DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

THE EFFECT OF THE FLEXIBILITY OF CNC MACHINES ON THE PRECISION OF ORTHOTIC INSOLE MANUFACTURING

by
Aykut SEVER

December, 2017
İZMİR

THE EFFECT OF THE FLEXIBILITY OF CNC MACHINES ON THE PRECISION OF ORTHOTIC INSOLE MANUFACTURING

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We have read the thesis entitled **"THE EFFECT OF THE FLEXIBILITY OF CNC MACHINES ON THE PRECISION OF ORTHOTIC INSOLE MANUFACTURING"** completed by **AYKUT SEVER** under supervision of **ASST.PROF.DR. MURAT AKDAĞ** 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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ABSTRACT

Nowadays, CNC machines are also used in the production of custom prosthetic socket molds and customized insoles. High density polyurethane foam and EVA (ethylene vinyl acetate) materials of different densities are used in this sector. It is suitable for high speed manufacturing due to the fact that the materials used have low cutting loads in terms of processing. For this reason, it is desirable to use the highest feed speeds that can be provided by the machine in the manufacture of prosthetic socket molds and customized insoles. The inertia loads caused by higher feed speeds cause vibrations on the structure. Therefore, the weight of the moving parts must be reduced, and at the same time, the machine rigidity must be high.

In this study, the vibration analysis of a CNC machine manufactured for this purpose was examined with the finite element method and experimentally. The design of 4 Axis CNC Machine was created in SolidWorks program according to industrial requirement. The analysis model of the machine was created in ANSYS/Workbench program. The assembly model consists of sub-assemblies called members. The members are connected to each other by connectors. The analysis model consists of solid and shell elements. Static and modal analyses were performed by using analysis model and stress, displacement and natural frequencies are obtained. Experimental results and analysis results were compared. New flexible model was designed for the compare effect of flexibility between rigid and flexible design on the milling process. Milling process was performed both design and the results were measured via Coordinate Measure Machine (CMM). Outcomes of milling process were compared and the precision differences between flexible and rigid design was specified.

Keywords: CNC, machine, milling, finite elements, vibration, flexibility, EVA

CNC MAKİNALARINDAKİ ESNEKLİĞİN ORTEZ TABANLIK ÜRETİM HASSASİYETİNE OLAN ETKİSİ

ÖZ

Günümüzde, CNC tezgâhları kişiye özel protez soket kalıbı ve tabanlık üretimleri gibi bir çok farklı alanda kullanılmaktadır. Yüksek yoğunluklu poliüretan köpük ve farklı yoğunluklardaki EVA(Etil Vinil Asetat) malzemeleri bu sektörde yaygın şekilde kullanılmaktadır. Kullanılan malzemelerin işleme açısından düşük kesme yüklerine sahip olması nedeniyle yüksek hızda üretilmeye uygundur. Bu nedenle protez soket kalıbı ve kişiye özel tabanlık imalatında kullanılan tezgâhların verebildiği en yüksek ilerleme hızlarının kullanılması tercih edilir. Yüksek ilerleme hızları nedeniyle karşılaşılan atalet yükleri tezgâh üzerinde titreşimlere neden olmaktadır. Bu yüzden hareketli kısımların ağırlıklarının azaltılması, aynı zamanda tezgâh rijitliğinin yüksek olması gerekmektedir.

Bu çalışmada, bu amaçla üretilen CNC tezgâhının titreşim analizi sonlu elemanlar yöntemi ile ve deneysel olarak incelenmiştir. 4 eksenli CNC tezgâhının tasarımı endüstriyel gereksinimlere göre SolidWorks programında tasarlanmıştır. Tezgâhın analiz modeli ANSYS/Workbench programında oluşturulmuştur. Montaj modeli uzuv olarak adlandırılan hareketli alt montajlardan meydana gelmektedir. Uzuvlar birbirlerine konektörlerle bağlıdır. Analiz modeli katı ve kabuk elemanlardan oluşmaktadır. Statik ve doğal frekans analizleri analiz modelini kullanarak yapılmış ve gerilme, deplasman ve doğal frekanslar elde edilmiştir. Analiz sonuçları ve deney sonuçları birbiri ile karşılaştırılmıştır. Talaş alma işleminde rijit ve esnek tasarımın arasındaki esnekliğin etkisini belirmek için yeni esnek tasarım yapılmıştır. Talaş alma işlemi her iki durum için de yapılmış, sonuçlar koordinat ölçüm cihazı (CMM) ile ölçülmüştür. Talaş alma işleminin sonuçları birbiri ile karşılaştırılmış ve esnek ve rijit tasarım arasındaki hassaslık farkları belirlenmiştir.

Anahtar kelimeler: CNC, tezgâh, talaş alma, sonlu elemanlar, titreşim, esneklik, EVA

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CHAPTER ONE
INTRODUCTION

1.1 Introduction

Computer Numerical Control (CNC) is the automation of machine tools by means of computers fulfilling pre-programmed series of machine control orders. This is in contradiction to machines that are manually controlled by hand wheels or levers, or mechanically automated by cams alone. In modern CNC systems, the design of a mechanical component and its manufacturing program is highly automated. The part's mechanical dimensions are defined using computer-aided design (CAD) software, and then translated into manufacturing instructions by computer-aided manufacturing (CAM) software. The resulting instructions are transformed (by "post processor" software) into the specific commands necessary for a particular machine to produce the component, and then loaded into the CNC machine.

CNC-like systems are now used for any process that can be characterized as a series of movements and treatments. These comprise laser cutting, welding, friction stir welding, ultrasonic welding, plasma and flame cutting, spinning, bending, hole-punching, gluing, pinning, sewing, fabric cutting, tape and fiber placement, routing and picking and placing.

1.2 Literature Survey

The usage of CNC machines in industrial applications are increasing quickly. Metal cutting is a widely used method of producing manufactured products. The technology of metal cutting has advanced considerably along with new materials, computers and sensors. This new edition treats the scientific principles of metal cutting and their practical application to manufacturing problems. It begins with metal cutting mechanics, principles of vibration, and experimental modal analysis applied to solving shop floor problems. (Altıntas, Y. (2012). Manufacturing Automation (2nd ed.). New York: Cambridge University Press.).

Theory and Design of CNC Systems covers the elements of control, the design of control systems, and modern open-architecture control systems. Topics covered include Numerical Control Kernel (NCK) design of CNC, Programmable Logic Control (PLC), and the Man-Machine Interface (MMI), as well as the major modules for the development of conversational programming methods. The concepts and primary elements of STEP-NC are also introduced. (Suh, S.-H., Kang, S.K., Chung, D.-H., Stroud, I. (2008). Theory and Design of CNC Systems (1st ed.). Cardiff: Springer.).

Jun Ni (1997) presented real-time error compensation methods as applied to reduce both geometric and thermally induced quasi static machine tool errors.

Portman, Weill & Shuster (1996) presented the calculations of the functional accuracy of machines, in particular when estimating the machine tool set-up errors or when calculating the influence of machine setting displacements.

Altintas & Khoshdarregi (2012) presented vibration avoidance and contouring error compensation algorithm for feed drives. The residual vibrations are avoided by applying input shaping filters on the reference axis commands. The input shaping filter avoids the excitation of the structural modes but at the expense of increasing tracking and contouring errors.

Altintas, Verl, Brecher, Uriarte & Pritschow (2011) presented a new approach in reducing the excitement of inertial vibrations through coupled input shaping and contour error compensation. The inertial vibrations occur when accelerating large masses of machine tool components. The inertial vibrations are usually avoided in industry by notch filtering them in the position feedback so that the vibration frequencies are not transmitted to the controller.

Singer & Seering (1990) proposed an input shaping method that avoids triggering the excitation of structural vibration frequencies.

Chen & Chen (2011) presented a geometric relationship between the tracking and contouring errors, and improved the contouring accuracy by a cross coupling command shaping controller.

Lia, Caib, Maob, Huangb & Luo (2013) presented a random excitation signal for operational modal analysis is modeled and simulate. A technique to realize this excitation on CNC machine–tool is proposed. Dynamic properties will change under machining compared with static state. The dynamics of lower bandwidth is of great significance to machining behavior.

Niehues, Schwarz & Zaeh (2012) used a filter-based logarithmic decrement and a frequency resolution enhanced bandwidth method to observe material damping ratios in machine tools. Indeed, to determine of the determination and uncertainty of damping ratios of very lightly damped structures experimental and theoretical results were compared. To overcome drawbacks of conventional bandwidth method for very lightly MDOF systems, combined use of a filter-based logarithmic decrement and a frequency resolution enhanced bandwidth method were developed.

Aggogeri, Borboni & Pellegrini (2017) presented a set of hybrid materials that may be used an alternating material to fabricate of machine tools moving parts. To perform this, the kinematic model of a milling machine was established and produced a number of prototypes made of Al foam sandwiches, Al corrugated sandwiches and composite materials reinforced by carbon fibers. These prototypes represented the Z-axis ram of a commercial milling machine. Also, finite element analysis and experimental analysis were performed and a machine, which has a better vibration performance, was presented.

Lacalle, Celaya & Lamikiz (2008) presented main machine tool design, construction and testing aspects to achieve high precision on machined parts. This study was mentioned about the identification of error sources, studying their physical causes and relevance to the final uncertainty. Also, vibration forms of different machine construction types were presented and cutting force calculation, as well.

1.3 Objective of the Thesis

The objective of this thesis is to design, produce and analyze a multi axis CNC machine which is suitable to process more than one material like wood, foam, metal etc. In this study, The 2.5 axis cnc that was made in previous studies will be developed and a 4-axis CNC machine will be created. The CNC machine will have a 4 axis and these axes consists of three linear axis (X,Y,Z) and one rotary axis (A) that are driven by servo motors. Vibration measurements will be taken over the manufactured CNC machine and compared with the analysis results. Also in this study two designs will be created. One of them will be rigid and the other flexible. The vibration measurements and Coordinate Measure Machine measurements will be taken with both and the differences will be compared. At the end of this study the effect of the flexibility of CNC machine on the milling precision will be determined.

1.4 Organization of the Thesis

This thesis consists of six chapters.

Chapter 1 presents the literature survey and the organization of the thesis. Chapter 2 presents history of the tool machines. Components of CNC machines and different implementation in industry are also shown in this chapter. Chapter 3 presents the mechanical design of the machine and the control panel as well as calculation of axis, linear modules and motors. Chapter 4 presents the finite elements models of machine and experimental results. Chapter 5 presents the effect of machine flexibility on the milling precision. And Chapter 6 includes the conclusion of the thesis and discussions for future works.

CHAPTER TWO

COMPUTER NUMERICAL CONTROL MACHINES

In this chapter the Computer Numerical Control machines history, it's parts and it's applications in the healthcare field will be presented.

2.1 Introduction of CNC Machines and Applications

A process that is normally performed by humans or controlled by machines or systems is called automation. In another way; Automation is the process by which machines can’t perform operations that can’t be realized.

People have been searching for ways of starting some very difficult work with the help of mechanical devices. Remains of reels, cranes and other lifting machines from 2000 BC were found. But real mechanization, the emergence of systems of different machines, occurred during the Industrial Revolution of the 18th century. First, the development of steam engines and then electric motors led to the realization of these individual tasks by machines. This is shown schematically in Figure 2.1.

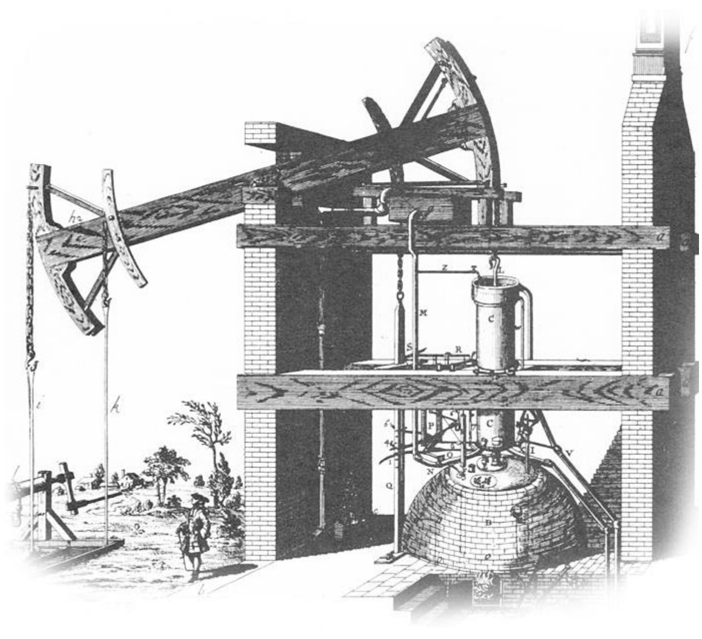


Figure 2.1 Newcomen’s steam engine

The actual automation, which is different from the mechanics without quality, came out with the development of feedback systems; As a matter of fact, these two concepts are distinguished from each other by the existence of this system. Feedback refers to a machine's ability to self-organize.

The idea of numerical control has been put forward towards the end of the Second World War for the production of complex aircraft parts that the United States of America needs the air force. Because this kind of parts weren't be possible to produce with manufacturing machines of those days. Parsons Corporation and MIT (Massachusetts Institute of Technology) started collaborating to achieve this. In 1952, they first implemented a CINCINNATTI-HYDROTEL milling machine with Numerical Control and performed the first successful work in this area. Since then, many machine tools manufacturers have begun to manufacture machine with Numeric Control. Initially, vacuum cylinders, electrical relays, complicated control interfaces were used in NC machine tools. However, they often had to be repaired or even renewed. Later, miniature electronic tubes and monolithic circuits, which are more useful in NC machine tools, have begun to be used. The rapid developments in computer technology have also affected numerically controlled systems. Nowadays, in NC machines, more advanced integrated circuit elements, cheap and reliable hardware are used. With the use of ROM (Read Only Memory) technology, it was possible to store programs in memory.

Numerical control (NC) is the operation of machine tools with the help of commands which are derived from symbols such as number letters, etc. and encoded according to certain logic. The commands are loaded in the form of data blocks on the respective machine tool. Each data block consists of a set of commands that the machine can understand. Numerical control is used on all machine tools used in the processing with metal removing of all kinds of metal and non-metal materials. First NC machine is shown in Figure 2.2.

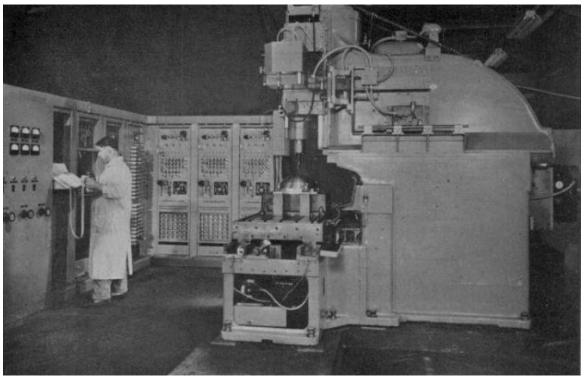


Figure 2.2 The first NC milling machine at MIT in 1950

Computer Numerical Control (CNC) is the computerized control of machine tools with numerical commands. CNC machines have a computerized control unit, unlike NC machines. Thus, NC programs, some technical and offset information about the cutters can be permanently stored in the machine's memory. In addition, the program is interrupted at every stage of production and any changes are made to the program.

To understand the CNC machine development period, we should consider the CAD/CAM progress. In this context we cannot investigate these matters independent of each other. The CAD / CAM system is the consolidation of the design and manufacturing process in a computer environment to increase productivity in the businesses. CAD / CAM users, using design and production software to carry out; first, the product performs technical modeling and modeling and then, by using this drawing, they generate the NC codes necessary for part production by computer. A Lathe machine is shown in Figure 2.3.

Figure 2.3 CNC Lathe machine overview

Improvements in CAD / CAM systems began during MIT's NC machine manufacturing work in the 1950s. MIT produced simple pictures by connecting the first graphical display (CRT-Cathode Ray Tube) similar to television to Whirlwind computers. After this development, the most common programming language, APT (Automatically Programmed Tools) was developed. CAD-CAM algorithm interface is shown in Figure 2.4.

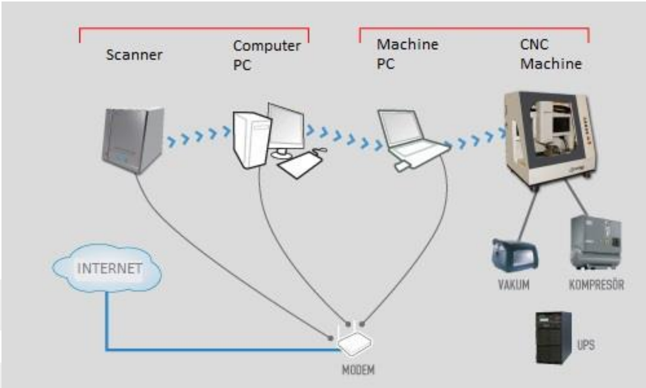


Figure 2.4 CAD-CAM algorithms

The Sketch Pad system, which Ivan Sutherland published in 1962 as a thesis, is the CAD milestone. As a result of the various groups' development work on this thesis, Computer Aided Design (CAD) concept has emerged and is being used. Among the developments in the 1970s was the use of the Initial Graphics Exchange Specification (IGES) as well.

The 1970s are also known as computer design applications. Turnkey (ready) systems provided three-dimensional centralized databases for designers to model and draw. These systems initially supported wireframe modeling, while surface applications were limited. For this reason, only basic design applications could be done, but it was far from solving the real design problems of the industry. 1980's are considered as the fastest development of CAD / CAM technology. In this period new theories and algorithms were developed. The main goal was to automate by integrating the different elements of design and manufacture to build the factory of the future.

Nowadays, CNC Machine have a significant role in the manufacturing industry. The developments of the CNC Machines and also automation system triggered the industrial manufacturing revolution.

Numerical Control (NC) is widely applied in all types of machine tools used in the machining of metal and other materials. A grinding machine is shown in Figure 2.5.
Here are some of these machines:

- Lathe Machine
- Milling Machine
- Drilling Machine
- Boring Machine
- Grinding Machine

Figure 2.5 Grinding machine

Along with the development of Numerical Control systems, many works, which is manually done before, turned into programmable control and automated. With improving technology, usual manufacturing systems changed very quickly. CNC machines and automation systems are some of the most important technologies which are leading forth this transformation.

2.2 Construction Type of CNC Machines

Computer Numerical Control refers to ways that can command the functions of a manufacturing tool or machine through computer programming. CNC machines use a language called g-code, developed in the late 1950s, which instructs the machine how to cut, grind, shape, mold or melt a source material like metal or plastic into whatever finished product the operator desires. Many different types of CNC machines exist in the marketplace, with several today that are prominent thanks to their diverse range of applications.

Retrofitted Machines; Retrofitting refers to machines that were originally constructed using older, pre-CNC technology, but later were updated to handle CNC programming as a way to improve their efficiency and functionality. Milling machines, lathes and grinders are the most common examples. A retrofitted machine is shown in Figure 2.6.

Figure 2.6 Retrofitted machines

Milling Machines; Mills use rotary cutters to cut a variety of manufacturing materials and rely on CNC commands to dictate the depth, direction and angle of the cut. The precision of a cut is far greater now using CNC technology than when these machines were operated by hand.

The milling process removes material by performing many separate, small cuts. This is accomplished by using a cutter with many teeth, spinning the cutter at high speed, or advancing the material through the cutter slowly; most often it is some combination of these three approaches. The speeds and feeds used are varied to suit a combination of variables. The speed at which the piece advances through the cutter is called feed rate, or just feed; it is most often measured in length of material per full revolution of the cutter. A CNC milling machine is shown in Figure 2.7.

Figure 2.7 CNC Milling machine

Lathes; These machines rapidly rotate the manufacturing material on a spindle. The material is then pressed against a carving or abrading tool while it spins to cut or shape it. Lathes are used primarily for symmetrical objects such as cylinders, cones and spheres. A lathe machine is shown in Figure 2.8.

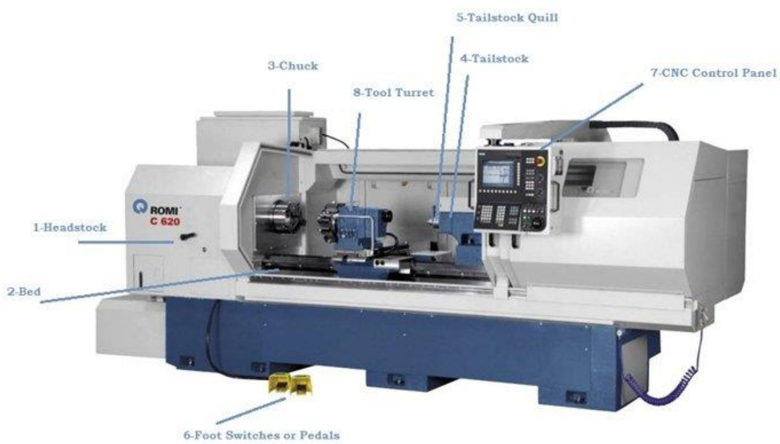


Figure 2.8 CNC Lathe machine

Grinders; A spinning wheel is used to either grate and abrade materials or mold them into a desired shape. These machines are the easiest to program because they typically don't require the same level of precision as a lathe or mill.

CNC Routers; Routers cut wood, plastic and sheet metal on an X, Y and Z axis and are primarily used for manufacturing larger scale products. While three-dimensional routing is the most common, some routers are four-, five- or six-axis, which is ideal for more complex products. A router machine is shown in Figure 2.9.

Figure 2.9 CNC Router machine

Pick and Place Machines; Also called surface mount technology, these machines are used to help assemble electronics like circuit boards, capacitors and resistors. They feature a number of small mechanical nozzles that lift up electronic components, move them to the specified location, and place them down. A pick and place machine is shown in Figure 2.10.

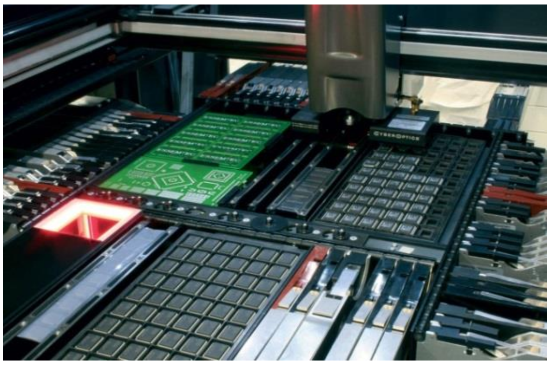


Figure 2.10 Pick and Place machine

2.3 Control System of CNC Machines

The CNC system is basically a precise control of the position of the cutting tool. To perform this operation, actuators (servo, step, dc motors etc.) of the machine must be precisely controlled by control unit. CNC systems require motor drives to control both the position and the velocity of the machine axes. Each axis must be driven separately and follow the command signal generated by the NC control. There are two ways to activate the servo drives: the open-loop system and the closed-loop system.

Open Loop - Programmed instructions are fed into the controller through an input device. These instructions are then converted to electrical pulses (signals) by the controller and sent to the servo amplifier to energize the servo motors. The cumulative number of electrical pulses determines the distance each servo drive will move, and the pulse frequency determines the velocity. The primary drawback of the open-loop system is that there is no feedback system to check whether the program position and velocity has been achieved. If the system performance is affected by load, temperature, humidity, or lubrication then the actual output could deviate from the desired output. Therefore, the open-loop system is generally used in point-to-point systems where the accuracy requirements are not critical. Very few, if any, continuous-path systems utilize open-loop control. System is shown in Figure 2.11.

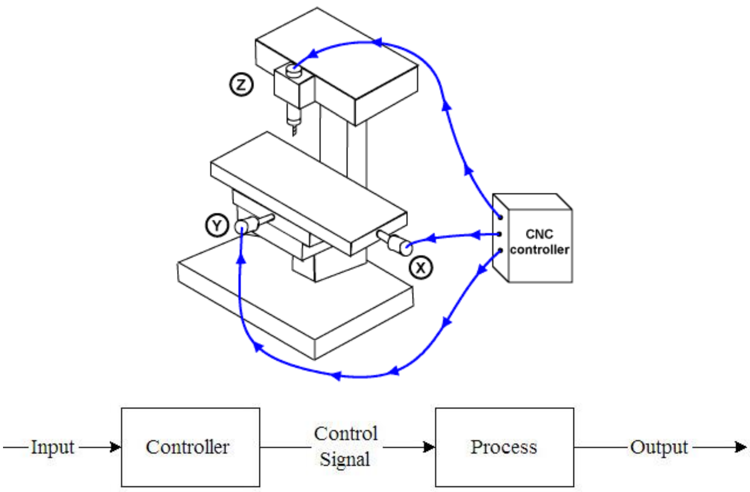


Figure 2.11 Open Loop System and block diagram

Closed Loop - The closed-loop system has a feedback subsystem to monitor the actual output and correct any discrepancy from the programmed input. The feedback system could be either analog or digital. The analog systems measure the variation of physical variables such as position and velocity in terms of voltage levels. Digital systems monitor output variations by means of electrical pulses. Closed-loop systems are very powerful and accurate because they are capable of monitoring operating conditions through feedback subsystems and automatically compensating for any variations in real-time. Most modern closed-loop CNC systems are able to provide precise resolution up to 0.001 of a millimeter. Closed-looped systems would, naturally, require more control devices and circuitry in order for them to implement both position and velocity control. This, obviously, makes them more complex and more expensive than the open-loop system.

Closed loop control systems are used at the professional CNC Machines frequently. On the other hand, open loop control systems are used at unprofessional machines which are precise control negligible. System is shown in Figure 2.12.

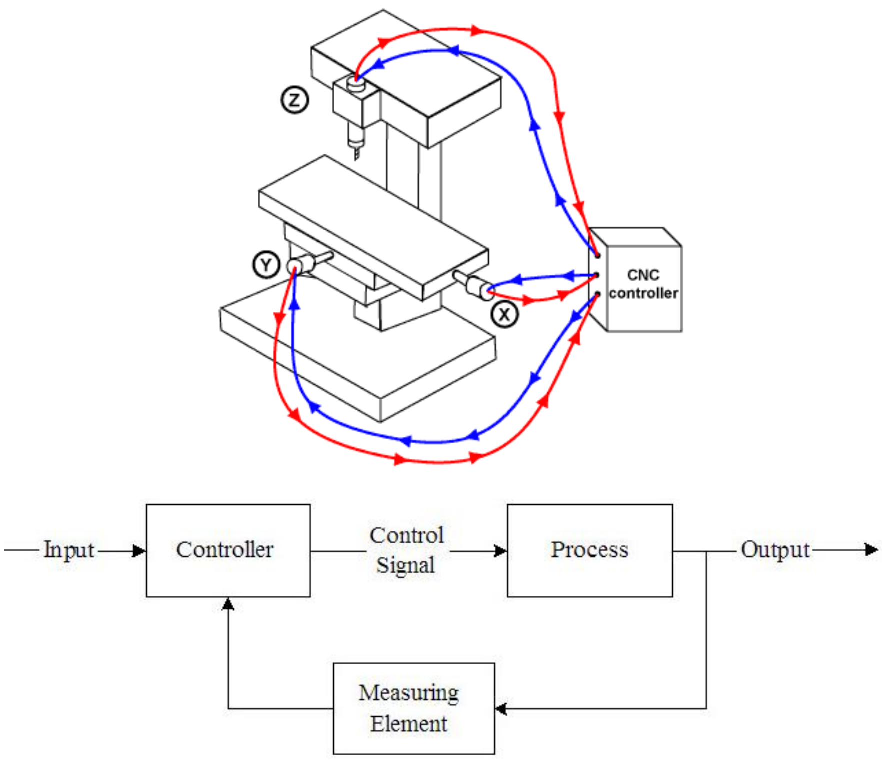


Figure 2.12 Closed Loop Systems

2.4 Mechanical Components of CNC Machines

In CNC Machine Systems, there are many mechanical components involved in the machine in order to figure out successfully perform the process. Many of them are essential for the machine. These can be listed as below.

