DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DESIGN AND ANALYSIS OF AN AUTO SPRAY ROBOT FOR AN ALUMINIUM DIE CASTING SYSTEM

by
Özgür KAYRAN

October, 2011
IZMIR

DESIGN AND ANALYSIS OF AN AUTO SPRAY ROBOT FOR AN ALUMINIUM DIE CASTING SYSTEM

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"DESIGN AND ANALYSIS OF AN AUTO SPRAY ROBOT FOR AN ALUMINUM DIE CASTING SYSTEM"** completed by **ÖZGÜR KAYRAN** under supervision of **PROF. DR. HİRA KARAGÜLLE** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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Özgür KAYRAN

DESIGN AND ANALYSIS OF AN AUTO SPRAY ROBOT FOR AN ALUMINIUM DIE CASTING SYSTEM

ABSTRACT

Today, in a variety of industrial applications, robots are used extensively in all areas. For these robot applications to work efficiently in real sense, the robot system chosen must have the most proper construction for the work performed.

In such applications, theoretical knowledge giving the correct results from selection of both fixed and moving elements in the system installed to the design should be utilized and these should be practiced fast.Results obtained by standardized calculations and analysis to be applied to every system at the stage of design allow design easiness and increase of reliability of the project. Designs created systematically require fast and accurate solutions for the said robot applications.

In this study, principles, to be considered for Cartesian robot application were determined. Appropriate modules were selected for the actual design by means of linear module selection program in line with these principles and compliance of modules used for the prototype was verified. Frequency and static analysis of Cartesian robot designed with the modules chosen were conducted in computer environment and results were compared with practical applications.

Keywords: Spray robot, cartesian robot, linear module

ALÜMİNYUM DÖKÜM TEZGAHLARI İÇİN SPREY ROBOTU TASARIMI VE ANALİZİ

ÖZ

Günümüzde endüstriyel uygulamalarda çeşitli robotlar her alanda yaygın bir biçimde kullanılmaktadır. Bu robot uygulamalarının gerçek anlamda verimli olarak çalışması için seçilen robot sisteminin yapılan işe göre en uygun yapıya sahip olması gerekmektedir.

Bu tür uygulamalarda kurulan sistem içinde hem hareketli elemanların hem de sabit elemanların malzeme ve ürün seçiminden tasarımına kadar olan kısımda doğru sonuçlar alınan teorik bilgilerden yararlanıp bunları hızlı bir şekilde pratiğe çevirebilmek gerekmektedir. Tasarım aşamasında her sisteme uygulanabilen standartlaştırılmış hesaplar ve analizler ile elde edilen sonuçlar tasarım kolaylığı ve projede güvenirliğinin artmasını sağlamaktadır. Bu sistematik içerisinde yapılan tasarımlar söz konusu robot uygulamaları için hızlı ve doğru çözümler getirmektedir.

Bu tez çalışmasında kartezyen robot uygulamaları için dikkat edilmesi gereken prensipler belirlenmiştir. Bu prensipler doğrultusunda hazırlanan Lineer modül seçim programı ile gerçek tasarım için uygun modüller seçilmiş ve prototip için kullanılan modüllerin de uygunluğu kontrol edilmiştir. Seçilen modüller ile tasarımı yapılan kartezyen robotun bilgisayar ortamında frekans ve statik analizleri yapılıp pratik uygulamalarla karşılaştırması yapılmıştır.

Anahtar Sözcükler : Sprey robot, kartezyen robot, lineer modüller

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CHAPTER ONE
INTRODUCTION

The robot is the manipulator used in industrial applications, having three or more programmable axes, automatic-controlled, reprogrammable, multi-purpose, fixed or movable according to the definition of International Standards Institute (ISO) numbered TR-8373. An industrial robot is designed to carry materials, parts and special units to perform various works via programmed actuator and defined as reprogrammable, multi-functional unit by Robotic Industries Association. In examining the historical development of robots, it is seen that all of the early studies comprised of mechanical systems and started at about 14. Century. However, first systems having the features of robot are seen as weaving loom operating with punched card in the 19. Century. Especially with the contribution of progresses of electronic systems after the 1940's, functions and abilities of robotic systems have increased incrementally every passing year. Following successes of electric engines and control systems, the first industrial robots acquired enough characteristics to be employed in industrial applications and started to be used as robot arms or manipulators in the production lines in the 1960's. However, developments of robot types called human-like robots recently allowed these robots to show human-like behaviours, even to be able to walk like a human and respond to the events with face expressions.

In general, a robot consists of four main parts.

a.Manipulator: consists of serial objects (limbs) fixed to each other rigidly by joints or a mechanical structure. Manipulator comprises of a terminator (end effector) designed for the operation to be performed by the robot and arm ensuring freedom and wrist, ensuring hand skill.

b.Control system managing and controlling the action of manipulator.

c.Data generating sensors (Sensor) monitoring the status of manipulator and the environment.

d.Actuators providing the action of manipulator via movements of joints (actuators-motors).

Robot systems are studied in different groups by their structures and functions. Study groups created for this purpose and information about the said groups is as follows:

a) Industrial robots: Industrial robot is the general-purpose, programmable, hulky and fixed and has arms to carry out different duties. Industrial robots are used in full-automatic and semi-automatic welding operations, especially spot welding in automotive industry, Mig/Mag. Tig and Plasma welding, casting, industry spray painting works, furniture industry, white goods industry.

b) Operational robots: Such types of robots are the robots designed for a specific aim, remote-controlled and used for loading machine tools, packaging, external cleaning of aircrafts, bomb disposal operations, mining, space research, submarine works, rescue works after earthquakes and military works.

c) Medical and health robots: they actuate orthopedic-purpose human limbs and prosthesis by detecting tensions in tendons of cerebrum via Piezzo electric sensors and actuate manipulators in limbs. Moreover, they are the robots enabling surgeons to contact cross-continental to operate for medical operations.

There are cybernetics robots, robots used in movie industry, toy industry robots and hobby robots other than these.Above-mentioned wide areas of use of robots arise from the advantages of robots especially. These advantages can be listed as follows:

- Production increase.
- Quality increase.
- Reduction of production cost.
- Production flexibility
- Management and supervision easiness
- Operation in dangerous environments.
- Long-service life.
- System organization in an integrated production.

Considering the use of robot in any areas depends on the following major factors;

- Increase of flexibility and efficiency for the production
- Dangers for human health
- Expensive labor cost, non-availability of labor force or people not requesting to be engaged in such works.
- Reduction of number of broken part in the production and material saving.
- Education, health, service and security facilities.

CHAPTER TWO

INDUSTRIAL ROBOTS

2.1 Classification Of The Industrial Robots

Industrial robots can be classified as follows.

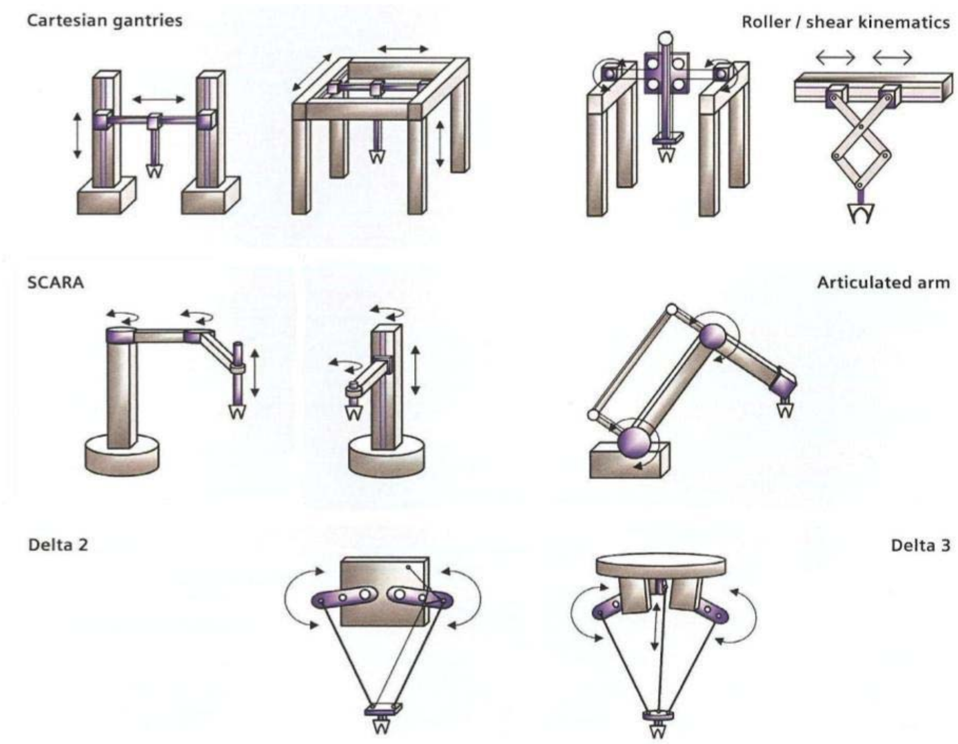


Figure 2.1 Classification of industrial robots.

2.1.1 Cartesian

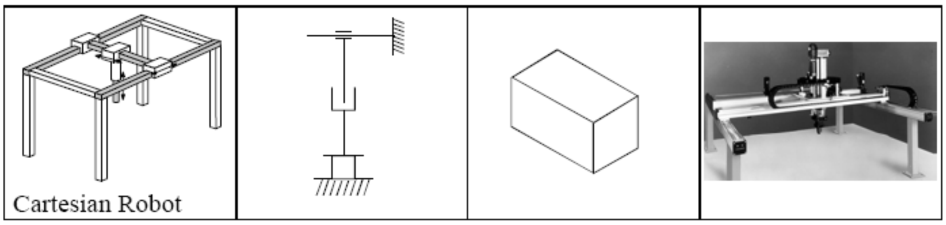


Figure 2.2 Cartesian robot

- All three joints are prismatic (PPP) Commonly used for positioning tools, such as dispensers, cutters, drivers, and routers.

- Often highly customizable, with options for X, Y, Z lengths
- Payloads and speeds vary based on axis length and support structures
- Simple kinematic equations

Advantages:

- Easy to visualize
- Better inherent
- More accuracy than other types
- Easy to program off-line
- Highly configurable - get the size needed

Disadvantages:

- Not space efficient
- External frame can be massive
- Z axis “post” frequently in the way
- Axes hard to seal
- Can only reach in front of itself

Applications:

- Pick-and-place operations.
- Adhesive applications (mostly long and straight).
- Advanced munition handling.
- Assembly and subassembly (mostly straight).
- Automated loading cnc lathe and milling operations.
- Nuclear material handling.
- Welding.

2.1.2 Scara

- SCARA stands for Selective Compliance Assembly Robot Arm
- First two links are revolute, last link is prismatic (RRP)
- Rigid in the vertical direction
- Compliant in the horizontal direction
- Used for assembly in a vertical direction
- Circuit board component insertion

Advantages:

- Fast cycle times
- Excellent repeatability good payload capacity large workspace
- Height axis is rigid

Disadvantages:

- Often limited to planar surfaces
- Typically small with relatively low load capacity
- Two ways to reach same point
- Hard to program off-line

2.1.3 Articulate Arm (Revolute/Jointed Configuration)

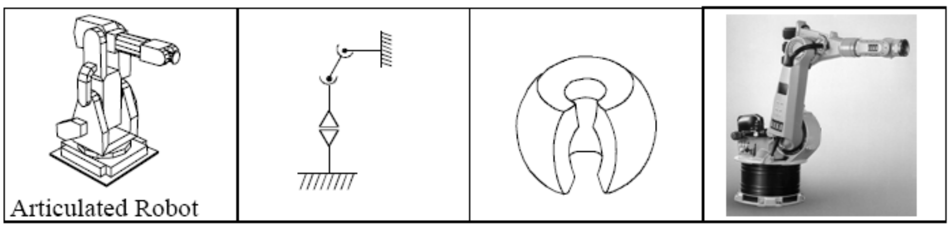


Figure 2.3 Articulate arm

- First three joints are revolute or rotational (RRR)
- Easily the most common type of modern robot

- Suitable for a wide variety of industrial tasks, ranging from welding to assembly
- Often called an anthropomorphic arm because it resembles a human arm

Advantages:

- Large workspace for size
- Excellent reach for size
- Can reach above or below obstacles
- Characteristics similar to human arm

Disadvantages:

- Complicated kinematics
- Difficult to program off-line
- Workspace difficult to visualize & compute
- Small errors in first few joints are amplified at end-effector

Applications:

- Die Casting
- Dip Coating
- Forging
- Glass Handling
- Heat Treating
- Injection Molding
- Machine Tool Handling
- Material Transfer
- Parts Cleaning
- Press Loading
- Stacking and Unstacking.

2.1.4 Delta 2- Delta 3 (Parallel Manipulators)

- A closed-loop kinematic chain mechanism end-effector of which is linked to the base by several independent kinematic chains
- Often consists of an actuated prismatic joint, connected to the platforms through passive (i.e. not actuated) spherical and/or universal joints
- Hence, the links feel only traction or compression, not bending, which increases their position accuracy and allows a lighter construction.
- Parallel manipulators have (in principle) high structural stiffness
- Wide range of motion capability
- Limited workspace

One of the most important types of robot having seen recently is the Cartesian robot. In this study, it is aimed to design, manufacture, conduct experimental tests and evaluate the experimental results of Cartesian robot systems having an important place in the new robotic systems owing to its specifications.

2.2 Design of the Cartesian Robots

As with all robotic applications, there are factors to be considered at the design stage of Cartesian robot applications. These factors can be grouped under the following headings.

2.2.1 Determination of working space

Maximum displacements of axis x, y ,z determine the working space. Maximum displacements should be determined by the duty that the robot will perform and meet the actions required. Creating the correct working space will enable us to determine strokes of linear axis to form a Cartesian robot. Positions and strokes of the axis designated by the working space should not prevent the operations of preceding and subsequent axis.

2.2.2 Determination of maximum axis loads:

While designing a Cartesian robot, the maximum loads delivered by the axes should be calculated. While calculating the maximum static loads on axes, weight of axis that axis carries if there is other than work load and moments to occur because of positions of these loads should be calculated. Static resistances and bearing forces of linear modules to be chosen considering these loads should be checked. These controls offer preliminary information about the selection of linear axes to form the axes. Dynamic forces are identified due to momentum to occur during the operation of the robot and dynamic analysis of the system is carried out. Specifications of the linear modules selected are confirmed by the controls.

2.2.3 Determination of maximum axis speeds:

Determination of maximum speeds of axes running depends on the maximum displacement and prerequisite of period of the work to be performed by the robot. While creating the maximum displacement of the axes and determining the axis speeds, each axis should be calculated by its displacement and period since they will work in a synchronized way.

You can see the classification of Cartesian robots to be chosen by the working loads, application area and working space.

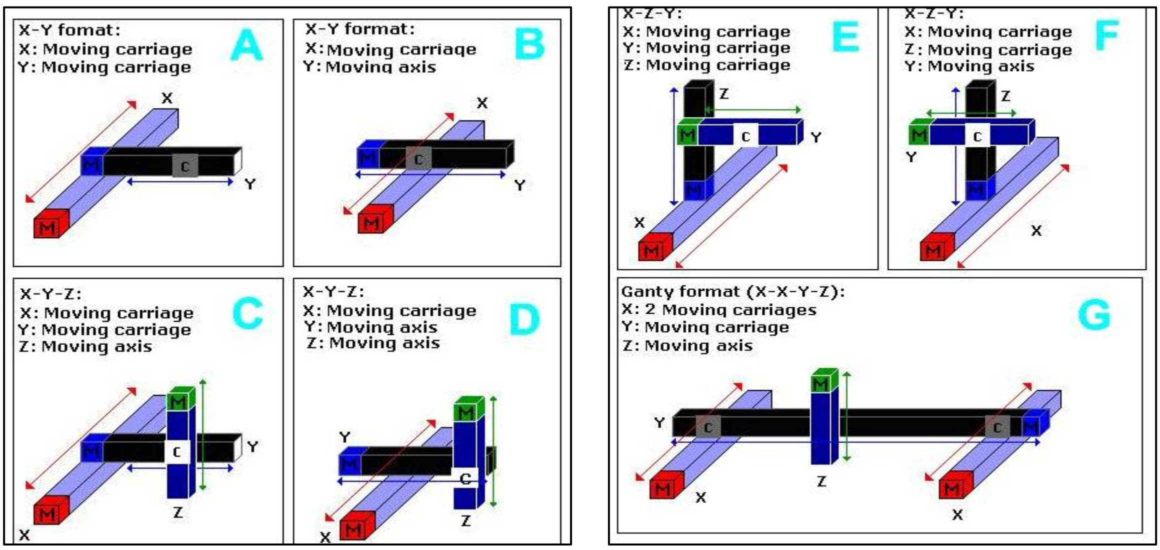


Figure 2.4 Cartesian robots models

2.2.4 Determination of the Motor Forces of The Axis

Specifications and powers of the motors to be used can be identified by means of information to be obtained by the above-mentioned selection factors.

2.3 Aluminium Injection Molding Machine for Spray Robot

Today, manufacture with aluminium injection casting technique is preferred more and more by many sectors as aluminium casting technologies develop. Reasons of preference include the fact that aluminium-based alloy materials are light, although they are not as resistant as steel, they are suitable to be used in the areas where high resistance is not necessary in the borders requested, casting as manufacture technique is easy and machining is fast, they are fit for mass production. Companies manufacturing aluminium injection machines in many sectors as mainly automotive sector require making high-quality, fast and cost-efficient production to compete in their sectors. In this sense, it is not only sufficient to develop technology, capacity and speeds of aluminium injection machines. Material supply, part removal and mold spraying robot applications are significant solutions.

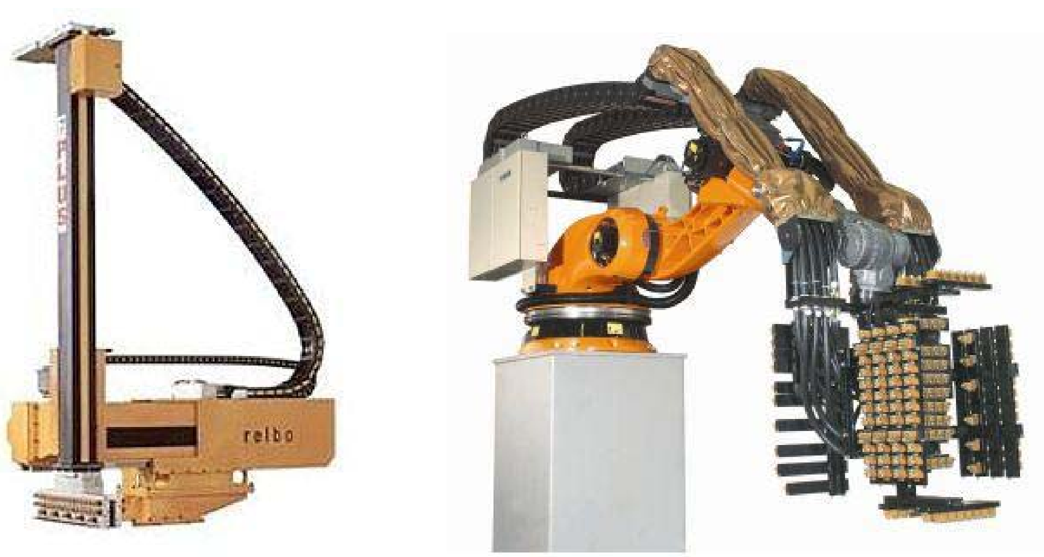


Figure 2.5 Spray robots

The primary prerequisite for spraying is that the die can be sprayed manually (without pastes and brush) and without problems (only with water-soluble spraying agents). All casting parameters must be defined and reproducible.

2.3.1 Separating

A separating film is required whenever aluminium and steel meets one another. Areas in which aluminium flows fast are especially critical as the separating film is especially stressed at high flow speeds

2.3.2 Lubrications

In order to achieve an efficient function of core slides and ejectors, as well as successful demoulding, a lubricating and sliding effect is required. Demoulding becomes more difficult as the diameter of a core becomes greater (shrink-on problem). The temperature effects steel/aluminium experience is diametrically opposed. Steel expands due to the hot aluminium in the die (heating), the aluminium shrinks due to heat dissipation (cooling).

