that the packages will not slide on the surface when accelerating. The measurements of the friction coefficients in section 3.4 were obtained using a force gauge and a piece of string. The string was attached between the force gauge and a package. The force gauge was then secured to the moving platform on the linear rig and the platform was then programmed to travel at a constant speed. From this the friction force was obtained which was needed to calculate the friction coefficient between the package and the sandpaper.

4.2.2 Measurement of tip angle

The sandpaper was attached to the inclined plane and then a package was placed on top of the sandpaper. The plane was then raised slowly by turning the wing nut until the package tipped. The angle could then be collected using a digital protractor. This procedure was carried out for all packages. The theoretical maximal acceleration could then be calculated for all packages using the formula derived in chapter 3.

Figure 8. Measurement of tip angle.

4.2.3 Measurement of acceleration

When the theoretical max acceleration was obtained it was time to prove the formula using the linear rig. The PLC connected to the rig was programmed using ladder diagram and structured text. The servo that operates the rig was coded to move the platform forward with a variable acceleration. The movement of the platform was done using two different types of profiles, Trapezoidal and S-curve, to see if it would affect the result. The software used for programming was RS logix5000.

A package was placed upon the platform and the code was then executed. The acceleration was gradually increased after each execution until the package tipped. The acceleration value was gathered from the servo feedback using RS logix5000 trend function. Trending is one of Logix5000's features to track values over time, both analog and digital values. The gathered values were approximated to the nearest five hundredths m/s^2.

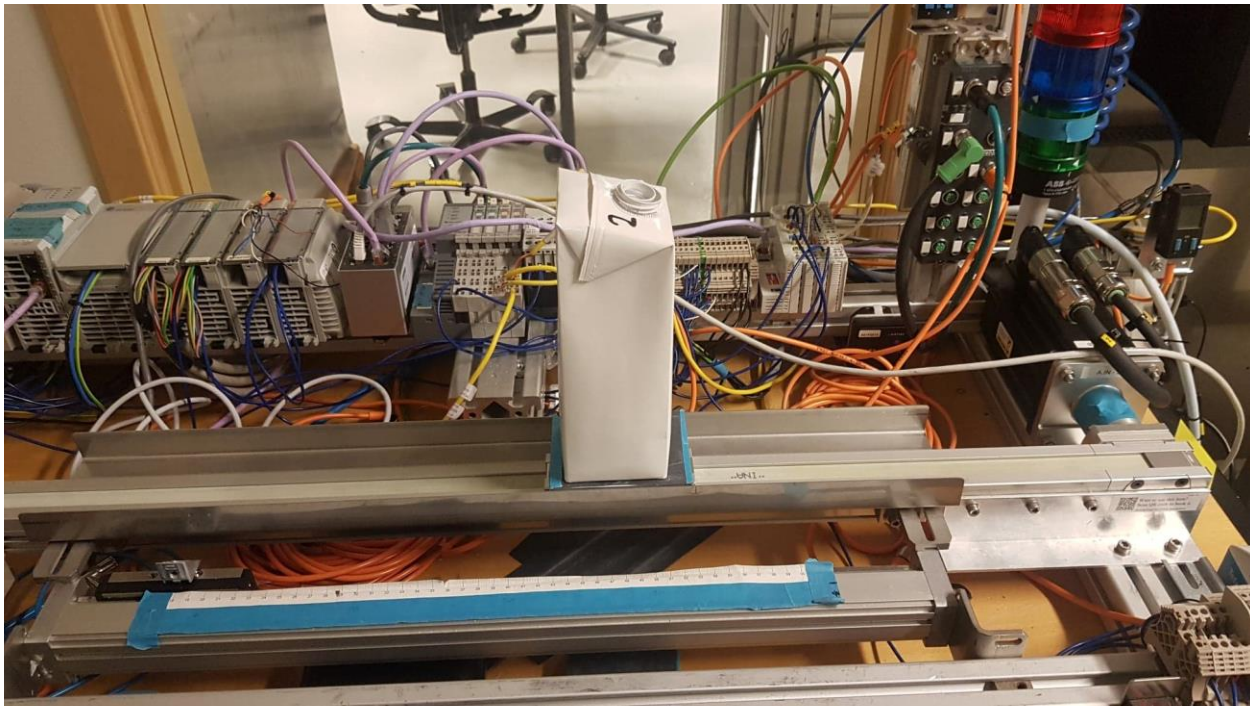

Figure 9. Measurement of acceleration.

4.2.4 Analysis of measurement method

To examine measurements conducted on the linear rig measurement data was plotted on a graph. A straight line was then created using a linear regression of the measurement values. This straight line representing the measurement values was compared with the theoretical curve that also was plotted.

4.3 Development of a concept

Developing a concept describing a Package Stability measurement station started with the authors own ideas on how measurements could be conducted on a production line. These ideas were concentrated on the process of detecting a fallen package.

Meetings were later held with a technology specialist working with design and construction at Tetra Pak. The meetings included discussions of the authors' own ideas of concepts and the mechanical aspect. The goal was to create a final concept.

The main idea was to create a concept for measurement of package tip angles on a production line without stopping the flow. The following questions were considered during the concept development:

- How can the measurements be conducted with minimal impact on the flow of packages?
- How can the inclination be adjusted?
- How can a fallen package be detected?
- How is the package tip angle gathered?

4.4 Source Criticism

[1], [2] and [4] are considered to be reliable since they are published books and can be found through LUBcat, the Library catalogue at Lund University.

[3], [5] and [6] can all be found at the official website of Rockwell Automation and are therefore considered to be reliable sources.

[7] is considered to be a reliable source since the article has an author with associated contact information.

5 Results

This chapter presents the results from the measurements of tip angles and max accelerations conducted with the incline plane and the linear rig. In total, the measurements resulted in 240 measurement values.

The blue trendline in the following graphs is the theoretical correlation between the tip angle and max acceleration of the packages. The orange dots show the real values collected from the measurements conducted on the linear rig. The orange trendline is the linear regression of the values. Note that the y-axis always starts at 1.

For every motion profile, two measurements for every package is shown: A and B. A and B are two different sides of the packages explained in section 4.2.

The final concepts of measurement stations are also presented and described in this chapter.

5.1 Trapezoidal results

5.1.1 TBA 200SL

TBA 200SL performed well on both sides. The measurements from the linear rig came close to the theoretical line with almost every value placed under their corresponding theoretical values. The linear regression shows a linear error. The average absolute error is 0,17 m/s^2 for side A and 0,09 m/s^2 for side B.

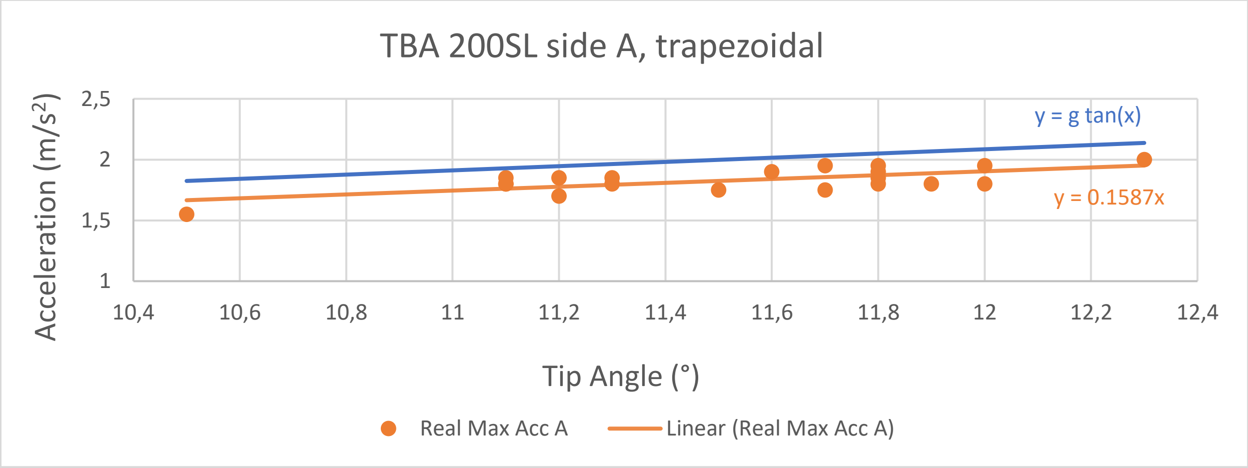

Figure 10. TBA 200SL side A, Trapezoidal.