Machine's body: The body forms the frame of the machine and all the moving parts are built on the body. The body is one of the most important parts for the machine. The rigidity of the body directly affects the rigidity of the machine. Machine body can be produced with casting and welding method. The body of professional machines is made of cast iron with due to the fact that it is a significant mechanical vibration absorber. A machine body which is produced welding method has great mechanical strength and ease of production in proportion to casting way.

Motors: In CNC systems, there are two type motors in use. One of them is step motor, the other one is servo motor. Both of them have pros and cons.

The name "stepper" comes from the steps made by the motor with every signal pulse. It is simple to operate, inexpensive compared to servo motors and has a high reported accuracy. Its low speed torque enables the use of a pulley reduction and timing belt, allowing several loads to be driven without gearing. On the other hand step motors have some drawbacks. Stepper motors typically have a lower efficiency than servo motors. It is also resonance prone, and smooth movement often requires micro stepping. Loads do not accelerate rapidly due to the low torque to inertia ratio. Despite the loud noise and overheating at high performance, stepper motors have an overall low power output for their weight and size.

The other type of CNC Machine's motor is servomotor. Servo motors use closed-loop circuitry to transfer information to the CNC machine. A regular DC or AC motor is connected to an encoder fixed with a sensor. Servo motors have high accuracy and resolution owing to the sensor-fixed encoder. The motor is powered by the servo amp, which also counts the steps made. Its high torque to inertia ratio enables rapid load acceleration. With lighter loads, efficiency may reach up to 90 percent. On the other hand servomotors have some drawbacks. Servo motors are generally more costly than stepper motors and more complicated to operate. As peak operating power only develops at high speed, and the ventilation system easily becomes contaminated, servo motors are more susceptible to damage due to overheating and overloading. They also require servicing after the brush reaches its 2,000-hour life span. Servo and step motor are shown in Figure 2.13.

(a) (b)

Figure 2.13 CNC Machine’s Motor : Servo motor (a) - Step Motor (b)

Motion transfer systems: There are several methods for transfer the motion to axes from motors. One of them is belt-pulley system, another one is ball screw and rack & pinion systems. These three methods are used frequently in CNC machines. All of them have some advantage and disadvantage relative to each other.

Most frequently used in CNC Machine’s is ball screw motion transfer mechanism. A ball screw is a mechanical linear actuator that translates rotational motion to linear motion with little friction. A threaded shaft provides a helical raceway for ball bearings which act as a precision screw. As well as being able to apply or withstand high thrust loads, they can do so with minimum internal friction. They are made to close tolerances and are therefore suitable for use in situations in which high precision is necessary. The ball assembly acts as the nut while the threaded shaft is the screw. In contrast to conventional lead screws, ball screws tend to be rather bulky, due to the need to have a mechanism to re-circulate the balls. Ball screw section is shown in Figure 2.14.

Figure 2.14 Ball-Screw Section View

In belt-pulley systems shown in Figure 2.15, motors drive an acting gear that is related with timing belt, and also timing belt carry the axes bearing. This method is usually used where the high axis speed needed. Also this way works very quiet. However, in this way, torque is limited in contrast with ball-screw and rack & pinion.

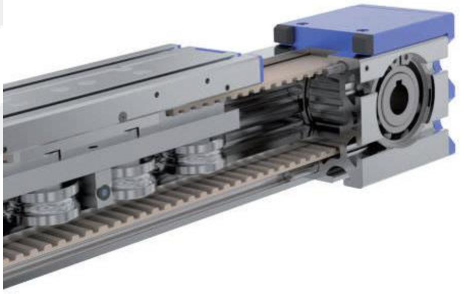


Figure 2.15 Trigger Belt-Pulley section view

Another type of motion transfer system, which is shown in Figure 2.16, is that rack & pinion gear system which is consist of bearing gear called rack and acting gear called pinion which is related with motor. This type of motion transfer system is usually used in heavy gantry type of CNC machine. Rack & pinion drive system have some disadvantage according to ball-screw and timing belt-pulley system. One of the most important one’s is that accuracy. Rack & pinion system have less precision than the ball-screw and timing belt-pulley system due to gearing sensitivity. On the other hand, rack & pinion system have great advantage in contrast with other motion transfer system that is used in which CNC gantry need to long travel distance. Ball-screw and timing belt-pulley have deflection in long distance application due to their own weight. This deflection influences the precision of machine adversely.

Figure 2.16 Rack & Pinion motion transfer system

All of the motion transfer systems have some advantage and disadvantage according to each other. Designer who create the machine should take into consideration these attributes in the design process and should choose the correct motion transfer system each axis. In summary;

- Rack & Pinion system can be used in long distance (1.5 meter and above) and heavy CNC gantry.
- Ball-screw system can be used in short distance (1.5 meter and below) and normal weight CNC gantry and also where the precision is needed.
- Timing belt-pulley system can be used in where the fast application, low weight and low inertia is needed.

2.5 The Use of CNC Machine in the Healthcare

Nowadays, CNC machines have many different application areas in the industry. CNC machines are widely used in many different sectors such as manufacturing, aviation, electronic and automotive. In recent years, CNC machines have also been started to be used in the healthcare field. CNC machines are widely used in many different healthcare fields such as implant teeth, prosthetic socket molds and personalized prosthesis manufacturing and these applications that make patients' lives easier and solve their problems best appropriate way. Different applications in the healthcare are is shown in Figure 2.17 and Figure 2.18.

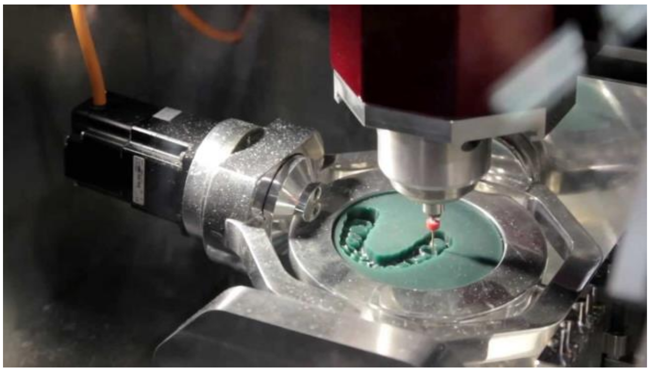


Figure 2.17 Implant teeth manufacturing in CNC Machine

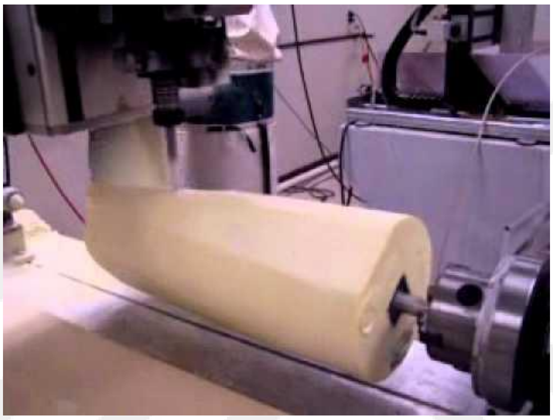


Figure 2.18 Prosthetic leg manufacturing in CNC Machine

Another application field is that personalized orthotic insole manufacturing. CNC machines are widely used in this area. The uses of personalized insoles are being rapidly increased in foot disorders, in patients with congenital foot problems, and especially in foot deformities which are common in sportsman. The most important difference between the personalized insoles and the standard insoles is that; personalized insoles are manufactured specially produced as a solution to disorder of patient's feet by making design improvements. Schematic view is shown in Figure 2.19.

The insoles are feet orthoses, and are applied in case of an ill, injured or deformed foot, so as to improve its function or prevent further deformation. In some cases they are also applied with healthy feet for example with athletes who use them to deal with large strain. Just about twenty years ago, manufacturing and design of insoles was based on application of technology in which was necessary to do plenty of labor.

Developing of computers, digitizing techniques, and CAD-CAM systems, new age of automation in insole manufacturing has started. Formerly, personalized orthotic insole was manufactured with plaster mold and pin systems. This obsolete method was highly compelling and labor intensive work. In these methods, creating a model of the patient's foot is both a difficult and one-time process. It is also very difficult to talk about a standard because the accuracy of the model depends on the qualification of the person performing the measurement.

Figure 2.19 Personalized insoles

Personalized insole manufacturing process can be summarized as follows;

Scanning process: There are many different ways to create the model of the patient's foot. The foot of the patient is plastered and the measurement can be taken in this way but this method is quite old-fashioned and inconvenient for patient.

Current technology, to create model of patient’s foot is that patient press the foam box with foot and then foam box is shaped. After the shaped of foam box, 3D laser scanner scan the foam and then solid model is transferred to computer and then improvements of the patient’s foot model is performed by physiotherapist according to needed treatments.

Another advanced technology to create model of patient’s foot is 3D gel-based scanner. This type of scanners can scan the patient’s foot very quickly. Because gel-based scanners eliminate the foam box and re-scan process. In addition, the data obtained with gel-based scanners give more accurate results than other methods because of the data directly transfer the 3D modelling program. Operating logic of gel-based scanners is that patient steps on the gel material of scanner, gel takes the shape of pressed foot and sensors measure the deformation of gel and then give electrical signal outputs to computer. This data is evaluated by the computer program and demonstrate the screen as a 3D CAD model.

The latest technology to create model of patient's foot is laser scanner. Patient's foot is on the tempered glass which has a laser scanner head moving on back and forth. And a receiver collect reflected rays which sent by laser. The data obtained by reflection create 3D CAD model of patient's foot. In this way, patient's foot can be scanned very quickly and accurately.

All of these methods need manufacturing machine to produce personalized insole. Generally, foot data is produced with CNC Router machine. To machining of foot model, CAM programs must be written according to foot CAD model. Some developers merge CAD and CAM process with special programs and CAM programs are written automatically by the program according to CAD model. Gel-based and Laser-based foot scanners are shown in Figure 2.20 and Figure 2.21.

Figure 2.20 Voxelcare brand gel-based and laser foot scanner

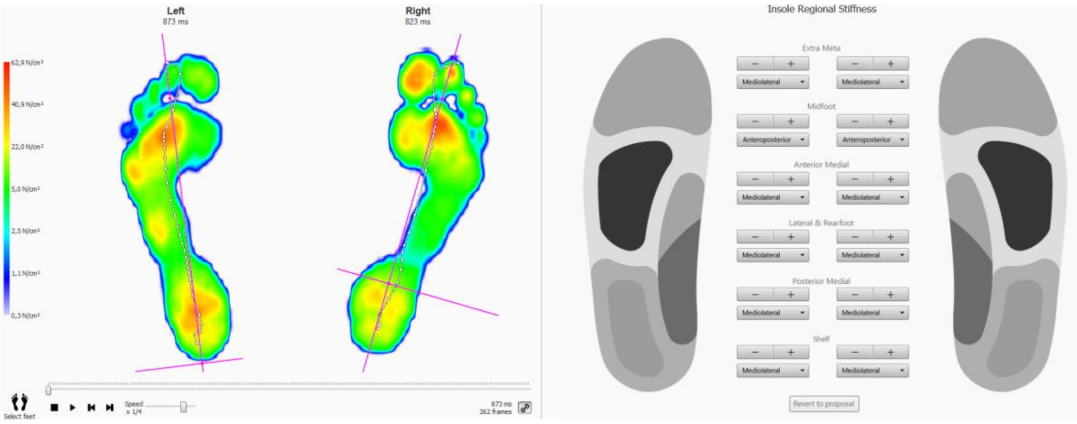


Figure 2.21 Foot pressure distribution in modelling program

In healthcare industry, there are many varied brand for production of designed parts. Some of them can be listed in Table 2.1 below.

Table 2.1 Production machine in healthcare industry

Manufacturer Brand	Figure	Features
Willow Wood Omega Carver		Dimensions:2184x825x2336mm Workspace: Ø610-length 635 mm X,Z and A axis
Biosculptor Biomill 4.5 XF-TM		Dimensions:860x1570x1930 mm Workspace: 410x560x1070 mm A axis:+45^{o}-0-45^{o} Weight:818 kg

Rodin 4D Model C		Workspace Ø 600 - length 1100 mm A axis:360°
Vorum Canfit IC 600		Dimensions: 1770x2040x2180 Workspace 700mm x 650mm x 240mm Control Unit :3 axis simultaneous movements
Voxel Care VCM-100		Dimensions: 1050x1100x1400 Work Table:780x640x100 Weight:250 kg Axis speed:20.000 mm/sec Spindle:24.000 rpm
Voxel Care VCM-350		Dimensions: 3500x2450x1500 Workspace: 3050x2020x150 Weight: 2.200 kg Axis speed:20.000 mm/sec Spindle:24.000 rpm

When the current manufacturers are examined, common machine type is that 3-Axis CNC Router machine but this machine only eligible to machine that parts composed of Cartesian coordinates (X, Y, Z). To overcome this situation, machine manufacturers have developed varied designs that can do many tasks at the same time and on the same machine. Since the market requirements are seen to be in this direction, a CNC machine was developed in this work in accordance with this aim.

In the healthcare field, machining process in CNC machines is performed with many different materials. For example; titanium implants used in dentures, engineering plastics (Polyethylene, Polypropylene, Polyvinylchloride, Polyurethane, Polypropylene, Silicon, Ethyl-vinyl-acetate) used in prostheses, artificial joints, surgical procedure and fasteners. Ethyl-vinyl-acetate (EVA) and polyurethane foam materials will be machined frequently with the 4-Axis CNC machine made in this study. Therefore, more detailed examination of these two materials has been made.

Ethylene-vinyl-acetate (EVA), also known as poly (ethylene-vinyl acetate) (PEVA), is the copolymer of ethylene and vinyl acetate. EVA material is shown in Figure 2.22. The weight percent vinyl acetate usually varies from 10 to 40%, with the remainder being ethylene. It is a polymer that approaches elastomeric materials in softness and flexibility, yet can be processed like other thermoplastics. The material has good clarity and gloss, low-temperature toughness, stress-crack resistance, hot-melt adhesive waterproof properties, and resistance to UV radiation. Application areas are that is biomedical engineering, equipment for various sports, orthotics.

Figure 2.22 Personalized insoles with EVA material

EVA material is a thermoplastic based polymer, so it requires special cutting tools because it adheres to standard inserts during machining process. The cutting tool developed for this purpose is shown in Figure 2.23. The cutting surface area of this cutting tool is wrapped around the entire surface with pyramid shaped cutting edges. Thus, during the machining process EVA chips do not cling to cutting tool and process is done trustfully.

Figure 2.23 Special cutting tool for EVA material

Polyurethane (PUR and PU) is a polymer consisted of organic units joined by carbamate links. Whereas most polyurethanes are thermosetting polymers that do not melt when heated, thermoplastic polyurethanes are also available. Polyurethane polymers are traditionally and most commonly formed by reacting a di- or poly-isocyanate with a polyol. Both the isocyanates and polyols used to make polyurethanes include, on average, two or more functional groups per molecule. PU material is shown in Figure 2.24.

Figure 2.24 Rigid polyurethane foam for prosthetic waist corset

CHAPTER THREE
DESIGN OF FOUR AXIS CNC MACHINE AND CONTROL PANEL

In this chapter the mechanical design of the 4-Axis CNC machine and the control panel will be presented along with calculations of axes.

3.1 Overview to Design of 4-Axis CNC Machine

Before starting to this study, information on previous work on the subject will be expressed.

In September 2014, with the consultation of Prof. Dr. Hira KARAGÜLLE, an A-axis CNC machine was designed and manufactured in 'DESIGN OF AN A AXIS CNC ROUTER' M.Sc. thesis by Duygu PAKTAŞ. In this study, produced A-Axis machine has X-Z linear axis and 360° rotating an A axis and this machine is shown in Figure 3.1. Furthermore, new design developed in this thesis is shown in Figure 3.2 and Figure 3.3.

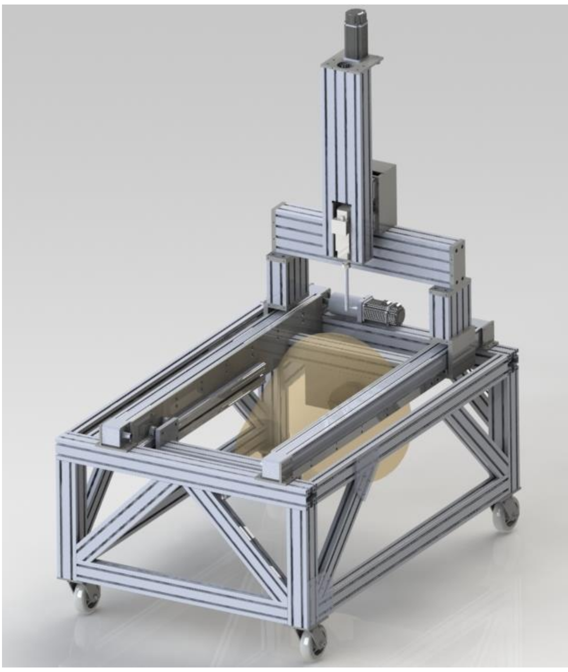


Figure 3.1 A-Axis CNC Router CAD model performed by previous study

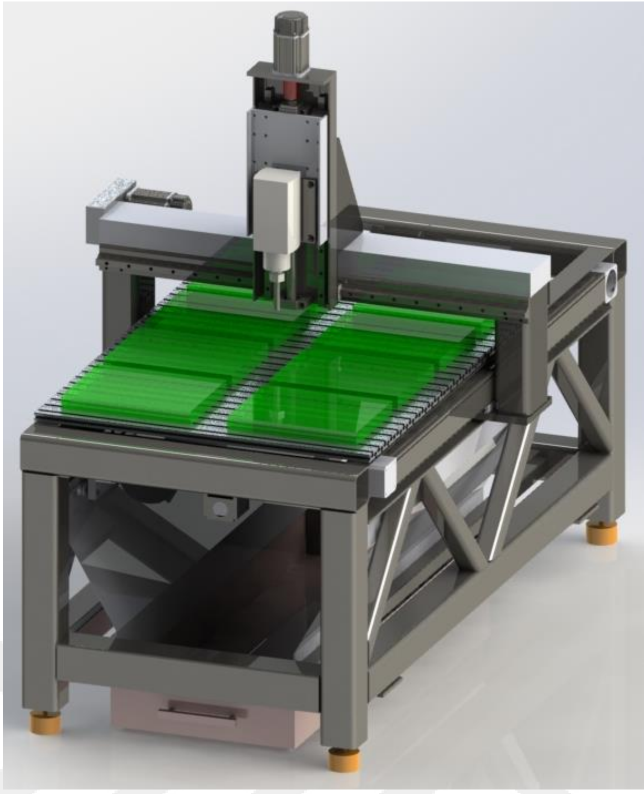


Figure 3.2 New design with 3-Axis (X, Y, Z) machining configuration

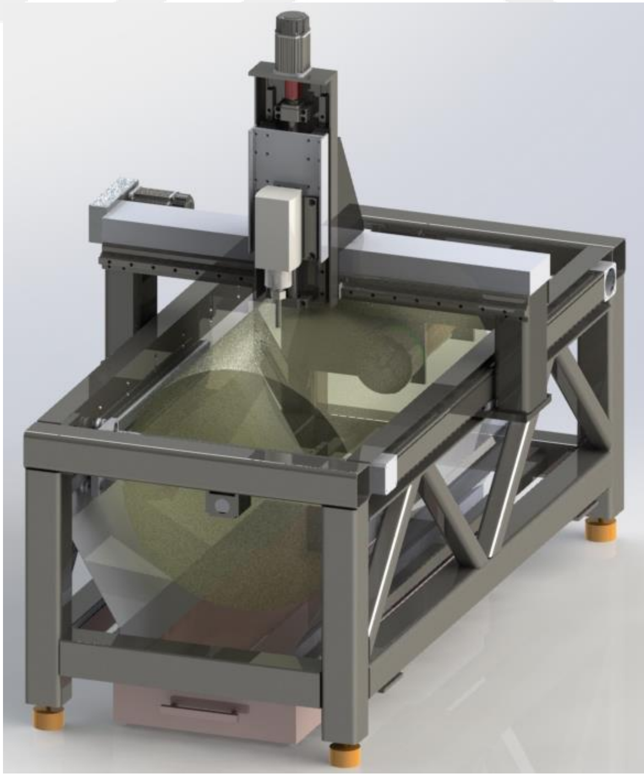


Figure 3.3 New design with 4-Axis (X, Y, Z and A) machining configuration

CNC Router that is produced in her thesis has 2 linear axes and a rotated axis. One of them is in direction of X axis and the other one in the direction of Z axis. Z axis moves upward and downward with the spindle. X axis moves along work-piece forward and backward. Work-piece rotates around itself. Aluminum profiles were used for CNC main body. Profiles in the main frame are placed in the form of cage system for more robust frame. Linear modules are used for both X and Z axis. In the X axis, 2 belt driven linear modules are chosen, in the Z axis ball screw driven linear module is used. Servo motors are used for actuation. Motion is transferred from one belt driven linear module which is actuated Servo motor in the X axis to the other belt driven linear module in the X axis by means of a shaft. General dimensions of A axis CNC Router are 1780 x 1050 x 2050 mm respectively X, Y and Z axis. Working space is 1350 x 450 mm respectively X, Z axis. (Paktaş, 2014, p.13)

In the above mentioned study an A-Axis CNC machine redesign to 4-Axis CNC machine with this study. New 4-Axis machine design has significant differences compared with previous design. Main differences and similarities between two machines are listed in Table 3.1.

Table 3.1 Differences and similarities between old and new design

Feature	New Design	Previous Design
Axis	4-Axis (X,Y,Z,A)	3-Axis (X,Z,A)
Construction Type	Steel Construction	Aluminum Sigma Profile Construction
Machine Dimensions (X,Y,Z)	1950x1220x1700mm	1780x1050x2050mm
Workspace	1350x910x400mm (X,Y,Z) 1150x400xØ600mm (X,Z,A)	1350x450xØ450mm (X,Z,A)
A-Axis	360°	360°
Motors	Estun 750W AC Servo	Estun 750W AC Servo

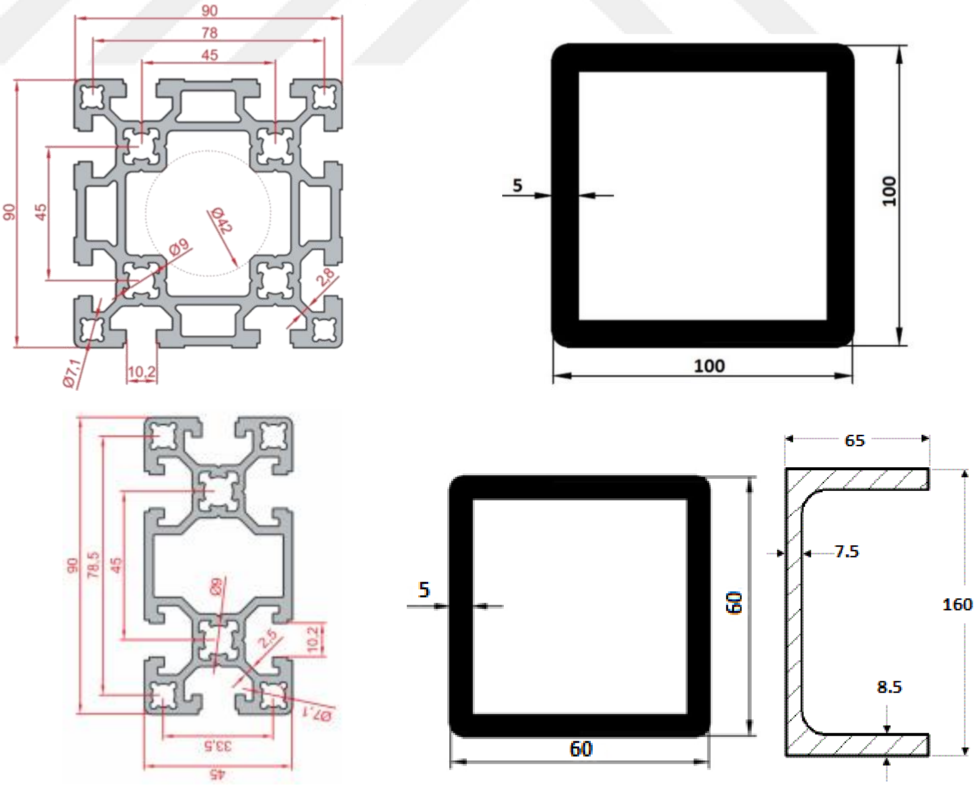
Axis Drive System	X-Axis Belt-Pulley Module Y-Axis Ballscrew Module Z-Axis Ballscrew A-Axis Belt-Pulley	X-Axis Belt-Pulley Module Z-Axis Ballscrew A-Axis Belt-Pulley
Control Unit	Fagor 8055-M CNC Controller	Mach3 Control Card
Motor Drive Method	±10V Analog Input Closed Loop Control	±5V Pulse Open Loop Control
Motion Type	3 Axis Simultaneous (X,Y,Z) 1 Axis positioning (A)	2 Axis Simultaneous (X,Z) 1 Axis positioning (A)
Spindle	2.2 kW 18.000 RPM (300 Hz)	0.37 kW 12.000 RPM (200 Hz)
Machining Type	Milling	Milling
Insole Manufacturing	8 pair insole at a time	-
Waist corset Manufacturing	Ø650mm Length 1000mm	Ø650mm Length 1000mm
Dedusting System	Available	Not Available

As shown in Table 3.1 above, new machine design has significant development according to previous design. The most important ones; machine construction was changed into steel construction from aluminum sigma profile construction and added one linear Y-Axis that upgrade the machining capability and also control unit was changed into closed loop analog drive system from the open loop pulse drive system. If 3-Axis (X, Y, Z) milling is wanted to use, machining table is placed the machine frame. If 4-Axis (X, Y, Z, A) milling process are wanted to use for rotating parts, machining table can be detached from the frame. Machining table is detachable structure from the machine frame, so as to machine all kinds of parts.

In the following sections design differences between old and new CNC machine design will be expressed comprehensively.

3.1.1 Frame Design of CNC Machine

New CNC machine frame is consisted of steel profile construction. Because old aluminum sigma profile design was not fulfill the expectation properly. Vibration and stiffness problems were encountered in the aluminum construction CNC machine. To avoid this kind of problem and enhance to rigidity of machine, frame design was changed to steel profile construction and welded connection from the aluminum sigma profile construction and bolt-nut connection. While aluminum construction frame weight is 140 kg with steel connection plate, steel construction frame weight is 220 kg with welded connection. Steel profile is determined 100x100mm square and 5 mm wall thickness in frame construction. The cross-sections of the sigma profiles used in the previous design and the steel profiles used in the new design are shown in Figure 3.4 and old and new designs are shown in Figure 3.5 and Figure 3.6 respectively. The steel plates, connecting the aluminum profiles each other, are shown in red in Figure 3.5.