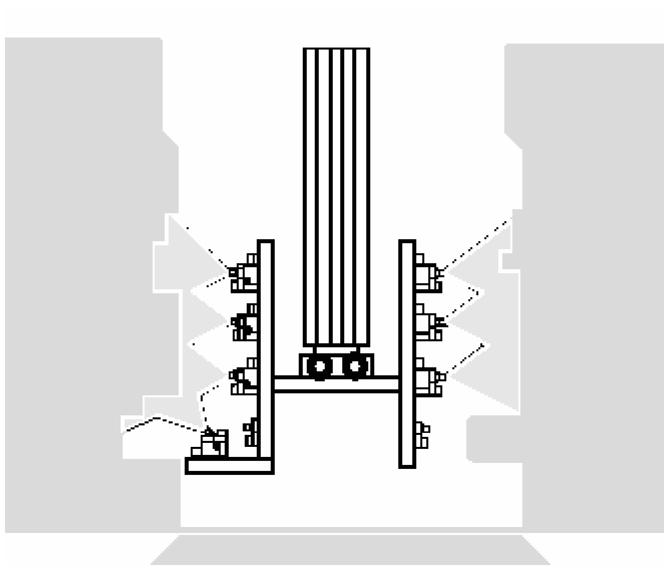


Figure 2.6 Spray manifold

2.3.3 Cooling

The die temperature is the interface between spraying and foundry technology. The liquid pressed in aluminium releases its heat energy to the surrounding steel on the die during cooling. The heat transmission is especially high on prominent die contours (cores, pins, edges etc.), but is lower on recessed contours (cavities). A spraying appliance cannot carry out a complete die cooling. A spraying appliance can only cool the surface for a very short time. This is, however, adequate for application of an adherent separating film.

Therefore, most of the assimilated heat energy should be dissipated via an internal die cooling. Exposed areas (thin cores or pins) on the surface must however be cooled externally with water or water-soluble separating agent. A comparison of the specific heat values of aluminium and water shows that only water evaporation can dissipate a large quantity of heat in a short time. On the other hand, washing the die (i.e. flooding the die with a lot of water) without evaporation just wastes time and separating agent.

Modern spray systems provide extensive flexibility. Depending on the desired effect, air blow-off and die lubricant can be fed either parallel or sequentially. Modular spray tools make a simultaneous spray to various locations possible. Depending on the procedure, blasting circuits and pressure can optimize any individual job.

2.3.4 Spray Nozzles

- If there is an ideal internal die cooling (surface 180 - 250°C) Agent 1 separation, Agent 2 lubrication.
- If external die cooling is required (>250°C in places) Agent 1 cooling (low concentration) Agent 2 separation and lubrication (higher concentration)

Simultaneous spraying of several areas or of one area from several sides (e.g. core) from one position or movement.

- Independent spraying of both die halves with two agents each
- Separating agent application only at desired areas
- Less risk of super cooling
- Less residue in the die, lower die lubricant consumption
- Individual after-blasting for each spraying circuit
  - Better spraying agent distribution
  - Water evaporation support ("drying")
  - Cleaning of the spraying nozzles (no "dripping")
- Separate high-pressure blasting circuit
  - Concentrated blasting of liquid residue
  - Accumulations blasted out of recesses and cracks

Table 2.1 Table of sprays

	PSR 2
Circuits	4
Die lubricant	2
Blasting circuits	2
Spray nozzles - Standard	16
Spray nozzles – Maximum	28
Blasting nozzles	4
PSR - length	470 mm
PSR - weight	17 kg

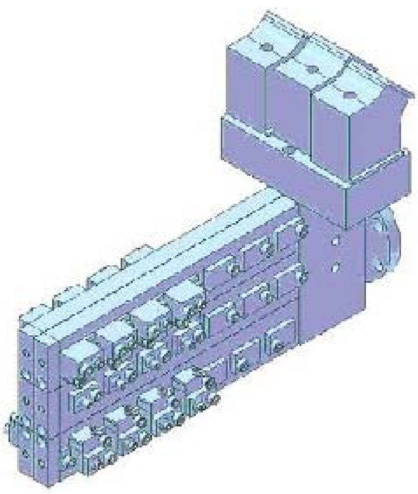


Figure 2.7 Spray manifold

In our thesis study titled "DESIGN AND ANALYSIS OF AN AUTO SPRAY ROBOT FOR AN ALUMINIUM DIE CASTING SYSTEM", we discussed design, design analyses, production of cast spraying robot for an aluminium injection bench of 15 tons and comparison of design analyses with product produced by tests and results obtained were evaluated.

CHAPTER THREE
DESIGN OF CAST SPRAYING ROBOT FOR ALUMINIUM INJECTION BENCHES

3.1 Determination the Preliminary Design

First of all, injection process should be completed for aluminium injection benches and after the part is removed from the mold, the mold should be cooled and made ready for the next injection process. This process is performed by the bench operator by applying cast lubricant liquid to the mold part in certain amount by spray gun. Lubrication of mold can be carried out by above-mentioned robot applications. Example of cast spraying robot applications is shown below.

Figure 3.1 Spray robot

First of all, we need to determine the working conditions to design the cast spraying robot.

* Cast spraying robot may be placed on a stationary body in the line of molds outside of bench or on a stationary body to be the outside of molds on the bench. In general, to prevent interference with the molds, cast spraying robot is operated by robot main body placed on the stationary body on the bench without an extra external

structure and as the robot can enter the space of mold upwards. The design will be performed by this model in the application to be designed.

* Cast spraying robot should enter the space of mold when the molds open and can lower up to most proper deep where spray manifold head will lubricate the molds.

*Robot should be in stand-by mode away from the molds during the injection process after spraying.

* The robot should carry the manifold head selected by the molds properly.

3.1.1 Determination of Working Space:

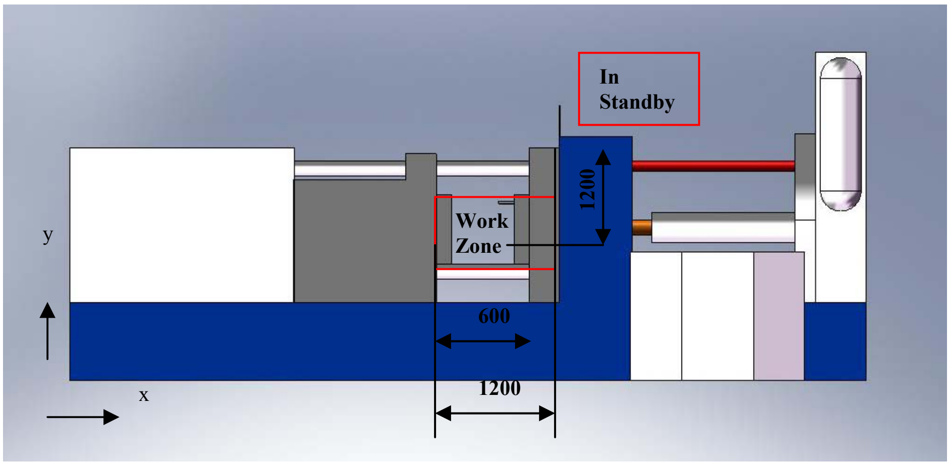


Figure 3.2 Working space

As it is seen on the above on-the-bench figure, the position that main body of robot is placed and the robot will be in stand-by mode when the molds are closed is determined as the top of the bench.

Mold surfaces that the robot will perform spraying process and mold space was determined as the working area.

If the spray manifold to spray the molds for the aluminium injection bench shown on the figure to which up to 550x800 mold can be fixed as the mold size is used, the robot can be placed in the center axis and all surfaces can be accessed. In this case, an axis is fixed by placing the robot in the axis of bench. The number of linear axes to move will have been reduced to 2. If we designate the working position as the center of the mold space, the travel distance is calculated as 1200 mm. Maximum stroke distance of linear modules to be chosen should be 1200 mm.

Considering these positions, linear axes of Cartesian robot should not be in the mold space and on the mold and the axes should be designed to carry themselves.

Working space of the robot is as follows under these circumstances:

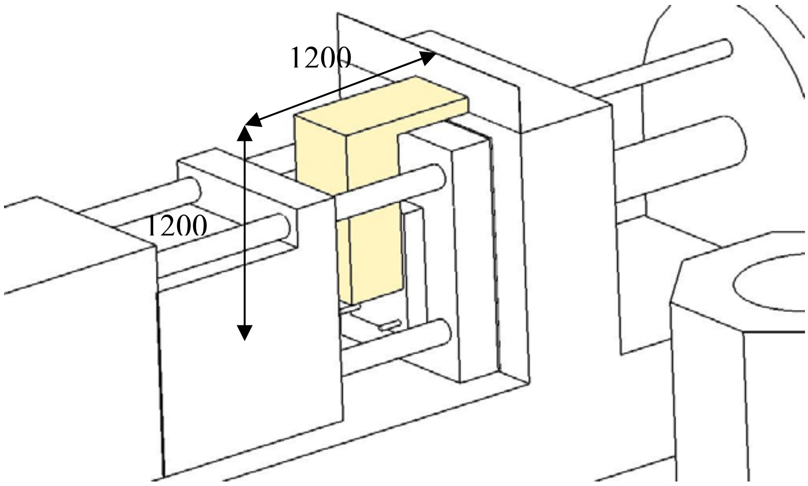


Figure 3.3 Working distance

The first preliminary design is established by designing the working space.

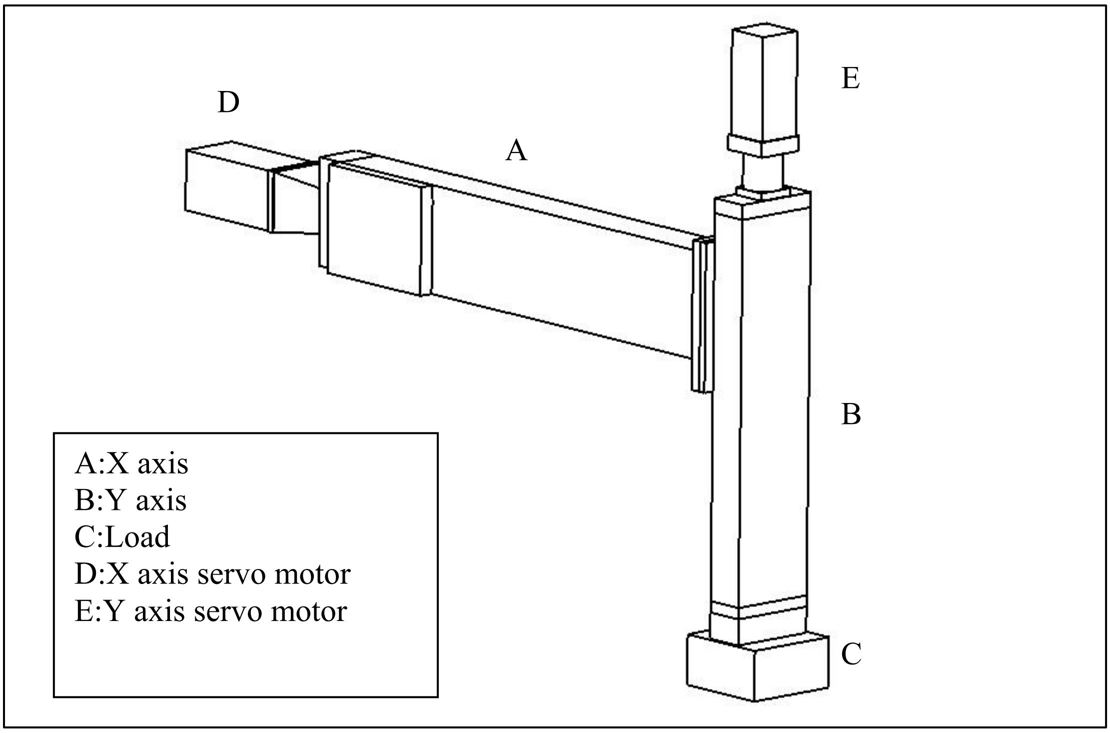


Figure 3.4 Preliminary design

To choose the proper linear modules for the Cartesian robot application designed as above, we need axes loads and bearing impact forces of these loads other than stroke data.

CKK serial linear modules catalogues and technical tables by BOSCH REXROTH company were used to calculate linear axis module static loads and to select the proper module.

3.1.2 Establishing the Loads and Calculating the Bearing Forces

While calculating the impact of forces affecting the system, the system should be broken down and impact forces should be examined.

Firstly when we look at the Y-axis

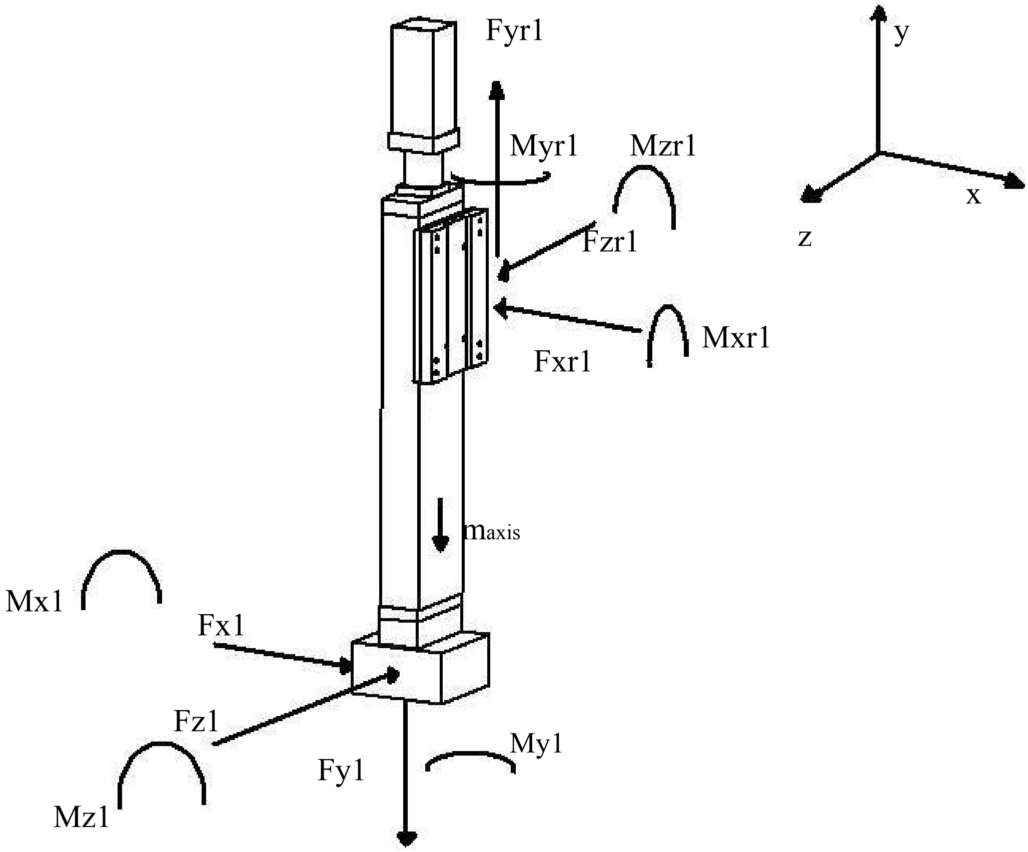


Figure 3.5 Y axis free-body diagram

As shown in the y-axis of the robot to create free-body diagram.

F_{x1}, F_{y1}, F_{z1} = impact force

F_{xr1}, F_{yr1}, F_{zr1}= bearing reaction force

maxis= own weight of the axis module

M_{x1}, M_{y1}, M_{z1}= external moments acting on the axis

M_{xr1}, M_{yr1}; M_{zr1}= moments acting on the bearings

$$\Sigma F_x=0 \qquad \Sigma M_x=0$$

$$\Sigma F_y=0 \quad \text{and} \quad \Sigma M_y=0$$

$$\Sigma F_z=0 \qquad \Sigma M_z=0$$

We can find the reaction forces and moments in the axes bearings by applying total force and total moment equations.

A program depending on force and moment variables was created by VISUAL BASIC program to see the force values of linear axes in different sizes when different force and moment values are applied. Force-moment catalogue values of screw mill modules in the body and four different diameters of BOSCH REXTROTH company were used for this program. Modules were compared at stroke and force conditions required and proper axis was chosen for the robot via this program.

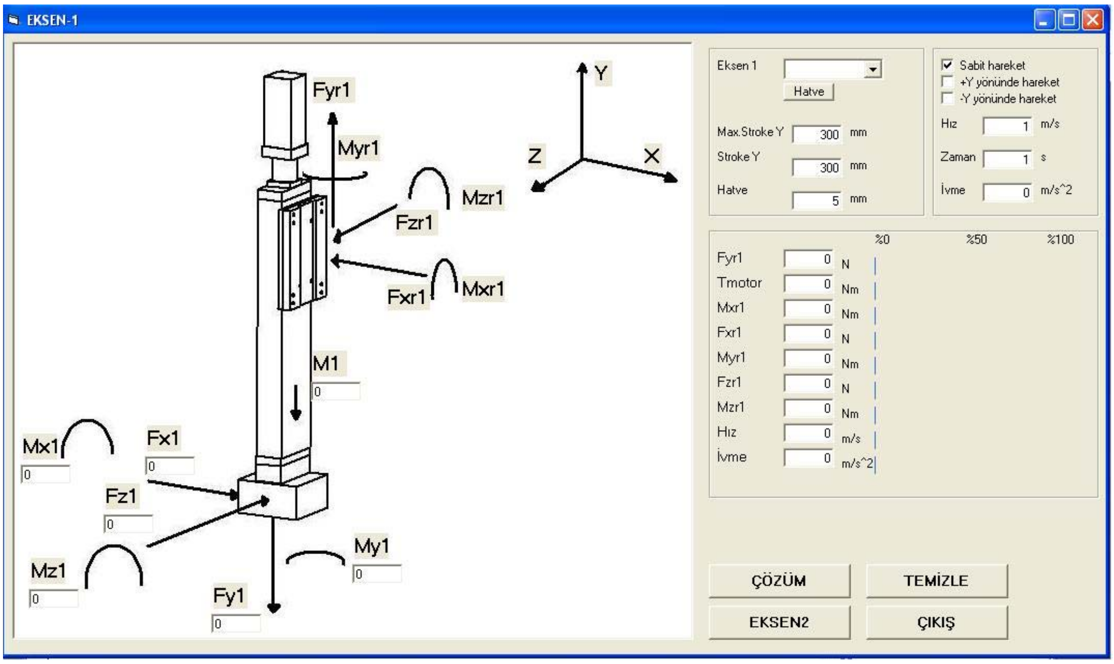


Figure 3.6 Y-axis program interface

Model, maximum stroke value, position to be calculated and screw mill pitch for the module to be calculated should be entered in the program axis 1. Code in the model line (cck20-145-2) indicate screw mill module diameter-body size-number of carriage in the body respectively. If the system is in the stationary mode at the moment and position of analysis or acts at fixed speed in other words, if the acceleration is zero, fixed movement should be chosen. If there is movement at the moment and position of the analysis and acceleration is different than zero, movement direction should be entered. Speed and time changing data or acceleration data should be entered directly for accelerated movement option.

In the analysis conducted in the case of accelerated movement, forces constituted by the acceleration should be taken into consideration as the impact force other than impact forces acting on the system and weight.

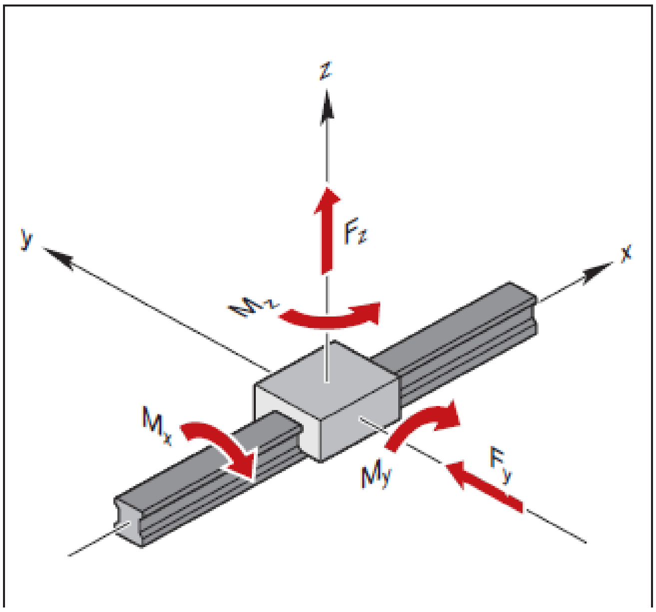


Figure 3.7 Main forces

2-row and 4-row ball and roller rail systems the raceways are arranged with a 45° angle of contact in relation to the main directions of loading. This results in the same high load capacity of the entire system in all four major planes of load application. The runner blocks can be subjected to forces and to load moments.