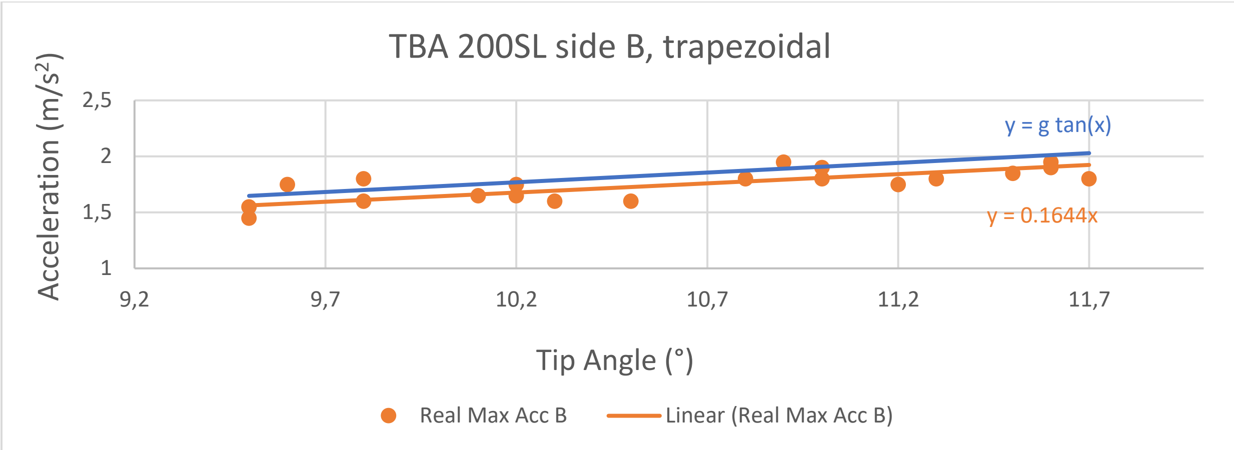

Figure 11. TBA 200SL side B, Trapezoidal.

5.1.2 TT 1000B

Just like TBA 200SL, the measurements of TT 1000B resulted in a linear error which also fell below the theoretical trendline on both side A and B. The average absolute error for side A is 0,28 m/s^2 and for side B it is 0,29 m/s^2.

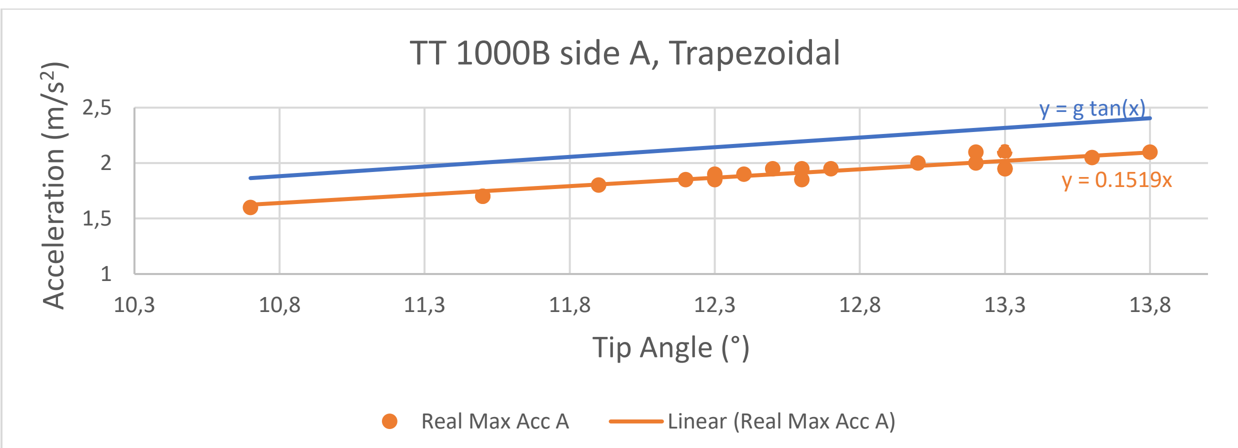

Figure 12. TT 1000B side A, Trapezoidal.

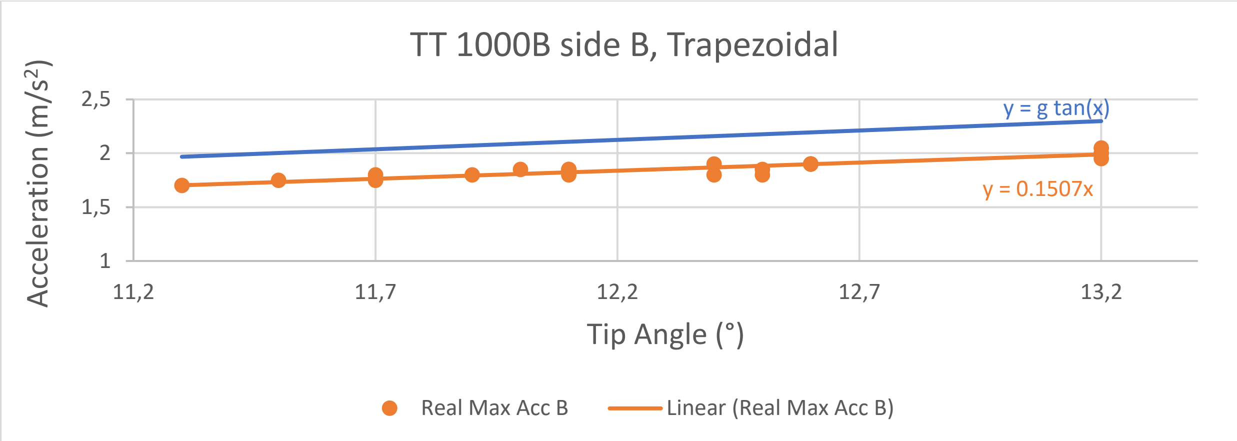

Figure 13. TT 1000B side B, Trapezoidal.

5.1.3 TBA 1000E

TBA 1000E performed very well using the Trapezoidal profile, on both side A and side B. The orange trendline fell just below the blue trendline, showing that all values gathered from the linear rig came very close to their corresponding theoretical values. The average absolute error is 0,03 m/s^2 for side A and 0,05 m/s^2 for side B.

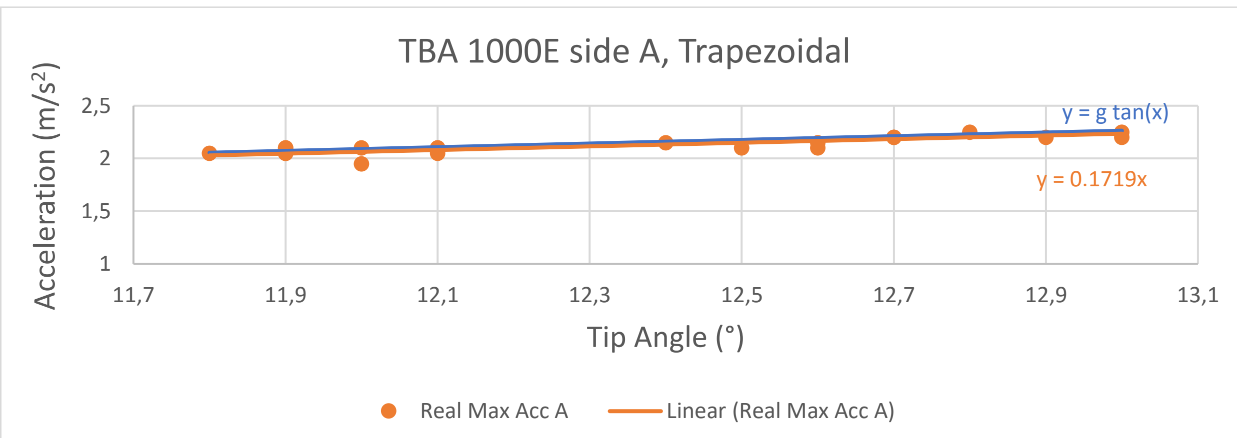

Figure 14. TBA 1000E side A, Trapezoidal.

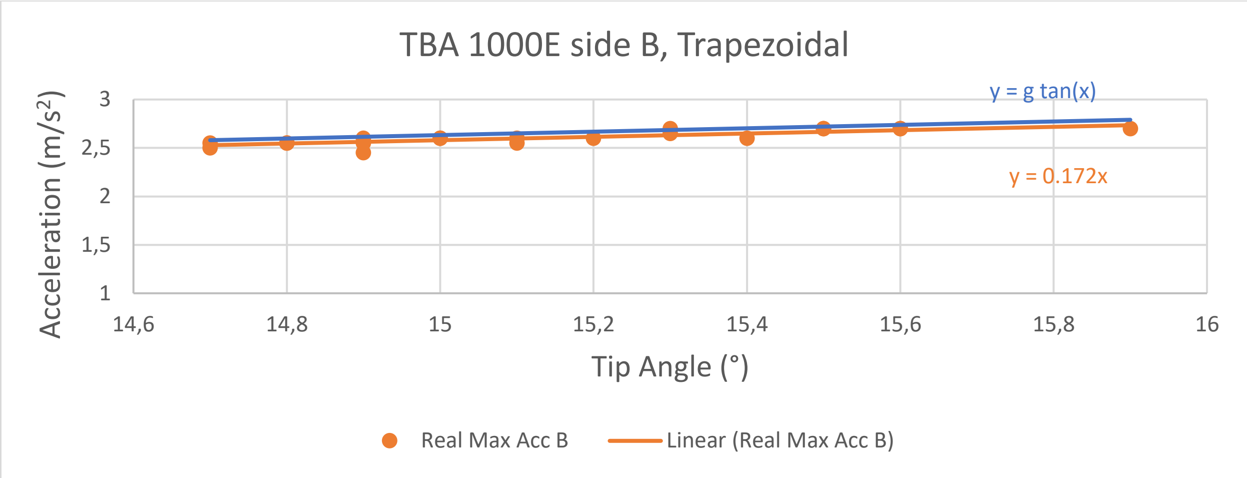

Figure 15. TBA 1000E side B, Trapezoidal.