(a) (b)

Figure 3.4 Profiles cross-section; (a) sigma profile - old design, (b) steel profile – new design

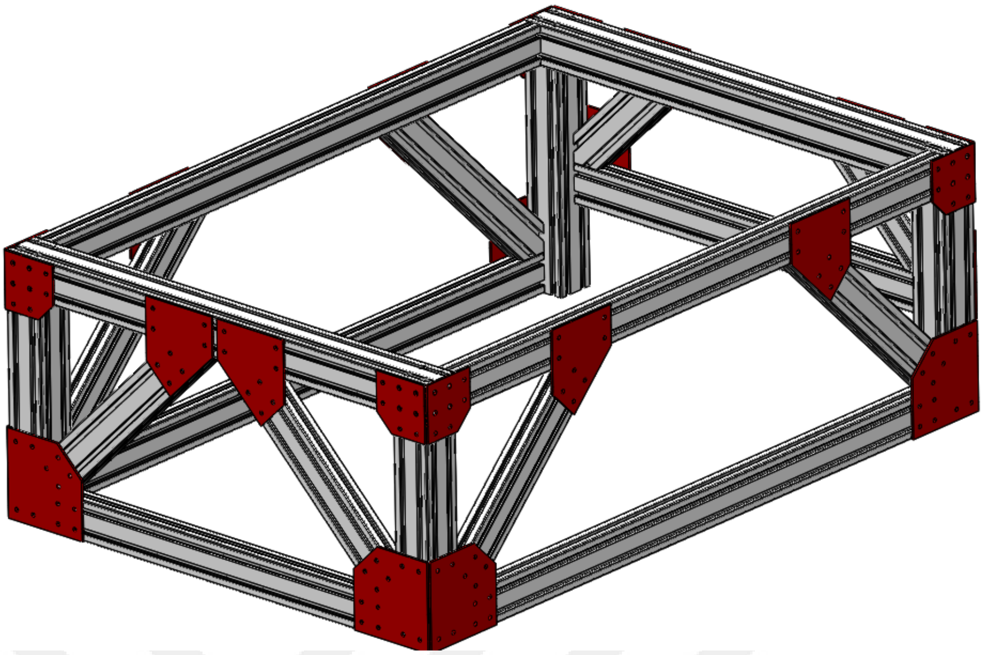


Figure 3.5 Old frame design with aluminum construction

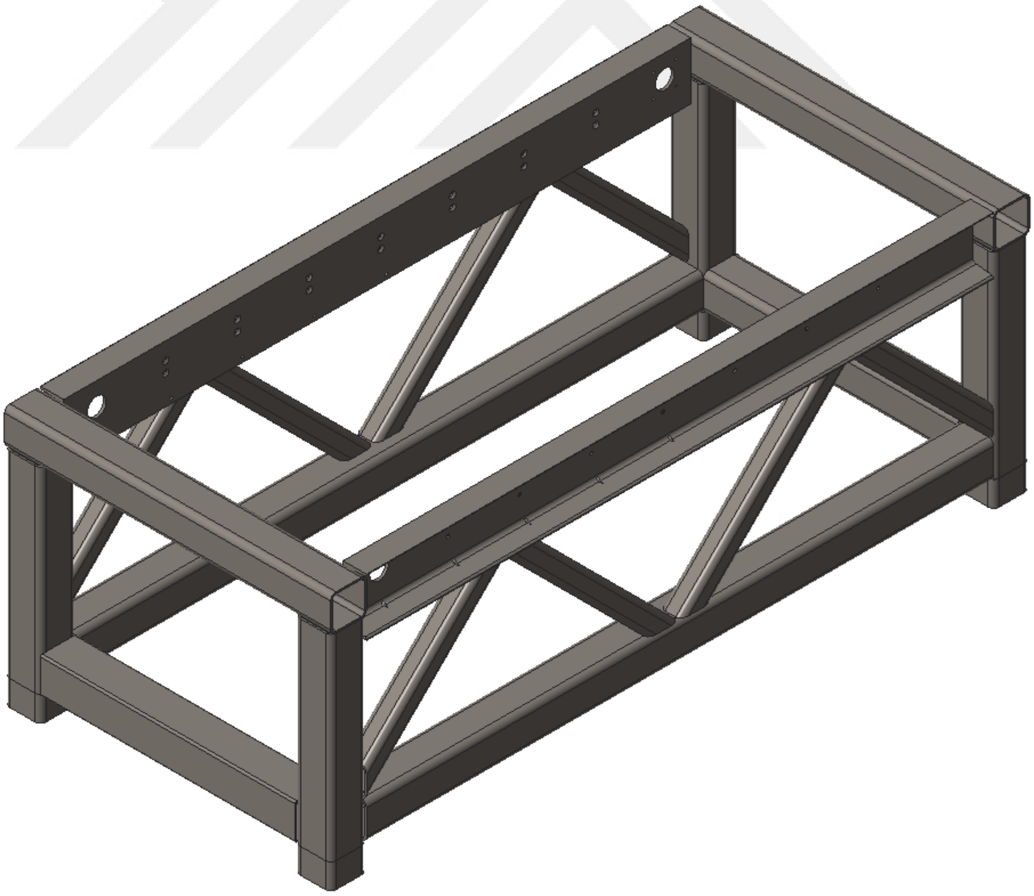


Figure 3.6 New frame design with steel construction

3.1.2 X-Axis Design of CNC Machine

New CNC machine X-Axis consists of two timing belt-pulley linear module which is same old design. One of them is actuating module and the other is slave module. 750 Watt AC Servo motor is used to drive X-Axis and transmitted to linear module via 50:1 transmission ratio PE090-10-APEX reducer. Calculations of the Axis are given the following section.

Old design CNC machine X-Axis view is shown in Figure 3.7. Red colored parts are represented the X-Axis. Here, modules are connected to frame via connection parts and there are strengthening plates on the inner side of the modules and X axis carry on the only Z axis. The moving load carried by the X axis is 108 kg.

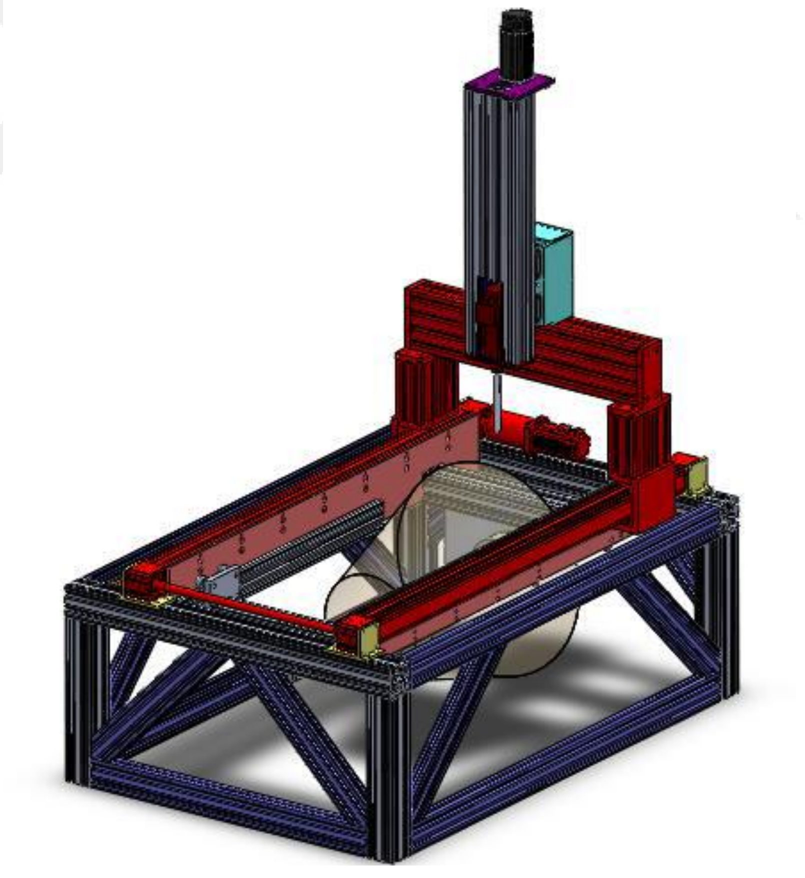


Figure 3.7 Old design CNC machine view and X-Axis is colored with red

New CNC machine X axis is shown in Figure 3.8. Here, timing belt-pulley modules are connected to inner side of frame’s U-profile via countersunk bolt in order to prevent gathering sawdust inside of the modules. X axis carry on the Y and Z axis. The moving load carried by the X axis is 132 kg.

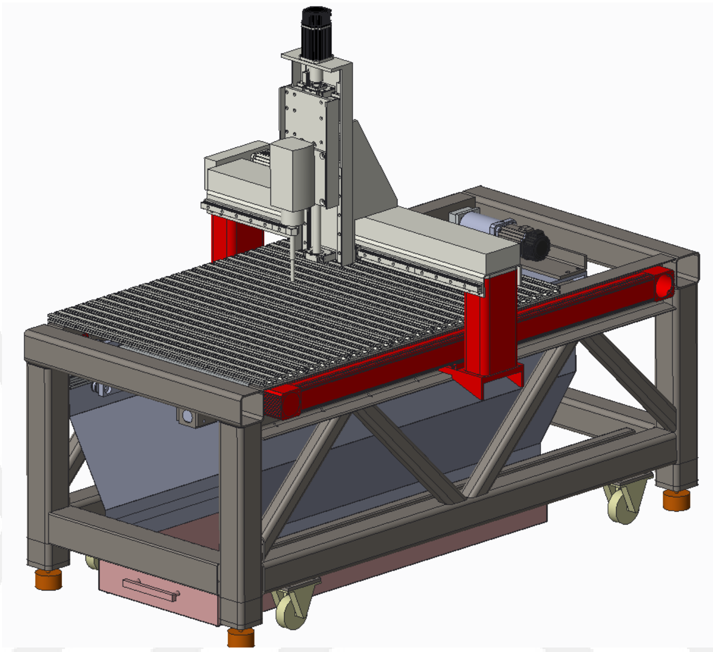


Figure 3.8 New design CNC machine view and X-Axis is colored with red

Timing-belt pulley linear modules type is KST8080M. Screw pitch of module is 200mm. Length of each module is 1500 mm. Static and dynamic loading limits are show in Figure 3.9.

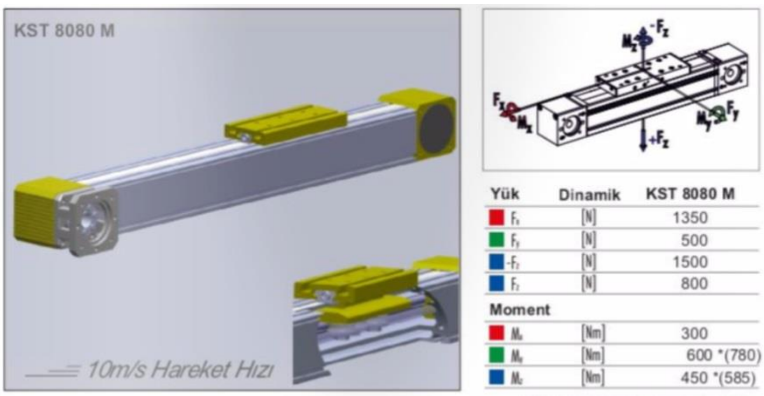


Figure 3.9 KST-8080M allowed loading limits (Endo, n.d.)

ESTUN brand AC Servo motors are chosen for new CNC machine drive system. Motor weight is 3.1 kg and motor shaft diameter is 19 mm. Servo motor nominal output power is 750W, rated rotational speed is 3000 rpm, rated torque value is 2.4 Nm. X axis maximum motion limit is 12 m/min due to the transmission ratio and servo motor characteristics are given in Figure 3.10 and Figure 3.11.

Rated Value and Specification

Voltage		100VAC/200VAC						
Servo Motor Model	EMJ–	A5ASA□□	01ASA□□	02ASA□□ 02AFA□□-TP	04ASA□□ 04AFB□□-TP	04A□H□□ 04AFH□□-TP	08ASB□□ 08AFB□□-TP	10ASB 10AFB□□-TP
Rated Output Power	kW	0.05	0.1	0.2	0.4		0.75	1.0
Rated Torque	N·m	0.16	0.32	0.64	1.27		2.39	3.18
Instantaneous Peak Torque	N·m	0.48	0.96	1.91	3.82		7.16	9.55
Rated Current	Arms	0.6	1.1	1.4	2.8		4.0	5.3
Instantaneous Max Current	Arms	1.7	3.0	4.2	8.4		12.0	15.9
Rated Speed	r/min	3000						
Max. Speed	r/min	5000		4500				
Rotor Moment of Inertia	$\times 10^{-4}$kg·m^2	0.019 (0.05)	0.035 (0.052)	0.19 (0.23)	0.31 (0.35)	0.7 (0.74)	1.35 (1.47)	1.74 (1.87)
Brake Rated Voltage		DC24V±10%						
Brake Rated Power	W	6.096		7.2			11.5	
Brake Holding Torque	N·m	0.3		1.3			3.2	
Encoder		17 bit Absolute Encoder 131072 P/R		20 bit Incremental Encoder 1048576P/R 17 bit Absolute Encoder 131072 P/R				
Insulation Class		F						
Ambient Temperature		0 to +40°C (no freezing)						
Ambient Humidity		20% to 80% RH (non-condensing)						
Vibration		49m/s^2						
Enclosure		Totally Enclosed, Self-cooled, IP65 (Except for shaft opening, when not equipped with oil seal; Except for connectors, when not equipped with waterproof connectors.)						

Figure 3.10 750 Watt Servo Motor Specs (ESTUN,n.d.)

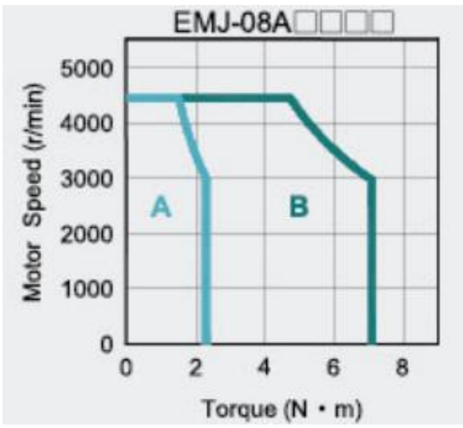


Figure 3.11 750 Servo motor torque curve (ESTUN,n.d.)

3.1.3 Y-Axis Design of CNC Machine

New CNC machine Y-Axis consists of ball screw linear module, which is screw pitch 10 mm, which is new feature according to old machine. Also in new design, Y-Axis is includes carrying parts on which bearing the Z-Axis. 750 Watt AC servo motor is used in acting the Y-Axis and motion is transferred to linear module shaft from motor shaft by U type 1:1 ratio trigger belt pulley mechanism. The moving load carried by the Y axis is 64 kg. New CNC machine Y-Axis is shown in Figure 3.12.

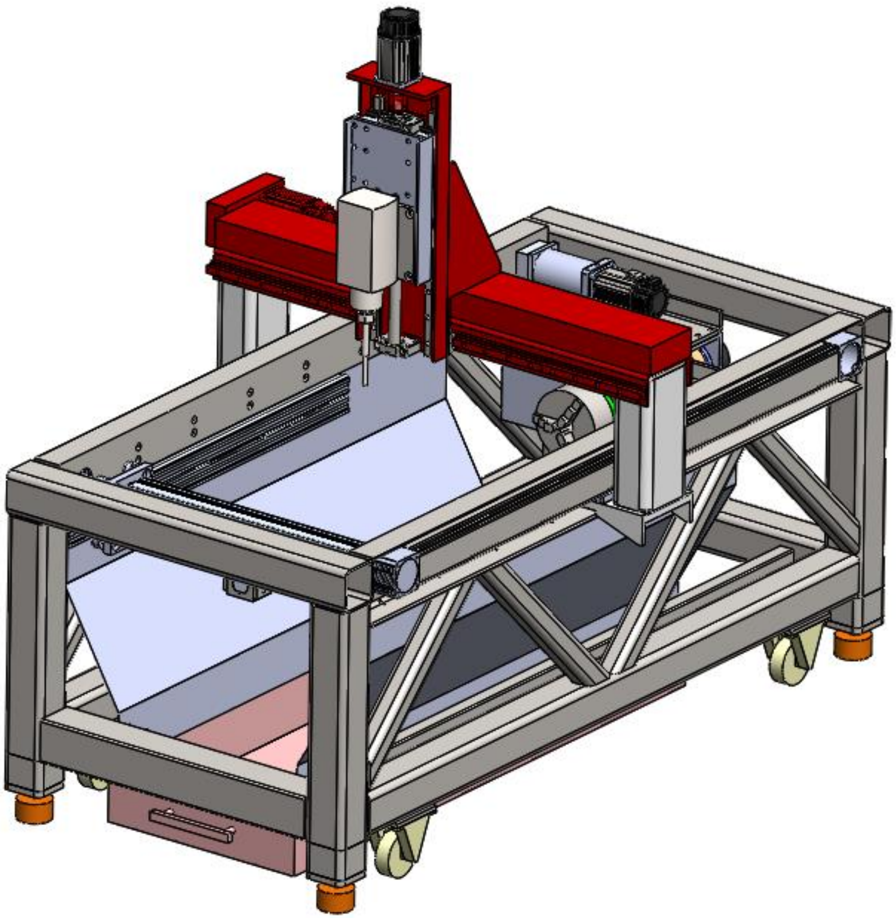


Figure 3.12 New design CNC machine view and Y-Axis is colored with red

Linear module with ball screw type is EMV-65 Single hub is used in Y-Axis. Screw pitch of module is 5mm. Length of module is 1170 mm. Static and dynamic loading limits are show in Figure 3.13.

Load	Dynamic	EMV 65 Single Hub
Fx	N	14300
Fy	N	8150
-Fz	N	14300
Fz	N	28450
Moment		
Mx	Nm	1580
My	Nm	278
Mz	Nm	375
Dynamic loads	N	32800

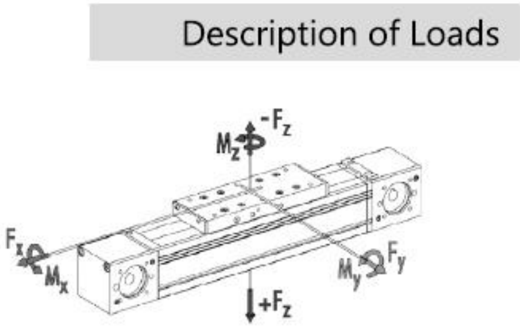


Figure 3.13 EMV-65 allowed loading limits (Endo, n.d.)

3.1.4 Z-Axis Design of CNC Machine

New CNC machine Z-Axis consists of ball screw and linear bearing parts. Ball screw pitch is 10mm that is the same with old design. Fundamental difference in Z-Axis between old and new design is that, while in the old CNC machine ball screw nut is fixed, in the new design ball screw nut is movable. Therefore, in the old design, Z-Axis body, bearing parts, ball-screw, spindle and axis motor move in vertical axis. This situation leads to more motor power and more rigid design requirement.

On the other hand, in the new design this drawback was eliminated due to new design method. Z-axis motor, axis body, bearing parts are fixed to the fixed part which is carried by Y-Axis. Hence, in the Z-Axis only two movable parts are including that are spindle and spindle fixed part. Due to the reduction of moving mass, motor power requirement is also reduced. Whereas, in the old design axis length is 800mm, in new the design axis length is 420mm. Both designs have the same working capacity in the Z-Axis.

750 Watt AC servo motor is used in Z-Axis that is directly linked with flexible coupling to axis drive shaft. Also, the moving load carried by the Z axis is 18 kg. New design CNC machine Z-Axis is shown in Figure 3.14. Z-Axis parts are colored with red and also old CNC machine design is shown in Figure 3.15 with same methodology.

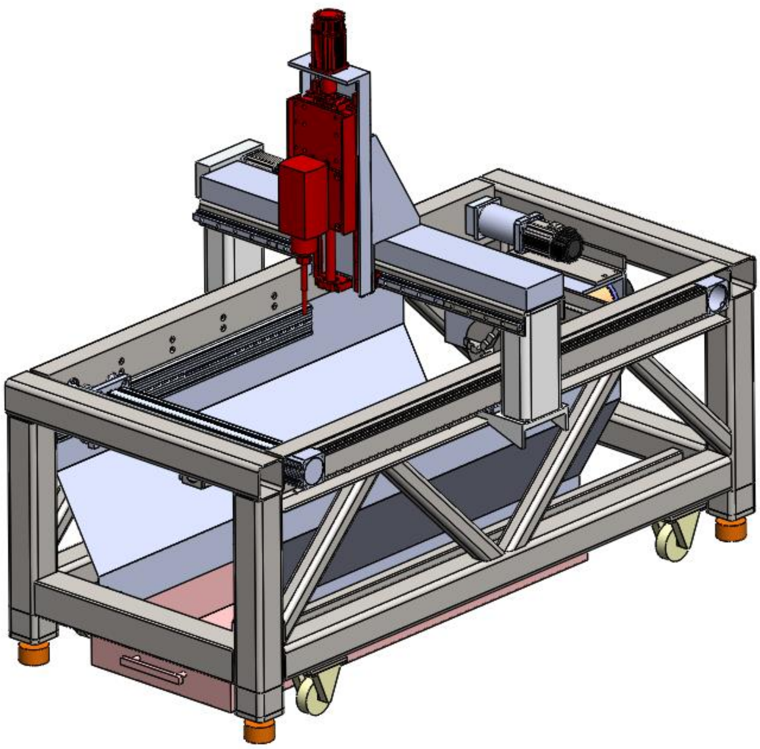


Figure 3.14 New design CNC machine view and Z-Axis is colored with red

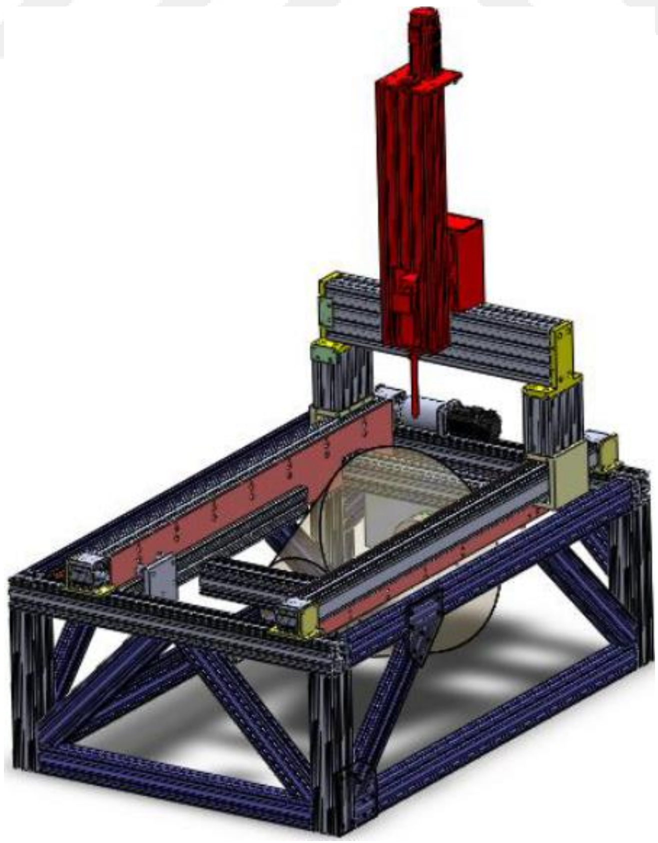
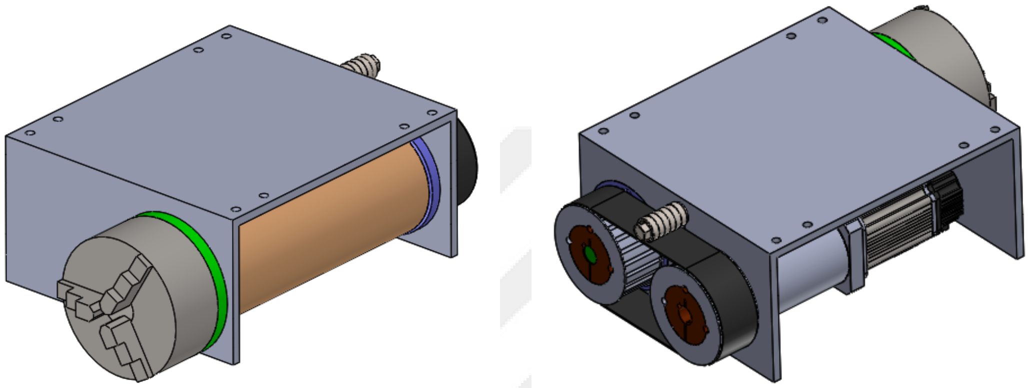


Figure 3.15 Old design CNC machine view and Z-Axis is colored with red

3.1.5 A-Axis Design of CNC Machine

A-Axis of CNC machine is same with old design. 750 Watt AC servo motor and 15:1 reducer are used in transmission component. Two type bearings are used in A-Axis, one of them is deep grove ball bearing, and the other is cylindrical roller bearing. A-Axis frame is fixed the machine frame by bolt-nut pairs. A-Axis of machine is shown in Figure 3.16 and Figure 3.17. and also parts in Table 3.2.



(a) (b)

Figure 3.16 A-Axis design; (a) front view, (b) back view

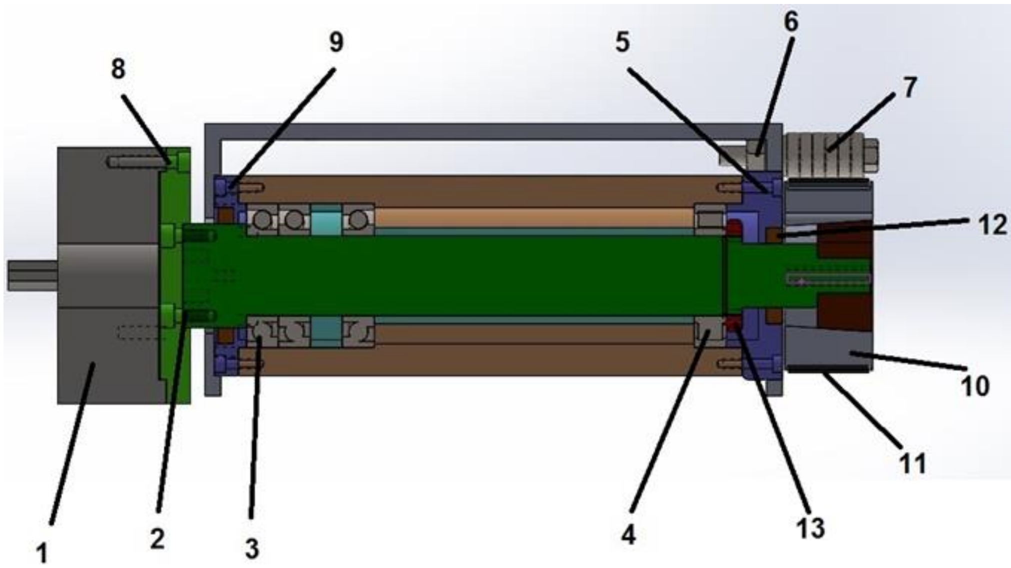


Figure 3.17 A-Axis section view

Table 3.2 Parts used in A-Axis

1	Lathe chuck
2	M8x20mm Hex socket head bolt
3	Radial single row angular contact bearing
4	Radial single row cylindrical roller bearing
5	M6x20mm Hex socket head bolt
6	M12 Hex nut
7	Radial Single row fixed ball bearing for stretching timing belt
8	M8x35mm Hex socket head bolt
9	M8x20mm Hex socket head bolt
10	Timing gearwheel
11	Timing belt
12	Spring seal
13	Nut lock

3.2 Calculations

In this section, engineering calculations of the new designed CNC machine are figured out according to machinery dynamics formulas. In literature, there are three different cutting force approaches for the CNC machines. These are;

- Light cutting force (for Aluminum cutting, roughly 1000 N)
- Medium-weight cutting force (for tempered steel, roughly 1000-3000 N)
- Heavy-weight cutting force (for cold work die steel roughly 3000-5000 N)

The cutting force will be calculated according to aluminum material, because its technical specifications are well known and also CNC machine which is produced in this thesis is not designed for cutting steel materials. In practice, weaker materials will be machined in this CNC machine instead of aluminum materials. So, if the CNC machine has the enough rigidity to machine aluminum material, weak materials such as EVA and PU foam will be machined much more safely.