Forces in the four major planes of load application:

Lift-off F_z (positive Z-direction)

Down load $-F_z$ (negative Z-direction)

Side load F_y (positive Y-direction)

Side load $-F_y$ (negative Y-direction)

Moment loads:
Moment M_x (about the X-axis)
Moment M_y (about the Y-axis)
Moment M_z (about the Z-axis)
(alt indislerin düzeltilmesi gerekli)

The load-bearing capability of profiled rail systems is described by the static load capacity C0 and the dynamic load capacity C. These load capacity ratings are key characteristics describing the performance capability of the systems. Rexroth verifies the dynamic load capacities for all of its products in endurance tests. Its profiled rail systems have the same load capacities in all major planes of load application. The methods for calculating load capacities are defined in the ISO 14728 standard.

The radial loading of constant magnitude and direction which a linear rolling bearing can theoretically endure for a nominal life of 100 km distance travelled (acc. to ISO 14728-1).

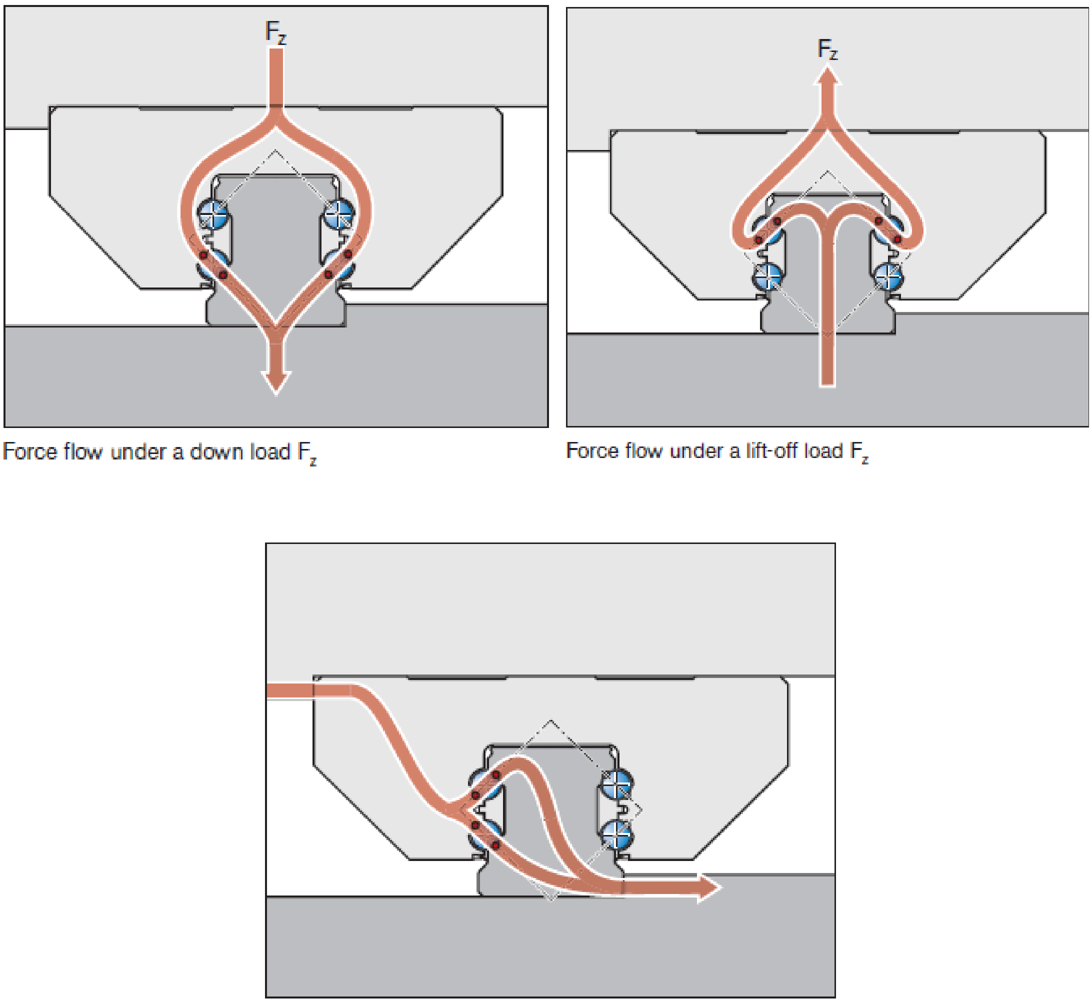
The static load in the direction of loading which results in a permanent overall deformation of approximately 0.0001 times the rolling element diameter at the center of the most heavily loaded rolling element/raceway contact (acc. To ISO 14728-2). According to ISO 14728-2, this corresponds to a calculated contact stress at the contact point of:

4200 to 4600 MPa for ball rail guides
4000 MPa for roller rail guides

The dynamic load moments M_t and M_L and the static load moments M_{t0} and M_{L0} are calculated from the load capacities, the geometry, the number of rolling element rows, the number of load-carrying rolling elements, and the contact angle. They are crucial factors when the runner blocks are subjected to torsional and longitudinal moment loads.

Runner blocks are normally subjected to loading in four major planes of load application. They may, however, also be subjected to loads acting at any angle between these planes. It should be remembered that the load-bearing capability of the elements will be reduced in such cases. The reasons for this become clear when one considers the flow of forces inside the runner block, as described below.

Under down loads, lift-off loads and side loads, the force is transmitted via two rows of rolling elements or via two raceways.



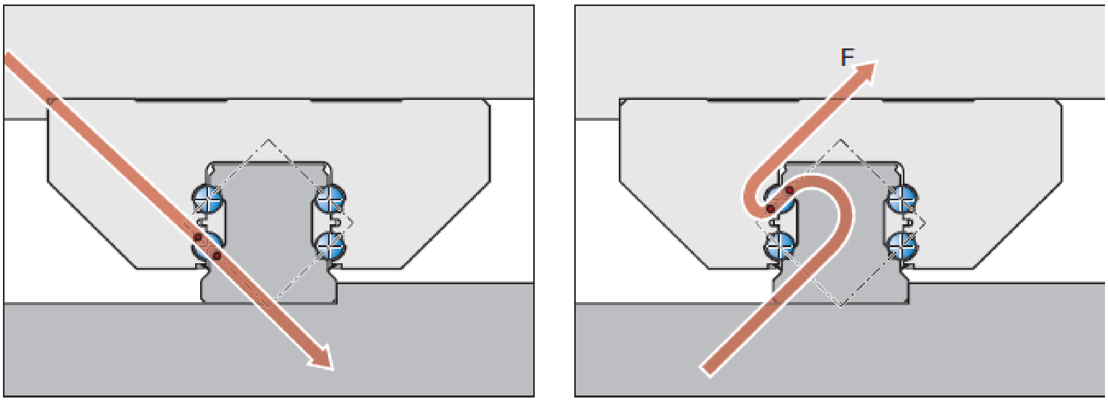
Force flow under a down load F_z

Force flow under a lift-off load F_z

Force flow under a side load F_y

Figure 3.8 Force flow

The most unfavourable direction of loading in profiled rail guides with a raceway contact angle of 45° is a load acting at an angle of 45°. In this case, the load is carried by only one row of rolling elements or one raceway.



Down load at a 45° angle | Lift-off load at a 45° angle

Figure 3.9 Angle force flow

Forces acting on the carriages attached to the module carriage were shown in the above figure of force distributions, axial load acting on screw mill axis was not shown. Since loads other than axial load affect the carriages in the module, maximum force values in these directions (axes y-z) are determined by model and number of carriage. Maximum permissible loads and moments depending on the number of carriage and model of screw mill modules are shown in the following table by calculating them based on above-mentioned principle and standards.

Table 3.1 Maximum permissible loads table

Maximum permissible loads

Size	Number of carriages	Maximum permissible forces (N)			Maximum permissible moments (Nm)	
		F_{z1max}	F_{z2max}	F_{ymax}	M_{tmax}	M_{Lmax}
CKK 12-90	1	4 620	4 620	2 490	125	16
	2	7 500	7 500	4 050	200	240
CKK 15-110	1	12 000	6 000	3 480	198	31
	2	19 490	9 740	5 650	322	414
CKK 20-145	1	29 000	14 500	8 410	638	100
	2	47 110	23 550	13 660	1 030	1 180
CKK 25-200	1	42 200	21 100	12 230	1 372	209
	2	68 550	34 270	19 880	2 228	2 999

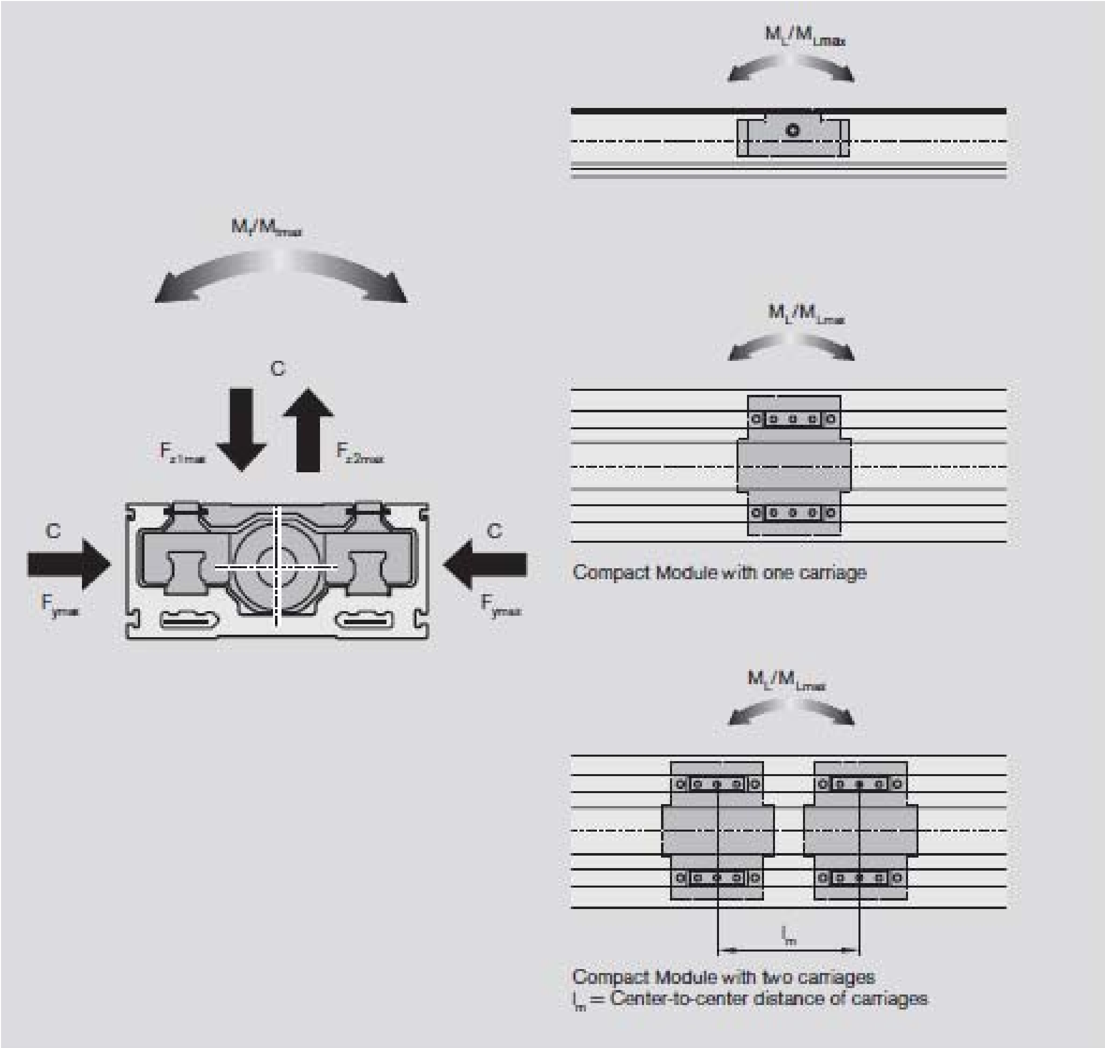


Figure 3.10 Forces acting on the module

Results of force- moment obtained by the program and catalogue force-moments were matched as follows.

Table 3.2 Y-axis force - torque matching table

Programme Presentation of force-moment	Catalogue Presentation of force-moment
F_{xr1}	F_{z1max}
$-F_{xr1}$	F_{z2max}
$\pm F_{zr1}$	$\pm F_{ymax}$
$\pm M_{xr1}$	$\pm M_l/M_{lmax}$
$\pm M_{yr1}$	$\pm M_t/M_{tmax}$
$\pm M_{zr1}$	$\pm M_l/M_{lmax}$

Since loads on screw mill axis impact nut and screw mill directly, maximum loads in this direction determine the resistance of screw mill depending on diameter and pitch of screw mill.

Unlike linear motion guides, ball screw drives can only absorb axial forces. They may not be subjected to radial forces or torque loads. These loads must be taken up by the system's linear motion guides.

The load-carrying capacity of a ball screw assembly in the axial direction is described by the ball nut's static load rating C0 and dynamic load rating C (for precise definitions, see below). The load ratings are the most important parameters describing the system's performance capability. Details of the load ratings C and C0 can be found in the product catalogues. The methods for calculating the load ratings are defined in the standard DIN 69051 Part 4.

Depending on the conditions of use, the screw (buckling risk) and the end bearings can limit the permissible loads or affect the choice of product.

The axial force of constant magnitude and direction under which a ball screw can theoretically achieve a nominal service life of one million revolutions.

The static load in the direction of loading which results in a permanent overall deformation of approximately 0.0001 times the ball diameter at the center of the most heavily loaded ball/raceway contact.

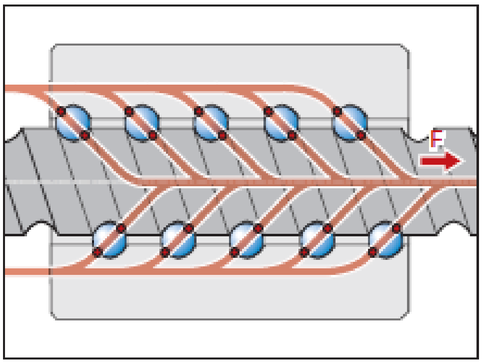


Figure 3.11 Ball screw force flow

A ball screw driver can only take up forces acting in the axial direction. All other loads must be carried by the guide units. Depending on the application, the axial forces may include weight forces F_g, acceleration forces F_a ,process forces F_p , and friction forces F_R .

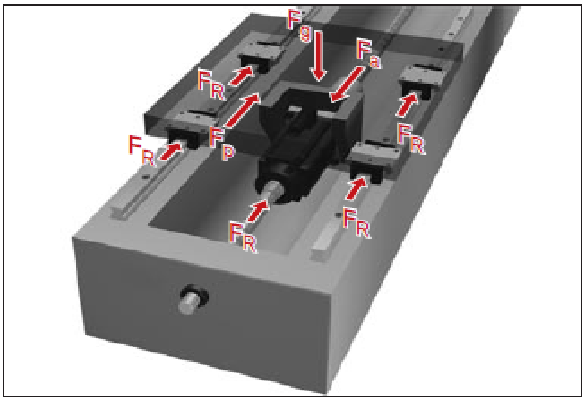


Figure 3.12 Ball screw axial force

The table below provides a summary of the forces that may arise in a system with a ball screw drive.

Table 3.3 Force definition table

Force	Formula	Description
Weight force	$F_g = m \cdot g$	The effective weight force F_g is calculated from the mass m and the acceleration due to gravity g = 9.81 m/s².
Acceleration force	$F_a = m \cdot a$	The effective acceleration force is the force that must be applied to accelerate a mass.
Friction force	$F_R = \mu \cdot F_N$	The effective friction force is opposed to the direction of movement. Its magnitude is determined, among other factors, by the ball screw assembly's preload, load, sealing and lubrication as well as by the end bearings and the guides.
Process force	F_p	The effective process forces will depend on the specific processing operation. These may be, for instance, forces arising during molding/extrusion, forming, machining, etc.

When performing calculations, particular attention must be paid to the direction in which the individual forces act permissible axial screw load.

$$F_k = f_{Fk} \times \frac{d_2^4}{I_k^2} \times 10^4 \text{ (N)}$$

$$F_{kperm} = \frac{F_k}{2}$$

F_k = theoretical buckling load of the screw (N)

$F_{k\,perm}$ = permissible axial load on the screw in service (N)

f_{Fk} = coefficient as a function of the end bearings (–)

d_2 = screw core diameter (see product catalogue) (mm)

l_k = effective buckling length of the screw (mm)

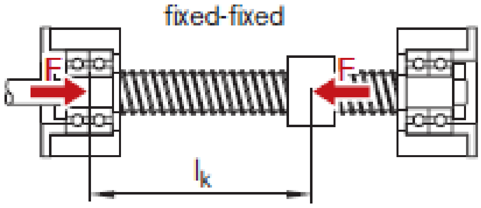
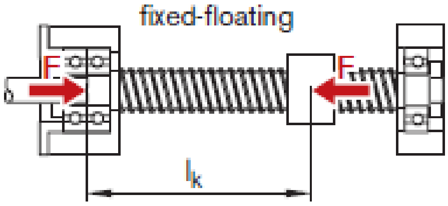
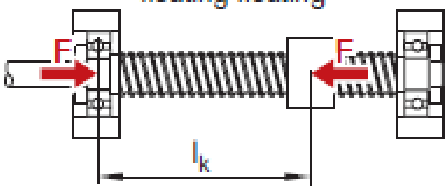
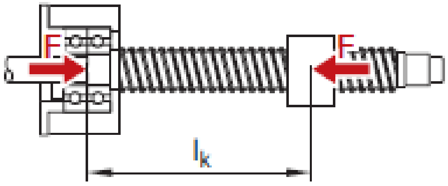
End fixity	Coefficient f_{Fk}
fixed-fixed 	40.6
fixed-floating 	20.4
floating-floating 	10.2
fixed-free 	2.6

Figure 3.13 Ball screw bearing

The following formulas can be used for an initial estimation of the required drive torque and power.

An applied drive torque Mta causes the screw to rotate. As a reaction to the screw's rotation, a linear force F is generated in the ball nut, which causes linear motion of the nut.

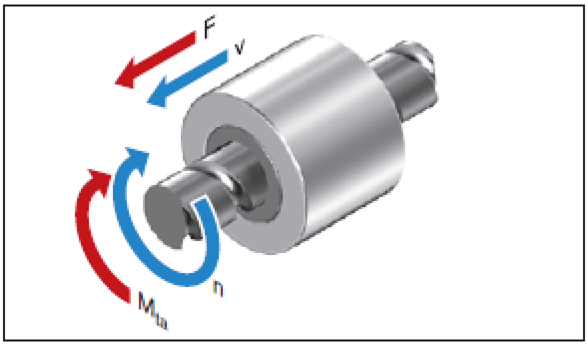


Figure 3.14 Conversion of rotary to linear motion

$$M_{ta} = \frac{f \times P}{2000 \times \pi \times \eta} \text{(Nm)}$$

M_{ta} = drive torque (Nm)

M_{te} = transmitted torque (Nm)

F = operating load (N)

P = lead (mm)

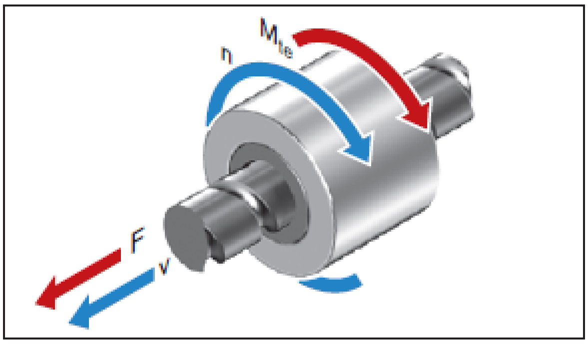


Figure 3.15 Conversion of linear to rotary motion

$$M_{te} = \frac{f \times P \times \eta'}{2000 \times \pi} \text{ (Nm)}$$

η = mechanical efficiency

η ≈ 0.9 for drive torque

η′ ≈ 0.8 for transmitted torque

$$Pa = \frac{M_{ta} \times n}{9550} \text{ (Kw)}$$

P_a = drive power (kW)

M_{ta} = drive torque (Nm)

n = rotary speed (min-1)

Maximum permissible loads and moments of screw mill modules depending on screw mill diameter and pinch are shown below by calculating as per above-mentioned principle and standards.