5.2 S-curve results

5.2.1 TBA 200SL

Unlike the measurements conducted with the Trapezoidal profile, using the S-curve profile resulted in the orange trendline falling above the theoretical line. The average absolute error is 0,1 m/s^2 for both side A and B.

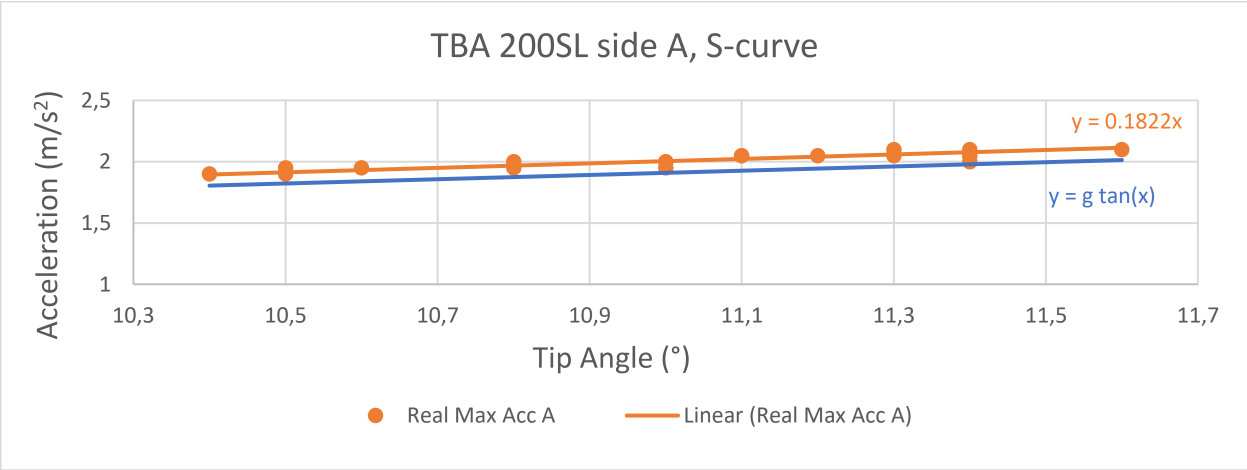

Figure 16. TBA 200SL side A, S-curve.

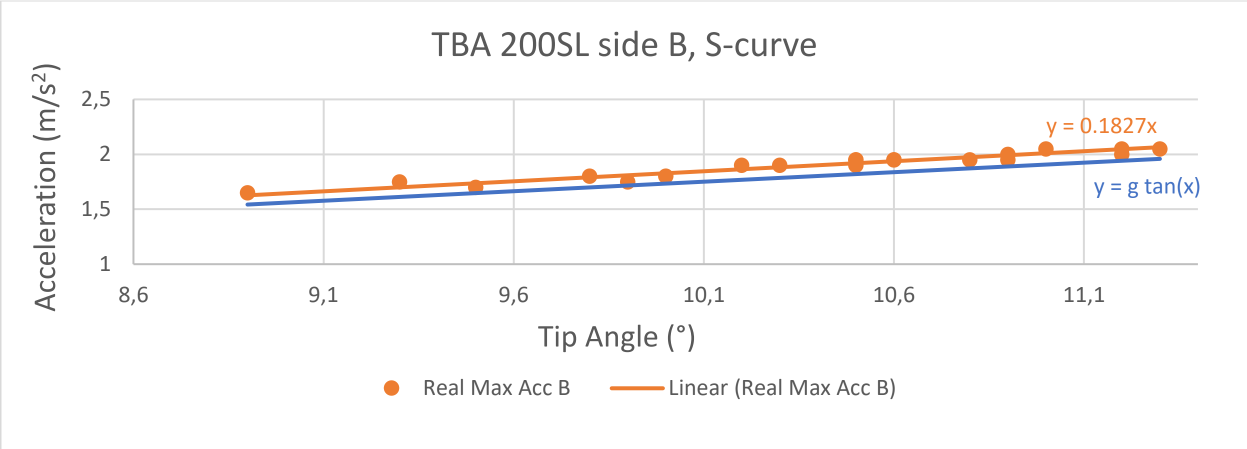

Figure 17. TBA 200SL side B, S-curve.

5.2.2 TT 1000B

Measurements on TT 1000B gave a good result. The orange trendline is located just above the theoretical line. The error is small on both sides. For side A the average absolute error is 0,03 m/s^2 and for side B 0,01 m/s^2.

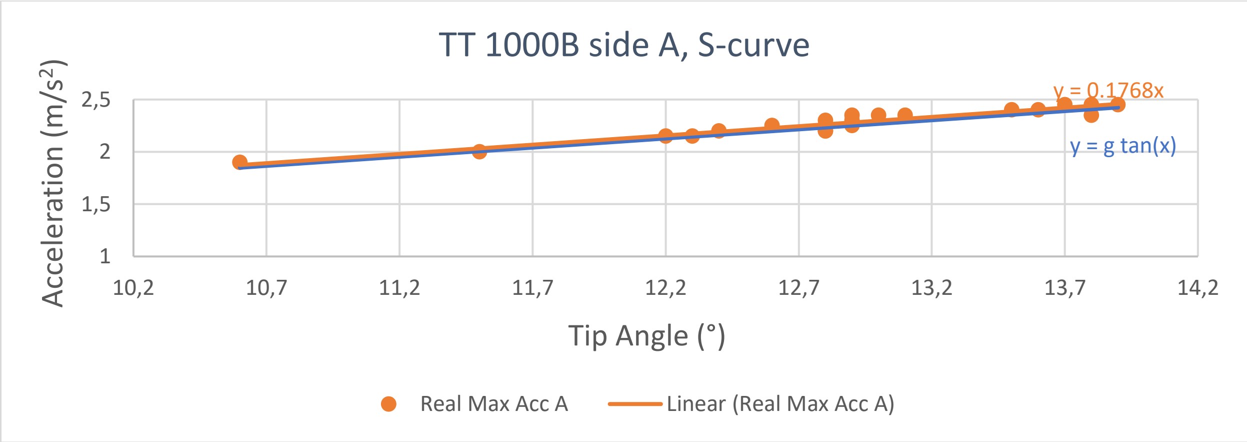

Figure 18. TT 1000B side A, S-curve.

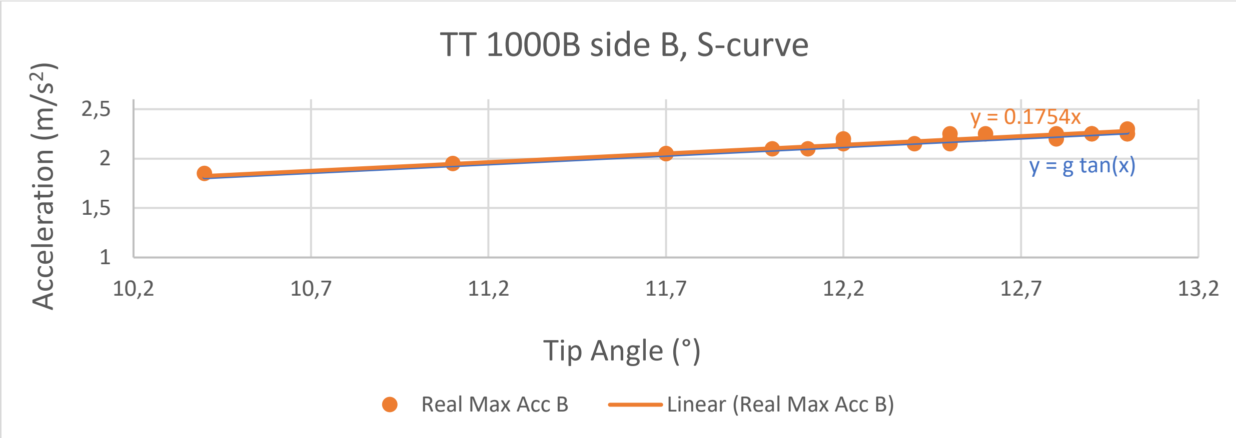

Figure 19. TT 1000B side B, S-curve.