Calculations will be begun with average cutting force and required spindle power. As the cutting method, the slot milling operation which creates the maximum cutting force is selected.

Cutting force and required spindle power are shown in Table 3.3. Specific cutting forces are shown in Figure 3.18.

Table 3.3 Cutting force and Spindle power

Formulation	**Calculation**	**Results**
Cutting cross-section $A = a_p * f_z * z$ a_p: deep of cut (mm) f_z: feed per tooth (mm) z: number of teeth (pcs)	A = 2*0.14*4 a_p= 2mm (approximation) f_z = 0.14mm z= 4 (tooth of cutter)	$A = 1.12\ mm^2$
$\boldsymbol{f_z = \frac{v_f}{n * z_c}}$ n: Spindle speed (RPM) v_f: Table feed (mm/min) z_c: number of effective teeth (pcs)	$f_z = \frac{5000}{18000 * 2}$ v_f = 5000 mm/min n= 18000 RPM z_c = 2 (effective tooth in slot milling)	f_z = 0.14mm
k_s: specific cutting force	$k_s=800\ N/mm^2$	$k_s=800\ N/mm^2$
Cutting force $F_c = A * k_s$	F_c= 1.12*800	**F_c = 900 N**
$\boldsymbol{P_c = \frac{a_p * a_e * v_f * k_s}{60 * 10^6 * \eta}}$ **P_c= Cutting power (spindle power)** **a_e = cutting width** **η= machine coefficient**	$P_c = \frac{2 * 10 * 5000 * 800}{60 * 10^6 * 0.98}$ a_e = 10 mm (tool diameter for slot milling)	**P_c= 1,36 kW** **(<u>2.2 kW selected</u>)**

Specific cutting force (k_s) is selected according to below list.

Parça Malzemesi	k_s [N/mm²]
St 60	1600
St 70	1900
Islah çelikleri ($\sigma_k \leqslant$ 100 N/mm)	2350
Islah çelikleri ($\sigma_k \leqslant$ 1400 N/mm)	3500
Cr - Ni - Çelikleri	3000
Mn - Çelikleri	4800
Dökme Çelik	1500
Dökme Demir	2000
Al - Cu - Mg Alaşımı (Duraliminyum)	800

Figure 3.18 Specific cutting forces for some metals (Akkurt, 1985)

3.2.1 X Axis Calculations

The X-Axis calculations consist of total force, total moment and required motor power calculations. Calculations are shown in Table 3.4, Table 3.5 and Table 3.6. These calculations are performed with the middle position of CNC machine due to the fact that weakest position of machine is on the middle position.

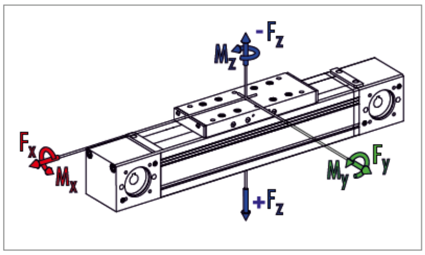
Table 3.4 X-Axis force calculations

Acceleration value of Each-Axis	0.4	m/s^2
Moving total mass on X-Axis	132	kg
Moving total mass on Y-Axis	64	kg
Moving total mass on Z-Axis	18	kg
Z direction, force of inertia	18*0.4 = 7.2	N
Y direction, force of inertia	64*0.4 = 25.6	N
X direction, force of inertia	132*0.4 = 52.8	N
Gravitational force on X-Axis	132*9.81 = 1294.9	N
Friction force	(1294.9+7.2)*0.1 = 130	N
Cutting force	$F_c = 900$ $F_x = 0.5*F_c = 450$ $F_y = 0.5*F_c = 450$ $F_z = 0.7*F_c = 630$	N
Moment effect force on Axes	$M_x = 90$ Nm , $d_y = 0.95$m $F_y = M_x / d_y = 90 / 0.95$ $F_y = 95$ $M_y = 280$ Nm , $d_x = 0.18$m $F_z = M_y / d_x = 280 / 0.18$ $F_z = 1555.5$ $M_z = 310,5$ Nm , $d_y = 0.95$m $F_x = M_z / d_y = 310.5 / 0.95$ $F_x = 327$	N
Total force on X direction	450+130+52.8+327 = 959.8	N
Total force on Y direction	450+25.6+95 = 570.6	N
Total force on Z direction	1294.9 - 630 + 7.2+1555.5 = 2227.6	N
Total force distribution on each module	$F_x = 959.8 / 2 = 479.9$ $F_y = 570.6 / 2 = 258.3$ $F_z = 2227.6 / 2 = 1113.8$	N
Comparison	$F_x = 479.9 < 1350$ → Safe $F_y = 258.3 < 500$ → Safe $F_z = 1113.8 < 1500$ → Safe	✓

Table 3.5 X-Axis moment calculations

Moment effect of cutting force components	$M_x = F_y * r_z = 450 * 0.2 = 90$ $M_x = 90$ $M_y = F_x * r_z = 450 * 0.2 = 90$ $M_y = F_z * r_x = 630 * 0.27 = 170$ $M_y = 280$ $M_z = F_x * r_y = 450 * 0.42 = 189$ $M_z = F_y * r_x = 450 * 0.27 = 121.5$ $M_z = 310,5$	Nm
Comparison	$M_y = 280$ (Shared by two modules) $M_{y\text{-module}} = 280 / 2$ $140 < 600 \rightarrow$ Safe	✓

CNC machine X axis has 2 linear timing belt-pulley modules. Hence, total force effected on X axis is shared by these 2 linear modules. Also, M_x and M_z moment can't occur a moment as expected due to the used of two modules, but M_x and M_z moment affect to modules as a force effect. For this reason, only M_y moment (Longitudinal moment) was checked. Linear module technical specifications are given in the Figure 3.19. And also, calculation position view is shown in Figure 3.20. And the distances in using calculate of the moment are shown in Figure 3.21.



Yük	Dinamik	KST 8080 M
F_x	[N]	1350
F_y	[N]	500
$-F_z$	[N]	1500
F_z	[N]	800
Moment		
M_x	[Nm]	300
M_y	[Nm]	600
M_z	[Nm]	450

Figure 3.19 KST-8080M allowed loading limits (Endo, n.d.)

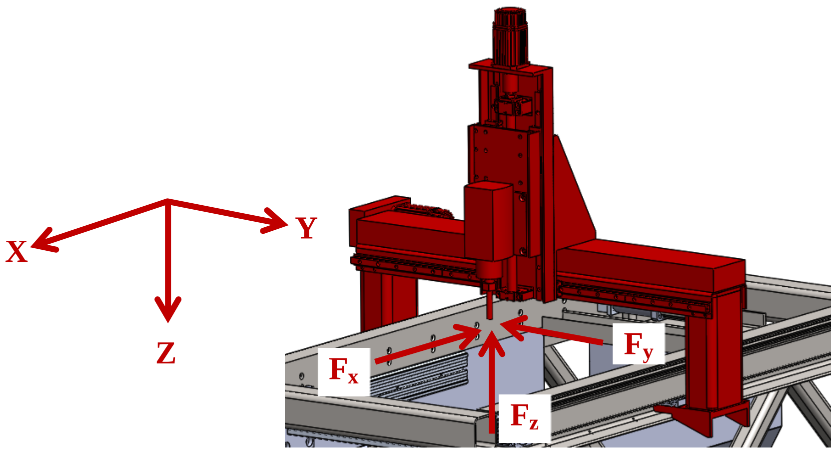


Figure 3.20 Force and moment calculation position view (midpoint of machine)

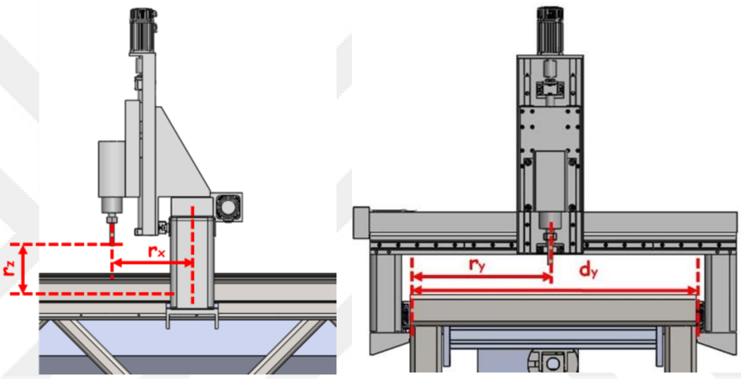


Figure 3.21 Force and moment calculation distances for X-Axis

Required motor power calculations are given in Table 3.6.

Table 3.6 X-Axis required motor calculations

Motor RPM in stable torque	3000	RPM
Reducer	50:1	rev
X-Axis module pitch	200	mm/rev
Maximum axis velocity	(3000/60)*(1/50)*200 = 200 =0.2	mm/s m/s
Maximum X axis force	959.8	N
Motor efficiency	90	%
Required motor power	(959.8 * 0.2) / 0.9 = 213.3	Watt
Selected motor power	750	Watt
Torque	P= T*w 213.3 = T * (2*pi*3000/60) T= 0.68	Nm
Comparison	213.3 < 750 → Safe 0.68 < 2.39 → Safe	✓

3.2.2 Y Axis Calculations

The Y-Axis calculations consist of total force, total moment and required motor power calculations. Calculations are shown in Table 3.7, Table 3.8 and Table 3.9.

Table 3.7 Y-Axis force calculations

Acceleration value of Each-Axis	0.4	m/s^2
Moving total mass on Y-Axis	64	kg
Moving total mass on Z-Axis	18	kg
Z direction, force of inertia	18*0.4 = 7.2	N
Y direction, force of inertia	64*0.4 = 25.6	N
X direction, force of inertia	64*0.4 = 25.6	N
Gravitational force on Y-Axis	64*9.81 = 627.8	N
Friction force	(627.8+25.6+7.2)*0.1 = 66	N
Cutting force	$F_c = 900$ $F_x = 0.5*F_c = 450$ $F_y = 0.5*F_c = 450$ $F_z = 0.7*F_c = 630$	N
Moment effect force on Axes	$M_x = 60.75$ Nm , $d_z = 0.1$m $F_y = M_x / d_y = 60.75 / 0.1$ $F_y = 607.5$ $M_y = 230.85$ Nm , $d_z = 0.1$m $F_z = M_y / d_z = 230.85 / 0.1$ $F_z = 2308.5$ $M_z = 121,5$ Nm , $d_z = 0.1$m $F_x = M_z / d_y = 121.5 / 0.1$ $F_x = 1215$	N
Total force on X direction	450+1215+25.6 = 1690.6	N
Total force on Y direction	450+607.5+25.6+66 = 1149.1	N
Total force on Z direction	627.8 – 630 + 2308 + 7.2 = 2313	N
Comparison	$F_x = 1690.6 < 8150$ → Safe $F_y = 1149.1 < 14300$ → Safe $F_z = 2313 < 28450$ → Safe	✓

Table 3.8 Y-Axis moment calculations

Moment effect of cutting force components	$M_x = F_y * r_z = 450 * 0.135 = 60.75$ $M_x = 60.75$ $M_y = F_x * r_z = 450 * 0.135 = 60.75$ $M_y = F_z * r_x = 630 * 0.27 = 170.1$ $M_y = 230.85$ $M_z = F_y * r_x = 450 * 0.27 = 121.5$ $M_z = 121.5$	Nm
Comparison	The module’s moment carrying capacity is safe on each axis due to the mechanical design.	✓

CNC machine Y axis has one linear ball-screw modules and one guide-rail couple. Total force affected on Y axis is beared by this linear module and guide-rail couple. Torsional, bending and longitudinal moment can’t occur in the Y-Axis due to mechanical design but these moments affect on the Y-module as a force effect. Linear module technical specifications are given in the Figure 3.22. And also, calculation position view is shown in Figure 3.23. And the distances in using calculate of the moment are shown in Figure 3.24.

Load	Dynamic	EMV 65 Single Hub
Fx	N	8150
Fy	N	14300
-Fz	N	14300
Fz	N	28450
Moment		
Mx	Nm	278
My	Nm	1580
Mz	Nm	375
Dynamic loads	N	32800

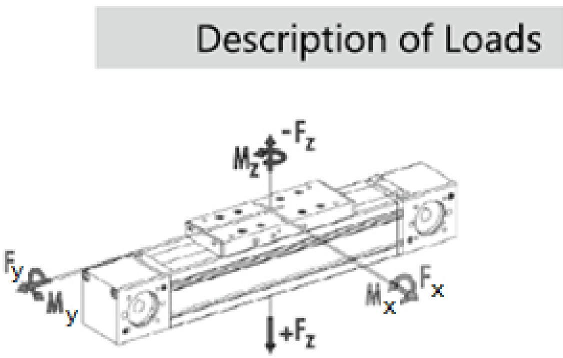


Figure 3.22 EMV-65 linear module allowed loading limits (Endo, n.d.)

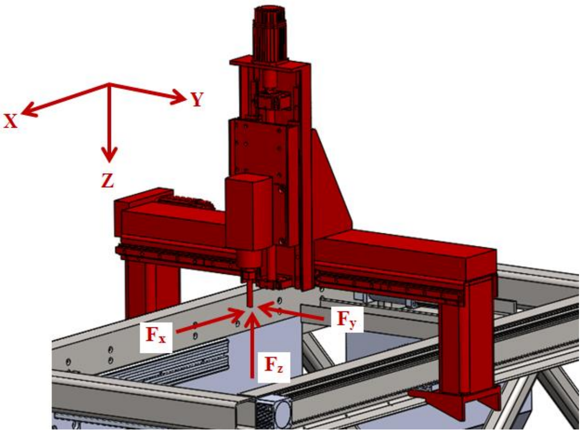


Figure 3.23 Force and moment calculation position view (midpoint of machine)

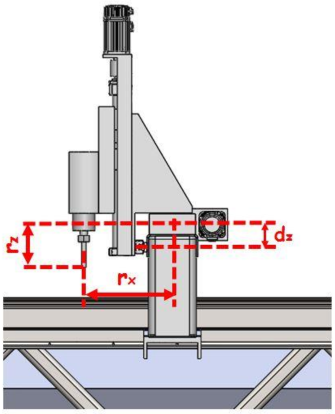


Figure 3.24 Force and moment calculation distances for Y-Axis

Required motor power calculations are given in Table 3.9

Table 3.9 Y-Axis required motor calculations

Motor RPM in stable torque	3000	RPM
Reducer	1:1	rev
Y-Axis module pitch	5	mm/rev
Maximum axis velocity	(3000/60)*(1/1)*5 = 250 =0.25	mm/s m/s
Maximum Y axis force	1149.1	N
Motor efficiency	90	%
Required motor power	(1149.1 * 0.25) / 0.9 = 319.16	Watt
Selected motor power	750	Watt
Torque	P= T*w 319.16 = T * (2*pi*3000/60) T= 1.02	Nm
Comparison	319.16 < 750 → Safe 1.02 < 2.39 → Safe	✓

3.2.3 Z Axis Calculations

The Z-Axis calculations consist of total force, total moment and required motor power calculations. Calculations are shown in Table 3.10, Table 3.11 and Table 3.12.

Table 3.10 Z-Axis force calculations

Acceleration value of Each-Axis	0.4	m/s^2
Moving total mass on Z-Axis	18	kg
Z direction, force of inertia	18*0.4 = 7.2	N
Gravitational force on Z-Axis	18*9.81 = 176.58	N
Friction force	(176.58+7.2)*0.1 = 18.4	N
Cutting force	$F_c = 900$ $F_x = 0.5{*}F_c = 450$ $F_y = 0.5{*}F_c = 450$ $F_z = 0.7{*}F_c = 630$	N
Moment effect force on Axes	$M_x = 180$ Nm , $d_y = 0.145$m $F_y = M_x / d_y = 180 / 0.145$ $F_y = 1241.4$ $M_y = 258.75$ Nm , $d_y = 0.145$m $F_z = M_y / d_y = 258.75 / 0.145$ $F_z = 1784.5$ $M_z = 88.65$ Nm , $d_y = 0.145$m $F_x = M_z / d_y = 88.65 / 0.145$ $F_x = 611.4$	N
Total force on X direction	450 + 611.4 = 1061.4	N
Total force on Y direction	450 + 1241.4 = 1691.4	N
Total force on Z direction	176.58 - 630 + 7.2 + 1784.5 = 1338.28	N
Vector sum of forces	Sqr($1061.4^2+1691.4^2+1338.28^2$) = 2403.8	N
Comparison	$F_R = 2403.8 < 16200 \rightarrow$ Safe	✓

Table 3.11 Z-Axis moment calculations

Moment effect of cutting force components	$M_x = F_y * r_z = 450 * 0.4 = 180$ $M_x = 180$ $M_y = F_x * r_z = 450 * 0.4 = 180$ $M_y = F_z * r_x = 630 * 0.125 = 78.75$ $M_y = 258.75$ $M_z = F_y * r_x = 450 * 0.125 = 56.25$ $M_z = F_x * r_y = 450 * 0.072 = 32.4$ $M_z = 88.65$	Nm
Comparison	Guide-rail moment carrying capacity is safe on each axis due to the mechanical design.	✓

CNC machine Z axis has four linear guide bearings and one ball-screw. Total force affected on Z axis is beared by these linear guide bearings. Mechanical design of Z-Axis consists of 4 linear guide bearings and 2 rails. For this reason, moments can’t occur on the X-Y-Z directions due to the mechanical design. Moment effect act on the Z-Axis as a force effect. Axis Linear guide bearing technical specifications are given in the Figure 3.25. And also, calculation position view is shown in Figure 3.26. And the distances in using calculate of the moment are shown in Figure 3.27.

	Load carrying capacity 1) Basic load ratings C N	C_0 N	Moment ratings M_{0x} Nm	M_{0y} Nm	M_{0z} Nm
KUVE20-B-SL KUVE20-B-SNL	16200	36500	452	430	430
KUVE25-B-HL KUVE25-B-SL KUVE25-B-SNL	23400	54000	745	825	825
KUVE30-B-HL KUVE30-B-SL KUVE30-B-SNL	34500	74000	1310	1240	1240
KUVE35-B-HL KUVE35-B-SL KUVE35-B-SNL	47500	100000	2025	1890	1890
KUVE45-B-HL KUVE45-B-SL KUVE45-B-SNL	82000	181000	4635	4000	4000
KUVE55-B-SL	127000	285000	7500	4725	4800

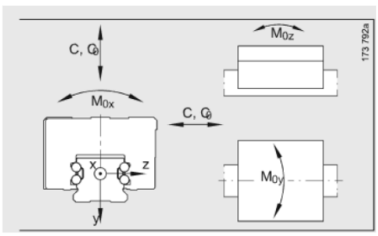


Figure 3.25 Linear guide bearing allowed loading limits (Endo, n.d.)

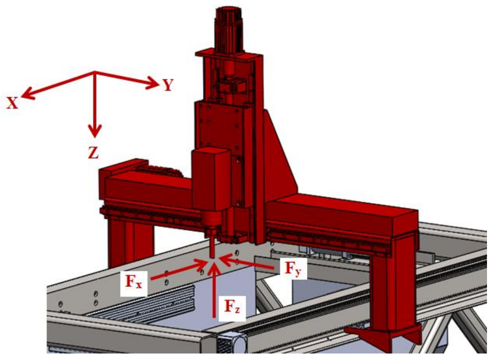


Figure 3.26 Force and moment calculation position view (midpoint of machine)

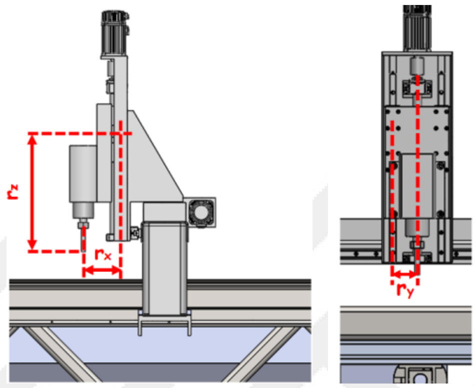


Figure 3.27 Force and moment calculation distances for Z-Axis

Required motor power calculations are given in Table 3.12.

Table 3.12 Z-Axis required motor calculations

Motor RPM in stable torque	3000	RPM
Reducer	1:1	rev
Z-Axis module pitch	10	mm/rev
Maximum axis velocity	(3000/60)*(1/1)*10 = 500 =0.5	mm/s m/s
Maximum Z axis force	1338.28	N
Motor efficiency	90	%
Required motor power	(1338.28 * 0.5) / 0.9 = 743.5	Watt
Selected motor power	750	Watt
Torque	P= T*w 743.5 = T * (2*pi*3000/60) T= 2.36	Nm
Comparison	743.5 < 750 → Safe 2.36 < 2.39 → Safe	✓

3.2.4 A Axis Calculations

The A-Axis calculations consist of required motor power and chosen timing belt. Details of A-Axis are shown in Figure 3.28 and Figure 3.29. Formulations are shown in Figure 3.30.

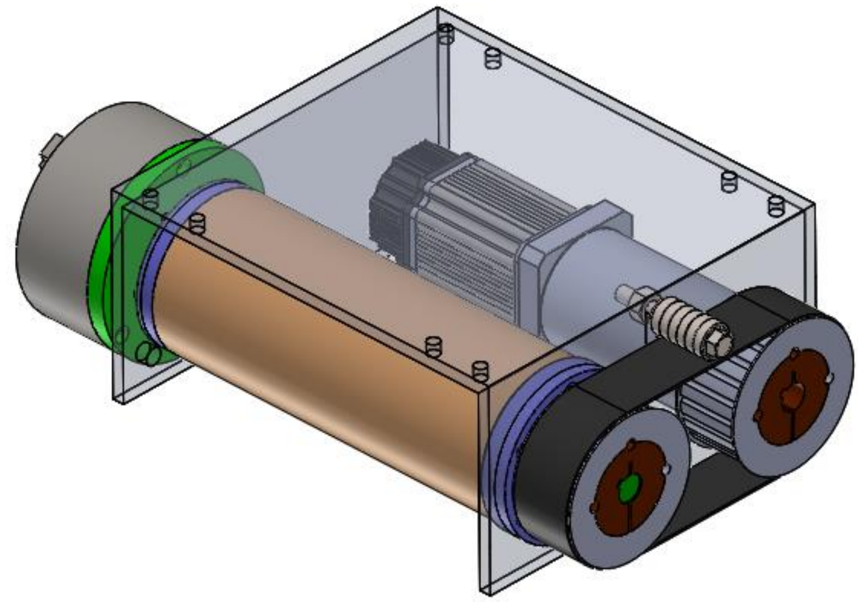


Figure 3.28 General view of A-Axis

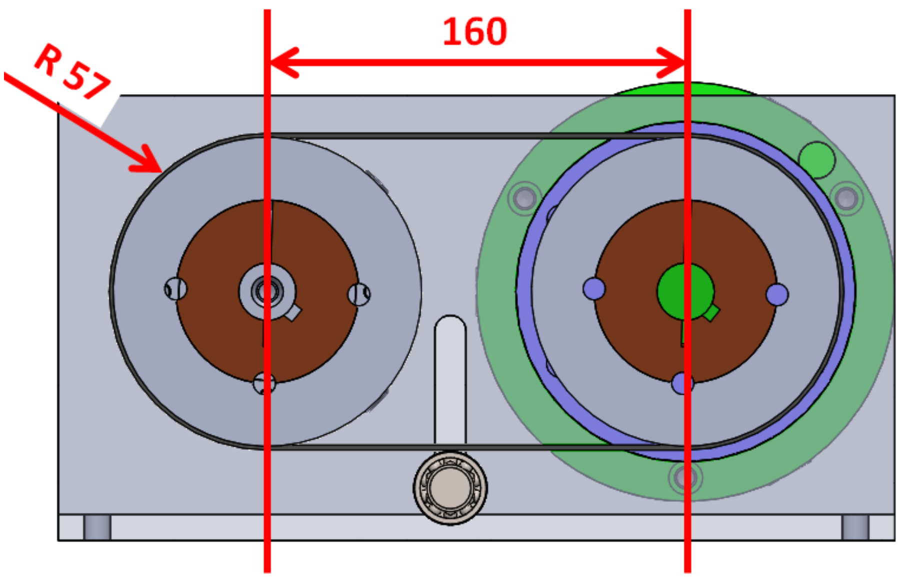
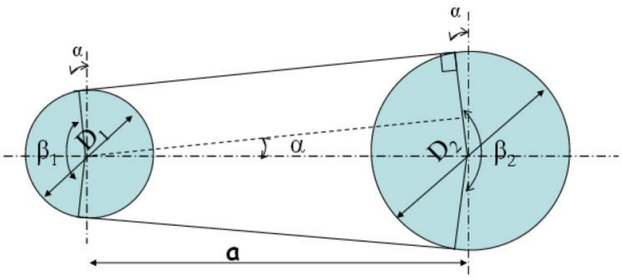


Figure 3.29 A-Axis dimensions



$$L = 2a\cos a + \frac{\pi}{2}(D_1 + D_2) + \frac{\pi}{180}a(D_2 - D_1)$$

$$L = 2a + \frac{\pi}{2}(D_1 + D_2) + \frac{(D_2 - D_1)^2}{4a}$$

Figure 3.30 Belt-pulley calculation formulas

Axis distance between the motor and shaft is 160 mm. Wheel diameter is 114mm. Hence, L= 2*160 + (π/2)*(114+114); L=678.14mm and timing belt length is chosen 680mm from standard table.

Required motor power is calculated according the below Table 3.13.

Table 3.13 A-Axis required motor calculations

Motor RPM in stable torque	3000	RPM
Reducer	1:30	rev
Maximum axis velocity	(3000/60)*(1/30) = 1.666 100	rev/s rpm
Maximum force in A axis	Cutting force = 900 (for Aluminum) Cutting force = 150 (for PU foam roughly)	N
Distance between motor axis and work piece maximum point	Work piece diameter = 600 Radius = 300 Radius = 0.3	mm mm m
Motor efficiency	90	%
Required motor power	(150 * 0.3) *(2*π*1.66) / 0.9 = 521.5	Watt
Selected motor power	750	Watt
Torque	P= T*w 521.5 = T * 2*π*(3000/60) T = 1.66	Nm
Comparison	521.5 < 750 → Safe 1.66 < 2.39 → Safe	✓

3.3 Control Unit of CNC Machine

CNC machine control unit is selected Fagor 8055-M CNC controller. Fagor 8055-M CNC controller's technical specifications are given in Figure 3.31.