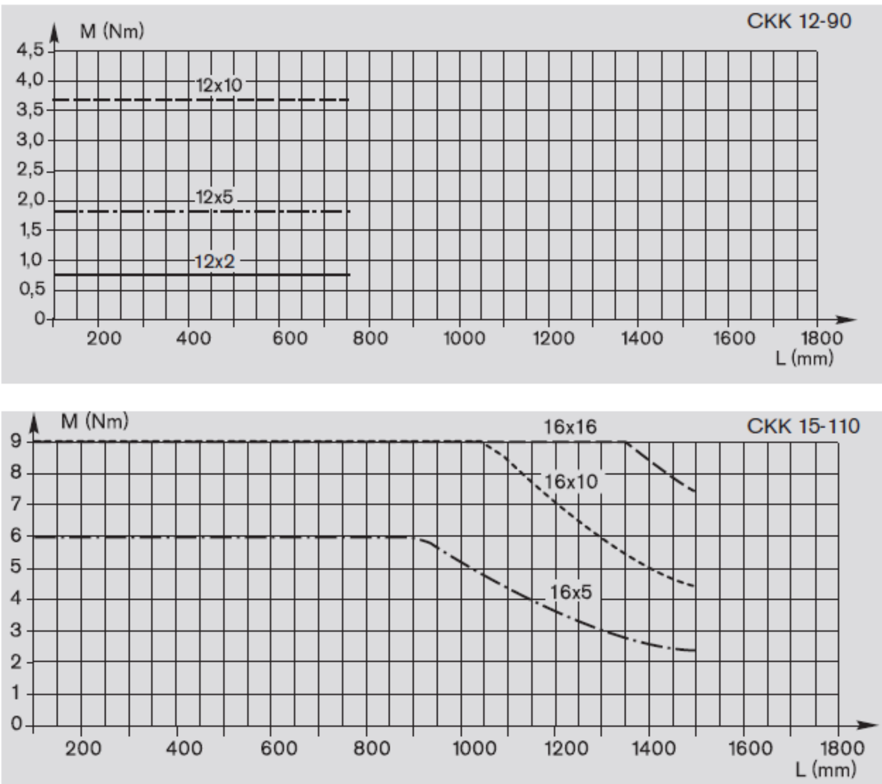


Figure 3.16 Moment graphs

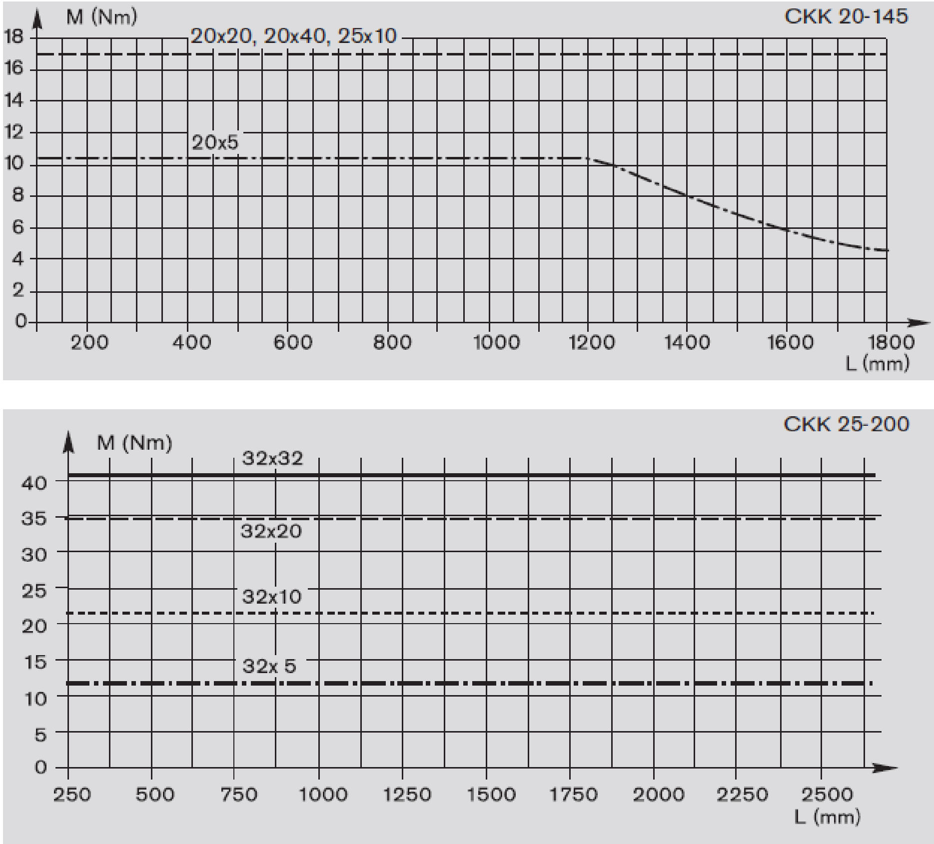


Figure 3.16 Continued

Operating moments and axial loads can be calculated by the diameter, pinch and stroke variables by means of the equations obtained by these graphs in the calculation program.

As a result of this calculation, values of Fyrl and Tmotor are found.

3.1.3 Critical speed

The rotation of the screw causes bending vibrations (also known as screw whip). The frequency of these vibrations is the screw's rotation frequency. The "critical speed" is the rotary speed that is equivalent to the first order frequency of the screw. If the ball screw assembly is operated at the critical speed, resonance occurs, which can lead to destruction of the system. To avoid this, the critical speed must be determined when performing the design calculations for the ball screw.

The critical speed nk depends on:

- the type of end bearings, coefficient f_{nk}
- the screw's core diameter d_2
- the critical screw length l_n , i.e. the maximum unsupported screw length.

In the case of ball nuts with backlash, the critical screw length is the same as the bearing-to-bearing length l1. In preloaded systems, the position of the ball nut is taken into account.

The product catalogue contains charts for quickly checking the calculation results. When dimensioning and selecting ball screw drives, the operating speed should never be more than 80% of the critical speed. The characteristic speed and the maximum permissible linear speed must not be exceeded.

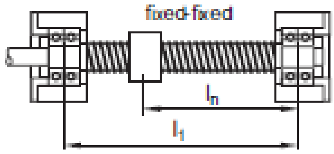
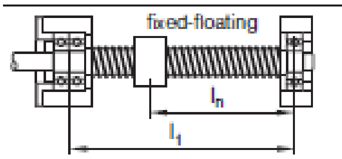
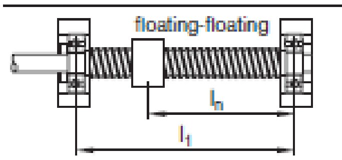
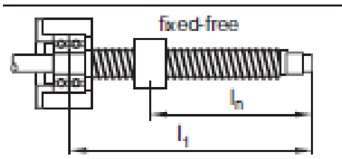
End fixity	Coefficient f_{nk}
fixed-fixed 	27.4
fixed-floating 	18.9
floating-floating 	12.1
fixed-free 	4.3

Figure 3.17 Bearing of ball screw

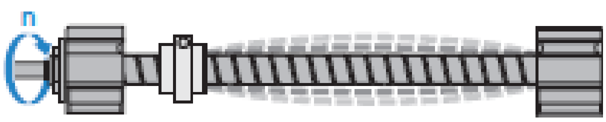


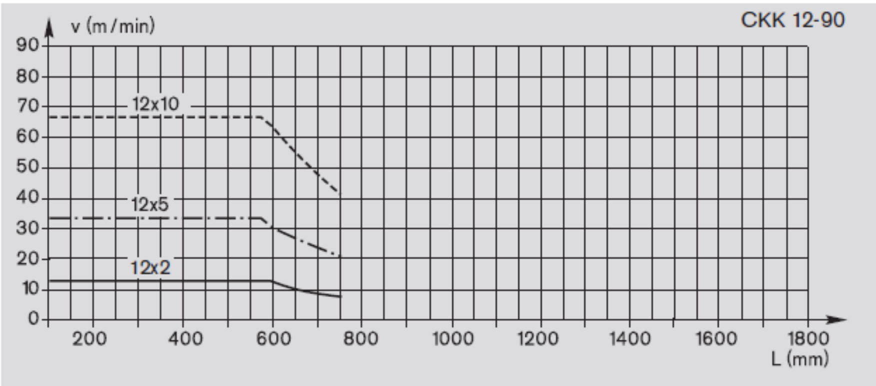
Figure 3.18 Bending vibrations

$$n_k = f_{nk} \times \frac{d_2}{I_n^2} \times 10^7 \,(\min^{-1})$$

$$n_{kperm} = n_k \times 0{,}8$$

n_k = critical speed (min–1)
$n_{k\,perm}$ = permissible operating speed (min–1)
f_{nk} = coefficient as a function of the
end bearings (–)
d_2 = screw core diameter
(see product catalogue) (mm)
l_1 = bearing-to-bearing distance (mm)
l_n = critical screw length for preloaded
nut systems (mm)
(For nuts with backlash: $l_n = l_1$)

Graphics for the speed for the modules depending on stroke values, pitch and screw mill diameters used in screw mill modules are as follows. Critical speed and acceleration values can be calculated by the variables of diameter, pitch and stroke by means of equation found by the graphics in the calculation program.



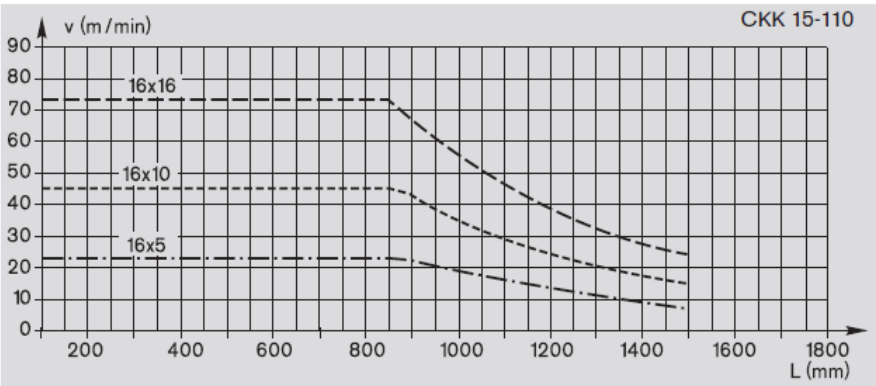
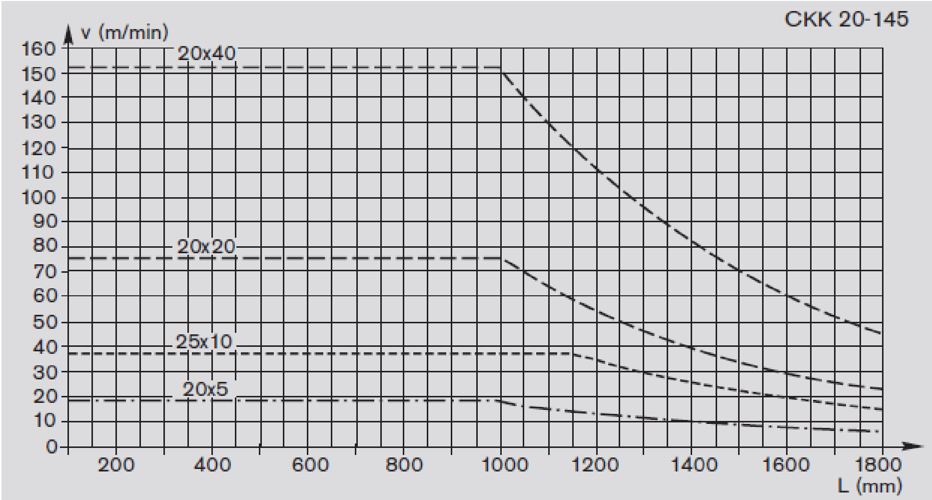


Figure 3.19 Speed graphics



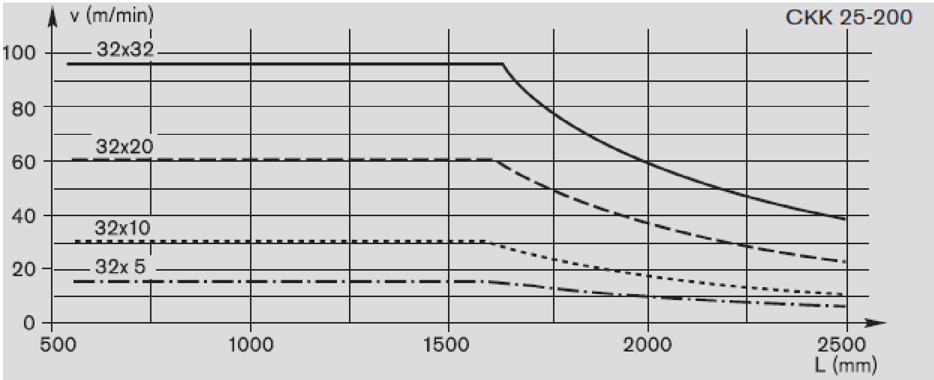


Figure 3.19 Continued

3.1.4 Choosing the Linear Module

When we examine axis Y at 1200 maximum stroke position with 20 kg manifold weight, we should add the spray pressure force and linear module weight to the forces acting on the axis.

If we suppose that air or water outlet is present at 10 bar from 16 nozzles being 3 mm in diameter under maximum conditions, force acting on the axis is 113N.

Fs = (16*10*(1.5^2)*3,14)/10 = 113N

We can find the weight of a linear module having 1200 mm progressing distance by the catalogue table values. Module weight is calculated as excluding motor weight by stroke variable and values of this table in the program.

Table 3.4 Table of weight by modules

Size	Ball screw	Number of carriages	Weight (kg)
CKK 12-90	with	1	0.0055 · L + 0.9
		2	0.0055 · L + 1.2
CKK 15-110	with	1	0.0092 · L + 1.6
		2	0.0092 · L + 2.0
CKK 20-145	with	1	0.0178 · L + 3.0
		2	0.0178 · L + 3.9
CKK 25-200	with	1	0.0299 · L + 6.7
		2	0.0299 · L + 8.7

Module weights for L = 1200 mm.

Table 3.5 Table of Module Weights

CKK 12-90	1	7,5kg
CKK 12-90	2	7,8kg
CKK 15-110	1	12,64kg
CKK 15-110	2	13,04kg
CKK 20-145	1	24,36kg
CKK 20-145	2	25,28kg
CKK 25-200	1	42,58kg
CKK 25-200	2	44,58kg

Since selection of module has not been completed, we can designate the estimated weight of other materials necessary for the motor and system as 8 kg.

Table 3.6 Load table for the axis Y

Spraying Manifold (N)	200	Axis Y loading
Pressure reaction force(N)	113	Axis X loading
Module weight (N)	Calculated based on the module	Axis Y loading
Motor weight (kg)	8 (estimated value)	Axis Y loading

Cycle time for cast spraying operation was designated as 20 sec. Axes should be proceed with maximum stroke during this cycle time and return when spraying operation is realized. Spraying lasts for 5 – 10 seconds by the injection process and form of mold in general applications. Each axis can go and return up to 1200 mm being the maximum stroke distance within remaining 10 seconds. This can be calculated as 240 mm/s and 14400 mm/min. If screw mill linear axis module pitch of which is 10 mm is chosen, the speed of the motor may be calculated as 1440 cycle/min.

Since maximum forcing moment will be evaluated while calculating by means of the program, it will be accepted that it acts as accelerating at the above speed rates. For this reason, movement in the direction of +Y is selected as the program input and time data will be entered and it will be studied whether the speed and acceleration found by the calculations with the above-tables is fit for the system and modules or not.

Table 3.7 Speed table for the axis Y.