5.2.3 TBA 1000E

Like the other two package types, using the S-curve profile resulted in an orange trendline located above the theoretical line. Using the S-curve profile, TBA 1000E performed worse than with the Trapezoidal profile. The average absolute error is 0,17 m/s^2 for side A and 0,26 m/s^2 for side B.

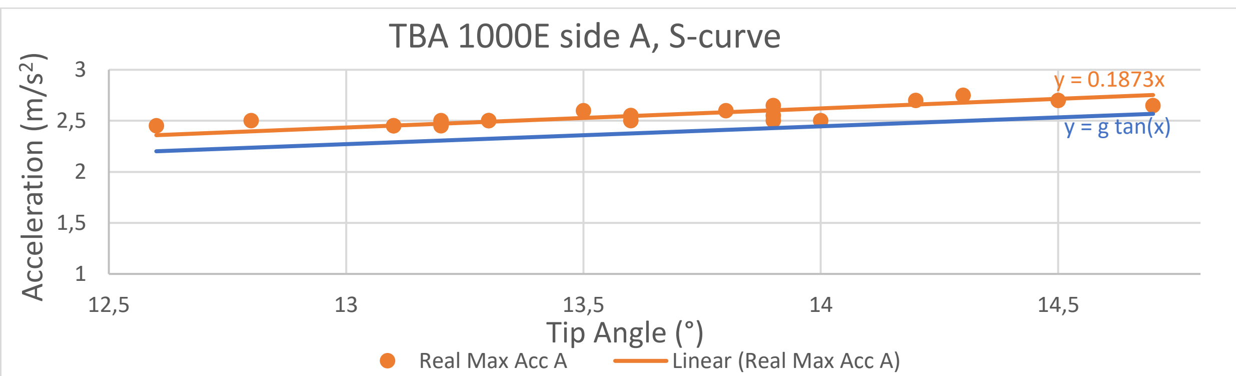

Figure 20. TBA 1000E side A, S-curve.

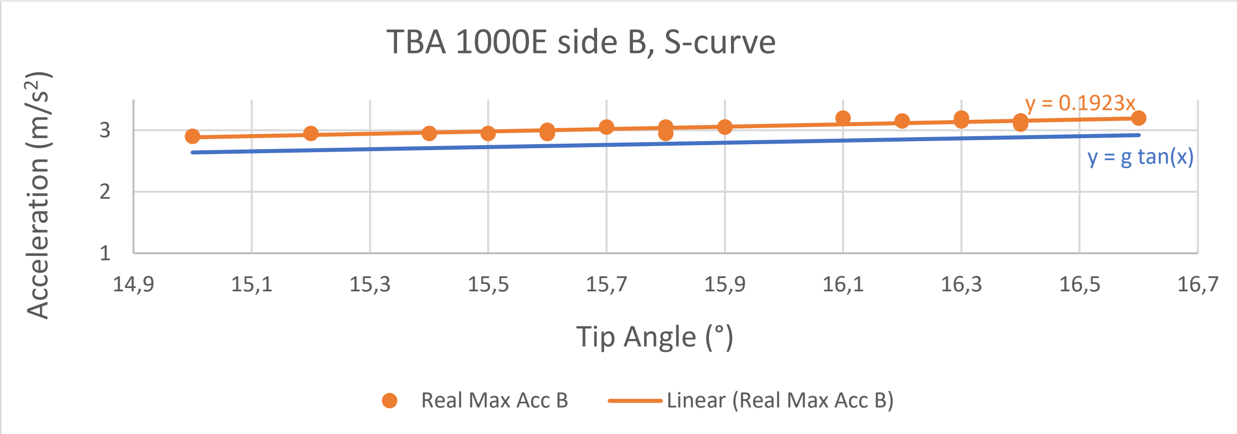

Figure 21. TBA 1000E side B, S-curve.

5.3 Final Concepts

Two final concepts were devised that applies the measurements on a real application. These two concepts are stations that measure the tip angle of the packages.

5.3.1 Concept A

Concept A is made up of two conveyors that run parallel to the main conveyor. With the help of moving rails, the packages can be transferred onto one of the two parallel conveyors.

The two parallel conveyors are constructed the same way. They are hinged on two bearings that allow the whole section to pivot. They can both be adjusted to a specific angle with the help of a servo. The servo is coupled to a ball screw that makes the conveyor tilt to a specific angle when the servo turns. The position of the servo can be converted to the angle of the conveyor.

A belt brake stops the package flow while the moving rails turns to one of the sides. The belt brake can then allow two packages to go on the parallel conveyor that at this point has an inclination of zero degrees. The rails can now return to their normal position and let the package flow continue as usual. At the same time, the parallel conveyor starts tilting relatively slowly until both of the packages have fallen. Sensors can detect that a package has fallen, and the angle can then be collected from the position of the servo.

Since there are two testing conveyors it is possible to test the tip angle in two directions. This also helps increase the capacity of how many packages that are tested per time unit.

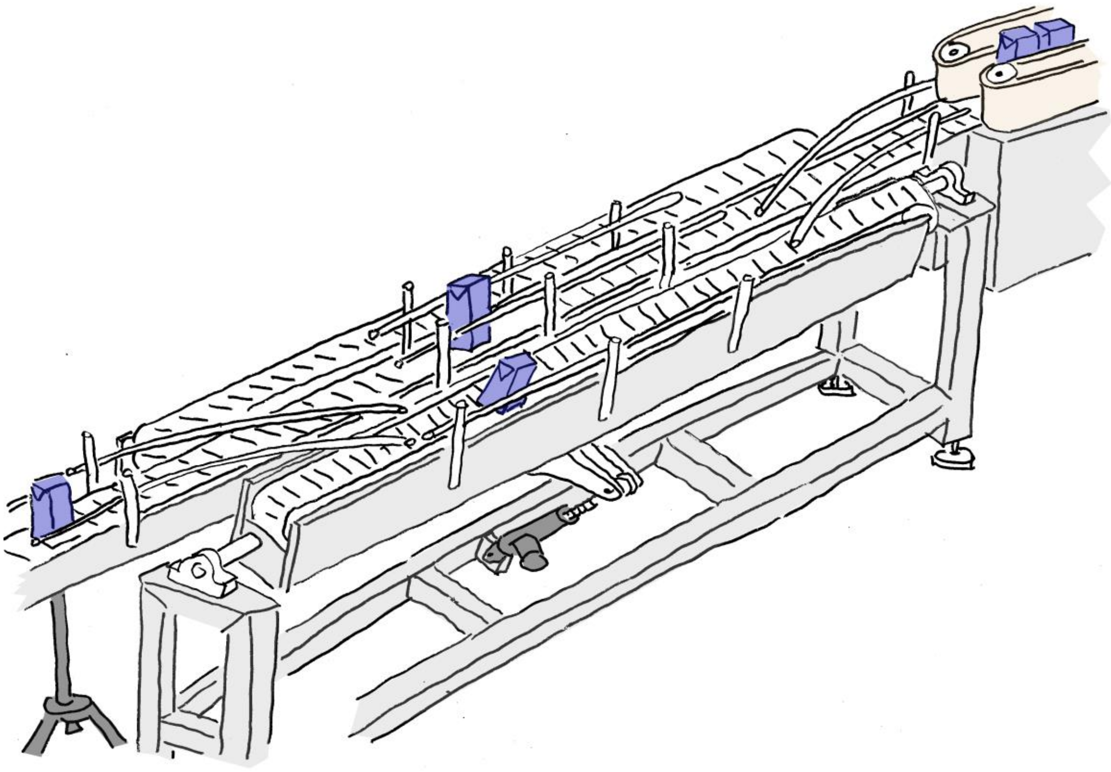

Figure 22. Concept A.

5.2.2 Concept B

Next to the main conveyor there is a belt that revolves around three rolls keeping the same pace as the main conveyor. In the middle of the belt there is a cradle that can tilt. The cradle has four wheels, two above and two below the belt. A servo makes the cradle pivot and due to the four wheels the belt is forced to follow the angle of the cradle.

The servo in this concept is also coupled to a ball screw, which means that the angle of the cradle can be calculated from the position of the servo.

A curved rail guides the package from the main conveyor onto the belt. While on the belt the packages stand on an angle that is getting gradually steeper until it reaches the position of the cradle. That is where the steepest angle is which is the set angle. Here it is possible to count the numbers of packages that has fallen. From there the belt starts leveling out until it reaches the roll where the angle is zero degrees again. Another curved rail guides the packages back onto the main conveyor. The measurements are completed without stopping the flow and every package can be tested for a specific angle.