CNC 8055

Central unit

- Frames with a power supply for 3 or 6 modules.
- The CPU and axes modules are part of all configurations.
- The I/O modules, SERCOS and the CPU-turbo cards are optional.

CPU module

- Up to 1Mb of user RAM memory.
- Compact flash of up to 2 Gb (optional) with flash memory to store user programs, OEM programs, PLC programs, customizing programs, parameter tables, etc.
- Ethernet (optional). TCP-IP protocol.
- Sercos interface (optional). For digital communication through fiber optics between the FAGOR 8055 CNC and FAGOR digital servo drives (AXD/SPD).
- CAN interface (optional) for digital communication between the FAGOR 8055 CNC and FAGOR digital servo drives.

Axis modules

- **Complete module for analog solution**
  With 4 analog inputs and 8 analog outputs, 1 probe input, 8 feedback inputs and 40 PLC digital inputs / 24 PLC digital outputs (24 V DC 150 mA, opto-coupled).
- **Half module for digital solution**
  With 4 analog inputs and 8 analog outputs, 1 probe input, 8 feedback inputs and 40 PLC digital inputs / 24 PLC digital outputs (24 V DC 150 mA, opto-coupled).

Optional cards

- **CPU TURBO card**
  Additional 32-bit processor with math co-processor. It closes the position loop and interpolation of the axes increasing the system's power by improving block processing time.

Optional modules

- **I/O module**
  It is used to expand the basic configuration increasing the number of PLC digital inputs and outputs.
  Up to five I/O modules are possible and each offers 64 inputs and 32 outputs (24 Vdc, 150 mA) all digital and opto-coupled.
- **SERCOS module**
  For digital communication through fiber optics between the FAGOR 8055 CNC and FAGOR digital servo drives (AXD / SPD). It must be used when having the CPU-turbo card.

Figure 3.31 Fagor 8055-M display view and control unit specifications

3.3.1 Control Unit and Motor Connections

The control unit and Estun servo motor connections are performed according to the figures in below. Details are Shown in Figure 3.32, Figure 3.33, Figure 3.34, Figure 3.35 and Figure 3.36.

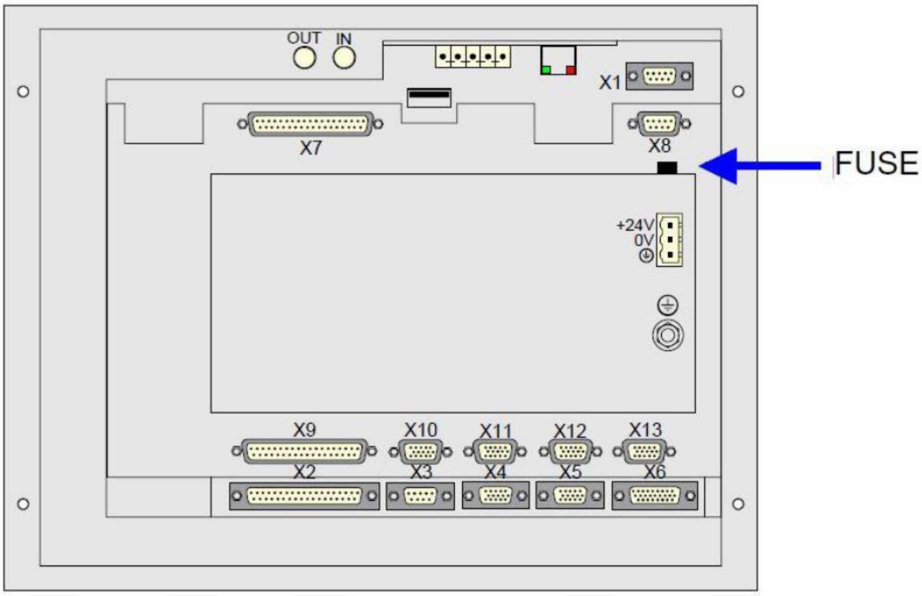


Figure 3.32 Fagor 8055-M connection ports in back view

CN-1 (36 PİN)		
Pin Numarası	Renk	Açıklama
1	Siyah	Analog +
2	Beyaz	Analog -
13	Gri	COM
14	Kırmızı	Servo ON
39	Mavi	Alrm rst
5	Pembe	Fren+ (24V)
6	Mor	Fren- (0V)
7	Sarı	Alarm+
8	Yeşil	Alarm-
20	Yeşil	PAO+
21	Yeşil-Siyah	PAO-
22	Mavi	PBO+
23	Mavi-Siyah	PBO-
24	Sarı	PCO+
25	Sarı-Siyah	PCO-
50	Siyah	GND

CN-1 (36 PİN)		
Pin Numarası	Renk	Açıklama
19	Siyah	Analog +
20	Beyaz	Analog -
9	Gri	COM
10	Kırmızı	Servo ON
14	Mavi	Alrm rst
4	Sarı	Alarm+
3	Yeşil	Alarm-
34	Yeşil	PAO+
35	Yeşil-Siyah	PAO-
32	Mavi	PBO+
33	Mavi-Siyah	PBO-
30	Sarı	PCO+
31	Sarı-Siyah	PCO-
36-18	Siyah	GND

Figure 3.33 Estun servo motor pin connections

X2 Digital I/O			
Pin Numarası	Renk	I/O Numarası	Açıklama
1,20	Kırmızı	-	24V
3	Yeşil	O3	X servo ON
10	Mavi	I1	EMG Input
11	Sarı	I3	X Alrm -
12	Mor	I5	Y Alrm -
13	Gri	I7	A Alrm -
14	Beyaz	I9	Z Alrm -
15	Kahverengi	I11	X+ limit switch
16	Sarı-Beyaz	I13	X- limit switch (HOME)
17	Mavi-Beyaz	I15	Y+ limit switch
18,19	Siyah	-	0 V
29	Kırmızı - Beyaz	I2	Y- limit switch(HOME)
30	Yeşil - Beyaz	I4	Z+ limit switch (HOME)
31	Kahve-Beyaz	I6	
32	Siyah-Beyaz	I8	X (EL ÇARKI)
33	Kahve-Sarı	I10	Y (EL ÇARKI)
34	Kahve-Mavi	I12	A (EL ÇARKI)
35	Kahve-Yeşil	I14	Z (EL ÇARKI)
36	Kahve-Siyah	I16	X1 (EL ÇARKI)

X7 Digital I/O			
Pin Numarası	Renk	I/O Numarası	Açıklama
1,20	Kırmızı	-	24V
3	Mavi-Beyaz	O35	X Alrm RST
4	Mor	O37	Y Servo On
5	Yeşil-Beyaz	O39	Y Alrm RST
6	Mavi	O41	A Servo On
7	Kahve-Beyaz	O43	A Alrm RST
8	Pembe	O45	Z Servo On
9	Kırmızı-Beyaz	O47	Z Alrm RST
10	Yeşil	O49	-
11	Sarı-Beyaz	O51	-
12	Sarı	O53	-
13	Siyah-Beyaz	O55	-
18,19	Siyah	-	0V
22	Kahve-Siyah	O36	-
23	Gri	O38	-
24	Kahve-Mavi	O40	Spindle M1
25	Beyaz	O42	Spindle M2
26	Kahve-Sarı	O44	El çarkı led 24V
34	Kahverengi	I100	X10 (elçarkı)
35	Kahve-Yeşil	I102	X100 (el çarkı)
37	-	-	GND

Figure 3.34 Fagor X2 and X7 digital input output connections

X8 Analog Output (0-10V Analog)		
Pin Numarası	Renk	Açıklama
1	-	Blendaj
2	Mavi	X+
3	Yeşil	Y+
4	Sarı	Z+

X4 Spindle		
Pin Numarası	Renk	Açıklama
10	Sarı	Analog Output
12	Sarı-Siyah	GND
15	-	Blendaj

X5 El Çarkı		
Pin Numarası	Renk	Açıklama
1	Mavi	A
2	Mavi-Siyah	A/
3	Yeşil	B
4	Yeşil-Siyah	B/
10	Kırmızı	5V
11	Siyah	GND
15	-	Blendaj

Figure 3.35 Fagor X8 and X5 input output connections

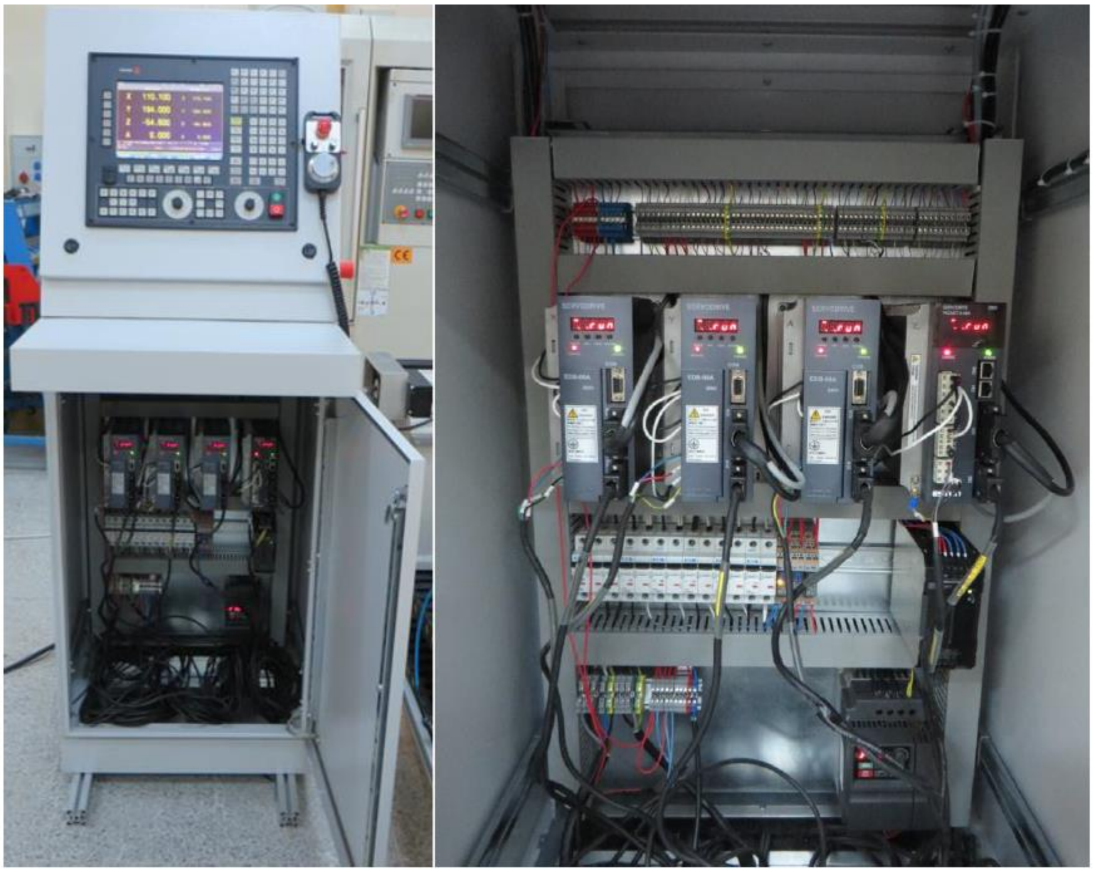


Figure 3.36 CNC control unit and control panel inner views (Personal archive, 2017)

3.3.2 Control Unit Differences between Old and New CNC Machines

The old CNC machine controller is Mach 3. In the old machine, motors are driven ±5 V Pulse Width Modulation (PWM) method by Mach 3 control card. Mach 3 control card connect with a computer which includes Windows XP operating system. The CAM program is loaded in the Mach 3 on computer interface. In this program, CAM codes are changed to electric signal which drive the servo motors. In this way, it is not possible to take motor feedbacks because of insufficient control unit. Hence, previous machine has open-loop control system. Mach 3 control unit drive the spindle motor with 0-10 Volt analog input.

The new CNC machine control unit is FAGOR 8055-M CNC control unit. This controller drives the servo motor with 0-10 Volt analog input according to the feedback signal. FAGOR control unit have internal computer (PLC) and CAM codes are changed to motor drive signals by this computer. Advantage of the FAGOR control unit is that, FAGOR controller takes the servo motor position feedback signal from the motor driver and compensate the drive signal with respect to these feedbacks. Spindle motor is driven with 0-10 Volt analog input by the FAGOR controller. Mach 3 controller is shown in Figure 3.37 and interface is shown in Figure 3.38. FAGOR controller is shown in Figure 3.39 and Figure 3.40.

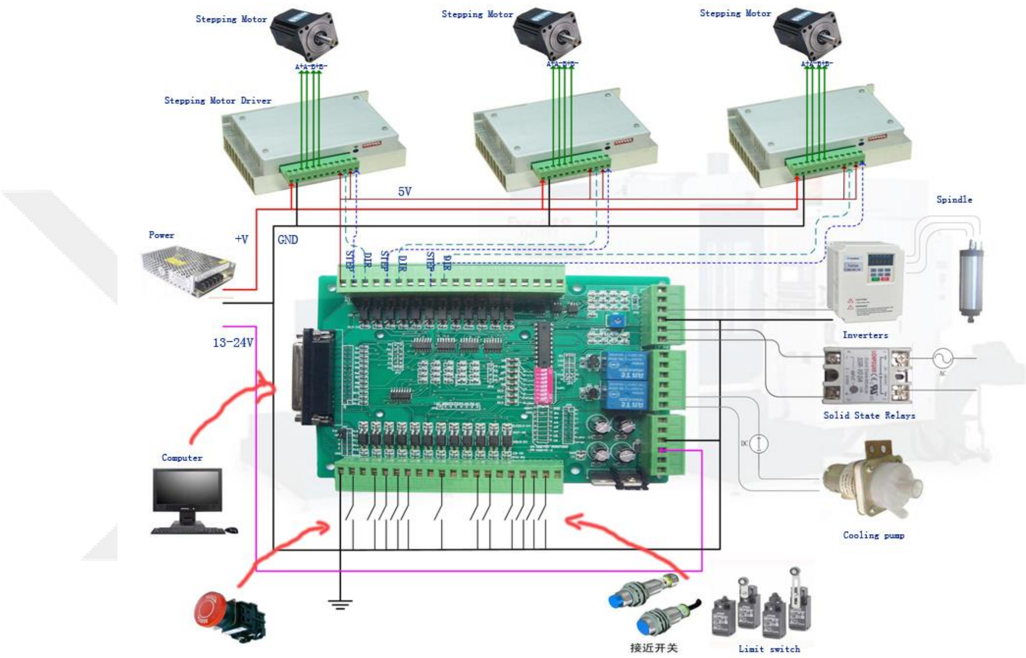


Figure 3.37 Mach 3 control card and connections

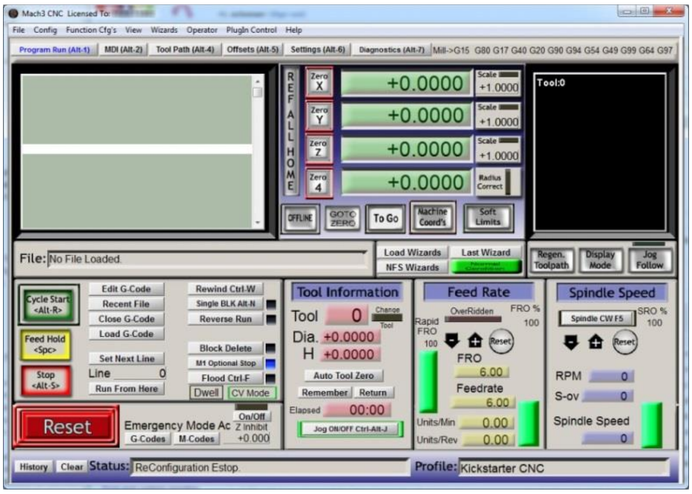


Figure 3.38 Mach 3 computer interface

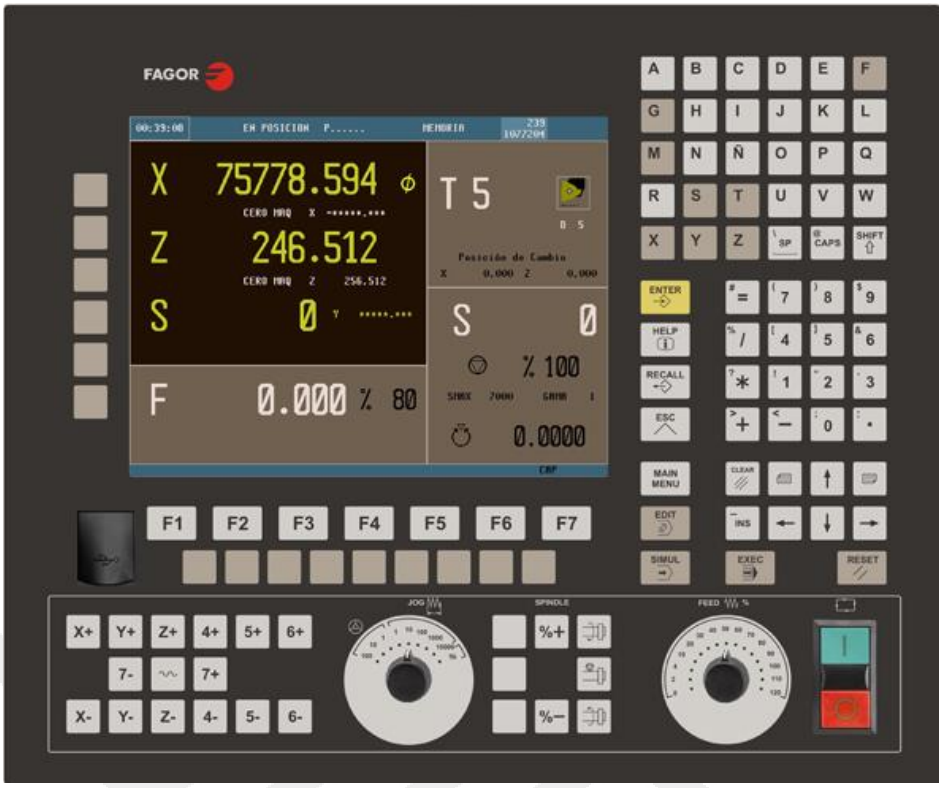


Figure 3.39 FAGOR-8055-M interface

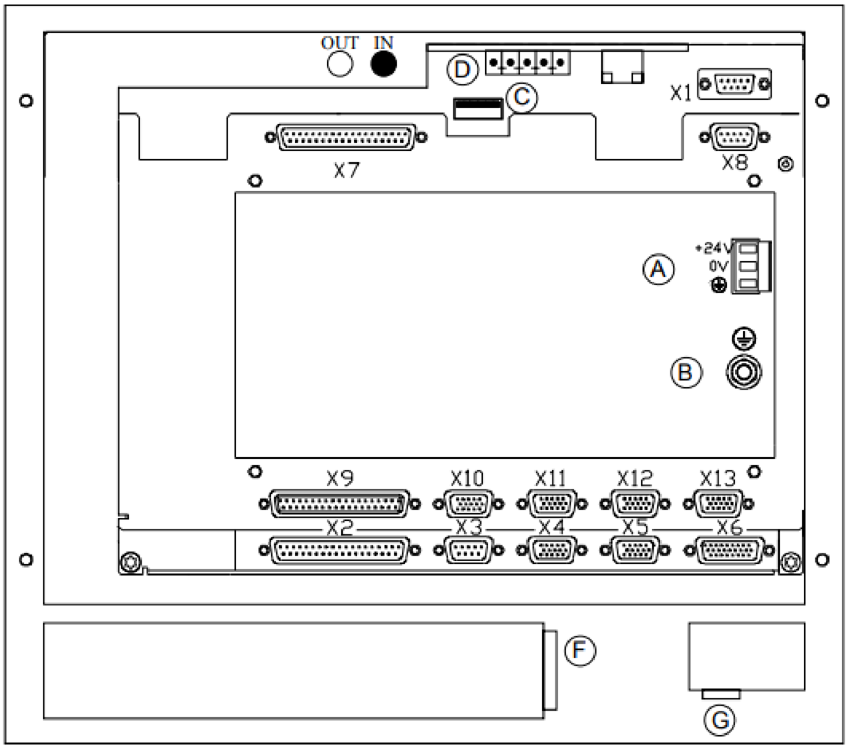


Figure 3.40 FAGOR-8055-M connections

3.4 Manufacturing Stages of CNC Machine

CNC machine manufacturing stages consist of two steps. One of them is that mechanical production and the other one is that control unit assembling and cabling. Manufacturing process is shown in the Figure 3.41, Figure 3.42, Figure 3.43 and Figure 3.44.

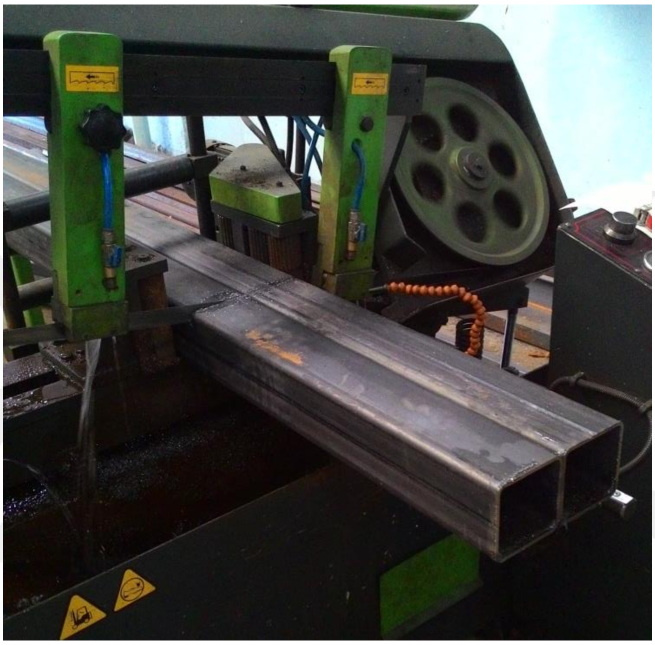


Figure 3.41 Profile cutting in band-saw machine (Personal archive, 2017)

Figure 3.42 Machine frame welding method (Personal archive, 2017)

Figure 3.43 Machine frame welding detail view (Personal archive, 2017)

CNC machine frame profiles are connected to each other with welding method. In welding method, in particular MIG-MAG welding, welded parts distortions are occurred commonly. Longitudinal U-profiles are linked to each other with rigid bars so as to prevent distortion of frame. These connections are shown in Figure 3.42 and Figure 3.43. After the welding process, these bars are cut off the machine frame and removed.

Figure 3.44 Other manufactured parts (Personal archive, 2017)

Parts of CNC machine was manufactured with milling and welding method. In manufactured parts with welding method, milling process was performed to prevent distortion.

CHAPTER FOUR
FINITE ELEMENT ANALYSIS AND EXPERIMENTAL RESULTS

In this chapter, finite element analysis and vibration measurements of CNC machine will be presented.

4.1 Finite Element Models of CNC Machine

In this section, two finite element models are created. One of them is solid model, and the other one is shell model. These two models have pros and cons according to each other. They will be explained in this section.

Before create the finite element model of CNC machine, machine CAD model was split up to parts and called as member. Separation process was made according to the relative position of the moving parts. The analysis model created with the undetailed parts in the initial position of the CNC machine is shown in Figure 4.1. This model is made up of 4 members that consisted with the assembly of 101 parts.

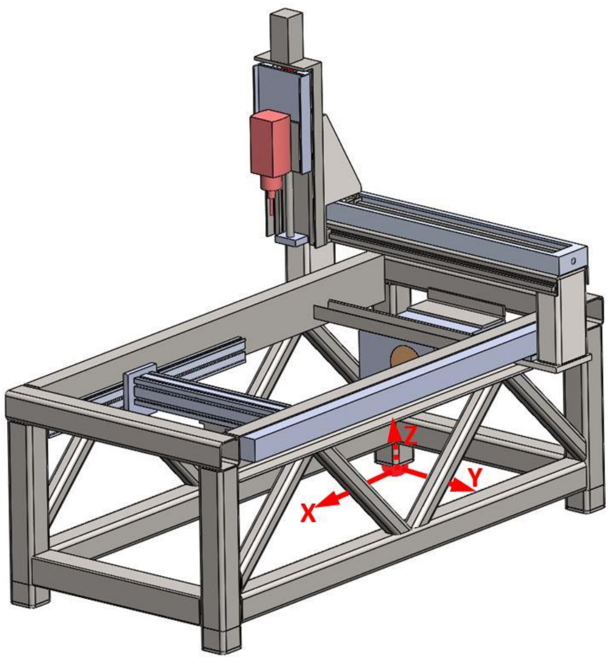
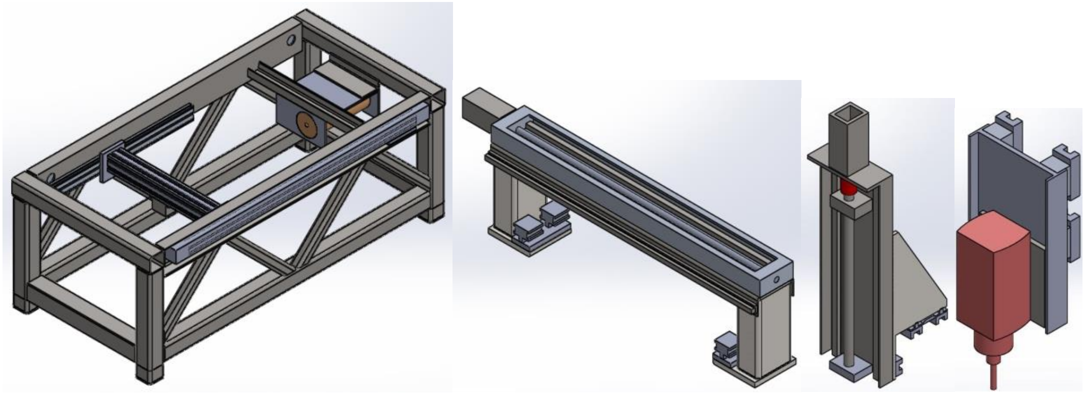


Figure 4.1 Undetailed CAD model for finite element analysis

Every member has come from parts with common solid body movements or from subassemblies. Model of the members are shown in Figure 4.2



Member-0 Member-1 Member-2 Member-3

Figure 4.2 Undetailed CAD models of members

The members are connected to each other by connectors for modal analysis. In this analysis model two type of connector are used.

- Bounded: Connects two surfaces together in a cohesive manner. There is no relative motion between the defined surfaces. It does not allow separation of surfaces or sliding between surfaces.
- No Separation: Allows minor sliding between two defined surfaces, but not allow to separation. Planar relative movement is allowed between the surfaces on which this connector is defined.

The origin of the global axis set of machine is below the right rear leg of the member-0 as seen in figure 4.1. Member-0 is connected to the floor under the rubber pads. The local axis sets of all members are parallel to the global axis set.

CAD models and assemblies were created using SolidWorks software. The assembly model of the CNC machine is transferred to the ANSYS Workbench program. All connector definitions are made in the ANSYS Workbench.

The inertia properties of the members are given in Table 4.1. The total weight of the CNC machine is 450 kg. The weight of the analysis model has been simplified to be the same as the actual machine.