Speed (m/sec)	0,24
Time (sec)	0.5

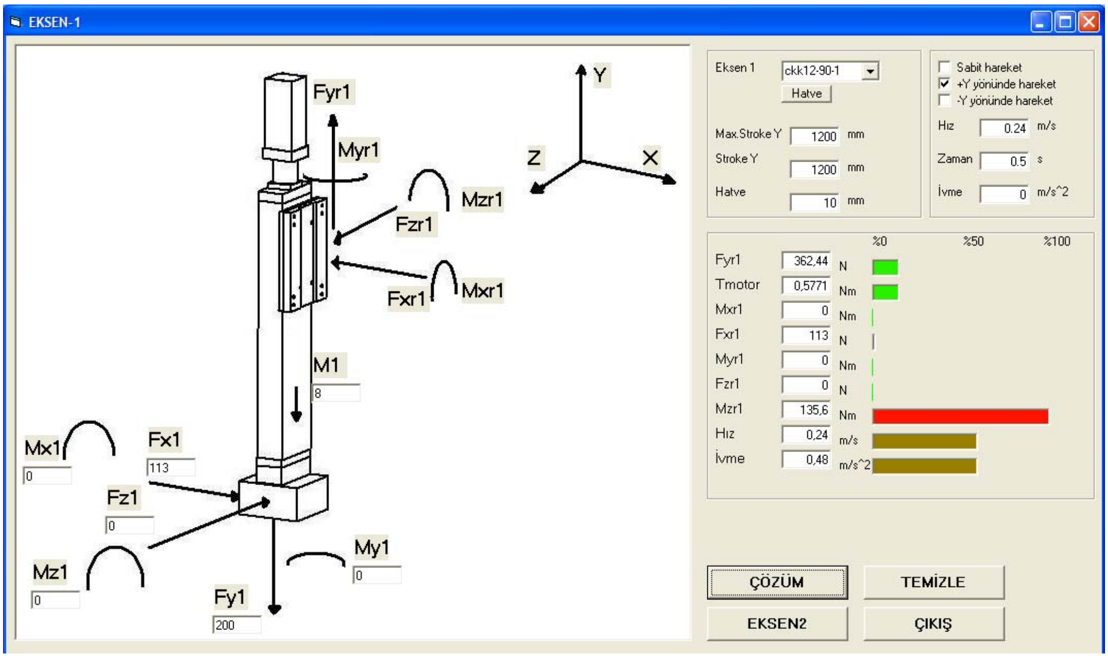


Figure 3.20 Results for Ckk 12-90-1

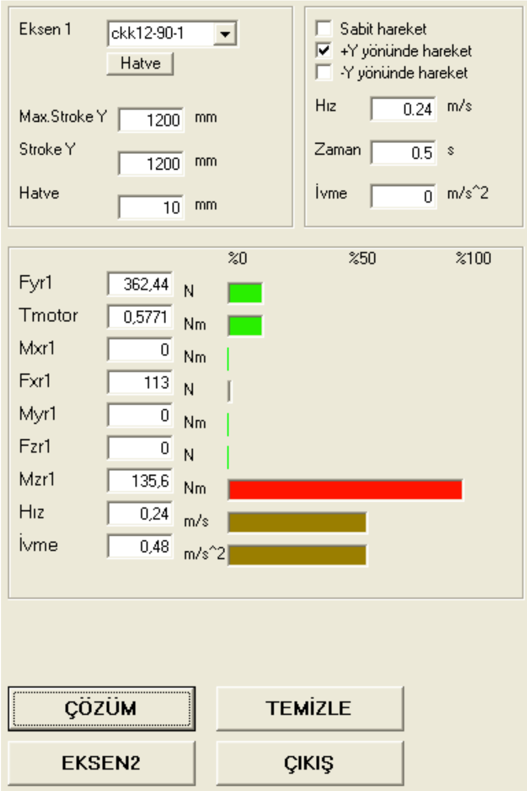


Figure 3.21 Results for Ckk 12-90-1

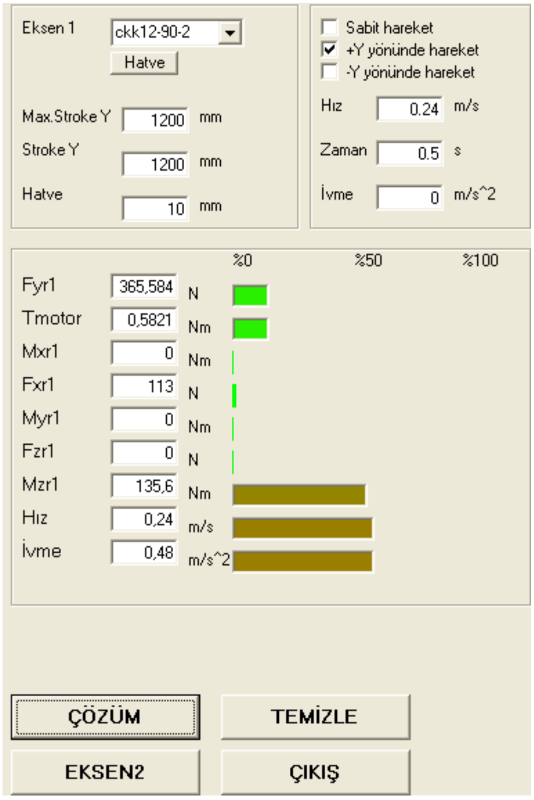


Figure 3.22 Results for Ckk 12-90-2

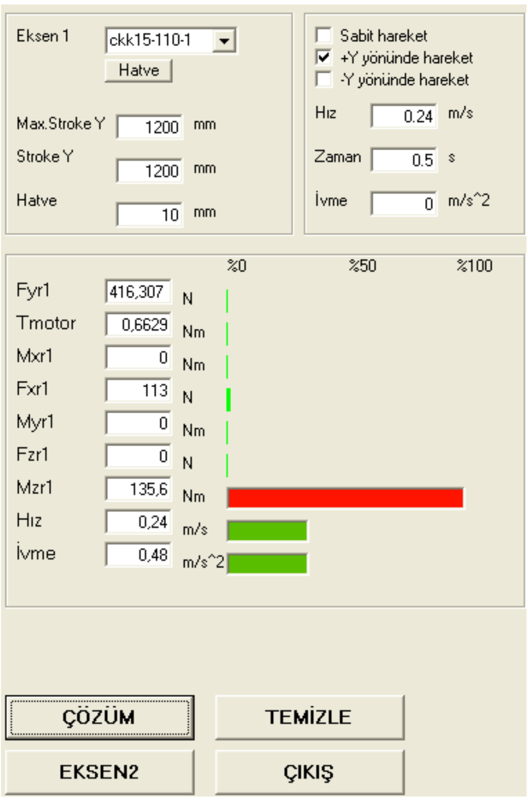


Figure 3.23 Results for Ckk 15-110-1

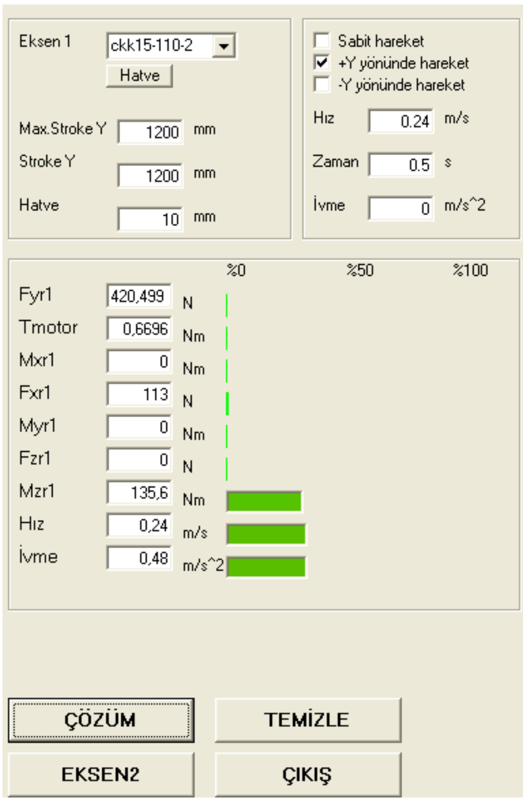


Figure 3.24 Results for Ckk 15-110-2

The most proper result of the product coded CKK 15-110-2 was given in the values entered. Since it is vertical axis, reaction forces in the direction of y met the nut and mill and motor torque could be calculated by the load from this axis. Pressure force from manifold acted as the force in the direction of x and moment in the direction of x. While motor torque was calculated as 0,67 Nm, M_{zr1}(M_{I}) moment was 50% below of the axis capacity and operates safely.

Let's examine the impact forces on axis Y and axis X as accepted axis Y as CKK 15-110-2.

Table 3.8 Load table for axis X

Fx(N)	113
Fy(N)	420
Mzr(Nm)	135
Module Weight (N)	Calculated based on the module
Motor Weight (kg)	8 (estimated value)

Table 3.9 Speed table for the axis X

Speed(m/sec)	0,24
Time (sec)	0.5

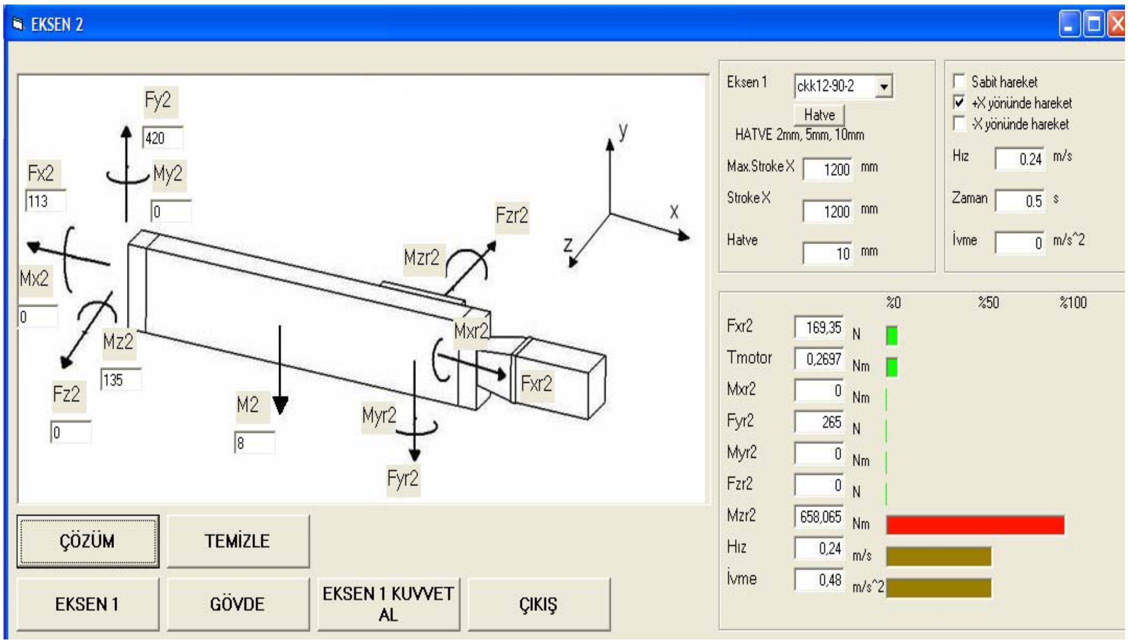


Figure 3.25 Results for Ckk 12-90-2

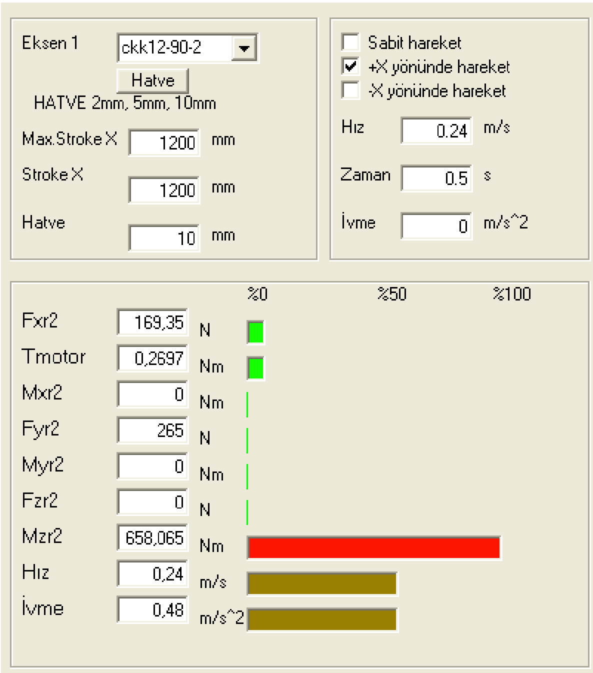


Figure 3.26 Results for Ckk 12-90-2

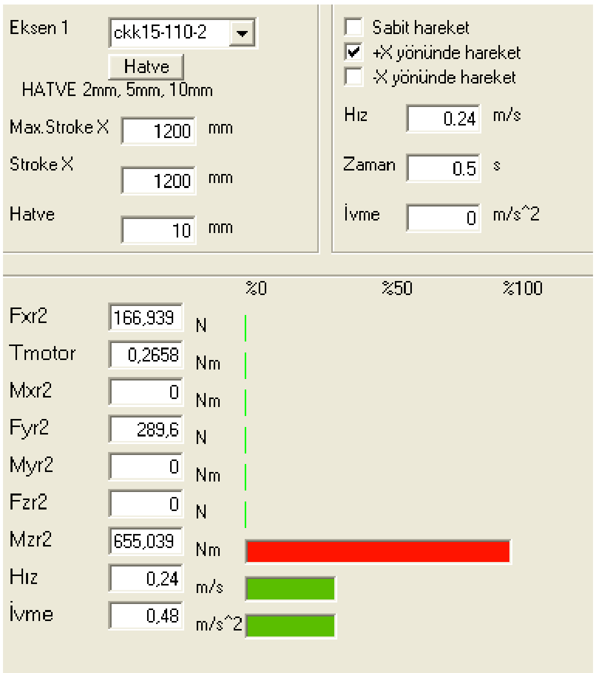


Figure 3.27 Results for Ckk 15-110-2

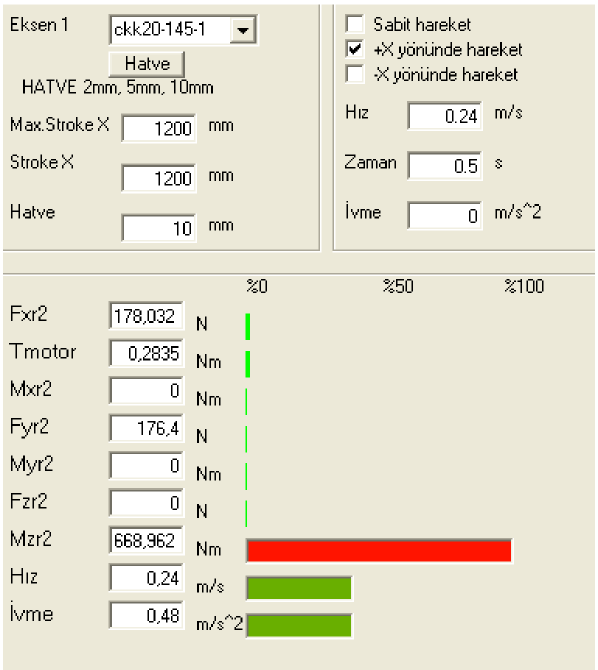


Figure 3.28 Results for Ckk 25-145-1

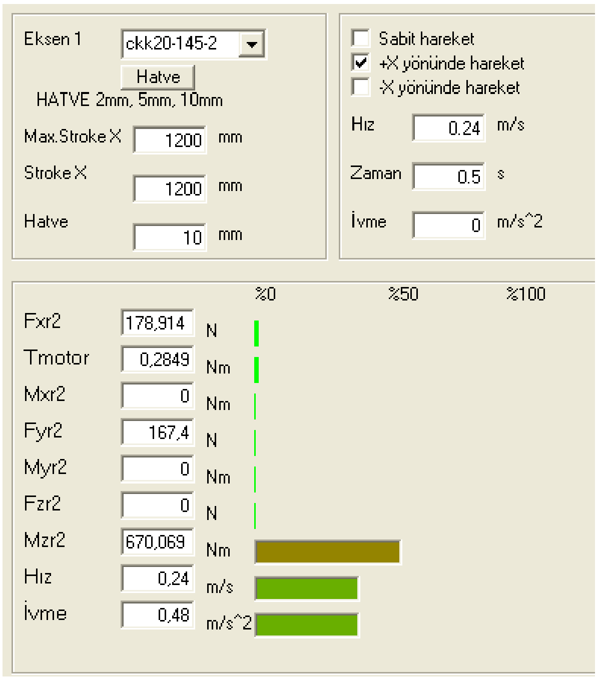


Figure 3.29 Results for Ckk 25-145-2

Total axis X was used to calculate the motor torque to use reaction force and shown as T_{motor}.

Table 3.10 Force-moment matching table for axis X

Expressing of force-moment on the program	Expressing of force-moment on the catalogue
F_{zr2}	F_{z1max}
$-F_{zr2}$	F_{z2max}
$\pm F_{yr2}$	$\pm F_{ymax}$
$\pm M_{xr2}$	$\pm M_{l}/M_{lmax}$
$\pm M_{yr2}$	$\pm M_{t}/M_{tmax}$
$\pm M_{zr2}$	$\pm M_{t}/M_{tmax}$

Products coded CKK 12-90-2, CKK 15-110-2, CKK 20-145-1, CKK 20-145-2 were tried for axis X in the values entered respectively and the product coded CKK 20-145-2 yielded the most proper result.

Forces on the vertical axis and all of axis loads constituted M_{zr2} (M_t) moment. M_{zr2} moment was close to 50% value of axis capacity and this value is considered as the safe operation. Although F_{xr2} and F_{yr2} forces were found as 178,9 N and 167,4 N, it is seen that these values are very low in terms of axial and lateral load capacity.
Motor torque value for axis X was calculated as 0, 285 Nm. Since axis Y is the vertical axis and should operate against gravity, although it carries more loads, it is seen that motor torque value is more than axis X.

We can examine the result that the system will yield to be created by existing modules to be used for prototype at the same load values.

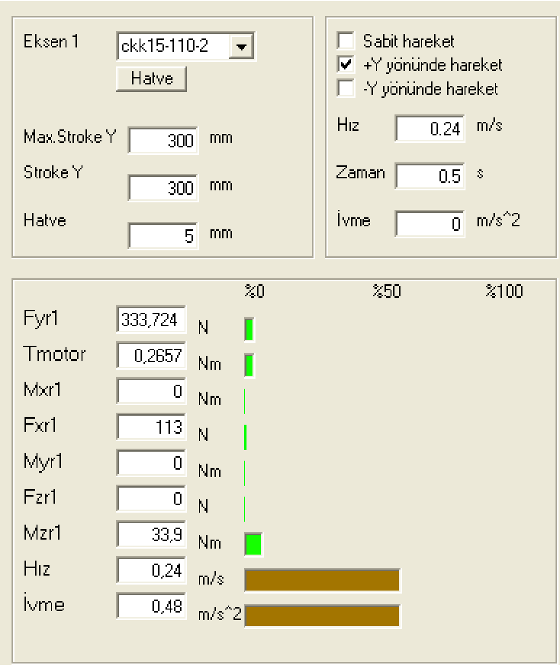


Figure 3.30 Results for Ckk 15-115-2

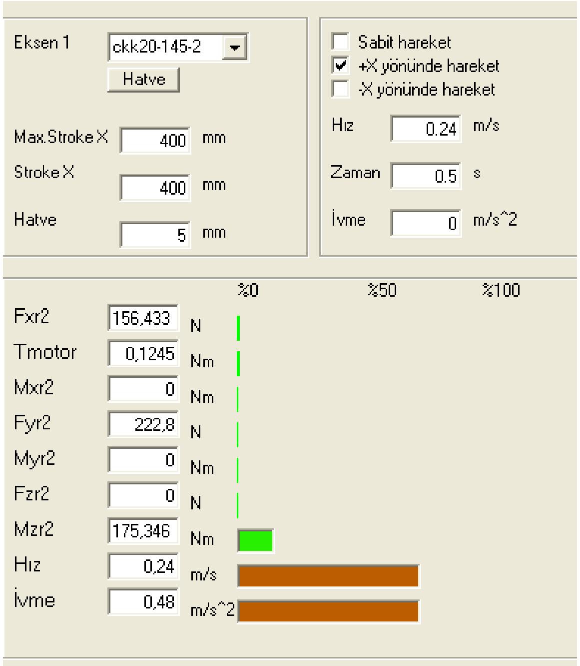


Figure 3.31 Results for Ckk 20-145-2

300 mm stroke, 5 mm pitch 110 body module in axis Y will be applied. As total module length shortened, force arm of F_{x1} force shortened. In this case, M_{xr1} moment reached to a low value.

Static operating values if 400 mm stroke and 5 mm pitch CKK-20-145-2 is used in the prototype system are as above. It is seen that moments delivered by the bearings are less than real system due to shortening of force arms in axis X.

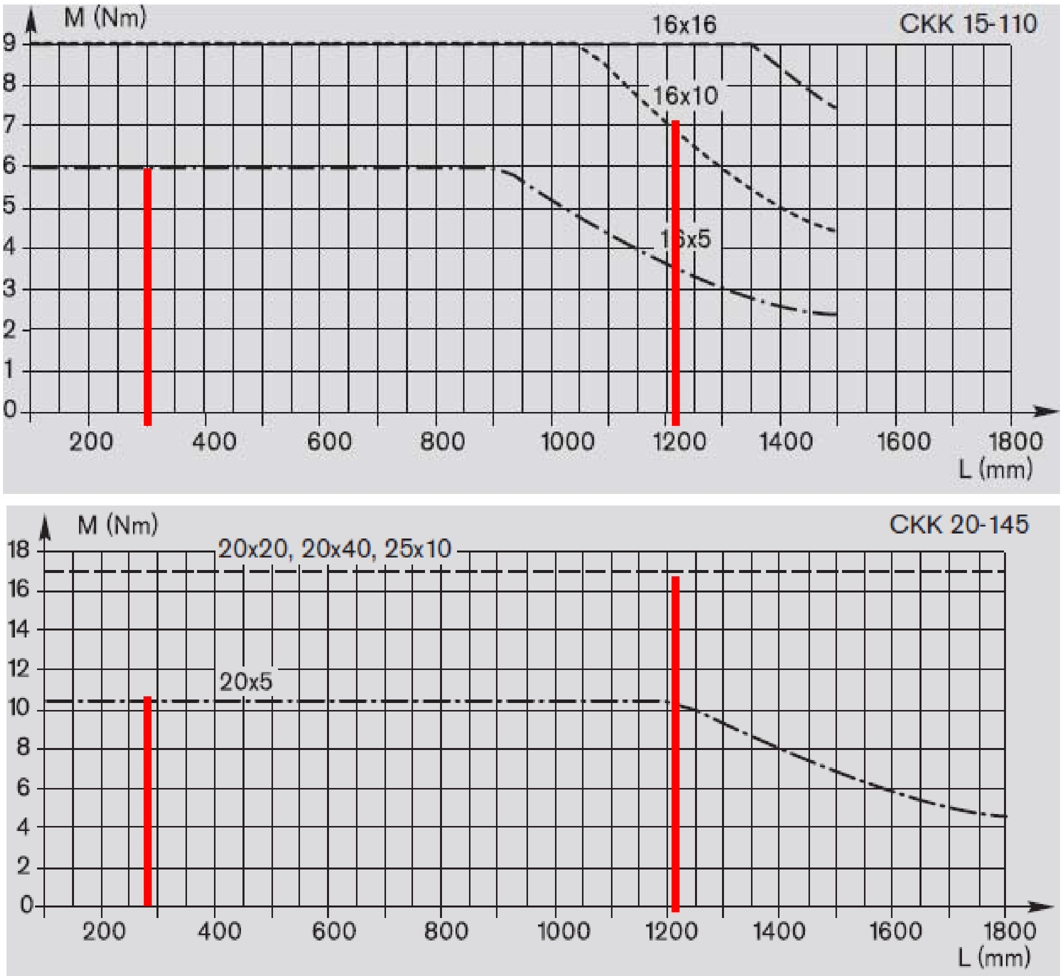


Figure 3.32 Moment- stroke tables for the axes X-Y

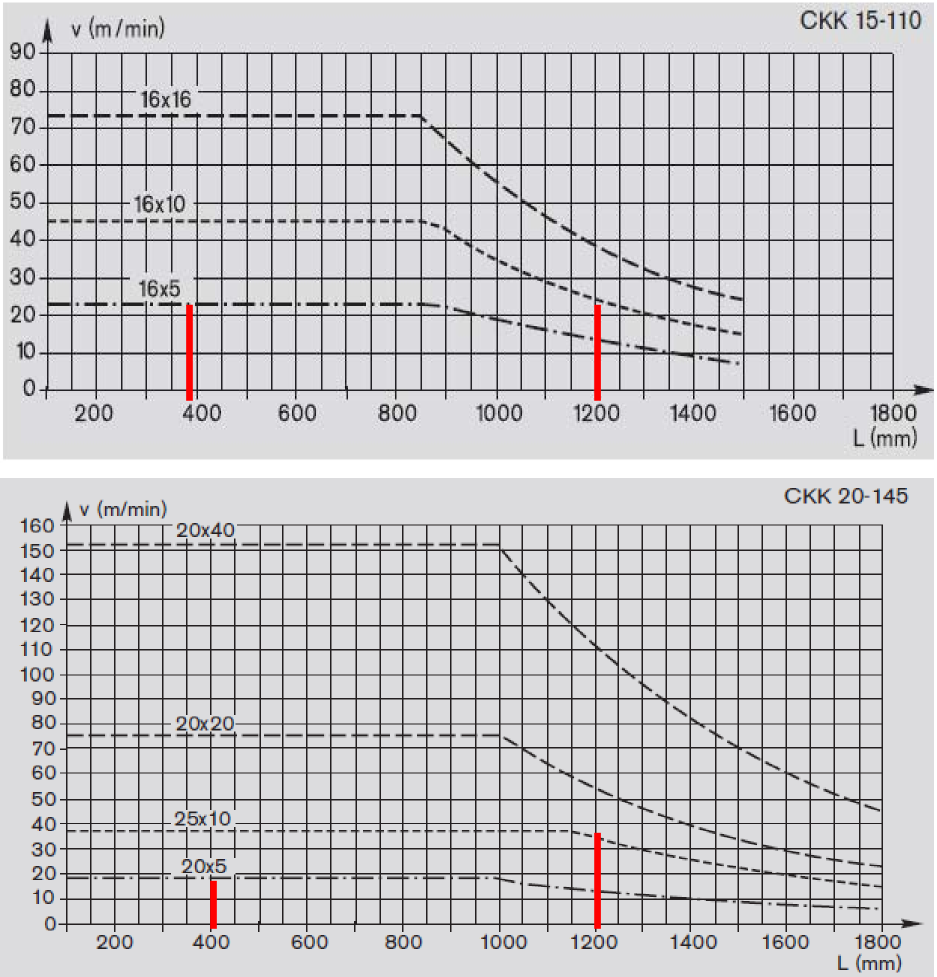


Figure 3.33 Speed- stroke tables for the axes X-Y

Maximum speed and moment values are seen in the above graphics for module and strokes chosen in real and prototype systems.