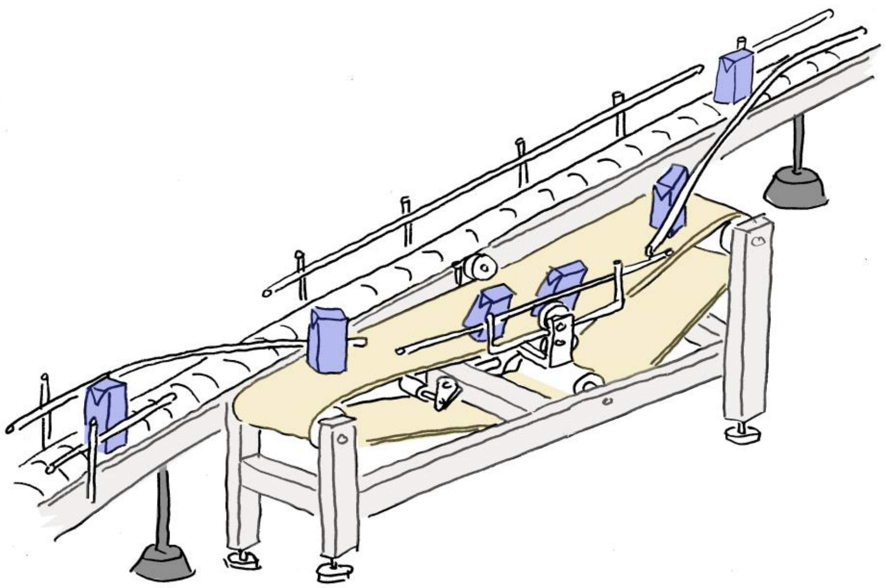

Figure 23. Concept B.

5.2.3 Detection of fallen packages

To be able to detect if a package has fallen, two concepts for detection were designed. One for A and one for B.

Concept A uses four photoelectric sensors and each sensor is composed of two units, transmitter and receiver. One sensor is used for each of the four packages on the measurement station. Transmitter and receiver are placed on each side of the package having contact with each other. Broken contact indicates that the package has fallen.

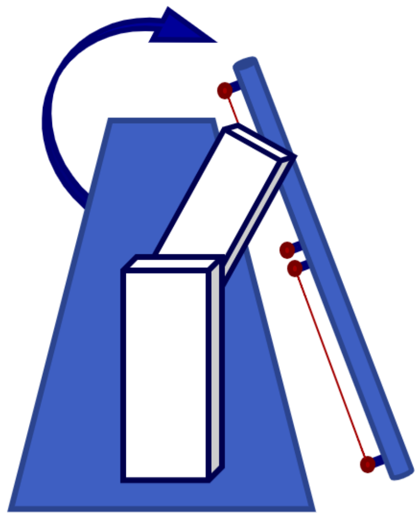

Figure 24. Detection of fallen package, concept A.

Concept B uses the same principle as concept A but is only utilizing one photoelectric sensor where transmitter and receiver are placed vertically.

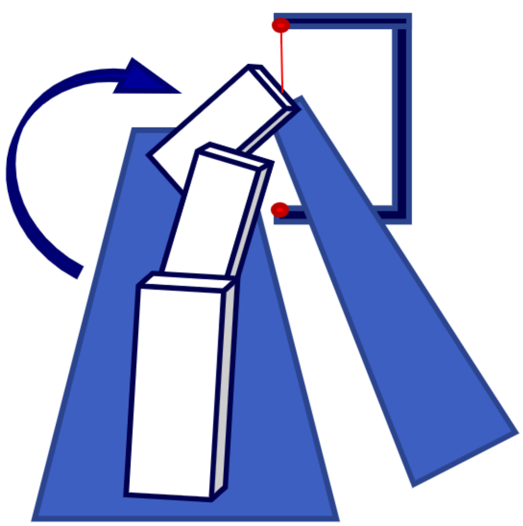

Figure 25. Detection of fallen package, concept B.

6 Analysis and Discussion

For regression of the measurement values, linear regression was used. But the theoretical formula is not linear which is shown by figure 26. However, within those intervals which have been examined the theoretical curve can be approximated to a straight line. For that reason, linear regression was used. Another matter that can be observed in the figure is that the curve goes to infinity when approaching 90 degrees. This is logical since a package that would fall first at an inclination of 90 degrees would impossibly tip over no matter how big accelerations it would be exposed to.

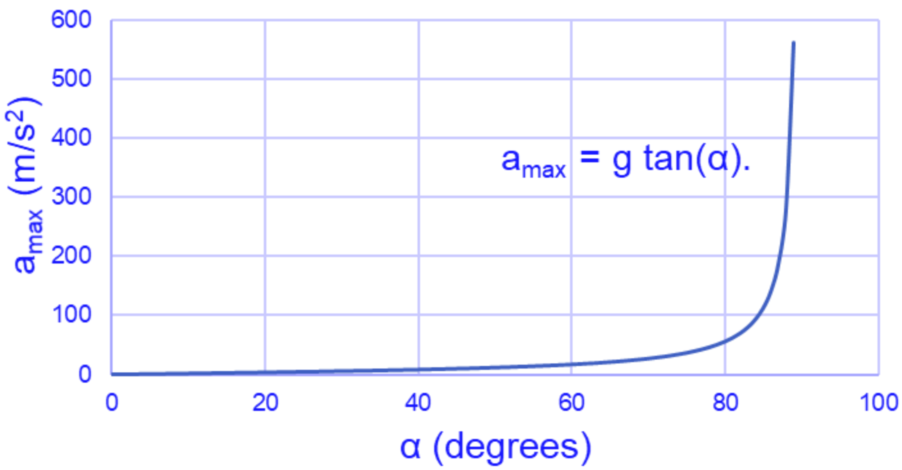

Figure 26. Theoretical formula.

Measurement of accelerations on the linear rig gave good results when being compared to the theoretical values. The theoretical formula that was derived in chapter 3 seems to be correct due to the fact that the two curves ended up close to each other during all measurements. TBA 200SL side A performed better using the S-curve profile whereas Side B did slightly better when the Trapezoidal profile was used. TT 1000B did better on both sides when the S-curve profile was used compared to the use of the Trapezoidal profile. TBA1000E however performed worse on both side A and B when the S-curve profile was utilized. Because of these differences, it cannot be decided which motion profile will give the most accurate answer.

The big difference that could be noticed when comparing the two motion profiles was the placement of the regression lines. When the S-curve profile was used the measured values could be found above the theoretical curve, this contrary to the Trapezoidal profile that placed the values underneath the theoretical curve. All three package types had this in common. The reason is considered to be the acceleration whose transition while using the Trapezoidal profile occurs instantly. When the S-curve profile is used, much smoother transitions occur which may be seen in figure 3. During the instant transitions, the acceleration goes from a constant value directly to zero and it is the same the other way around. The package on the platform is affected by these momentary jerks. A bigger swash is produced inside the package and when the swash hits the back of the package another force is affecting the package torque backwards making it fall earlier. But the S-curve profile will not contribute to the same amount of swash because of the smoother movement.

During the measurements, the feedback from the servo was very noisy which is shown by figure 27. The acceleration was unreadable.

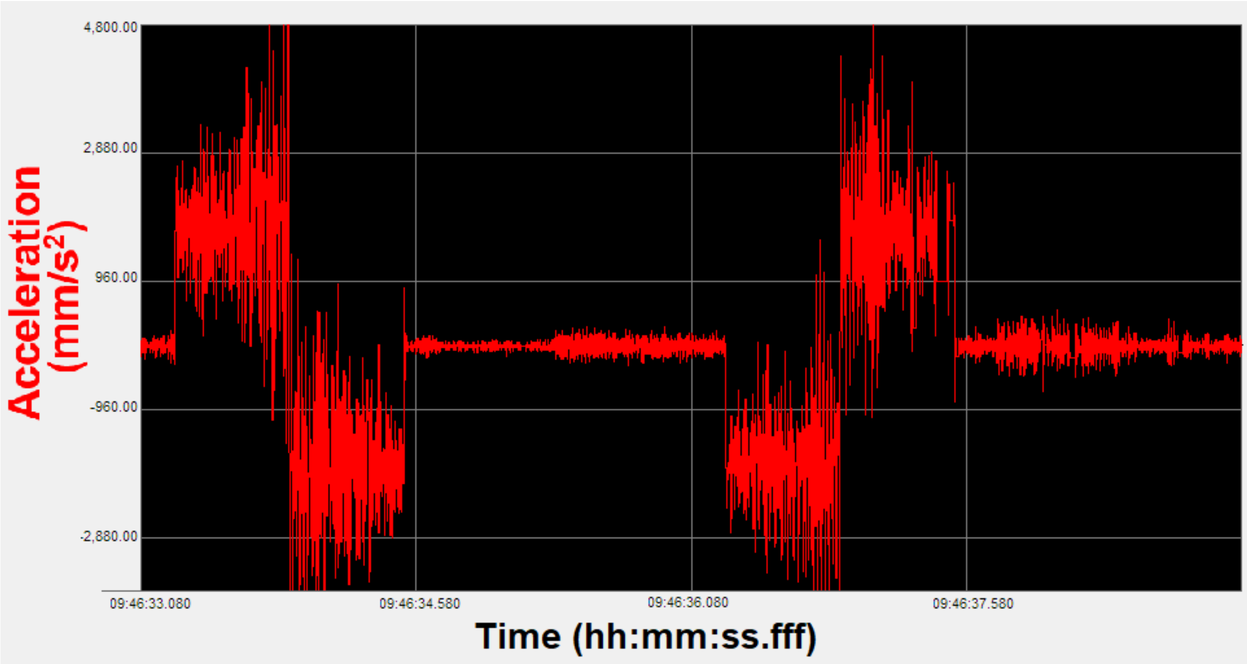

Figure 27. Untuned signal from servo.