Table 4.1 Inertia properties of the members (Center of gravity coordinates are given according to the global axis set)

	Member-0	**Member -1**	**Member -2**	**Member -3**
Center of gravity coordinates	$[788.02,402.33, 448.92]^T$	$[261.84,399.88, 833.64]^T$	$[372.34,-61.48, 1169.68]^T$	[485.13,-62.53, 1253.25]
Mass (kg)	315.77	70.26	44.85	18.77

Let the position vector of the spindle end-point w.r.t the global coordinates be $q_e=[x_e,\ y_e,\ z_e]^T$. $q_{eh}=[552.5,-62.5,1034.85]^T$ is for the home position. The displacements are in mm unless otherwise stated.

4.1.1 Solid Finite Element Model of CNC Machine

First finite element model of CNC machine is solid model. CNC machine assembly consisted of undetailed members is directly transferred to ANSYS Workbench program and then mesh progress is performed according to finite element method. Solid finite element model is shown in Figure 4.3.

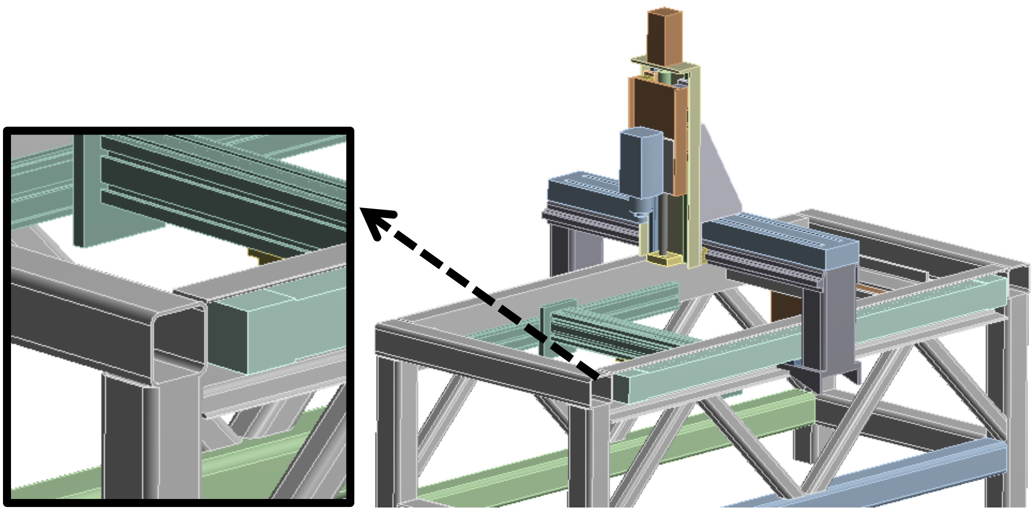


Figure 4.3 Solid Finite element model of CNC machine

Solid finite element model as shown in Figure 4.3 is composed of solid parts. That means thickness of the steel profile data come from solid model. Solid finite element model of CNC machine is formed from solid elements.

Linear tetrahedral solid elements (solid186) and linear brick solid elements (solid 187) are used. The element size and relevance are selected as 10 mm and %50 respectively. Bottom faces of rubber feet of Member-0 are fixed. The model has 496,598 elements and 1,432,926 nodes. Mesh view of solid finite element model is shown in Figure 4.4.

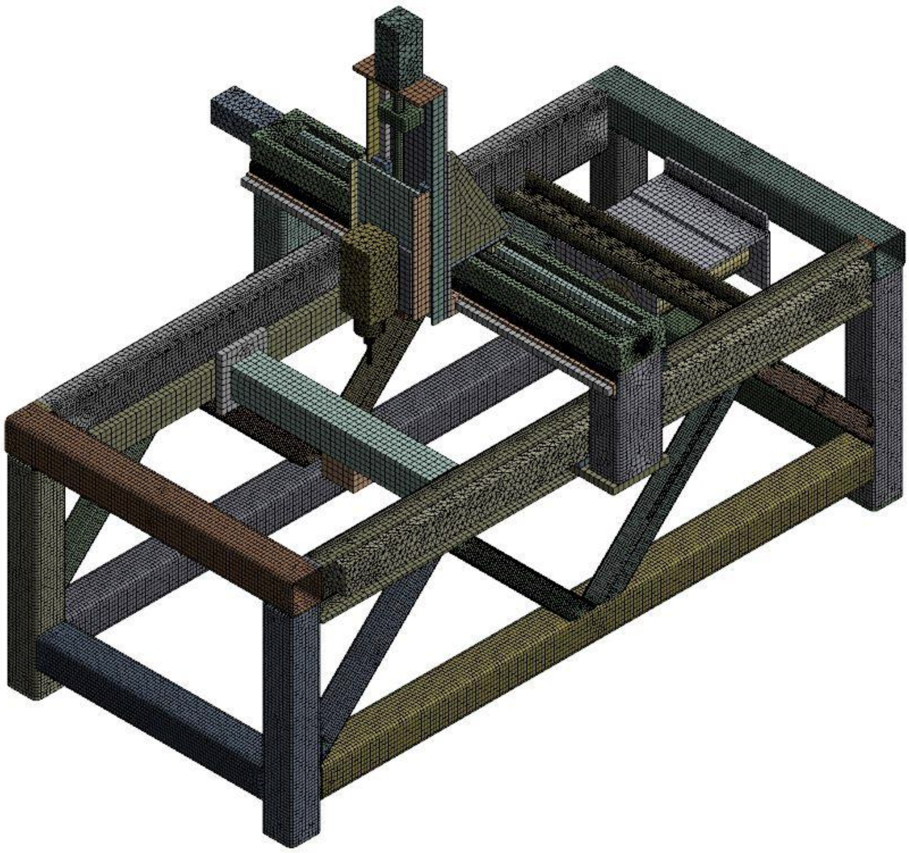


Figure 4.4 Mesh view of solid finite element model of CNC machine

4.1.2 Mixed Solid and Shell Finite Element Model of CNC Machine

Second finite element model of CNC machine is solid and shell mixed model. CNC machine assembly consisted of undetailed solid and shell members is directly transferred to ANSYS Workbench program and then mesh progress is performed according to finite element method. Solid and shell mixed finite element model is shown in Figure 4.5.

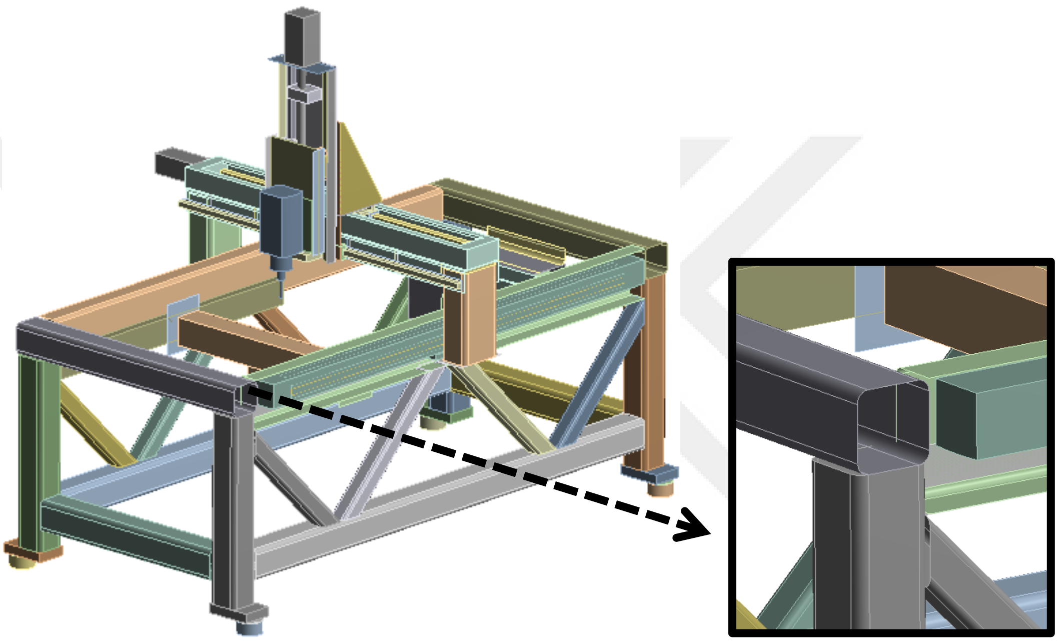


Figure 4.5 Solid and Shell mixed Finite element model of CNC machine

Mixed finite element model as shown in Figure 4.5 is composed of solid and shell parts. That means thickness of the steel profile data come from solid model for solid parts and thickness of shell models information are determined in ANSYS Workbench program. Mixed finite element model of CNC machine is formed from solid and shell elements.

The shell elements are used for the parts have 1/8 ratio of thickness to length. 44 parts from the 101 parts of model are modelled with solid elements in this finite element model (such as bearings, module parts, spindle part, motors and A-axis rotary parts) so that, 57 parts are modelled with shell element (all steel profiles spindle holder parts, Z-axis holder parts and A-axis supporting parts). 4 nodes linear shell elements (shell181), linear tetrahedral solid elements (solid186) and linear brick solid elements (solid 187) are used in the analysis model. Advanced size function is used for meshing the model. The maximum element size is 15.94 and minimum element size is 3.18 mm. Bottom faces of rubber feet of Member-0 are fixed. The model has 189,836 elements and 302,716 nodes. Mesh view of mixed finite element model is shown in Figure 4.6.

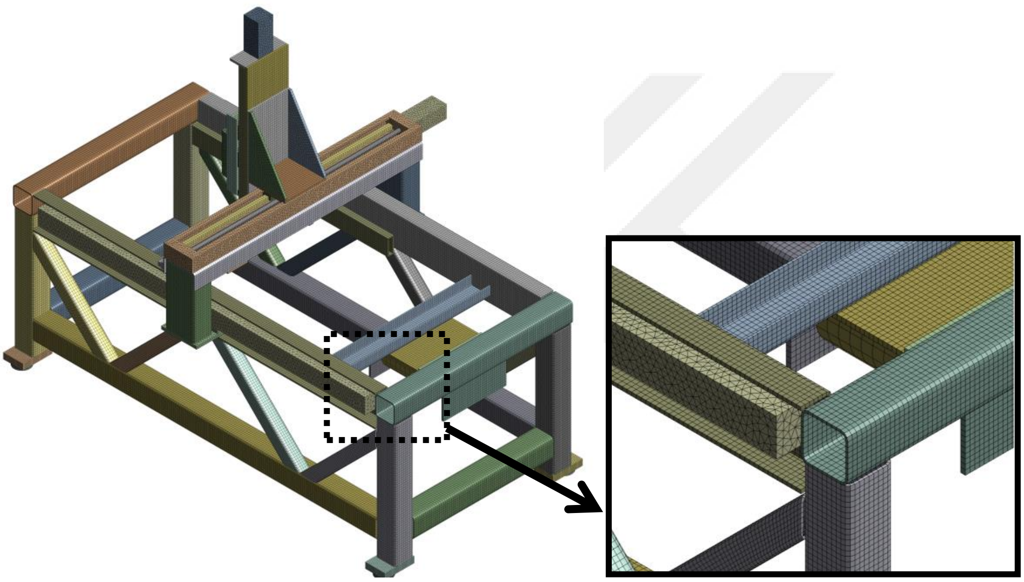


Figure 4.6 Mesh view of Solid and Shell mixed Finite element model of CNC machine

4.2 Static Analysis

Static analyses are made for both solid and mixed analysis model. Results are given in this section. Analyses are performed according to middle position of machine because of the flexibility is maximum on there.

The static analysis is performed to find deformation and equivalent stress. The specifications of the computer which is used for analysis is Intel(R) Xeon(R) CPU X5687 3.6 GHz and 24 GB Ram. Finite element model with solid elements has very high element number and the solution takes approximately 3 hours for CNC machine. The solution for the other finite element model which has mixed shell and solid elements takes 3 minutes for same conditions.

Static analysis details are given in the Table 4.2 and Figure 4.7. Solid model results are given in Figure 4.8 and Figure 4.9. Solid-Shell mixed model results are given in Figure 4.10 and Figure 4.11.

Table 4.2 Static analysis data

Attributes	Solid Model	Mixed (solid & shell) model
Nodes	1.432.926	302.716
Elements	496.598	189.836
Model Weight	460 kg	460 kg
Applied Force	F_x=450 N F_y=450 N F_z= 630 N	F_x=450 N F_y=450 N F_z= 630 N
Gravity Force	9.81 m/s^2	9.81 m/s^2
Connections	Bounded and No Separation	Bounded and No Separation
Results		
Total deformation of cutting tool	0,39	0,403
Max. equivalent stress	12.31	13,598
Solution Time	**180 min.**	**3 min.**

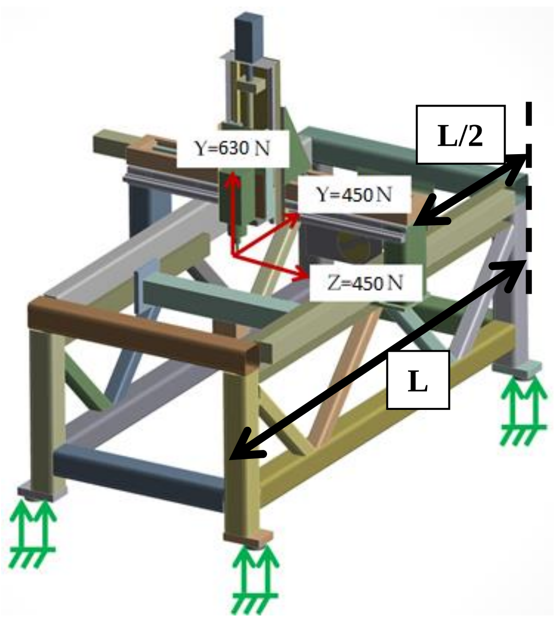


Figure 4.7 Static analysis boundary conditions

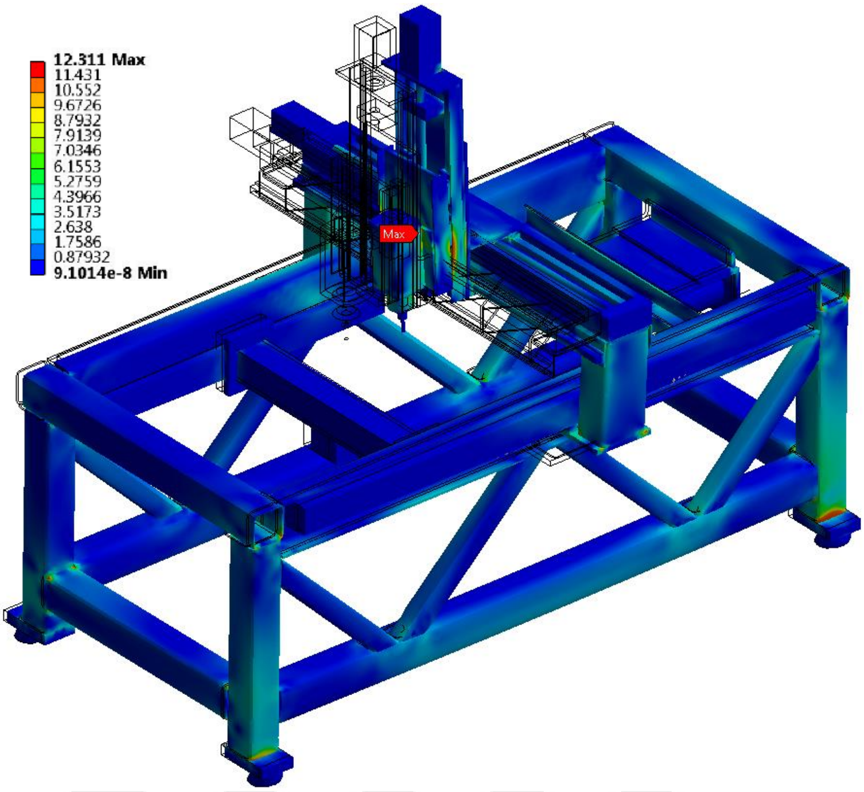


Figure 4.8 Solid model maximum Von-Mises stress

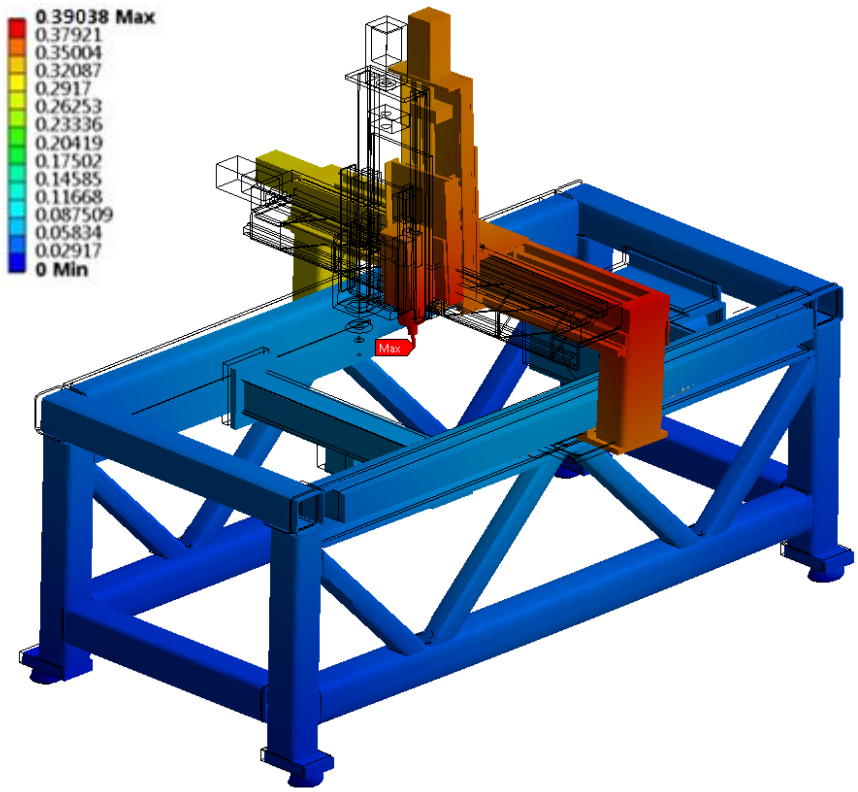


Figure 4.9 Solid model maximum deformation

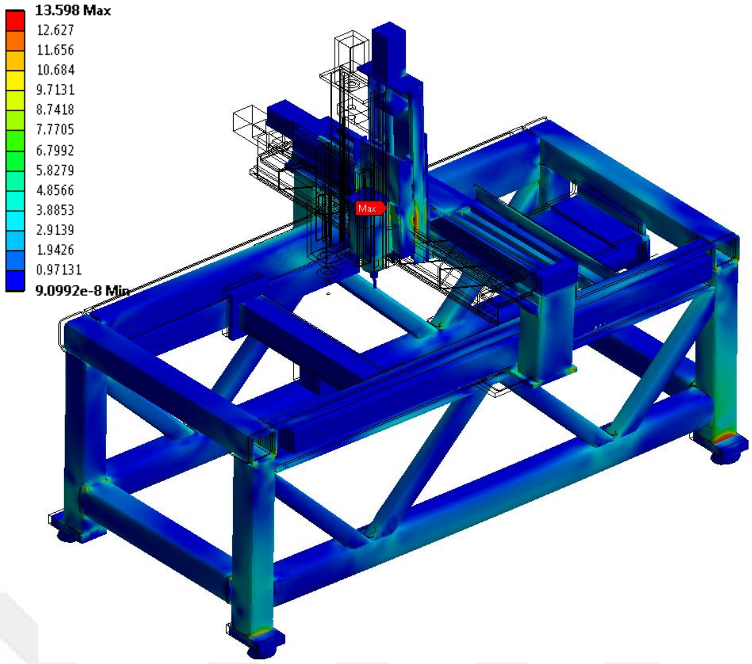


Figure 4.10 Solid-Shell model maximum Von-Mises stress

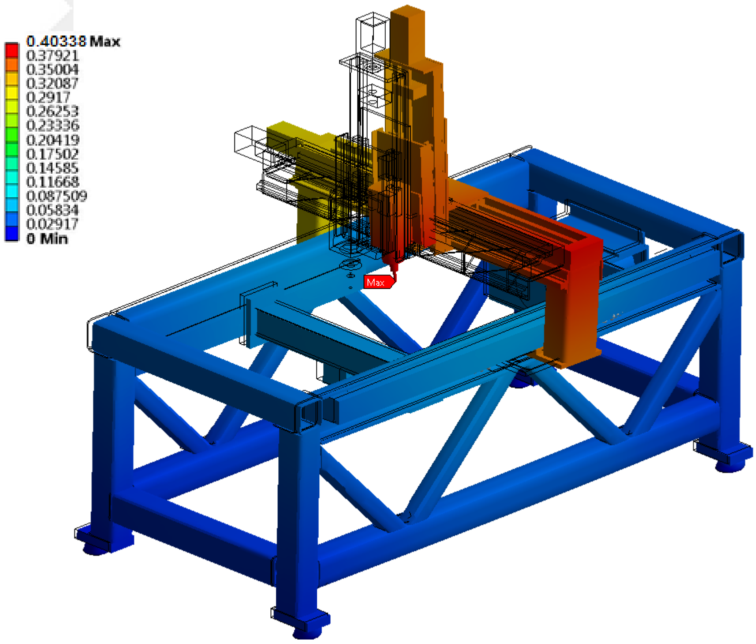


Figure 4.11 Solid-Shell model maximum deformation

As shown in static analysis results, solid model and mixed model have approximately same results, in spite of remarkable element number and solution time differences. Therefore, in the later analyses, mixed analysis model will be preferred instead of solid model.

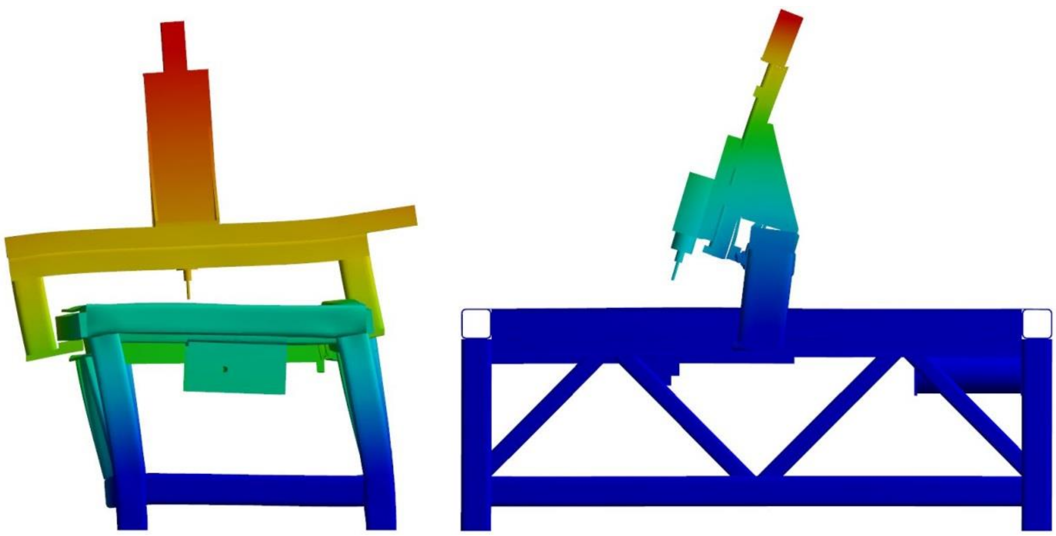
4.3 Modal Analysis

Modal analyses are made for both solid and mixed analysis model. Results are given in this section.

The modal analysis is performed to find natural frequencies. Mode shapes can be observed by animation. The specifications of the computer which is used for analysis is Intel(R) Xeon(R) CPU X5687 3.6 GHz and 24 GB Ram. Finite element model with solid elements has very high element number and the solution takes approximately 3 hours for CNC machine. The solution for the other finite element model which has mixed shell and solid elements takes 3 minutes for same conditions. First 4 natural frequencies results are seen in Table 4.3. Natural frequencies of machine are shown in Figure 4.12 and Figure 4.13.

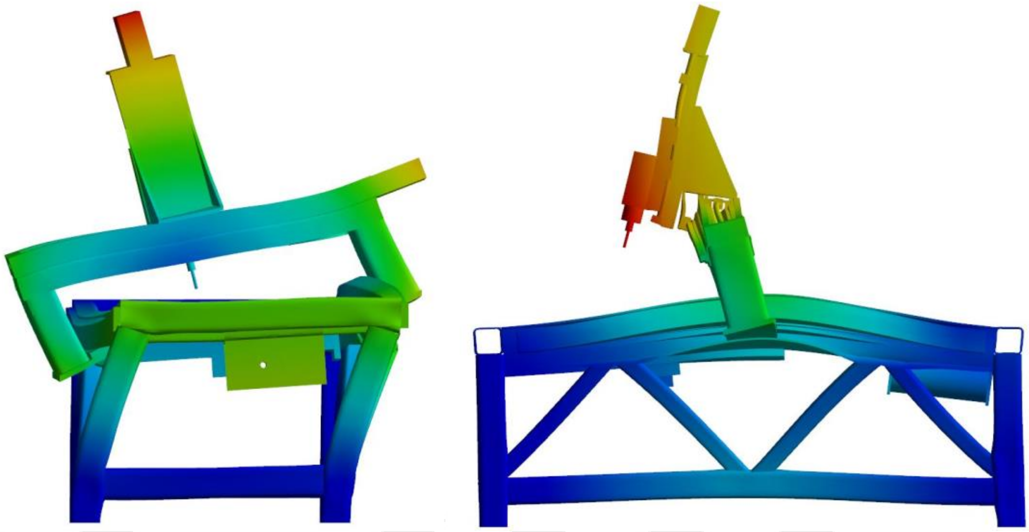
Table 4.3 Natural frequencies results for solid and mixed model

	f1	f2	f3	f4	Solution Time
Solid Model	39.861	38.871	80.526	87.772	**180 min.**
Mixed (solid-shell) Model	37.092	42.243	76.094	85.719	**3 min.**



First mode shape Second mode shape

Figure 4.12 Mode shape of first and second natural frequencies



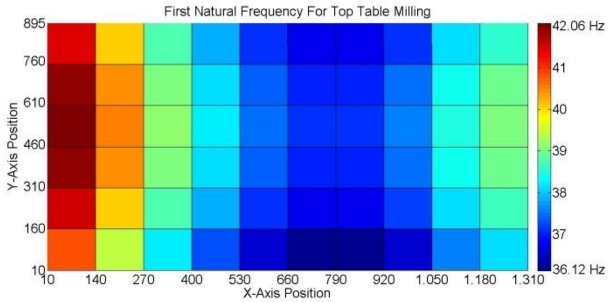
Third mode shape   Fourth mode shape

Figure 4.13 Mode shape of third and fourth natural frequencies

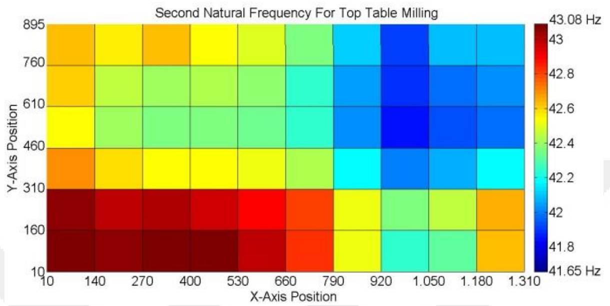
In the modal analyses shown above, the feet of steel profiles were considered to be rigid connection with ground. In the analysis results made under this assumption, differences of natural frequencies results between the solid and mixed model are acceptable level for make future analysis with mixed analysis model. Hence, future analyses and analysis model improvements will be performed on the mixed model.