CHAPTER FOUR
DESIGN AND PRODUCTION OF THE PROTOTYPE SYSTEM

4.1 Design Data

Elements to be used in the design are as follows:

Axis Y:

Table 4.1 Module data for the axis Y

Linear Module	CKK 15-110-2 Ball screw linear module
Stroke (mm)	300
Diameter (mm)	16
Pitch (mm)	5
Motor Power (Kw)	0,4
Motor Speed (d/min)	3000

Axis X:

Table 4.2 Module data for axis X

Linear Module	CKK 20-145-2 Ball screw linear module
Stroke (mm)	400
Diameter (mm)	20
Pitch (mm)	5
Motor Power (Kw)	0,75
Motor Speed (d/dk)	3000

The prototype system and elements and parts designed are shown below.

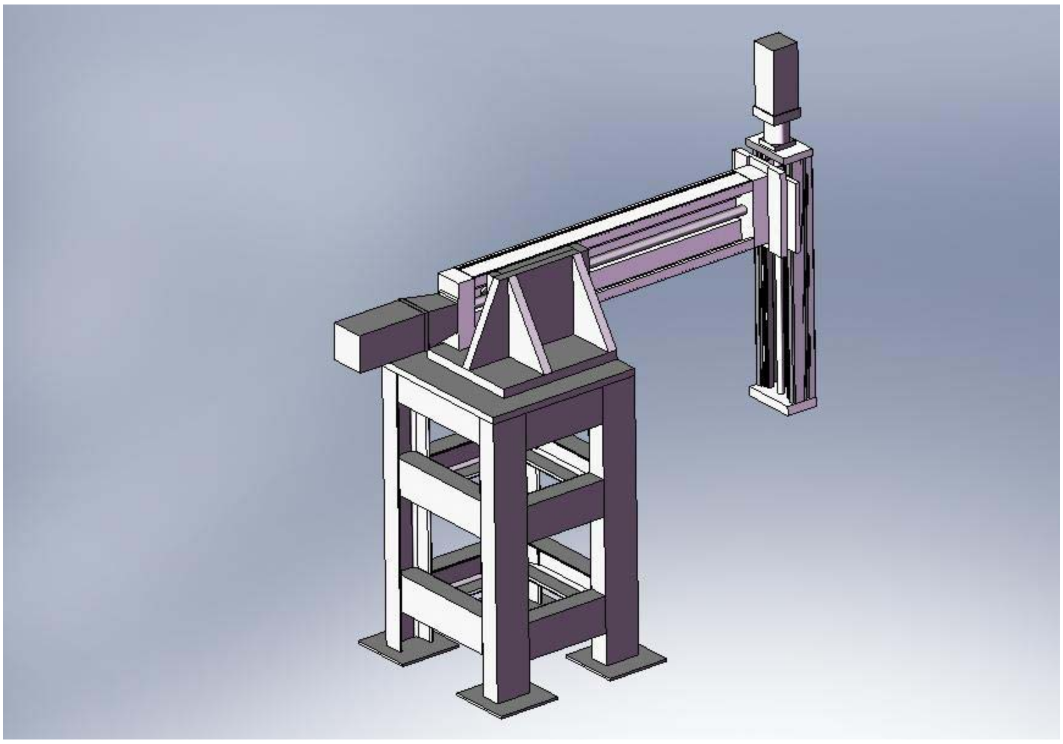


Figure 4.1 Design of the prototype

4.2 Analyses and Results

4.2.1 Frequency Analyses of the Cartesian System

For the Cartesian system to run stable, the lower table must have a structure that is not affected by the loads and vibration. Thus it would be useful to keep the natural frequency of the table greater than working frequency of the system. Frequency values of the designed table and system was calculated via finite elements method and compared using COSMOSWORKS software.

Frequency analysis and results of the lower table of which simple model without details in real size are given below. Evaluating analysis of the first three mode frequency should be sufficient for such systems.

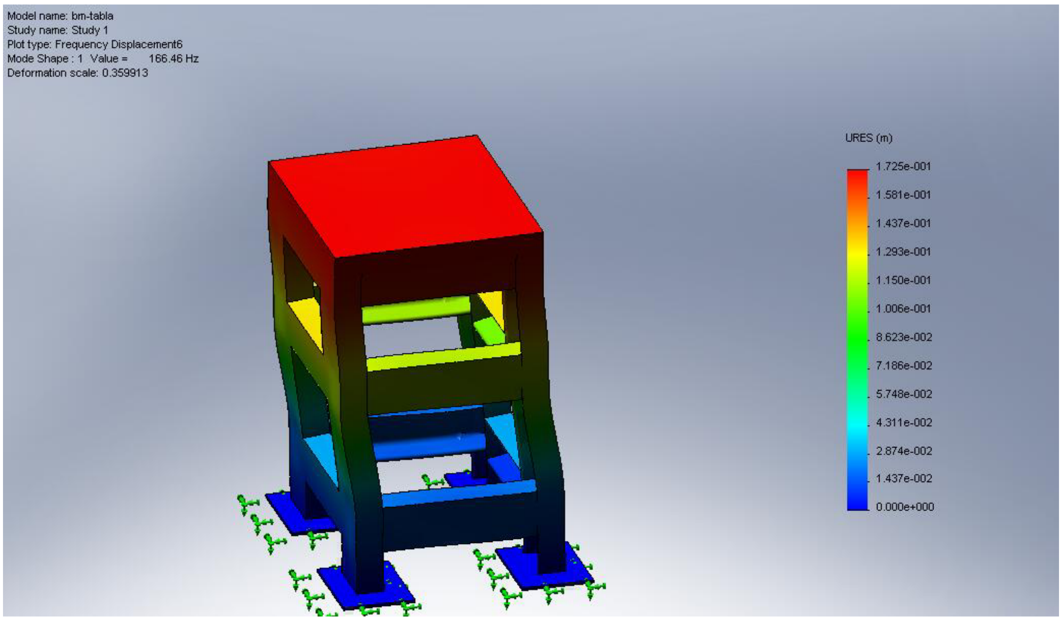


Figure 4.2 1. Mode frequency

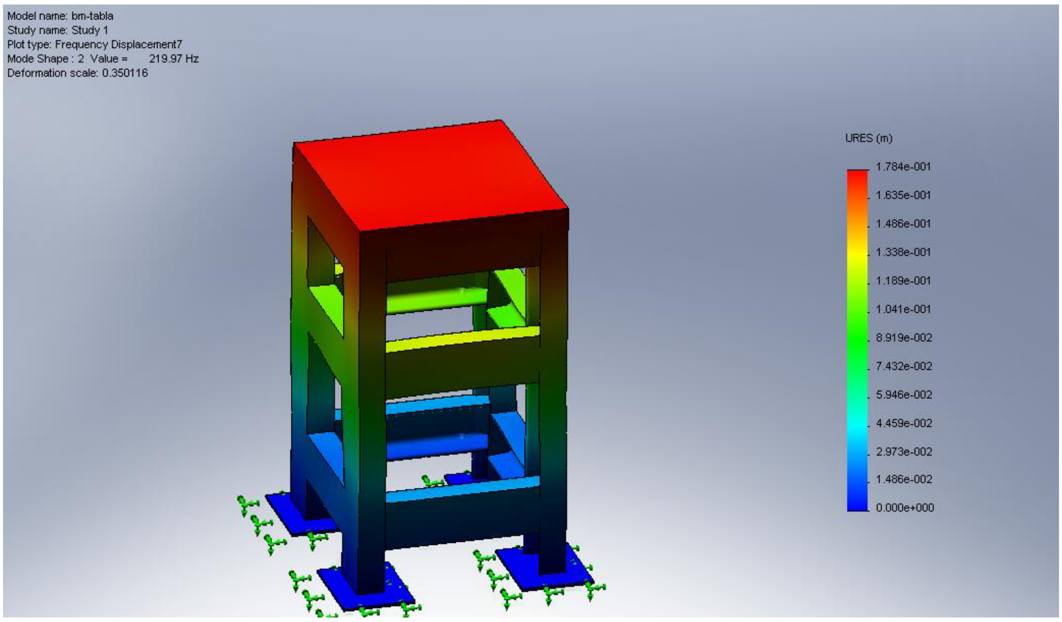


Figure 4.3 2. Mode frequency

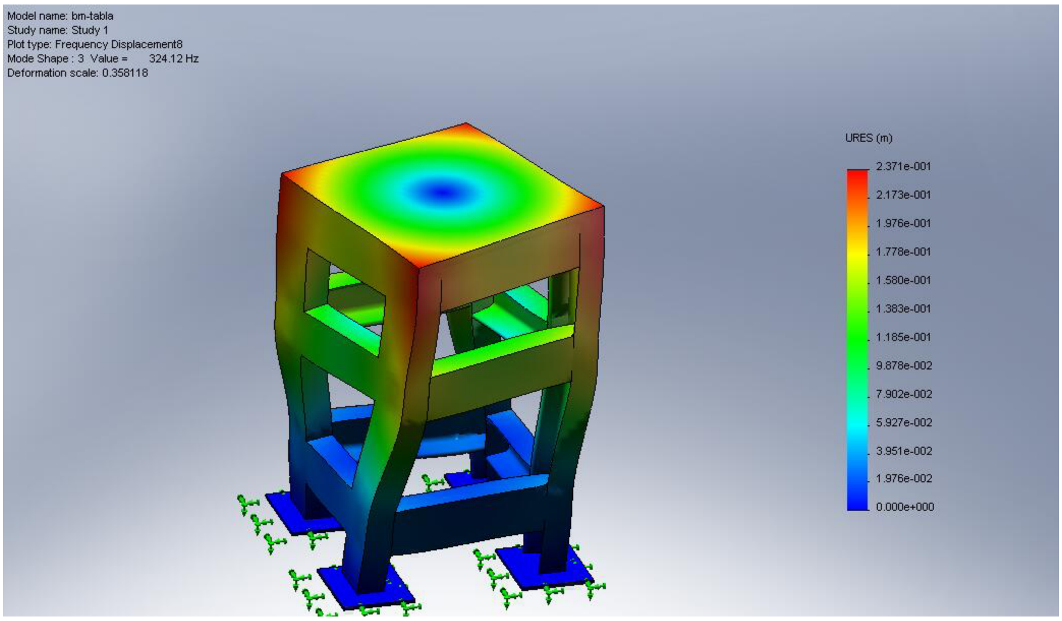


Figure 4.4 3. Mode frequency

Table 4.3 Results for Table Frequency

1. Mode Frequency	166,46 Hz
2. Mode Frequency	2199,97 Hz
3. Mode Frequency	324,12 Hz

Simple models of the modules were prepared to ease the finite element analyses of outer bodies of the linear modules which were in profile structure of Aluminium Sigma. The point to be paid attention in creating simple modules of the linear modules is that the main sizes of the linear module and actual models of the inertia moments sectioned must be the same with values of actual models.

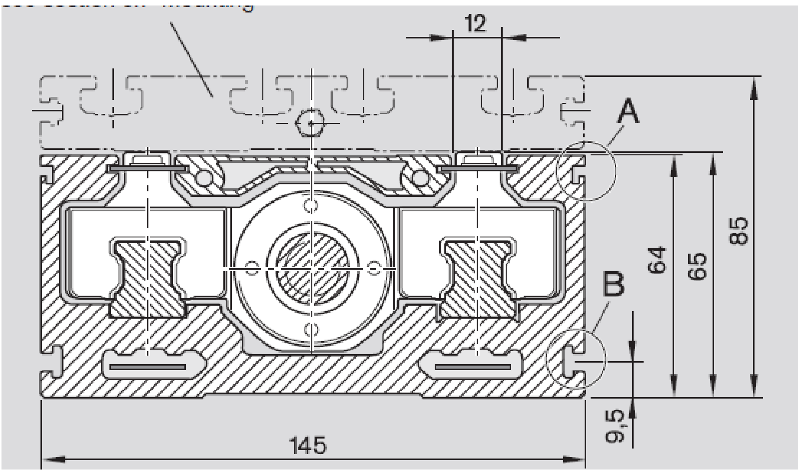


Figure 4.5 Section of the module

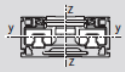
Size	Number of carriages	Ball screw	Dynamic load capacity C (N)			Dynamic moments		Planar moment of inertia 	
		d_0 x P	Guideway	Ball screw	Fixed bearing	M_t (Nm)	M_L (Nm)	I_y (cm^4)	I_z (cm^4)
CKK 12-90	1	12 x 2	4620	2240	6900	125	16	14.32	124.4
		12 x 5		3800					
		12 x 10		2500					
	2 (l_m = 65 mm)	12 x 2	7500	2240	6900	200	240	14.32	124.4
		12 x 5		3800					
		12 x 10		2500					
CKK 15-110	1	16 x 5	15600	12300	13400	515	80	37.74	318.7
		16 x 10		9600					
		16 x 16		6300					
	2 (l_m = 85 mm)	16 x 5	25340	12300	13400	835	1075	37.74	318.7
		16 x 10		9600					
		16 x 16		6300					
CKK 20-145	1	20 x 5	37600	14300	17000	1650	255	114.10	986.4
		20 x 20		9100					
		20 x 40		14000					
		25 x 10		15700					
	2 (l_m = 100 mm)	20 x 5	61080	14300	17000	2685	3050	114.10	986.4
		20 x 20		9100					
		20 x 40		14000					
		25 x 10		15700					

Figure 4.6 Area inertia moments

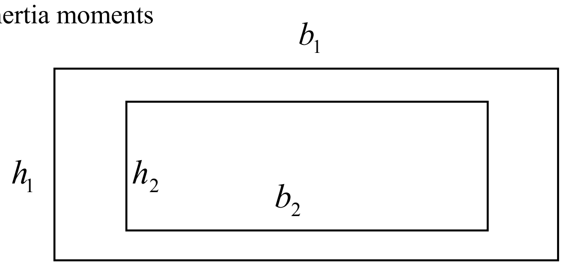


Figure 4.7 Section of the simple model

$$Iy = \frac{b_1 \times h_1^{\ 3}}{12} - \frac{b_2 \times h_2^3}{12}$$

$$114{,}10 = \frac{145 \times 64^3}{12} - \frac{b_2 \times h_2^3}{12} \quad \ldots\ldots\ldots..1$$

$$Iz = \frac{h_1 \times b_1^{\ 3}}{12} - \frac{h_2 \times b_2^3}{12}$$

$$966{,}4 = \frac{64_1 \times 145_1^{\ 3}}{12} - \frac{h_2 \times b_2^3}{12} \ldots\ldots\ldots2$$

From the equations 1 and 2:

b_2=108mm

h_2=60,91mm

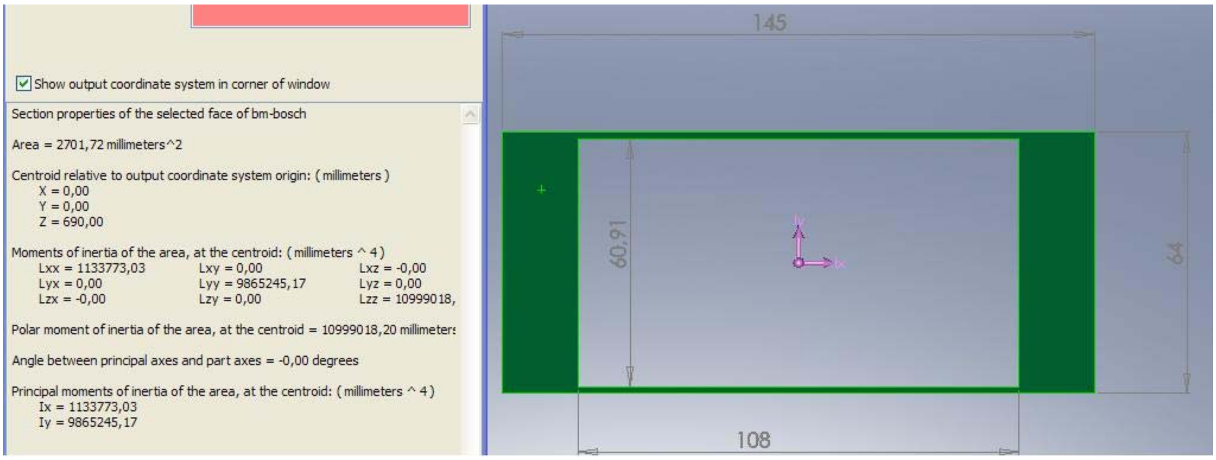


Figure 4.8 Section sizes for the simple model

Table 4.4 Section sizes and area inertia moments

	Width (mm)	Height (mm)	Iy (cm^4)	Iz (cm^4)
Actual Model	145	64	114,10	966,4
Simple Model	145	64	113,7	986,52

Frequency analysis and results for the first three modes made on the systems prepared by creating simple models of the modules are shown below.