This problem was resolved by writing code in structured text which resulted in a moving average. With the moving average the acceleration became easily readable in the trend which is shown by figure 28. Despite this measure there still existed an uncertainty in the measurements since the moving average always changed.

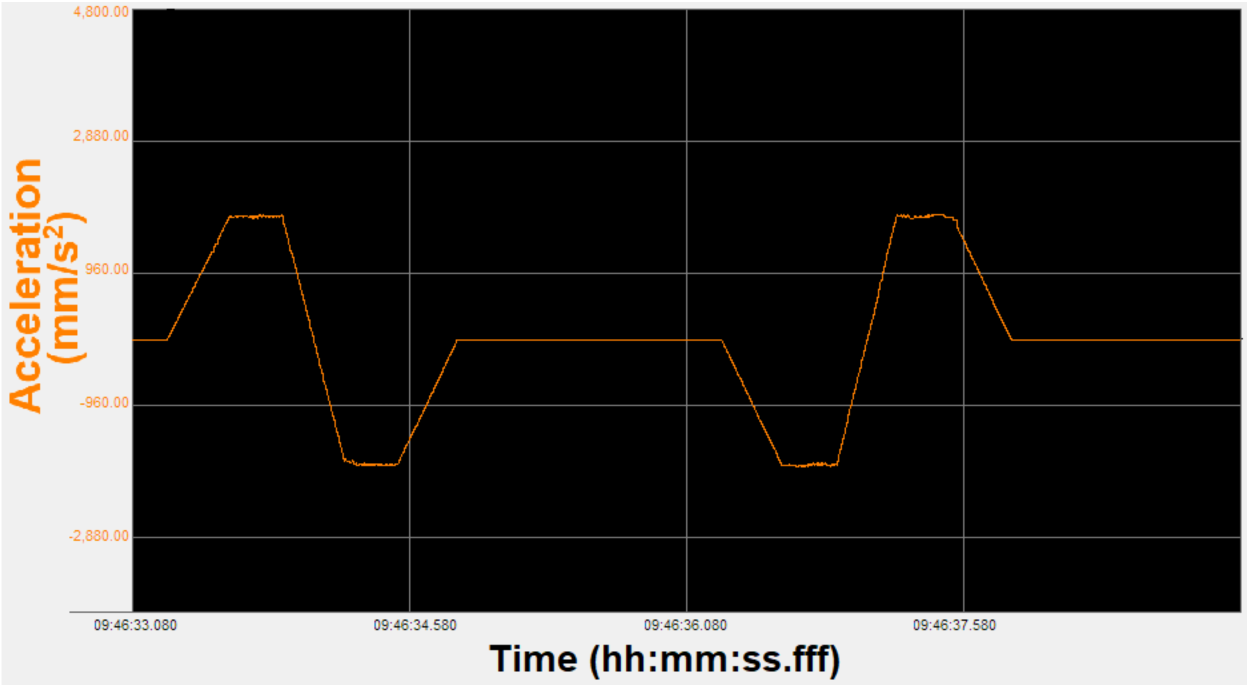

Figure 28. Tuned signal from servo

Because of that, several measurements were conducted on the same acceleration to ensure that the measured values were correct. This problem with the servo feedback is also considered to be one of the measurements error sources, but since many measurements were conducted on the same acceleration the uncertainty is considered to be on a level of five hundredths m/s^2.

Since the measurements of the accelerations are approximated, a more quantitative method with measurements on more packages would be needed to draw a more justified conclusion. But it is still considered to be enough for our application since a total of 240 measurements were conducted evenly distributed on three different types of packages.

Air resistance is considered to be a factor that the theoretical formula does not consider. When the package accelerates in a certain direction the air resistance will grow relative to the velocity of the package and counteract the packages movement in opposite direction. This results in the package falling earlier than it should have in theory, thus it falls at a lower acceleration. If air resistance were considered in the theoretical formula the theoretical curve would have moved down a bit. This leads to the Trapezoidal curve getting closer to the theoretical curve unlike the S-curve that ends up further away. Since measurement of air resistance was not included in this thesis it cannot be decided exactly how much impact the air resistance would have on the result. The packages were however exposed to velocities as high as a level of 1,5 m/s which is considered to have a minimal impact on the packages' tip angles.

There is a clear connection between the max acceleration of a package and its tip angle, which is the formula that was derived during the beginning of the thesis work. The formula is considered to be applicable since the measurement values fell close to their corresponding theoretical values, their differences small. This correlation is not considered to be a result of chance. If the results gathered from the linear rig are to be used on a measurement station it is considered to be an advantage if the applications located in the same production line as the station create their motions using S-curve profile. This because the real curve fell above the theoretical curve when the S-curve profile was used unlike the Trapezoidal profile that made the real curve fall under the theoretical curve. But an extra margin is necessary due to the fact that some measurement values fell in or under the theoretical curve. If the tip angle on the measurement station is to be connected to a max acceleration that a package manages to handle you want to be sure that the package really manages to endure that acceleration. This is a requirement the S-curve profile is considered to fulfill if a margin is used. Also, the S-curve profile is better regarding the fact that it does not put as much stress on the mechanics.

The two concepts of measurement stations have their advantages and disadvantages compared to each other. concept A slows down the flow by using the belt brake and waits until four packages have entered the measurement station before the flow can continue in its normal pace. When the packages leave the station, the flow must slow down again. Using concept A for measurement of Package Stability infers that the measurement values are only samples from the flow. concept B on the other hand allows a continuous flow without slowing down the pace, this is done by measuring stability of every single package in the flow. But this means that concept B only checks if the packages tips or not after a certain inclination on the belt. Meaning concept A provides the actual tip angle of a package while concept B just checks if the package tips after a certain inclination or not.

The optimal course of action would be to measure the exact tip angle of every packages to be able to get an individual max acceleration on every package. This would work with concept A that measures the exact tip angle, but to be able to test every single package the flow would have to slow down considerably, which is not desired in a production line.

Measurement of tip angles can be used to keep statistics, verify design and to adjust machine functions. What is meant by verifying design is the control of the manufacturing process. If several packages would fall on a tip angle which is considered deviant something is wrong, and the operator can be notified. The formula can be used to adjust machine functions. Depending on what liquid the package contains, the package can be handled differently. A high mean value of the tip angles of a batch implies that the package can handle high acceleration and thus can the machine function adapt.

The photoelectric sensor was chosen for detection of a fallen package because of its simplicity to easily detect a fallen package using the transmitter/receiver principle.

For concept A it is possible to increase the capacity of measurements by adding more sensors. Unlike concept A, concept B only uses one photoelectric sensor since it is a continuously flow that is controlled. Transmitter and receiver are placed vertically because of the short distance between the packages. Regarding concept B it is possible to add more sensors along the band where the inclination is increasing to be able to test more angles, but at the same time the complexity increases.

Regarding the manufacturing process of the two concepts, the costs are in the same range. But concept B is more complicated to manufacture because of the leaning belt. A tightened belt wants to be straight and not be exposed to bending in the direction it is leaning. That is why the belt may come to crawl in sideways and eventually jump out of its position. Thus, many components are needed to force the belt to stay in position. concept A on the other hand is easier to design since the inclination occurs on a separate unit. concept A uses more proven components and technology to create the inclination. That is why concept A is considered to be a reasonable alternative to implement in practice. It is also considered to be of greater importance to acquire the actual tip angle of the package than checking if it passes a certain tip angle or not.

7 Conclusion

The purpose of the thesis has been to investigate Package Stability. To make the work more concrete the following questions were developed at the beginning of the project:

- What measurable properties of a package can be connected to Package Stability? Are there any dependencies between these?
- What methods can be used to perform the measurements?
- How can Package Stability be measured in a production line?

It was decided early to investigate packages maximal acceleration and tip angles. A theoretical connection between these two parameters was examined and resulted in a formula which gave the packages the maximal acceleration they manage to handle without falling as a function of the packages tip angle. With a purpose-built incline plane the packages tip angles could be measured. Using the formula, a theoretical maximal acceleration for the packages could then be derived. This theory was later investigated by exposing the packages to accelerations. A linear rig was used to produce the accelerations.

The measurement values acquired from the rig cohered well with their corresponding theoretical values and for that reason the theoretical formula is considered to be applicable on a production line whose applications uses S-curve profiles. This because the curve based on the real measurement values fell above the theoretical curve. But a margin is recommended due to the fact that some values ended up in the theoretical curve, and occasional values even ended up under the curve.