4.4 Frequency Map of CNC Machine

The frequency analyses are performed for different axis positions of the CNC machine. Two different Z positions which are top table milling and rotary part milling by using fourth axis are studied. In the frequency analysis for on top table milling X axis is divided by 10 and Y axis is divided by 6 parts. In this Z position frequency analysis are performed in 77 different points. Rigidity workspace graphic is plotted by using first and second natural frequencies. Results of these analyses are seen in figure 14. In the frequency analysis for rotary part milling X axis is divided by 6 and Y axis is divided by 4 parts. In this Z position frequency analysis are performed in 35 different points. Rigidity workspace 3-D graphic is shown in Figure 4.14 and Figure 4.15 for the first and second natural frequencies results.

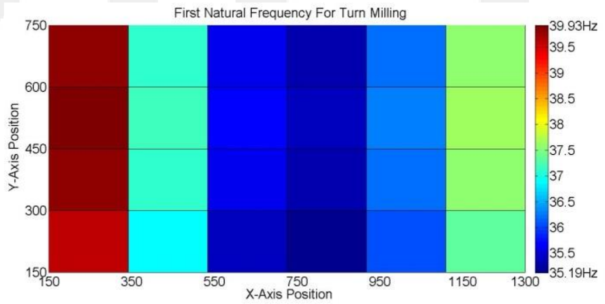


(a)

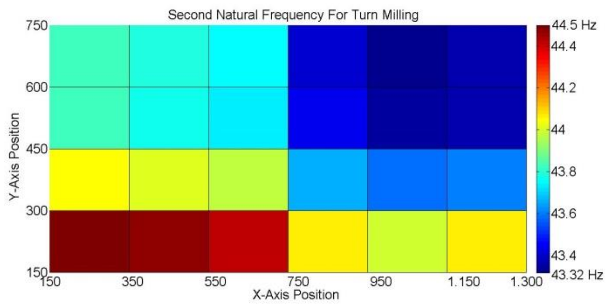


(b)

Figure 4.14 Rigidity workspace of top table milling by using first (a), second (b) natural frequencies



(a)



(b)

Figure 4.15 Rigidity workspace of rotary part milling by using first (a), second (b) natural frequencies

As shown in results above, the middle position of the machine is the most flexible situation for 3-Axis milling and 4-Axis milling. For this reason, in the future sections, milling process will be performed in the middle position in order to observe easily maximum deflection on the milled work piece.

4.5 Determine of CNC Machine Natural Frequency

Impact test was performed to determine the natural frequencies on the produced CNC machine. Experimental system composed of CNC machine, Microstrain wireless accelerometer and a computer. Experimental system is shown in Figure 4.16. The wireless measurement system consists of a base station and an acceleration meter module that can measure in 3 directions. Vibration signals are stored on the computer via a USB connection and a base station connected to the computer. The wireless vibration sensor can measure acceleration in three directions and is located at the top of the Z-axis of the worktop.

For vibration measurement, pulses are applied in X and Y directions to drive different vibrational shapes from the top of the z axis. In the measurement program (Node Commander v2.3), 5 second vibration signal was recorded with a sampling frequency of 617 Hz. Vibration signals were recorded in Excel files. Acceleration data in the recorded file was read by a program developed in Matlab and vibration analysis was carried out. A 100 Hz low pass filter was used in the program. The beginning of the pulse was determined with the change in threshold level in the program. Experimental setup is shown in Figure 4.16.

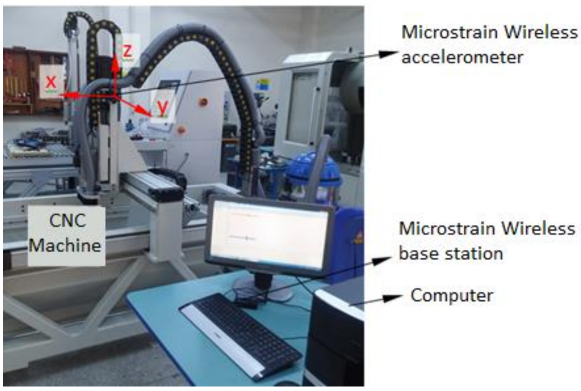
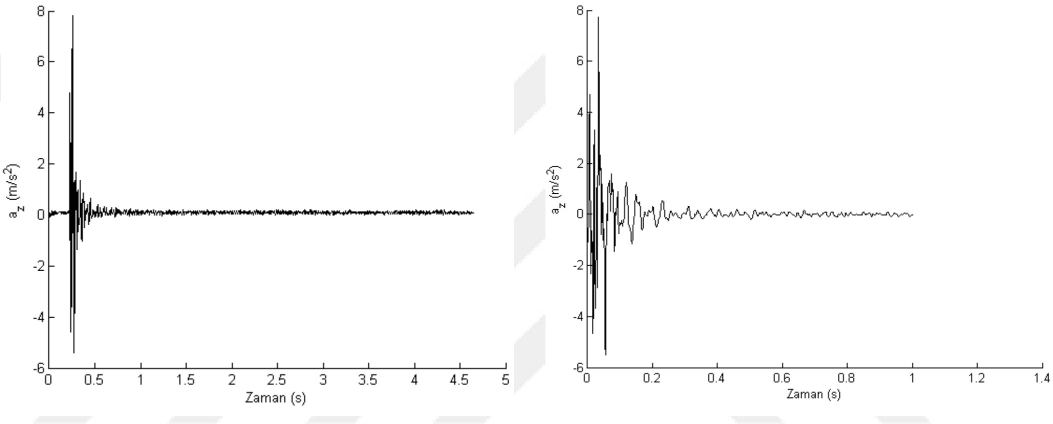


Figure 4.16 Experimental system (Personal archive, 2017)

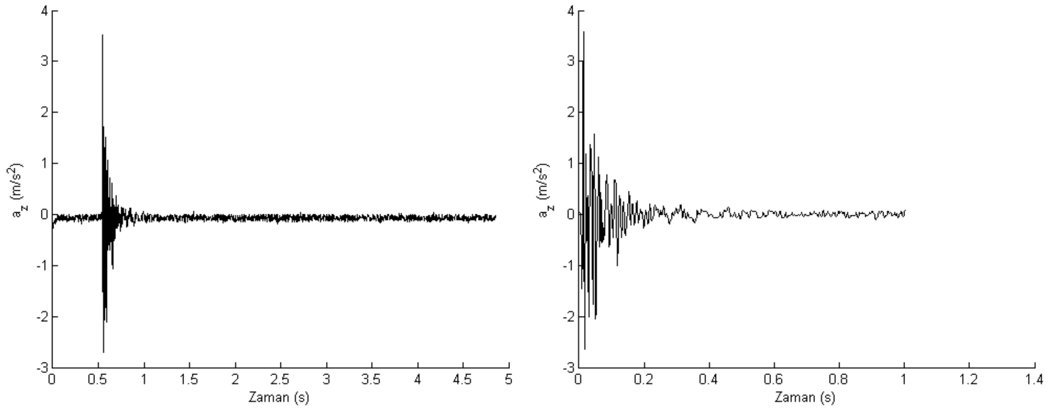
In Figure 4.17-(a), the entire vibration signal which is generated in the X direction with respect to the local axis-set of the pulse applied in the X direction from the upper part of the Z axis is shown. In Figure 4.17-(b), the signal generated after the pulse is shown as filtered of the vibration response. In Figure 4.18-(a), the entire vibration signal which is generated in the Y direction with respect to the local axis-set of the pulse applied in the Y direction from the upper part of the Z axis is shown. In Figure 4.18-(b), the signal generated after the pulse is shown as filtered of the vibration response.



(a) (b)

Figure 4.17 The pulse is applied in the X direction from the upper part of the Z axis;

(a) Vibration response in the X direction
(b) Vibration response with filtered of the signal after pulse



(a) (b)

Figure 4.18 The pulse is applied in the Y direction from the upper part of the Z axis;

(a) Vibration response in the Y direction
(b) Vibration response with filtered of the signal after pulse

In the developed Matlab program, the damped natural frequencies of the CNC machine are obtained by the Fast Fourier Transform (FFT) from the free vibration responses shown in Figure 4.17 and Figure 4.18. The obtained frequency spectrums are shown in Figure 4.19 and Figure 4.20.

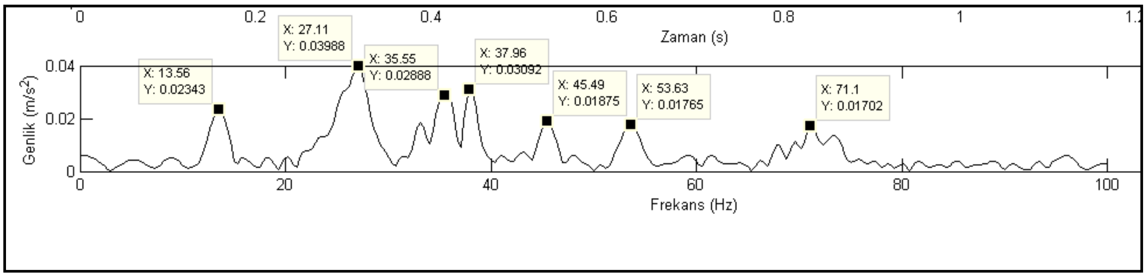


Figure 4.19 Frequency spectrum of the vibration signal generated in the X direction with respect to the local axis-set of the applied in the X direction

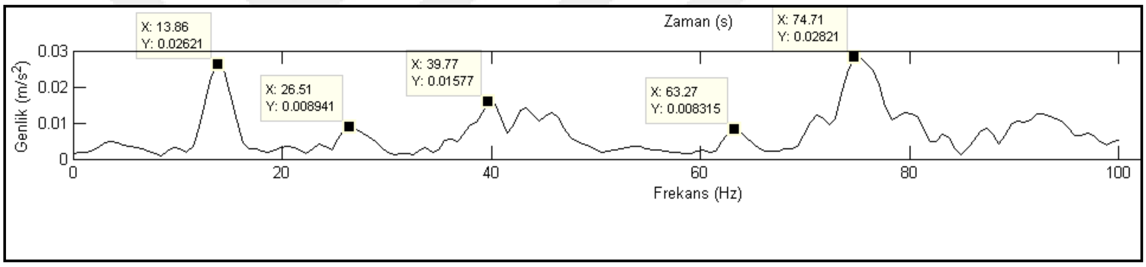


Figure 4.20 Frequency spectrum of the vibration signal generated in the Y direction with respect to the local axis-set of the applied in the Y direction

4.5.1 Development of the Analysis Model

When the analysis and the experimental results are compared, differences between the natural frequencies results quite high and this situation show that analysis model must be improved. In this context, in the analysis model, CNC machine rubber feet and connections between the members will be considered again.

In the first analysis model mentioned in Section 4.1 rubber feet were ignored and fixed to ground on the steel profile feet. When the experimental results are examined, seen that, some damped natural frequencies and mode shapes are not solved in the modal analysis. In order to prevent this situation, rubber feet and connections between the member-0 and member-1 are developed according to produced machine.

Improved rubber feet analysis model, timing belt-pulley equivalent spring analysis model and inner view of mechanism are shown in Figure 4.21, Figure 4.22 and Figure 4.23, respectively.

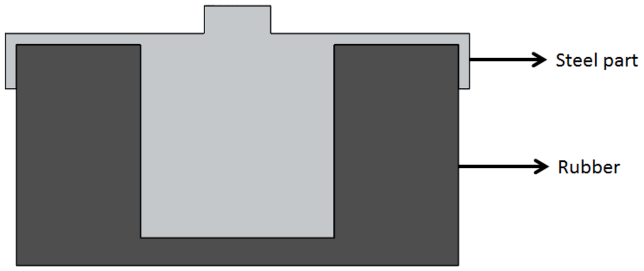


Figure 4.21 Improved rubber feet analysis model

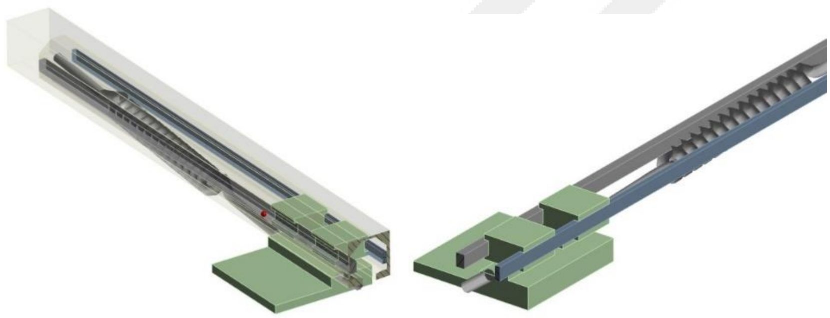


Figure 4.22 Timing belt-pulley equivalent spring analysis model

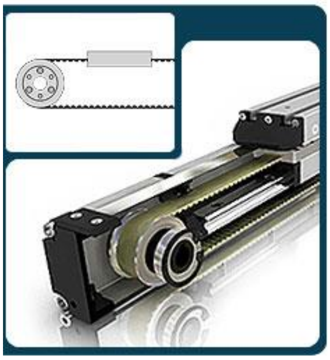


Figure 4.23 Inner view of timing belt-pulley mechanism

The body of the timing-belt modules located in the member-0, which is used in the X-axis motion and located on both sides of the body, and the ball-screw linear module, which is used in the movement of the Y-Axis, are aluminium alloy. Other parts of linear modules are steel. There are steel rails in these modules.

The ball screw system used in the Y axis and Z axis has a high stiffness in the direction of movement, while the stiffness in the direction of movement of the timing-belt system is low. For this reason, in the Y and Z axis, ball-screw module which are shaft and nut are considered rigid connection, so flexibility in the shaft and nuts disabled. As for X-axis, in order to take account of the flexibility of the belt, equivalent spring identification was made in the direction of motion. Timing belts are of two types according to the material of the cords inside. These are steel cord and fiberglass cord. Fiberglass type is more preferred than steel. The equivalent spring coefficient used for the timing belt in the analysis model of the CNC machine is 400 N/mm. Equivalent spring definitions in the analysis model is shown in Figure 4.22 and internal structure of the timing belt mechanism is shown in Figure 4.23. With the developed new analysis model, modal analysis is repeated. New results are given in the following section.

4.5.2 Modal Analysis with the Improved Analysis Model

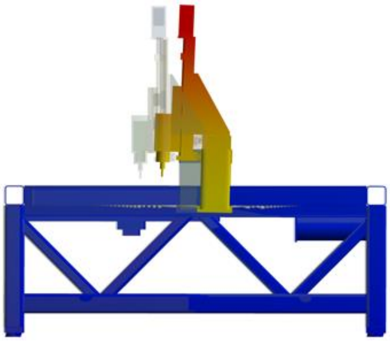
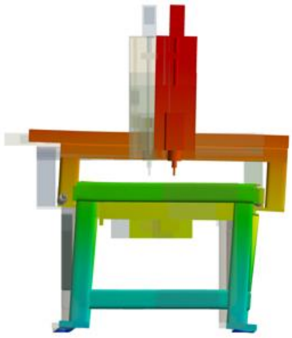
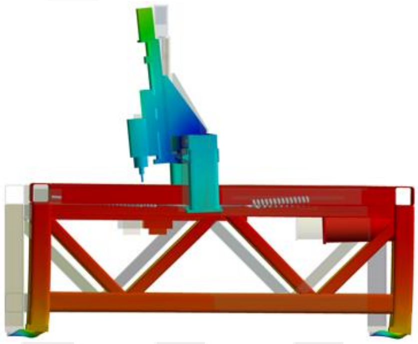
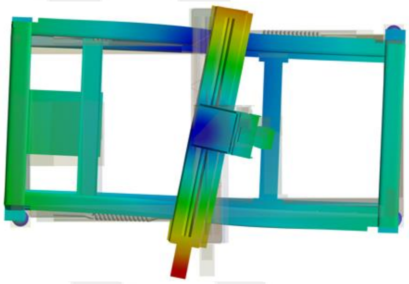
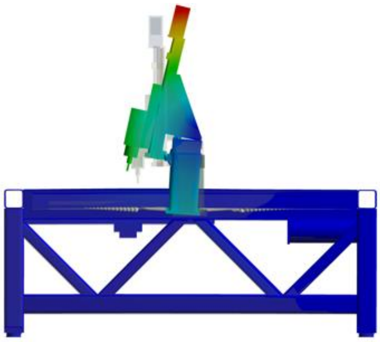
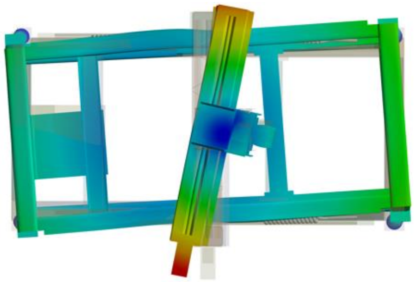
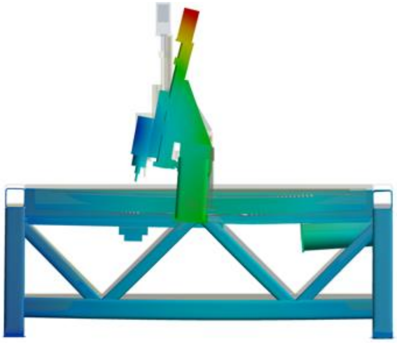
With the developed new analysis model, modal analysis is repeated and results are given in the Table below.

The boundary conditions are same with the mentioned analysis model in Section 4.3 and also analysis model is mixed analysis model due to the fact that solution time is so short and results are same with the solid model.

Element and node number are same with the first analysis model because mesh settings did not change. So, new analysis model has 302.716 node and 189.836 elements. Also in the new analysis model, rubber feet were considered fixed to ground. Rubber properties are that, density is 1200 kg / m^3, elasticity module is 80 MPa and poison’s ratio is 0.48.

The results of the modal analysis performed under these conditions are given in the Table 4.4.

Table 4.4 Natural frequencies results for new analysis model

f1 **15.218 Hz**	**f2** **23.325 Hz**
	
f3 **40.705 Hz**	**f4** **40.963 Hz**
	
f5 **53.968 Hz**	**f6** **58.521 Hz**
	
f7 **66.185 Hz**	**f8** **75.085 Hz**
	

4.5.3 Comparison of Analysis and Experimental Results

The natural frequency results obtained from the modal analysis and the natural frequency results obtained from the experiment are compared in Table 4.5. The vibration patterns determined by the experiment were obtained by evaluating the pulse direction selection in experiment and the signal received from the relevant channel. As can be seen from Table 4.5, the results of the modal analysis and the experiment are compatible with those of the second natural frequency value, but the tendency of the experimental results to be higher is not compatible with the other natural frequencies. So except the second natural frequency, modal analysis results are higher than the experimental results. Natural frequencies results of finite element analysis and experiment are in harmony with according to each other due to improvement of the rubber feet and timing belt model with respect to real state. Particularly in the vibrational shapes observed in the X direction, the equivalent spring definitions for the belts play an important role.

Table 4.5 Comparison of natural frequency results obtained from analysis and experiment

	f1	**f2**	**f3**	**f4**	**f5**	**f6**	**f7**	**f8**
Analysis Results	15.218 Hz	23.325 Hz	40.705 Hz	40.963 Hz	53.968 Hz	58.521 Hz	66.185 Hz	75.085 Hz
Experimental Results	13.565 Hz	27.113 Hz	35.558 Hz	37.963 Hz	45.492 Hz	53.636 Hz	63.214 Hz	74.713 Hz
Differences	+ %12.2	- %14	+ %14.5	+ %7.9	+ %18.6	+ %9.1	+ %4.7	+ %0.5

The differences between the finite element analysis and experimental results are given in the Table 4.5 above. It can be accepted level considering all frequencies in spite of percentage difference great. There are many reasons for this difference. For example, analysis model does not contain all detailed part of produced machine. In the finite element analyses, analysis model cannot be represented with infinite element as in the real model. Although the percentage differences are relatively high, these results are considered satisfactory when the model complexity take into account.

4.6 Stiffness Reduction Studies on the Analysis Model

In this study mentioned above, two different analysis models, which are solid and mixed (solid-shell), were created and static and modal analyses were performed. In this section, various analysis models will be created and a design with reduced rigidity according to current state will be tried to be achieved. In this context, there are many trials are made and the results of them are given in the Figure 4.24, Figure 4.25 and Figure 4.26.

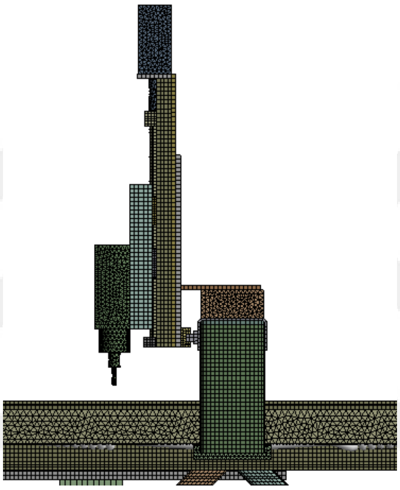


Figure 4.24 Flexible design of CNC machine with no rib

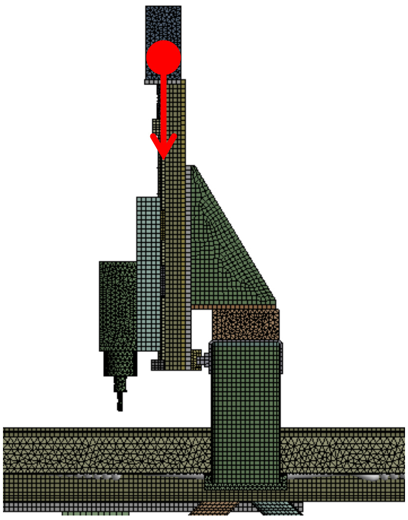


Figure 4.25 10 kg mass added on the near of Z axis motor

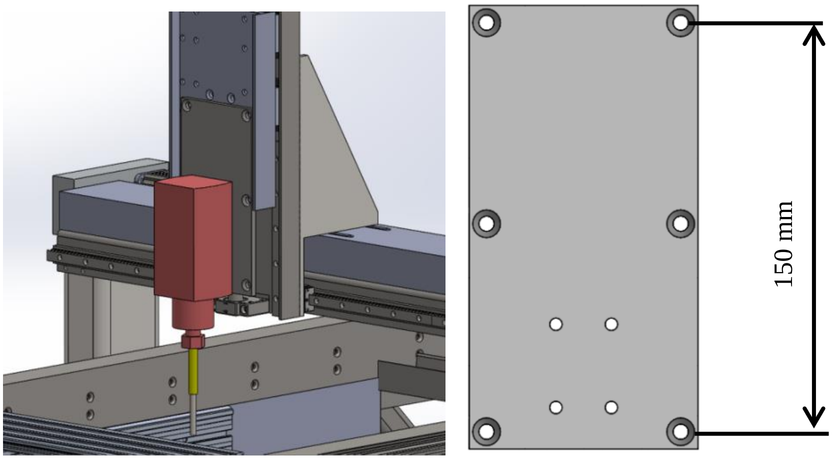


Figure 4.26 Extended spindle holder part with 150 mm

As shown in above figures three different approaches were made and results are given in figures below. Modal analyses are performed in same boundary conditions and mesh settings are same. Results are given in Figure 4.27, Figure 4.28, Figure 4.29 and Figure 4.30.

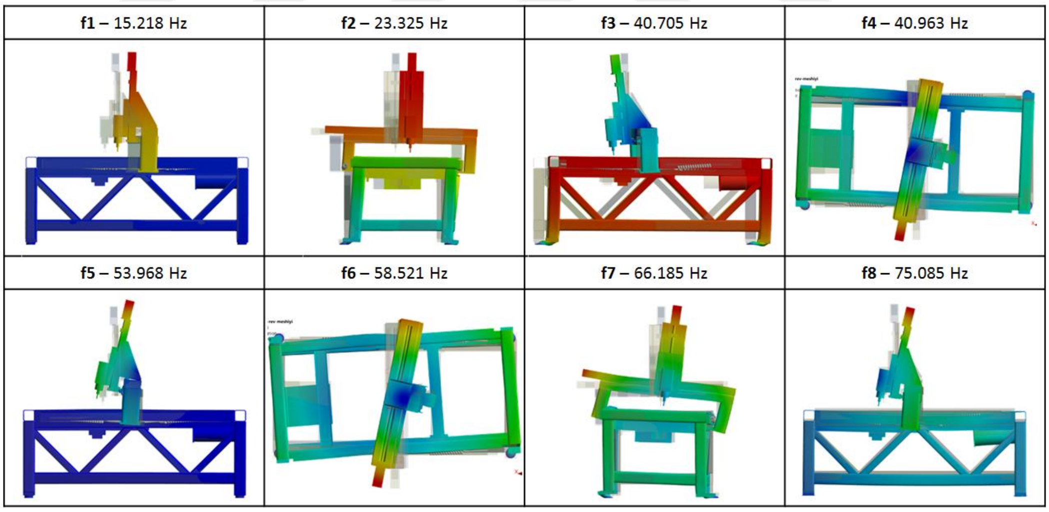


Figure 4.27Results of unmodified analysis model

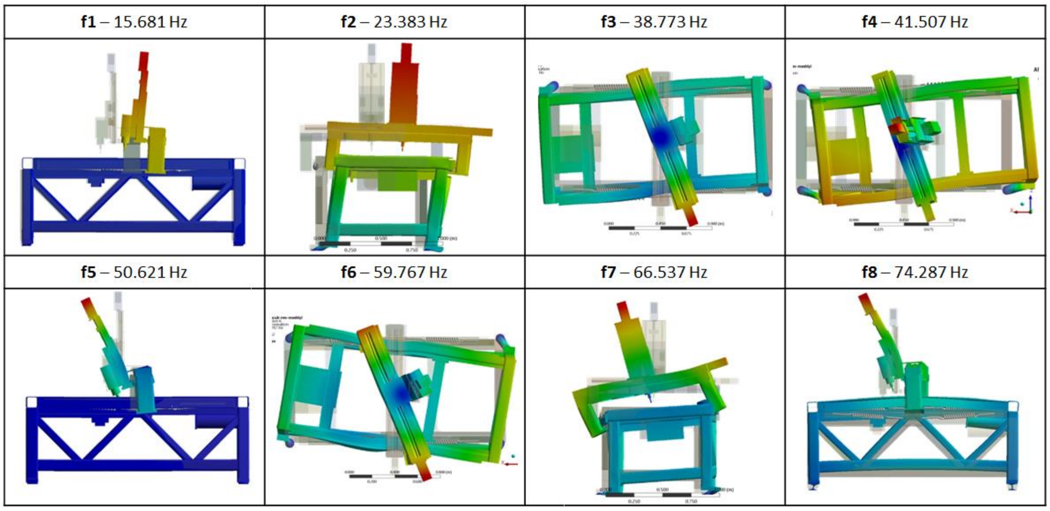


Figure 4.28 Results of flexible design of CNC machine with no rib

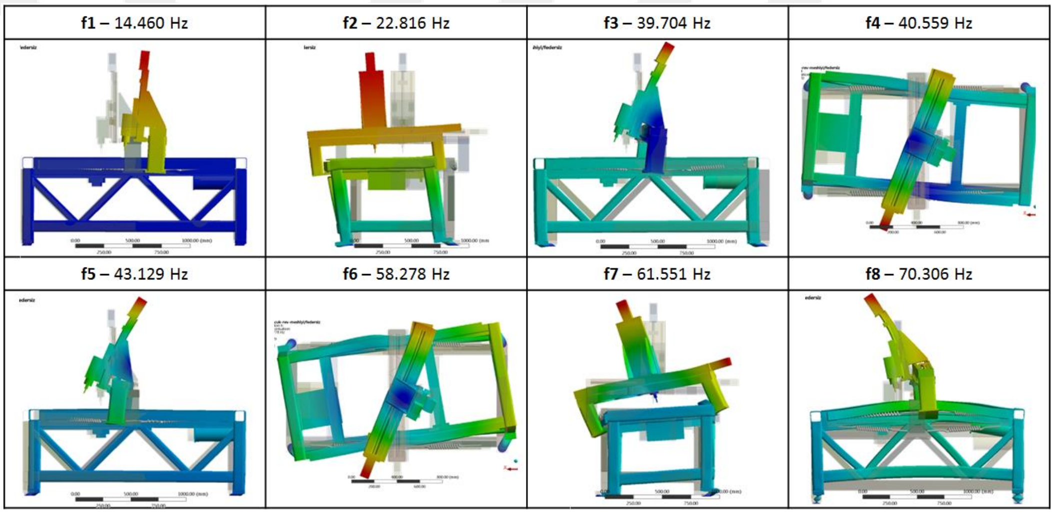


Figure 4.29 Results of 10 kg mass added on the near of Z axis motor

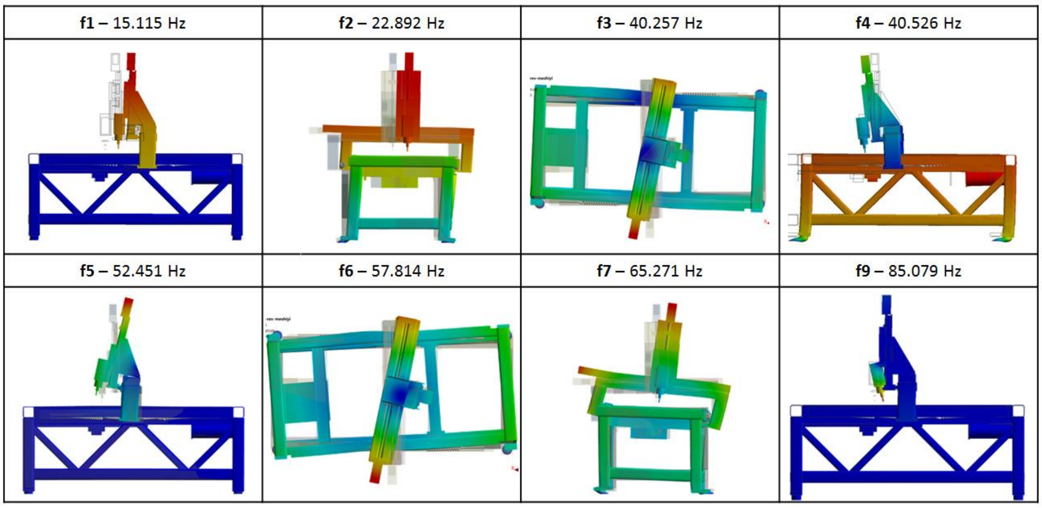


Figure 4.30 Results of extended spindle holder part with 150 mm

As shown in figures above, analysis with extended spindle part ninth natural frequency is different from other models. Local natural frequency occurred in the ninth natural frequency and mode shape of this frequency directly effect on the milling work piece. Other analysis model results have same mode shapes with the original model. Therefore, extended spindle holder part will be manufactured and experimental results will be taken on this case. Natural frequencies values are given in Table 4.6.