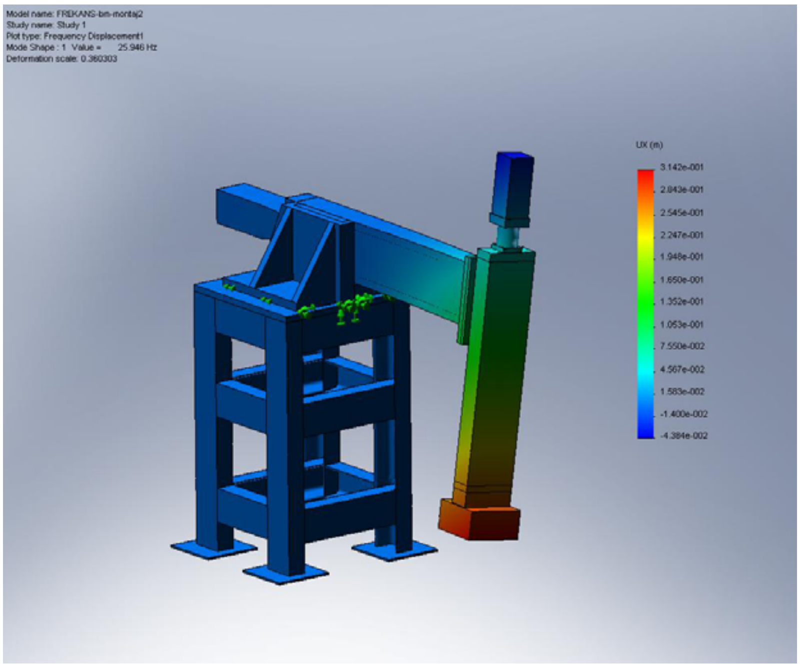


Figure 4.9 1. Mode frequency of the axes X-Y

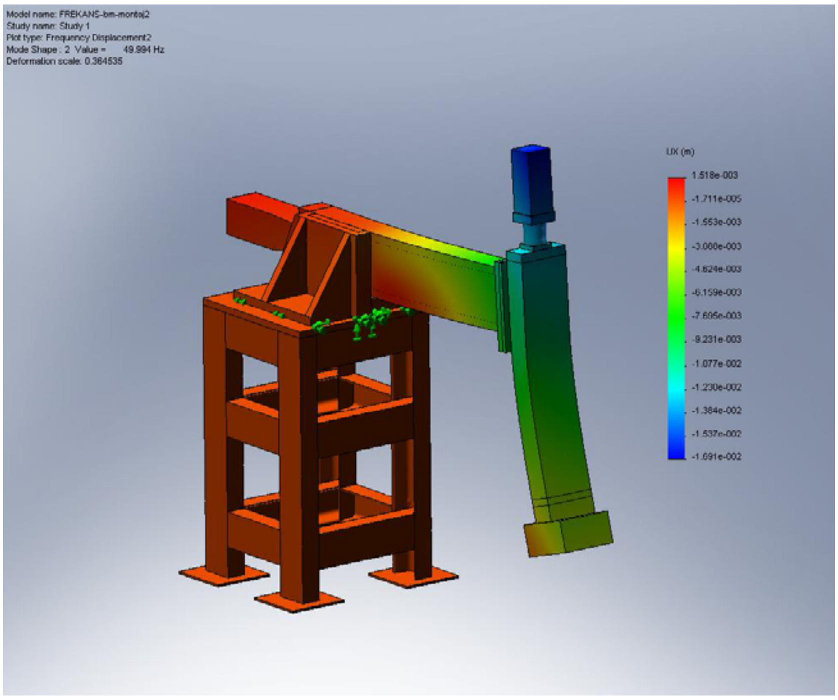


Figure 4.10 2. Mode frequency of the axes X-Y

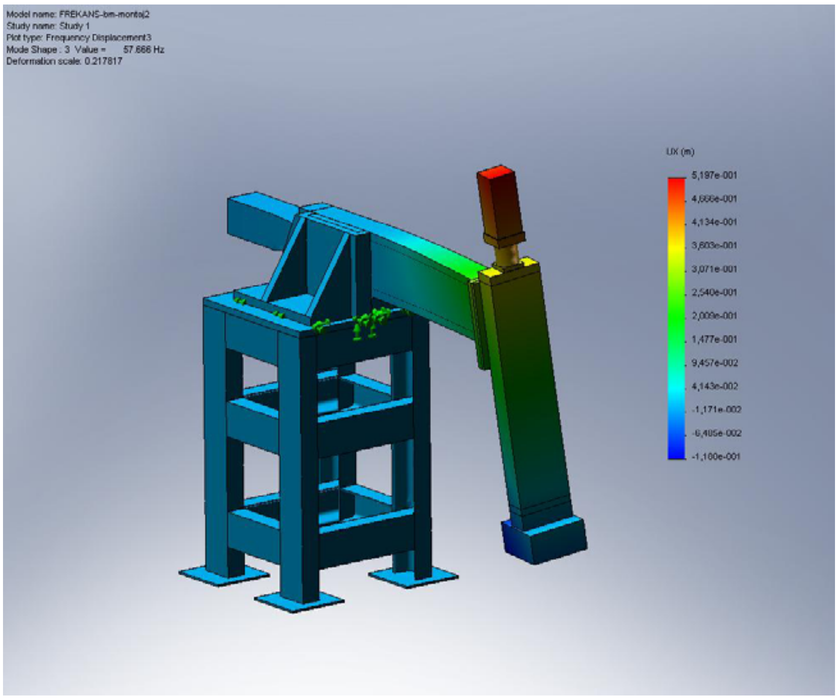


Figure 4.11 3. Mode frequency of the axes X-Y

Table 4.5 Frequency results for the axes X-Y

1.Mode Frequency	25,94 Hz
2. Mode Frequency	49,99Hz
3. Mode Frequency	57,66 Hz

Table 4.6 Results of table-axis frequency

	Lower table	Cartesian System
1. Mode Frequency	166,46 Hz	25,94 Hz
2. Mode Frequency	2199,97Hz	49,99Hz
3. Mode Frequency	324,12 Hz	57,66 Hz

As seen in the frequency comparing table, natural frequency was 25.94 Hz for the Cartesian system and 166.46 Hz for the fixed table. From this comparison, one can conclude that the fixed table was strong enough for the system, it was not affected by the vibrations from the system, and more importantly no vibration impact would come to the system from the fixed table.

4.2.1 Statistical Analyses of the Cartesian System:

Statistical analyses of the Cartesian system were conducted by use of COSMOSWORKS software in order to see whether strain and bending would occur in the system under loading conditions. Results of statistical analyses of the Cartesian system of which simple model were made without details in real sizes are given below.

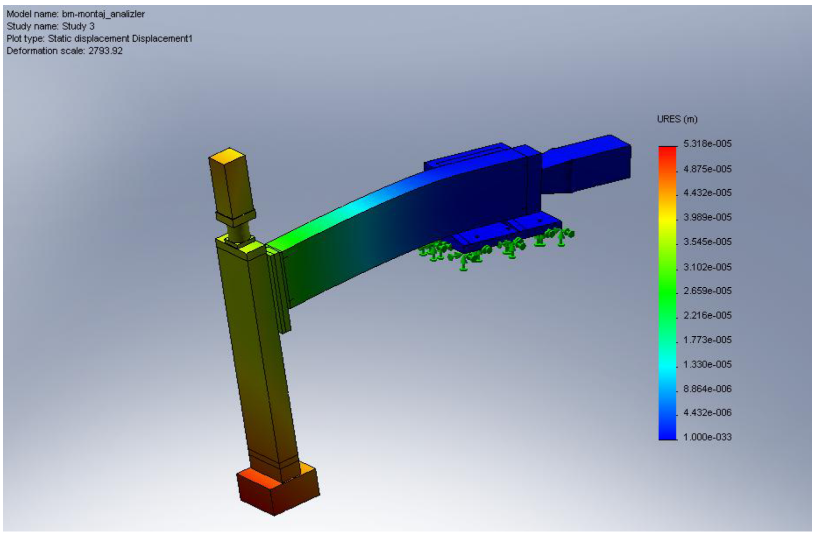


Figure 4.12 Situation 1: Results of statistical analyses for deflection with load of 20 kg.

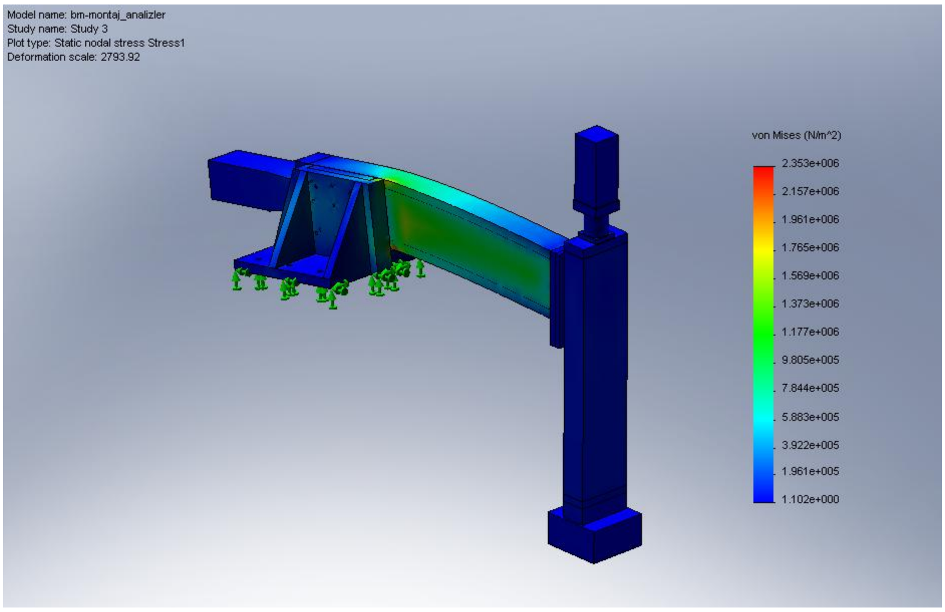


Figure 4.13 Situation 1.Inner stress results with load of 20 kg.

Table 4.7 Statistical analysis of situation 1.

Max. Deflection (mm)	Min. Deflection (mm)	Max. Stress (MPa)	Min. Stress (MPa)
0,053	0,0044	2,35	0,19

Statistical analyses were carried out under the effect of force at pressure occurred while spraying manifold of 20 kg and the manifold were working.

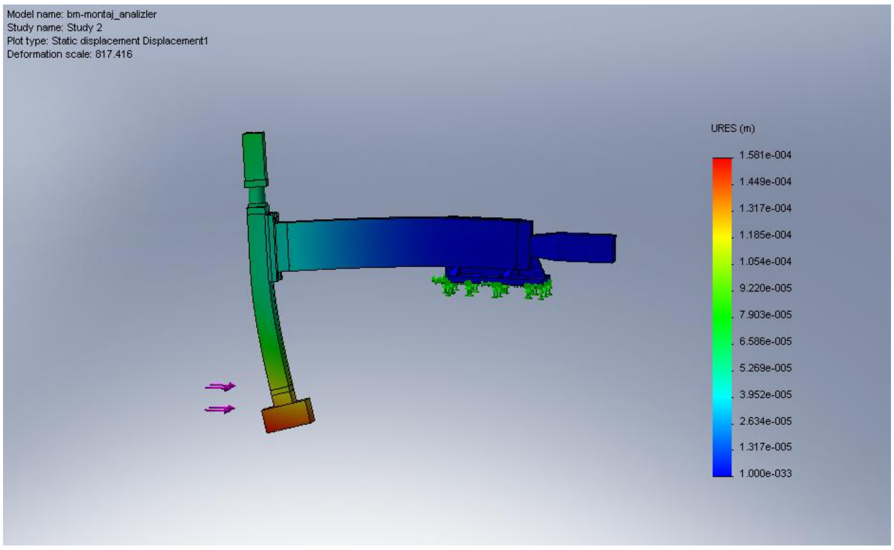


Figure 4.14 Situation 2: Results of statistical analyses for deflection with load of 20 kg and pressure reaction force.

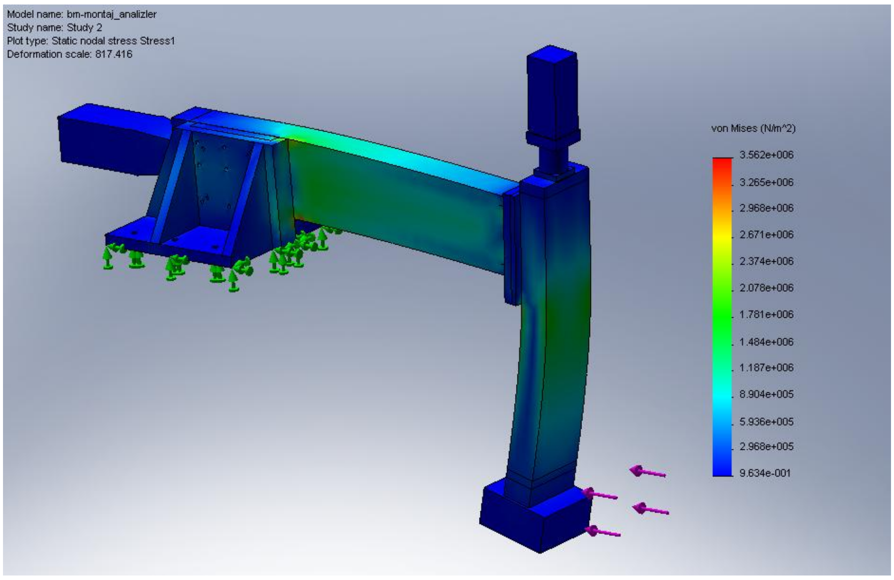


Figure 4.15 Situation 2: Results of statistical analyses for inner stress with load of 20 kg and pressure reaction force.

Table 4.8 Results of statistical analysis for the Situation 2.

Max. Deflection (mm)	Min. Deflection (mm)	Max. Stress (MPa)	Min. Stress (MPa)
0,15	0,013	3,56	0,296

Table 4.9 Comparison between statistical results for the situations 1 and 2.

	Max. Deflection (mm)	Min. Deflection (mm)	Max. Stress (MPa)	Min. Stress (MPa)
Situation 1.	0,053	0,0044	2,35	0,19
Situation 2.	0,15	0,013	3,56	0,296

4.3 Productions and Experiments

4.3.1 Production

Production of prototype system was carried out in accordance with the design prepared by static and frequency analysis. Technical drawings of the parts produced are presented in the annex.

Figure 4.16   General view of the prototype model

Figure 4.17 Prototype model

4.3.2 The Experiments

The prototype model produced was operated at the values calculated previously and it was checked whether it operated as requested or not.

It was observed during the experiments that the system operated properly.

Table 4.10 The results of test

Y axis							
Load (kg)	Acceleration (m/s^2)	Time (sec)	Torque (Nm)	Capacity	Motor Rotation (degree)	Acceleration Time (sec)	Motor Acceleration (m/s^2)
20	0.48	0.5	0.265	%50	4320	0.27	0.82
20	0.7	0.5	0.05	%95	5400	0,33	0,69

X axis							
Load (kg)	Acceleration (m/s^2)	Time (sec)	Torque (Nm)	Capacity	Motor Rotation (degree)	Acceleration Time (sec)	Motor Acceleration (m/s^2)
20	0.48	0.5	0.125	%60	4320	0.27	0.82
20	0.8	0.5	0.053	%95	6300	0,39	0.58

CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATIONS

In this study, cast spraying robots and Cartesian robots, which are the subject matter of the thesis were examined. Criteria to be regarded while installing Cartesian robot systems were determined. Considering the criteria, a study was conducted on proper selection of linear motion modules used in Cartesian systems. Parametric selection program was prepared to select the proper module correctly and practically. Working capacities of linear modules elected by the working data of Cartesian system to be installed with this program can be observed.

By use of linear modules, servo motors available in the laboratory, a design to be the prototype of cast spraying robot was created. Control of these linear modules used in this design was performed by linear module selection program with reverse engineering. Moreover, static and frequency analysis of the design was checked in the computer environment.

Experimental works were carried out for the prototype model and system was operated properly.

Selection can be made in a wider area for the proper system selection by increasing product groups to be selected in the linear module selection program created. Program can be organized for different Cartesian applications and different data input. When the program is developed in this way, Cartesian systems can be installed in more practical and healthier way.

As far as the selection of proper modules is important for Carterian systems, precision for connections during assembly and connectors of modules selected is important. Connections for which linearity and precision is ignored affect the operation of the system and prevent the requested productivity for modules and motor. These points should be paid attention during production and installation.

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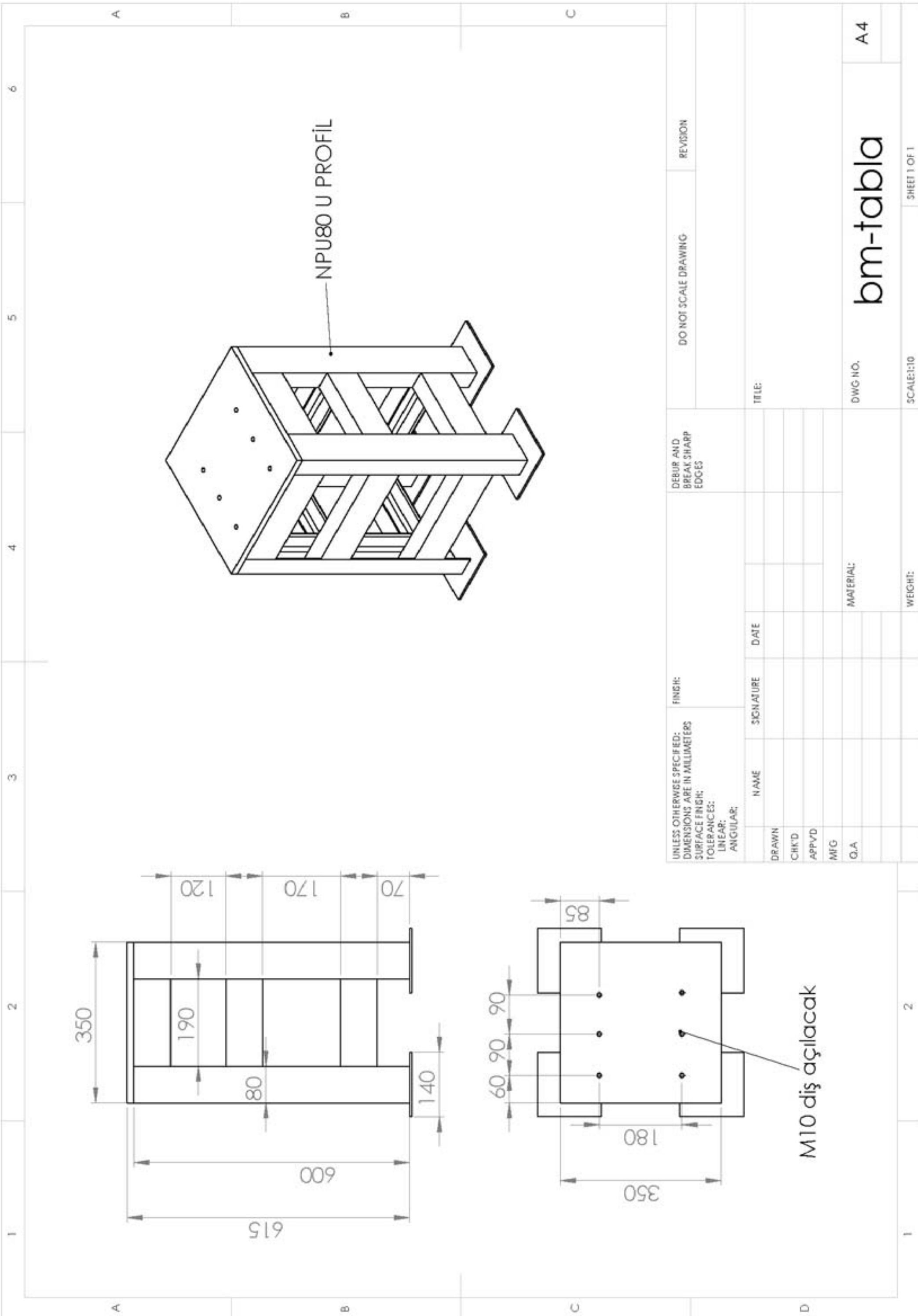
APPENDIX A
TECHNICAL DRAWINGS

Technical drawings of production parts are given in following pages.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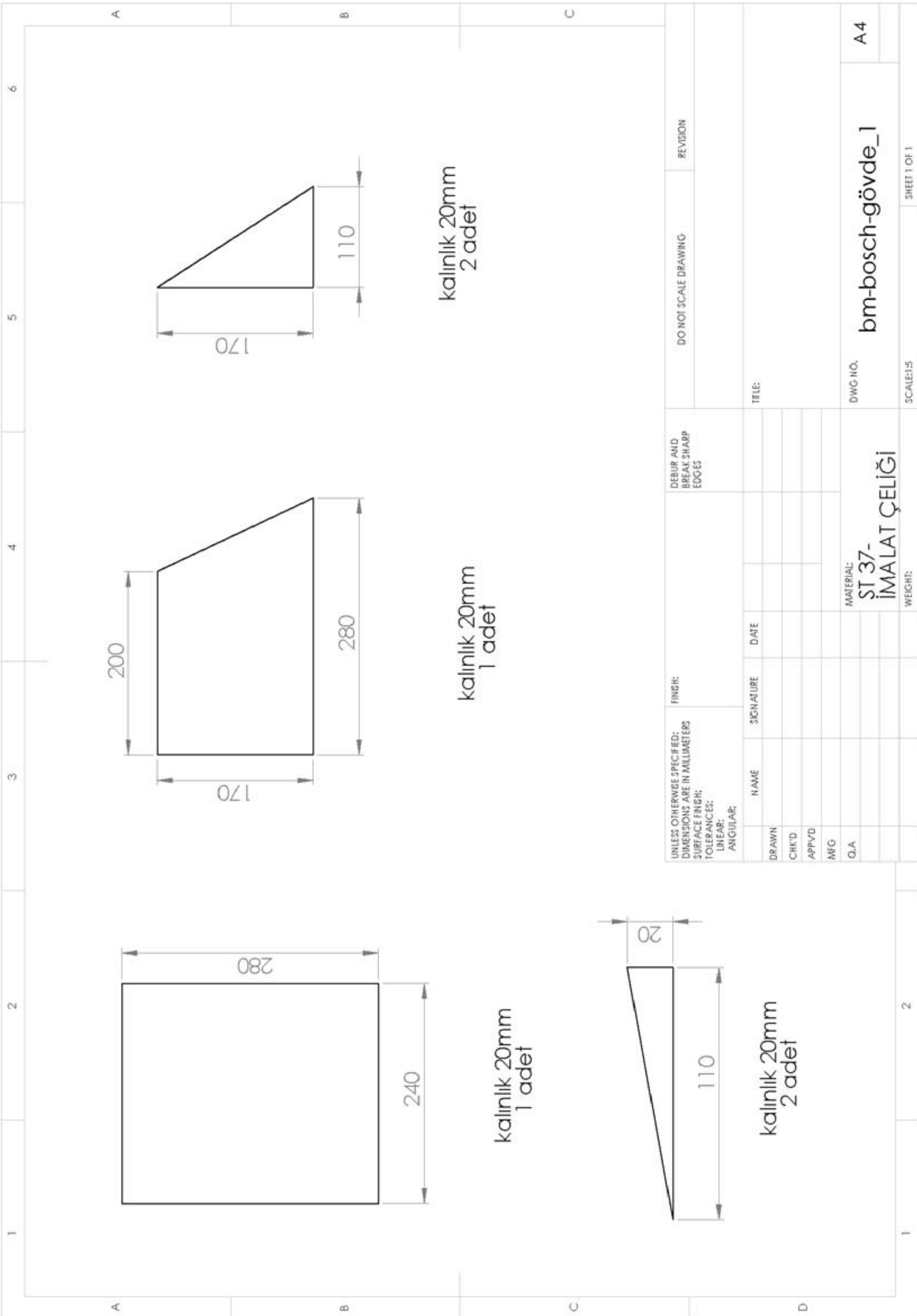