A concept of a measurement station that measures the exact tip angle of every individual package in a production flow could not be created. It would require the flow to slow down considerable. Of the two concepts developed for measurement of Package Stability concept A is recommended since the design is not as complex as the design of concept B. The measurement of the packages tip angles can be used to keep statistics, verify the design and adjust the applications on the same production line.

7.1 Reflection of ethical aspects

Secrecy was part of the thesis job. At the start of the job a confidentiality agreement was signed, where the thesis workers assured the company that they would not leak any secret information about the company's products and ideas.

When the report was written it was read by a Tetra Pak employee to assure that no confidential information was part of the text.

7.2 Future work

To be able to draw a more justifiable conclusion it is recommended to first construct a prototype of the concept and then do more tests.

In this thesis 20x4 samples per package type were examined. Due to all sources of error a quantitative research is essential to obtain useful results.

It would also be interesting to test different types of packages to see how they hold up to the theoretical formula. The company has hundreds of packages that can be tested.

All the packages that were tested in this report contained water. It would be interesting to see how the content affects the results, for example if a package contained a liquid with a higher viscosity or if they were only half full.

Air resistance and swash are considered to be two sources of error that the calculations did not account for. In future work these factors should be considered in the calculations.

There are several parameters concerning Package Stability that this report does not examine. It would be interesting to measure these parameters, for example investigate how the packages behave when exposed to vibrations. It would also be of interest to be able to measure the dimensions and mass of the packages. These parameters can be used to predict even better how stable a package is. Such measuring stations could be implemented in concept A since it is a separate conveyor.

Due to a couple of reasons concept A was the one recommended if ever to be manufactured. But if concept B were to be manufactured there are some potential improvement that can be implemented. It would be possible to attach more sensors of the same type along the gradually increasing slope. You could then get a more accurate reading of at what angle the packages tipped. The packages could then be given different Package Stability values depending on what interval they fell in.

8 Terminology

Belt Brake – A part with a motor that revolves two belts the other way in relation to the conveyor. Depending on the motor pace the packages slows down or stops.

MAM - Motion Axis Move, PLC instruction for motion control.

MATC - Motion Axis Time Cam, PLC instruction for motion control.

Linear regression – A function that applies a line in the form of $ax + b$ onto a graph and that best describes the scattered plots.

PLC - Programmable Logic Controller, industrial computer.

Protractor - Instrument for measurement of angles.

TBA 200SL - Tetra Brik Aseptic 200 Slim Leaf.

TT 1000B - Tetra Top 1000 Base.

TBA 1000E – Tetra Brik Aseptic 1000 Edge.

9 References

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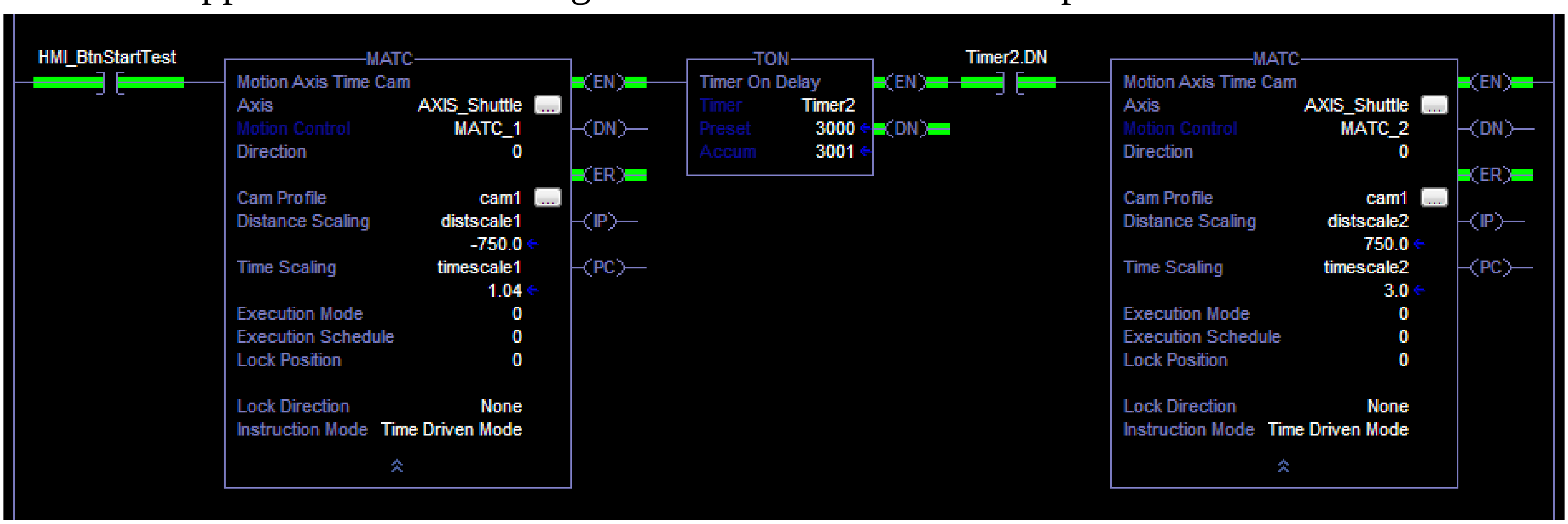
7. Linear Motion Tips. *How to calculate velocity from triangular and trapezoidal move profiles.* https://www.linearmotiontips.com/how-to-calculate-velocity/ (Accessed: 2020-07-21).

10 Appendix

Appendix 1: Ladder diagram code for Trapezoidal move profile

Appendix 2: Ladder diagram code for S-curve move profile



Appendix 3: Structured text code for moving average

```
IF S:FS THEN
Index := 1;
END_IF;

sum := 0;




nbrOfRounds := 170;
Acceleration_Array[Index] := AXIS_Shuttle.ActualAcceleration ;






If Index <=(nbrOfRounds-1) THEN
Index := Index +1;
ELSE
Index := 0;
END_IF;


FOR i := 1 TO nbrOfRounds BY 1 DO
    sum := sum + Acceleration_Array[i];
END_FOR;

AccelerationAvarage := sum/nbrOfRounds;
```

Appendix 4: Measurement data

4.1 TBA 200SL side A Trapezoidal

Tip Angle A (°)	Theoretical Max Acc A (m/s²)	Real Max Acc A (m/s²)
11,2	1,944410236	1,7
11,1	1,926607403	1,85
11,2	1,94441236	1,85
11,3	1,962229628	1,8
12,3	2,141106257	2
11,8	2,051504884	1,95
11,7	2,033624236	1,95
11,8	2,051504884	1,8
12	2,087305436	1,95
11,5	1,99790158	1,75
11,7	2,033624236	1,75
11,9	2,069398576	1,8
12	2,087305436	1,8
11,6	2,015756509	1,9
11,3	1,962229628	1,85
11,8	2,051504884	1,9
11,8	2,051504884	1,85
11,1	1,926607403	1,8
11,1	1,926607403	1,8
10,5	1,820029421	1,55

4.2 TBA 200SL side B Trapezoidal

Tip Angle B (°)	Theoretical Max Acc B (m/s²)	Real Max Acc B (m/s²)
10,3	1,784596457	1,6
11,6	2,015756509	1,9
10,9	1,891033937	1,95
11,5	1,99790158	1,85
9,5	1,643304421	1,55
11,3	1,962229628	1,8
10,2	1,766896881	1,65
11	1,908814636	1,9
9,6	1,660928676	1,75
10,2	1,766896881	1,75
10,5	1,820029421	1,6
9,8	1,696208529	1,6
10,1	1,749208418	1,65
11,6	2,015756509	1,95
10,8	1,873265186	1,8
11,7	2,033624236	1,8
11,2	1,94441236	1,75
9,8	1,696208529	1,8
11	1,908814636	1,8
9,5	1,643304421	1,45

4.3 TBA 1000E side A Trapezoidal

Tip angle A (°)	Theoretical Max Acc A (m/s^2)	Real Max Acc A (m/s^2)
12,7	2,213032578	2,2
11,8	2,051504884	2,05
12,6	2,195030062	2,15
11,9	2,069398576	2,05
12,8	2,231049261	2,25
12,6	2,195030062	2,1
11,9	2,069398576	2,1
12,1	2,105225586	2,1
13	2,267125637	2,2
12	2,087305436	1,95
12	2,087305436	2,1
12,9	2,249080239	2,2
12,1	2,105225586	2,1
12,4	2,159067027	2,15
11,9	2,069398576	2,05
12,7	2,213032578	2,2
12,5	2,177041587	2,1
13	2,267125637	2,25
11,9	2,069398576	2,1
12,1	2,105225586	2,05