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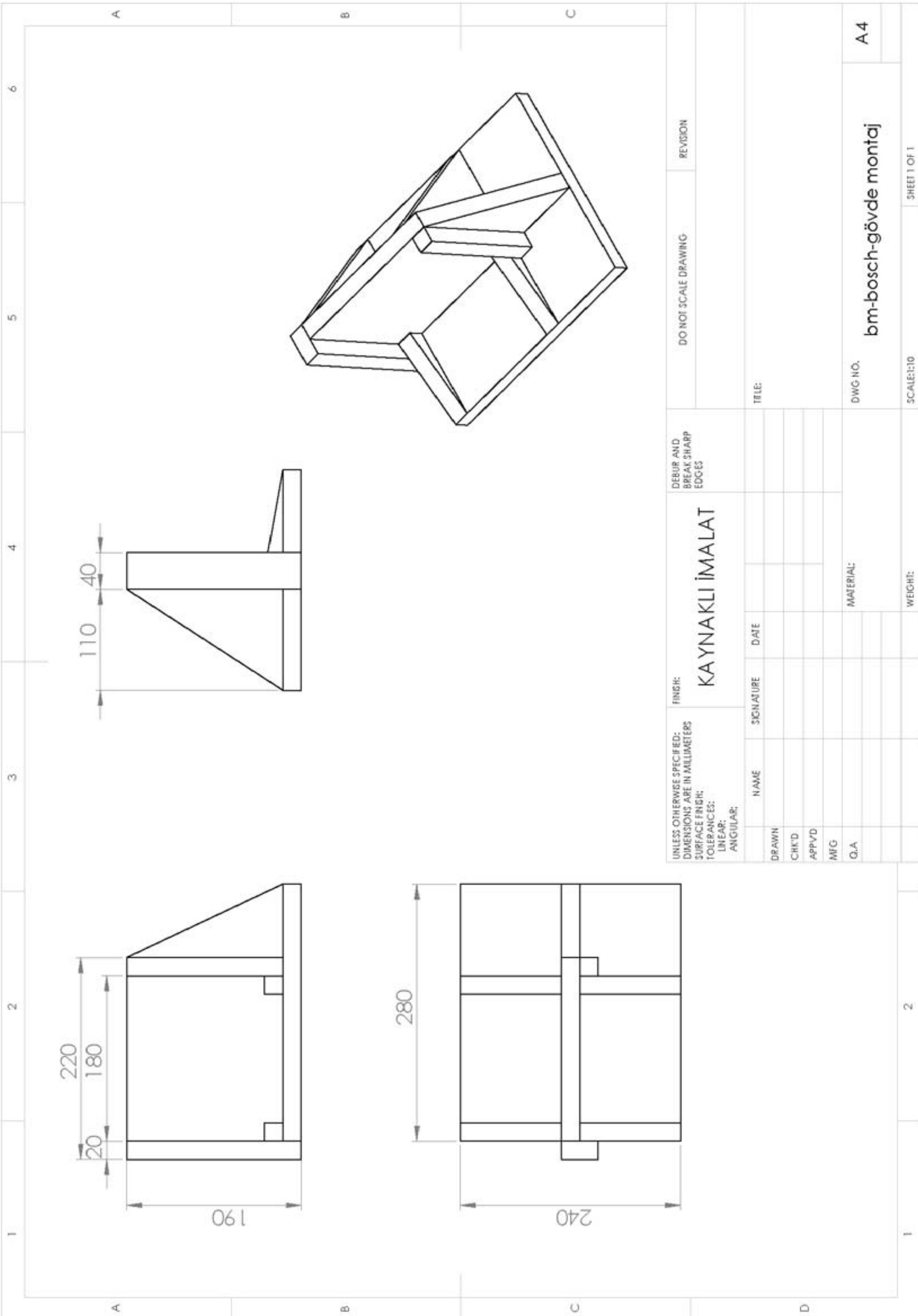

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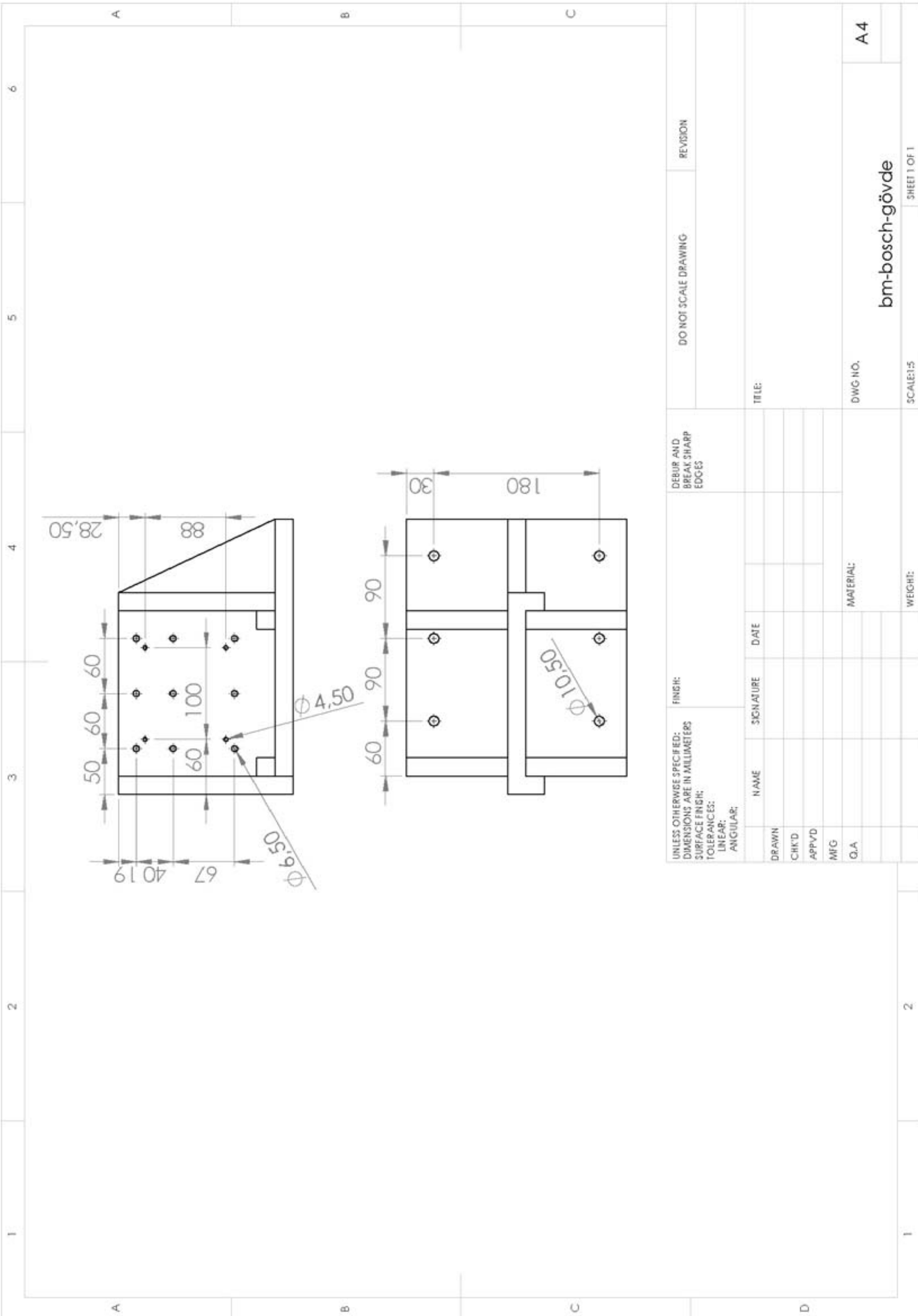
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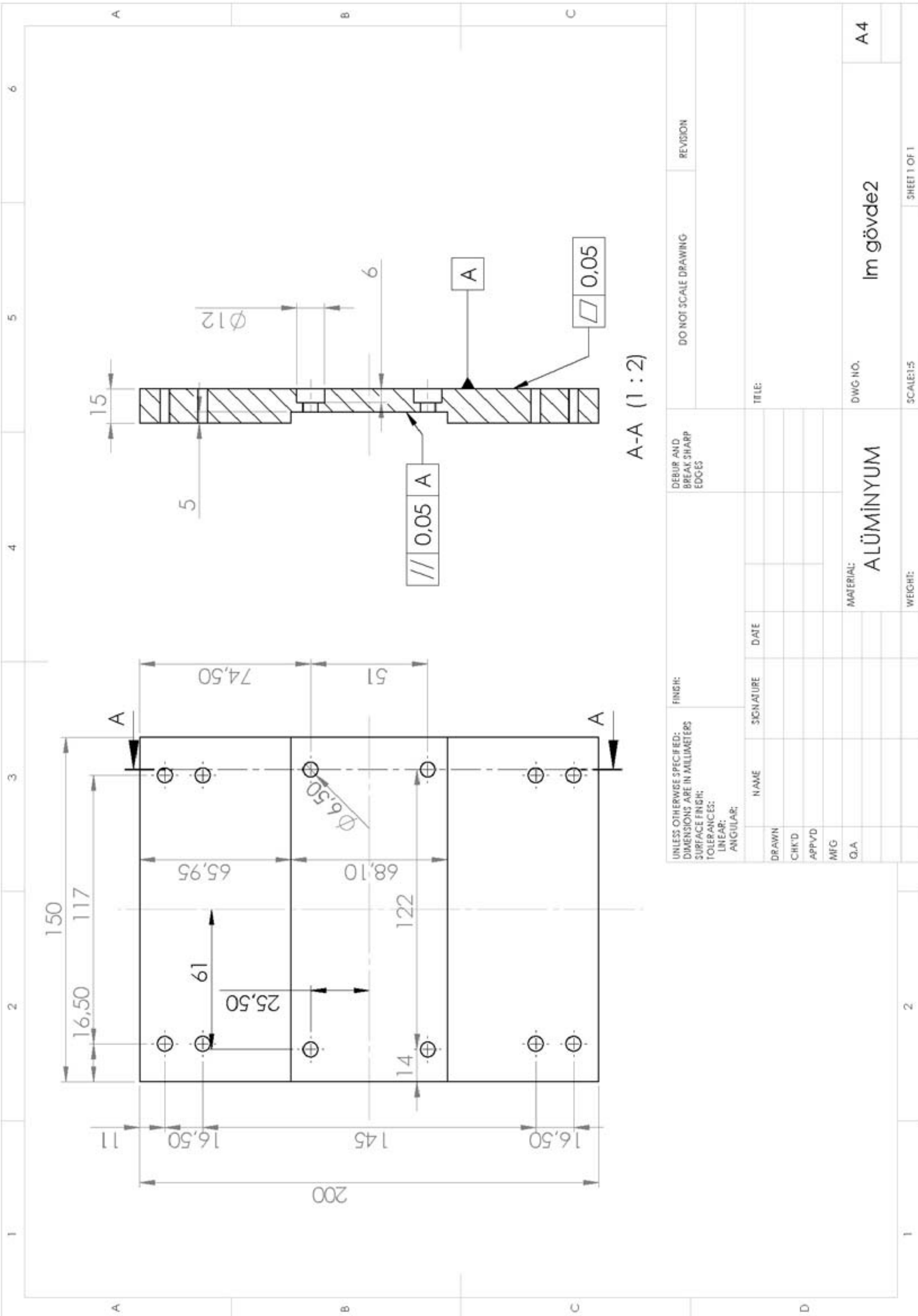
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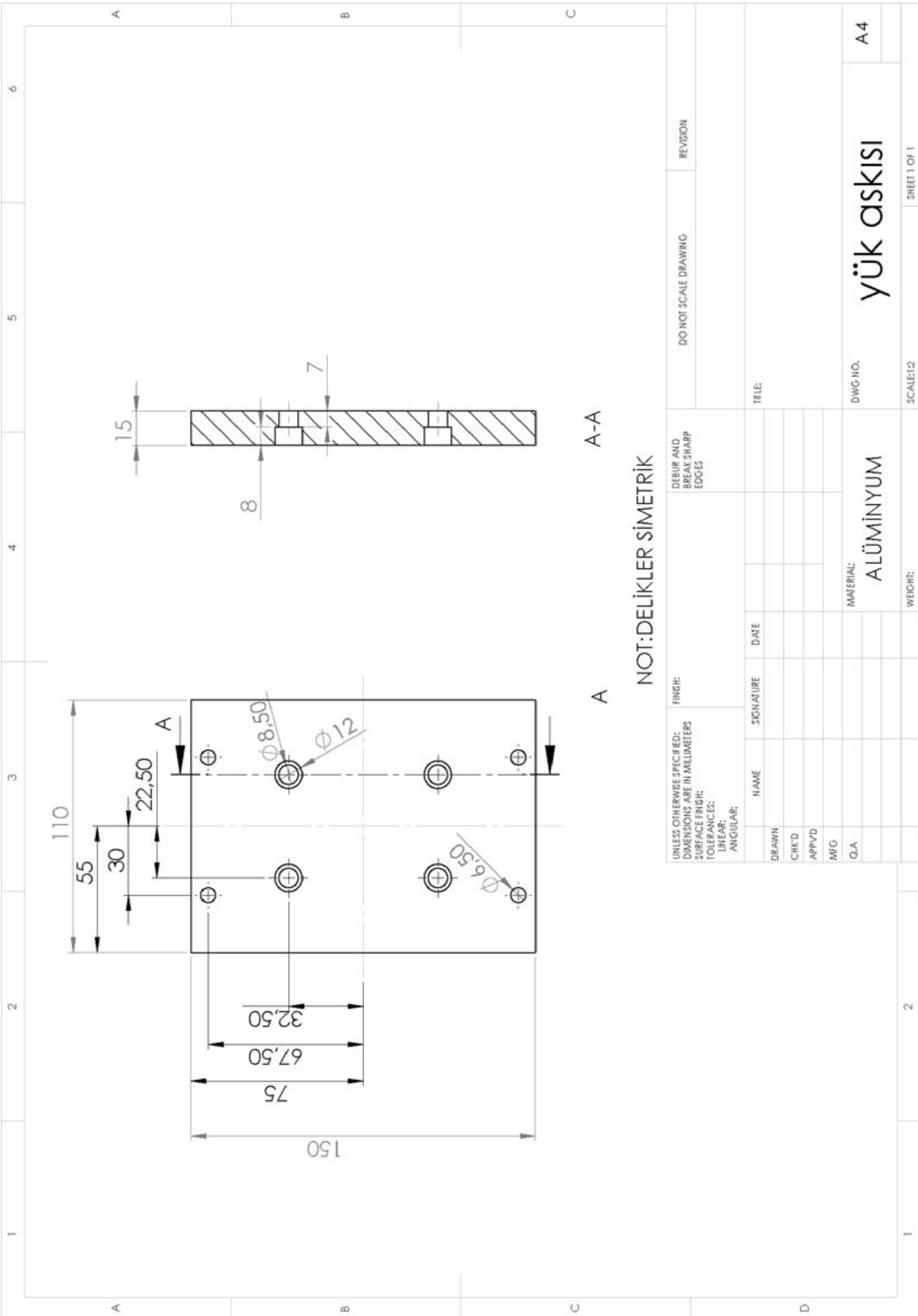
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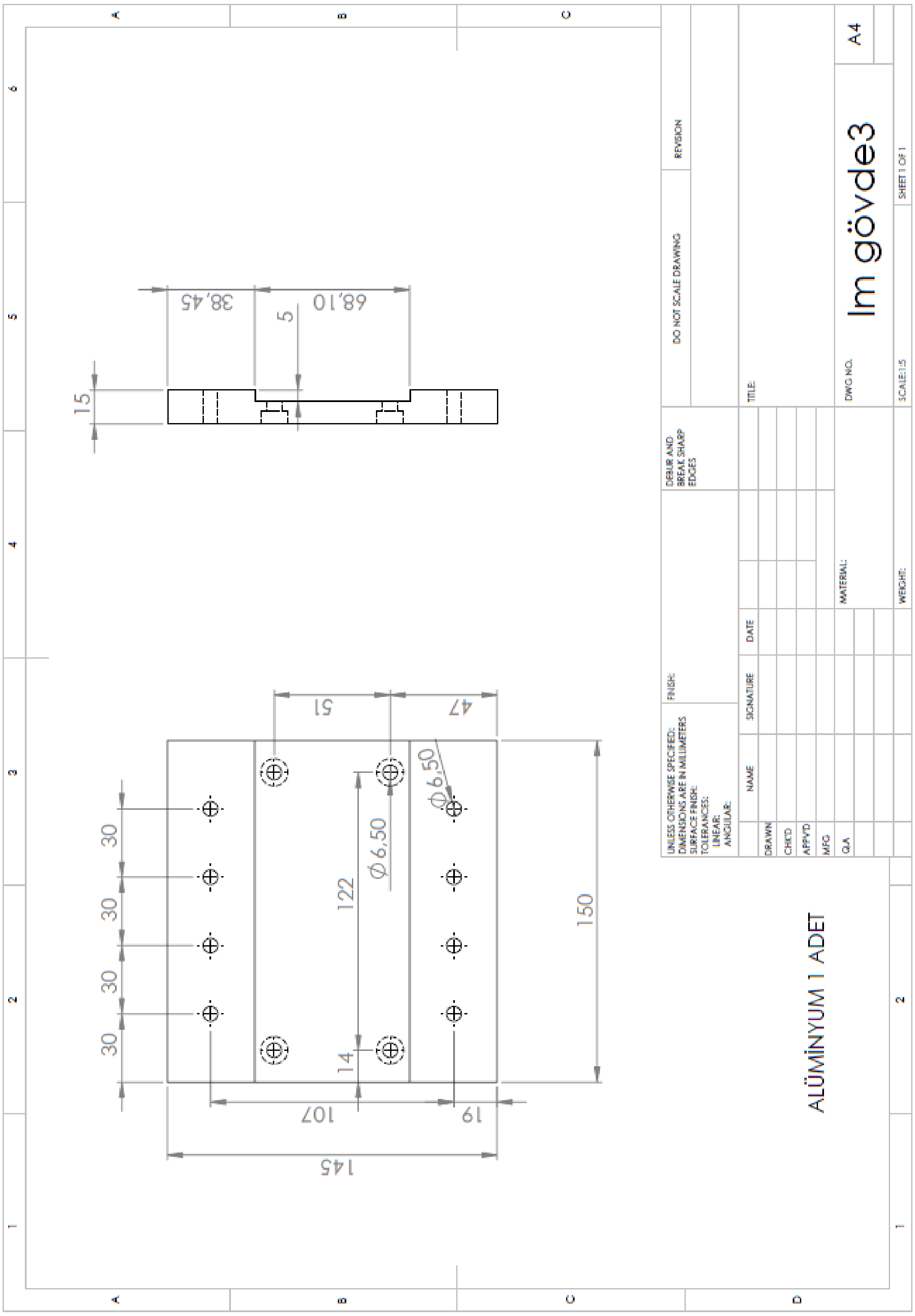

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