4.4 TBA 1000E side B Trapezoidal

Tip Angle B (°)	Theoretical Max Acc B (m/s^2)	Real Max Acc B (m/s^2)
15,6	2,741793265	2,7
15,3	2,686448003	2,65
14,9	2,61289997	2,6
15,3	2,686448003	2,7
15,9	2,797300585	2,7
14,7	2,576228773	2,55
14,8	2,594555916	2,55
15,6	2,741793265	2,7
15	2,63126107	2,6
15,2	2,66803495	2,6
15,1	2,649639351	2,55
15,5	2,723327023	2,7
14,8	2,594555916	2,55
15,4	2,704878648	2,6
15,5	2,723327023	2,7
15	2,63126107	2,6
14,9	2,61289997	2,45
14,9	2,61289997	2,55
15,1	2,649639351	2,6
14,7	2,576228773	2,5

4.5 TT 1000B side A Trapezoidal

Tip Angle A (°)	Theoretical Max Acc A (m/s²)	Real Max Acc A (m/s²)
13,3	2,321349633	2,1
12,3	2,141106257	1,85
12,2	2,123159152	1,85
13	2,267125637	2
12,6	2,195030062	1,95
13,2	2,303260206	2
12,5	2,177041587	1,95
11,9	2,069398576	1,8
11,5	1,99790158	1,7
12,3	2,141106257	1,9
12,7	2,213032578	1,95
11,5	1,99790158	1,7
10,7	1,855508263	1,6
13,3	2,321349633	1,95
13,2	2,303260206	2,1
12,4	2,159067027	1,9
13,6	2,375708027	2,05
12,6	2,195030062	1,85
13,8	2,412023344	2,1
13,3	2,321349633	1,95

4.6 TT 1000B side B Trapezoidal

Tip angle B (°)	Theoretical Max Acc B (m/s²)	Real Max Acc B (m/s²)
12,4	2,159067027	1,9
12,1	2,105225586	1,85
11,3	1,962229628	1,7
11,5	1,99790158	1,75
11,9	2,069398576	1,8
13,2	2,303260206	2,05
12,5	2,177041587	1,85
13,2	2,303260206	2
12,5	2,177041587	1,8
12,6	2,195030062	1,9
12,1	2,105225586	1,85
11,7	2,033624236	1,75
12,4	2,159067027	1,8
11,7	2,033624236	1,8
12,6	2,195030062	1,9
12	2,087305436	1,85
12,6	2,195030062	1,9
13,2	2,303260206	1,95
12,6	2,195030062	1,9
12,1	2,105225586	1,8

4.7 TBA 200SL side A S-curve

Tip Angle A (°)	Theoretical Max Acc A (m/s^2)	Real Max Acc A (m/s^2)
11	1,908814636	2
10,8	1,873265186	2
10,8	1,873265186	1,95
10,4	1,802307264	1,9
11,6	2,015756509	2,1
11,4	1,980059327	2,05
11,1	1,926607403	2,05
11,1	1,926607403	2,05
11,4	1,980059327	2,05
10,8	1,873265186	2
11,4	1,980059327	2,1
11,4	1,980059327	2
11,3	1,962229628	2,1
11	1,908814636	2
10,5	1,820029421	1,95
11,2	1,94441236	2,05
11,3	1,962229628	2,05
11	1,908814636	1,95
10,6	1,837763048	1,95
10,5	1,820029421	1,9

4.8 TBA 200SL side B S-curve

Tip Angle B (°)	Theoretical Max Acc B (m/s^2)	Real Max Acc B (m/s^2)
9,8	1,696208529	1,8
11,2	1,94441236	2,05
10,5	1,820029421	1,95
10,6	1,837763048	1,95
8,9	1,537770962	1,65
10,9	1,891033937	1,95
10	1,731530951	1,8
10,9	1,891033937	2
10,5	1,820029421	1,9
10,5	1,820029421	1,95
9,5	1,643304421	1,7
9,9	1,71386436	1,75
10,3	1,784596457	1,9
11,3	1,962229628	2,05
11	1,908814636	2,05
11,2	1,94441236	2
10,8	1,873265186	1,95
10,2	1,766896881	1,9
10,6	1,837763048	1,95
9,3	1,60808667	1,75

4.9 TBA 1000E side A S-curve

Tip Angle A (°)	Theoretical Max Acc A (m/s²)	Real Max Acc A (m/s²)
14	2,448400988	2,5
13,3	2,321349633	2,5
13,9	2,43020431	2,5
13,9	2,43020431	2,55
13,8	2,412023344	2,6
13,5	2,357573414	2,6
13,3	2,321349633	2,5
13,6	2,375708027	2,5
14,5	2,539624678	2,7
13,1	2,285185583	2,45
13,2	2,303260206	2,45
14,2	2,484842007	2,7
12,6	2,195030062	2,45
13,6	2,375708027	2,55
13,2	2,303260206	2,5
14,3	2,503086613	2,75
13,9	2,43020431	2,65
14,7	2,576228773	2,65
13,1	2,285185583	2,45
12,8	2,231049261	2,5

4.10 TBA 1000E side B S-curve

Tip Angle B (°)	Theoretical Max Acc B (m/s²)	Real Max Acc B (m/s²)
16,3	2,871568957	3,15
16,1	2,834397357	3,2
15,8	2,778779906	2,95
16,3	2,871568957	3,2
16,4	2,890183172	3,15
15,8	2,778779906	3,05
15,5	2,723327023	2,95
16,2	2,852973733	3,15
15,6	2,741793265	3
15,9	2,797300585	3,05
15,4	2,704878648	2,95
16,6	2,927469145	3,2
15,7	2,760277513	3,05
15,6	2,741793265	2,95
16,4	2,890183172	3,1
16,4	2,890183172	3,15
15,2	2,66803495	2,95
15,6	2,741793265	2,95
15,9	2,797300585	3,05
15	2,63126107	2,9

4.11 TT 1000B side A S-curve

Tip Angle A (°)	Theoretical Max Acc A (m/s²)	Real Max Acc A (m/s²)
13,5	2,357573414	2,4
13	2,267125637	2,35
12,9	2,249080239	2,3
12,9	2,249080239	2,35
12,4	2,159067027	2,2
12,6	2,195030062	2,25
11,5	1,99790158	2
12,2	2,123159152	2,15
12,3	2,141106257	2,15
12,8	2,231049261	2,2
13,7	2,39385796	2,45
12,8	2,231049261	2,2
10,6	1,837763048	1,9
13,9	2,43020431	2,45
13,1	2,285185583	2,35
12,9	2,249080239	2,25
13,6	2,375708027	2,4
12,8	2,231049261	2,3
13,8	2,412023344	2,45
13,8	2,412023344	2,35

4.12 TT 1000B side B S-curve

Tip Angle B (°)	Theoretical Max Acc B (m/s²)	Real Max Acc B (m/s²)
12,9	2,249080239	2,25
12,9	2,249080239	2,25
11,7	2,033624236	2,05
11,7	2,033624236	2,05
10,4	1,802307264	1,85
13	2,267125637	2,25
11,1	1,926607403	1,95
13	2,267125637	2,25
12	2,087305436	2,1
12,5	2,177041587	2,15
12,6	2,195030062	2,25
12,4	2,159067027	2,15
12,1	2,105225586	2,1
12,2	2,123159152	2,2
12,8	2,231049261	2,25
12,8	2,231049261	2,2
12,5	2,177041587	2,25
13	2,267125637	2,3
12,5	2,177041587	2,2
12,2	2,123159152	2,15

Appendix 5: Package dimensions

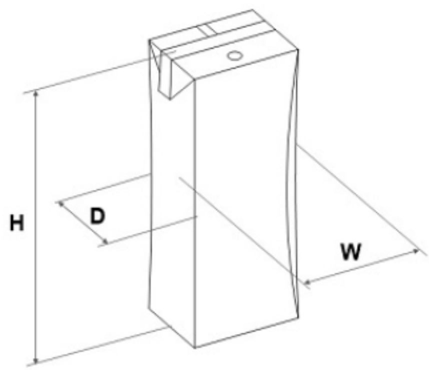
5.1 TBA 200SL

Package Data

TBA 200 SL Straw

Package Dimensions

		Width, W	Depth, D	Height, H
Measured dimensions (mm)	1	53	38,4	123
	2			n/a



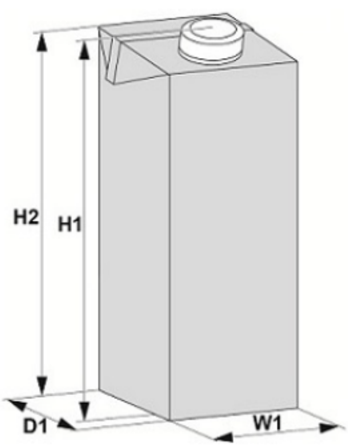
5.2 TBA 1000E

Package Data

TBA 1000 E LightCap 30

Package Dimensions

		Width, W	Depth, D	Height, H
Measured dimensions (mm)	1	76.7	77.9	209.2
	2			205.6



5.3 TT 1000B

Package Data

TT 1000 Base 70x70 Eifel C38

Package Dimensions

		Width, W	Depth, D	Height, H
Measured dimensions (mm)	1	78	77	235
	2	76	74	
	3	72	72