Table 4.6 Flexibility results of mentioned analysis model

	f1	**f2**	**f3**	**f4**	**f5**	**f6**	**f7**	**f8**
Experimental Results	13.56 Hz	27.11 Hz	35.55 Hz	37.96 Hz	45.49 Hz	53.63 Hz	63.21 Hz	74.71 Hz
Analysis Results (Original model)	15.218 Hz	23.325 Hz	40.705 Hz	40.963 Hz	53.968 Hz	58.521 Hz	66.185 Hz	75.085 Hz
No rib on Z axis	15.681 Hz	23.383 Hz	38.773 Hz	41.507 Hz	50.621 Hz	59.767 Hz	66.537 Hz	74.287 Hz
10 kg mass added	14.460 Hz	22.816 Hz	39.704 Hz	40.559 Hz	43.129 Hz	58.278 Hz	61.551 Hz	70.306 Hz
Extended spindle part	15.115 Hz	22.892 Hz	40.257 Hz	40.526 Hz	52.451 Hz	57.814 Hz	65.271 Hz	85.079 Hz (f9)

Besides modal analysis, static analysis is performed with the mentioned analysis model above, as well. Results are given in Table 4.7 and Figure 4.31.

Table 4.7 Static analysis results of mentioned analysis model

	Total tool deformation	X-Direction	Y-Direction	Z-Direction
Analysis Results (Original model)	0.40838 mm	0.4016	0.14	0.02
No rib on Z axis	0.42227 mm	0.4125	0.21	0.03
10 kg mass added	0.41023 mm	0.4098	0.18	0.02
Extended spindle part	1.18215 mm	0.982	0.35	0.26

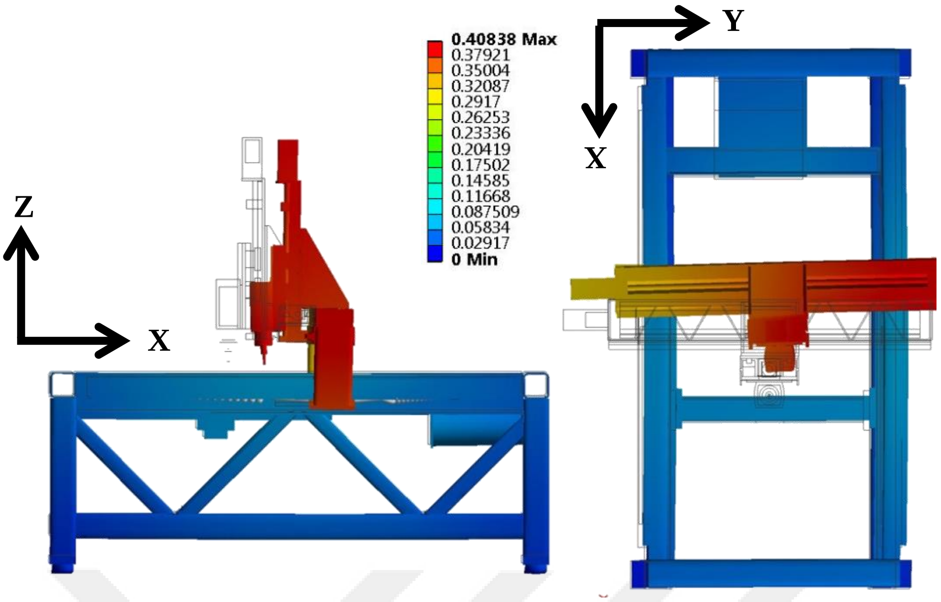


Figure 4.31 Static analysis displacement results of the original analysis model

When the static analysis results examined, analysis model of extended spindle holder is the most flexible design among the all analysis models. For this reason, it is easier to observe deviations than in other cases with the extended spindle holder in the milled work piece of the CNC machine.

CHAPTER FIVE
THE EFFECT OF THE CNC MACHINE FLEXIBILITY OVER THE MILLING PRECISION

In this chapter, flexibility of the CNC machine over the milling precision will be presented. In this context, two different designs, which one of them is flexible the other one is rigid, was created and experimental results were obtained on the CNC machine.

5.1 Flexible Design and Finite Elements Analysis

As mentioned chapter four in Section 4.6, static and modal analyses results of flexible design with extended spindle part and rigid design results are given in Table 5.1 and Table 5.2.

Table 5.1 Natural frequency results of analyses model and experimental results

	f1	**f2**	**f3**	**f4**	**f5**	**f6**	**f7**	**f8**
Experimental Results	13.56 Hz	27.11 Hz	35.55 Hz	37.96 Hz	45.49 Hz	53.63 Hz	63.21 Hz	74.71 Hz
Analysis Results of Original Model	15.218 Hz	23.325 Hz	40.705 Hz	40.963 Hz	53.968 Hz	58.521 Hz	66.185 Hz	75.085 Hz
Analysis Results of Extended Spindle Part	15.115 Hz	22.892 Hz	40.257 Hz	40.526 Hz	52.451 Hz	57.814 Hz	65.271 Hz	85.079 Hz (f9)

Table 5.2 Static analysis results of analyses model

Analysis model	Total tool deformation
Analysis Results (Original model)	0.40838 mm
Extended spindle part	1.18215 mm

As seen in Table 5.1 and Table 5.2 according to static and modal analysis results, with the extended spindle holder part to the CNC machine will be included sufficient flexibility for the observe of deflection on the milling parts. Local natural frequency on the spindle holder part and total deformation under the cutting force are shown in Figure 5.1 and Figure 5.2, respectively.

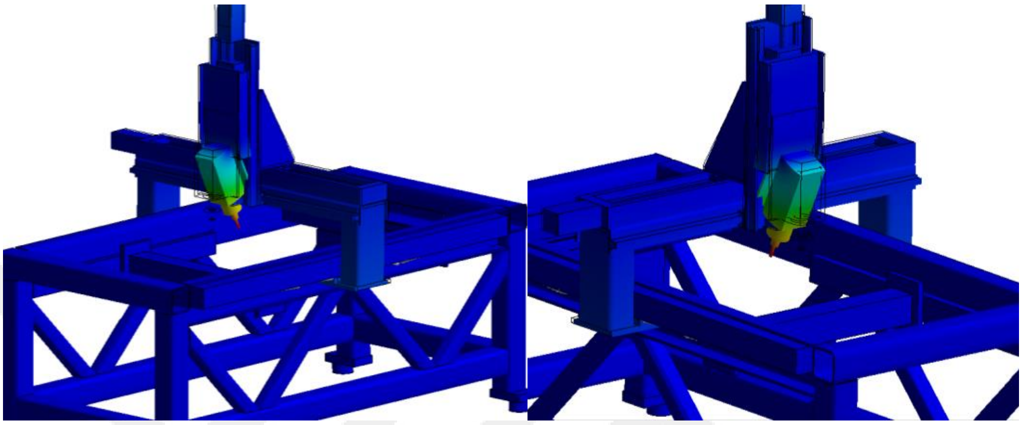


Figure 5.1 Local natural frequency on the spindle holder part (f_9 = 85.079 Hz)

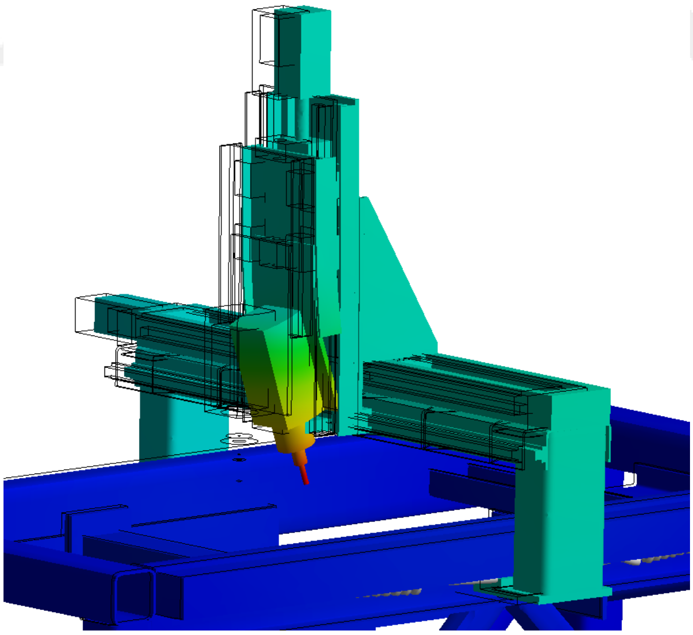


Figure 5.2 Total deformation under the cutting force

5.2 Natural Frequencies of CNC Machine's Flexible Position

For flexible position of CNC machine, natural frequency measurement was performed with same measuring tools and experimental setup were given in Figures 5.3 and Figure 5.4.

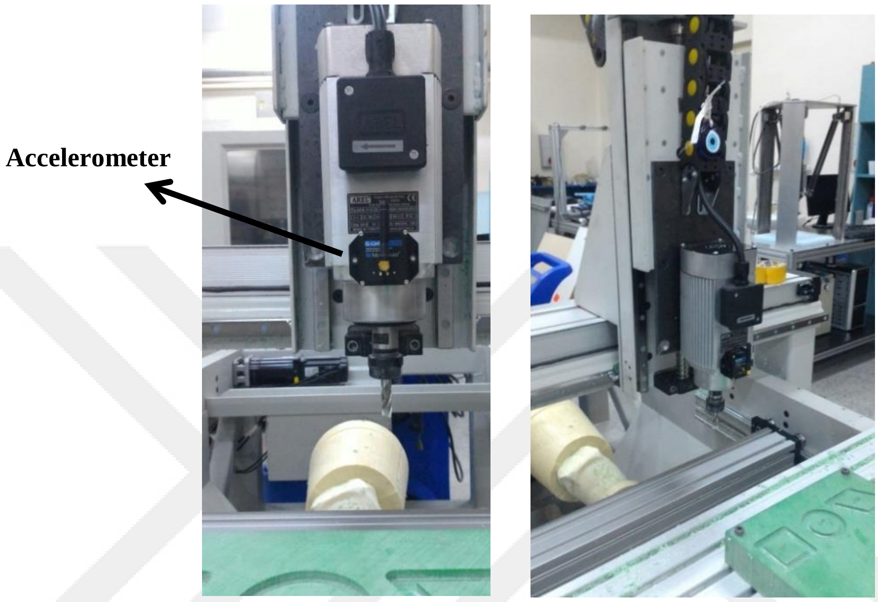


Figure 5.3 Experimental setup of the flexible position of CNC machine (Personal archive, 2017)

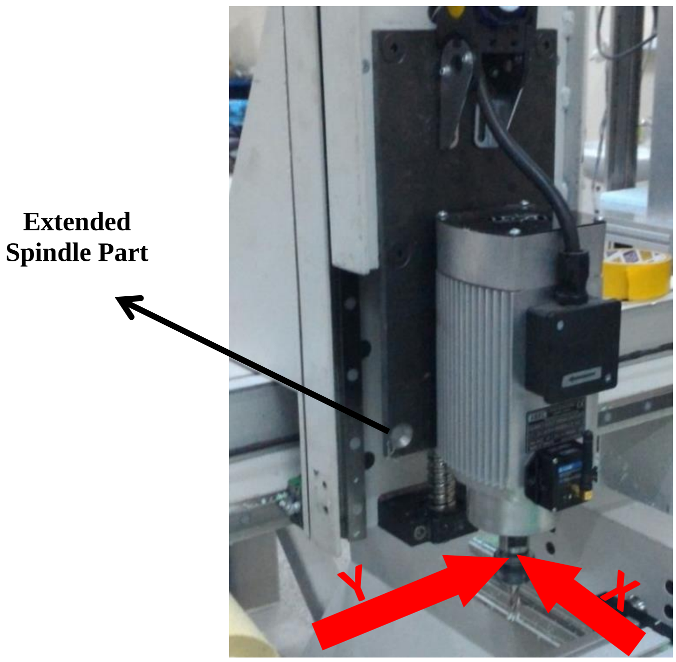
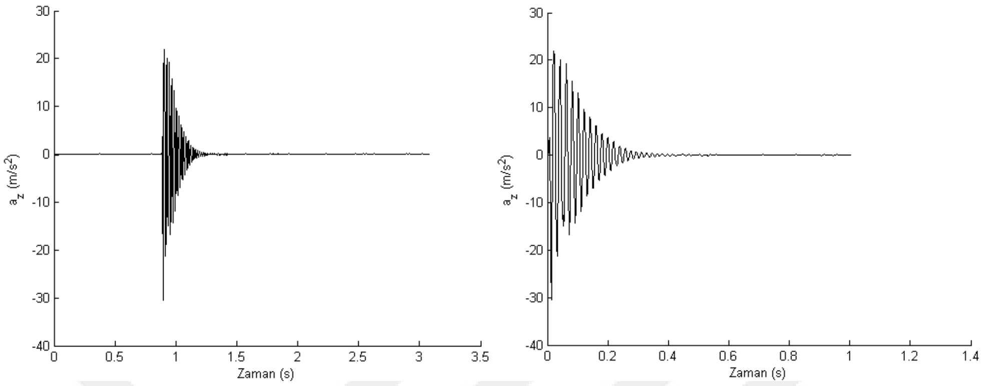


Figure 5.4 Applied impact direction to endpoint (Personal archive, 2017)

After applying the impact to the end point, acceleration data are collected by the accelerometer and these data are subjected to the FFT algorithm to obtain natural frequencies. Results are given in Figure 5.5, Figure 5.6 and Figure 5.7.



(a) (b)

Figure 5.5 The pulse is applied in the X direction from the spindle nut;

(a) Vibration response in the X direction
(b) Vibration response with filtered of the signal after pulse

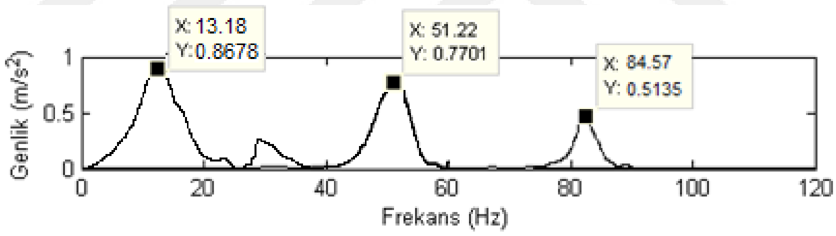


Figure 5.6 Frequency spectrum of the vibration signal generated in the X direction with respect to the local axis-set of the applied in the X direction

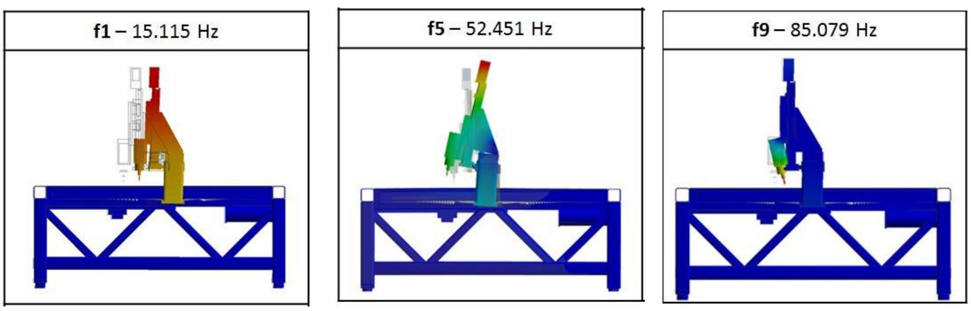


Figure 5.7 Modal analysis results and mode shapes with regard to related frequencies

According to experimental results, mode shapes and natural frequencies are harmony with the finite element modal analysis results. In particular, first, fifth and ninth natural frequencies directly affect over the milling process due to the fact that in this mode shapes, cutting tool moves independently from the machine body. With the extended spindle holder part, CNC machine have had a local natural frequency from spindle. This natural frequency also observed with the experimental result, as well. The differences between the experimental results and analysis results are given in the Table 5.3.

Table 5.3 Natural frequencies differences between analysis model and experimental results

	f1	f5	f9
Analysis Results	15.115	52.451 Hz	85.079 Hz
Experimental Results	13.18	51.22 Hz	84.57 Hz
Differences	+ %14.68	+ %2.5	+ %1.006

Finite element analysis results are higher than experimental results. These results are harmony with the earlier results, in terms of percentage differences.

5.3 Milling Process with Flexible and Rigid Design

Determined shapes are manufactured with both flexible design and rigid design. While the shapes being processed are determined, square, circle and parallelogram shapes were chosen in order to observe parallelism perpendicularity and circularity tolerance after the milling process. Specified shapes are shown in Figure 5.8 and Figure 5.9.

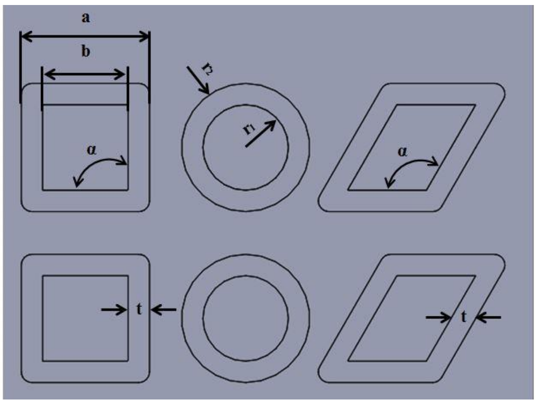


Figure 5.8 Determined milling shapes and dimensions

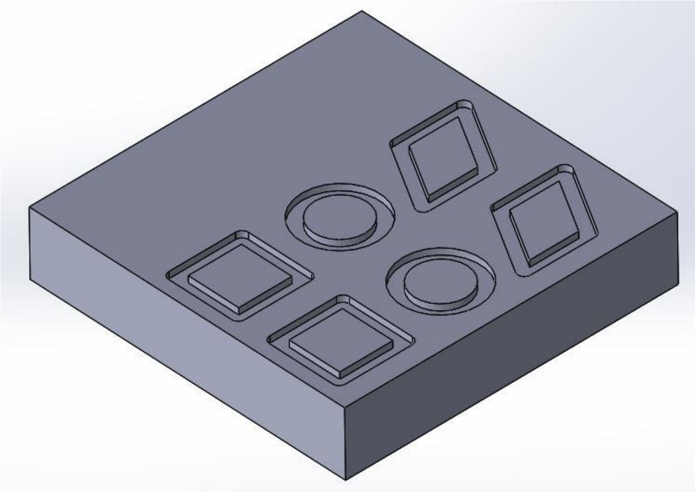


Figure 5.9 Contour milling

As seen in Figure 5.8 and Figure 5.9 above, milling method is chosen contour milling in order to observe deflection of cutting tool in both ways during the process namely, cutting tool follows the middle of two opposing sides in the milling operation. Milling parameters are given in Table 5.4.

Table 5.4 Determined shapes dimensions

Parameters	Dimensions (mm)
a	60
b	40
r_1	30
r_2	20
α	120°
d (tool diameter)	Ø10
chip depth	5

Milling parameters were determined according to work piece material. Work piece material was selected as sikablock due to excellent milling properties and good surface quality after milling process. Sikablock properties are given in the Table 5.5 and also milling process is shown in Figure 5.10.

Table 5.5 Sikablock properties

Physical data	Value
Density	1.3 g/cm^3
Shore hardness	D 83
Elasticity modulus	3400 MPa
Compressive strength	95 MPa
Heat distortion temperature	80 °C
Coefficient of thermal expansion	70 x 10^{-6} K^{-1}

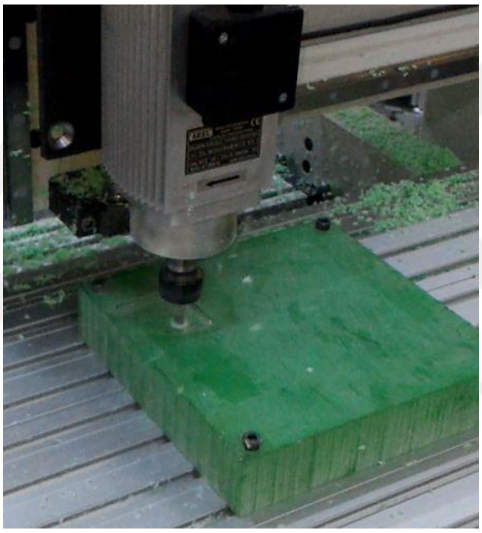


Figure 5.10 Sikablock milling process (Personal archive, 2017)

Cutting tool was selected, which is shown in Figure 5.11, as a 10 mm diameter, four cutting edge and end milling cutter.

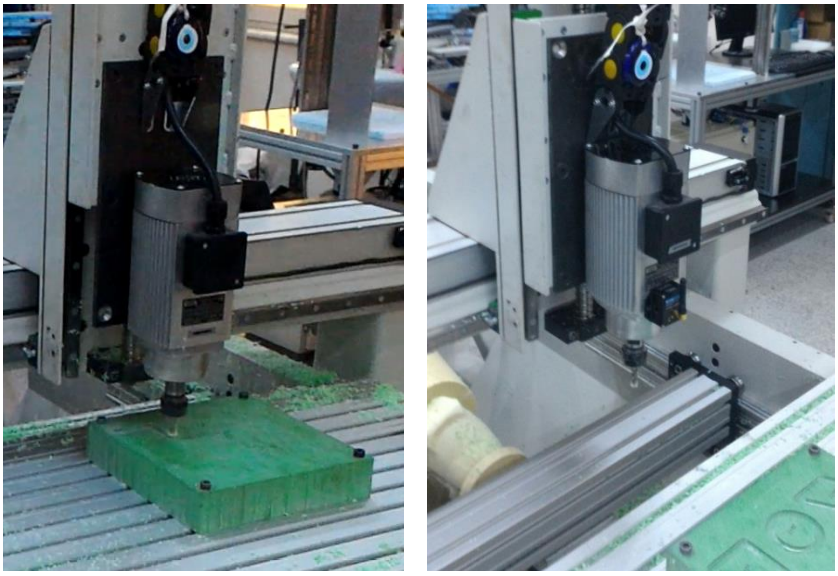
Figure 5.11 End milling cutter with four cutting edges

According to determined milling shapes and cutting tools above, computer aided manufacturing (CAM) codes are generated and given in Table 5.6. Plunge in feed rate and cutting feed rate are determined 80 mm/min and 250 mm/min, respectively and Z-Axis reference is selected as on the stock top, as well.

Table 5.6 CAM codes

G51 A255E1	G1 X65 Y90 Z5 F250
G90	G1 Z-5 F80
G54	G17 G2 X65 Y140 R25 F250
S12000 M3	G17 G2 X65 Y90 R25 F250
G1 X0 Y0 Z15 F250	Z5
G1 X40 Y15 Z15 F250	G1 X40 Y155 Z5 F250
G1 Z5 F250	G1 Z-5 F80
G1 Z-5 F80	G1 X40 Y205 Z-5 F250
G1 X40 Y65 Z-5 F250	G1 X90 Y233.8675 Z-5 F250
X90	Y183.8675
Y15	G1 X40 Y155 Z-5 F250
X40	Z5
Z5	M30

Milling process was performed with rigid and flexible design according to CAM codes with the CNC machine produced within this thesis scope. Milling process of both machine positions are given in Figure 5.12.



(a) (b)

Figure 5.12 Milling process with the flexible (a) and rigid position (b) (Personal archive, 2017)

Same CAM code was run with both flexible and rigid position of CNC machine so as to observe effect of flexibility on the work piece. As work piece material is selected sikablock due to high milling properties instead of EVA block. If milling process had performed with EVA block, milling results wouldn't have observed appropriately due to insufficient surface quality. With the EVA block CAM process have high surface roughness due to nature of material. Therefore, the milling process was carried out with a sikablock in order to prevent possible errors in the measurements after the milling.

After milling process, dimensional tolerances were measured with coordinate measurement machine (CMM) and differences between the rigid and flexible position are presented in the following section. Machined sikablock is shown in Figure 5.13.

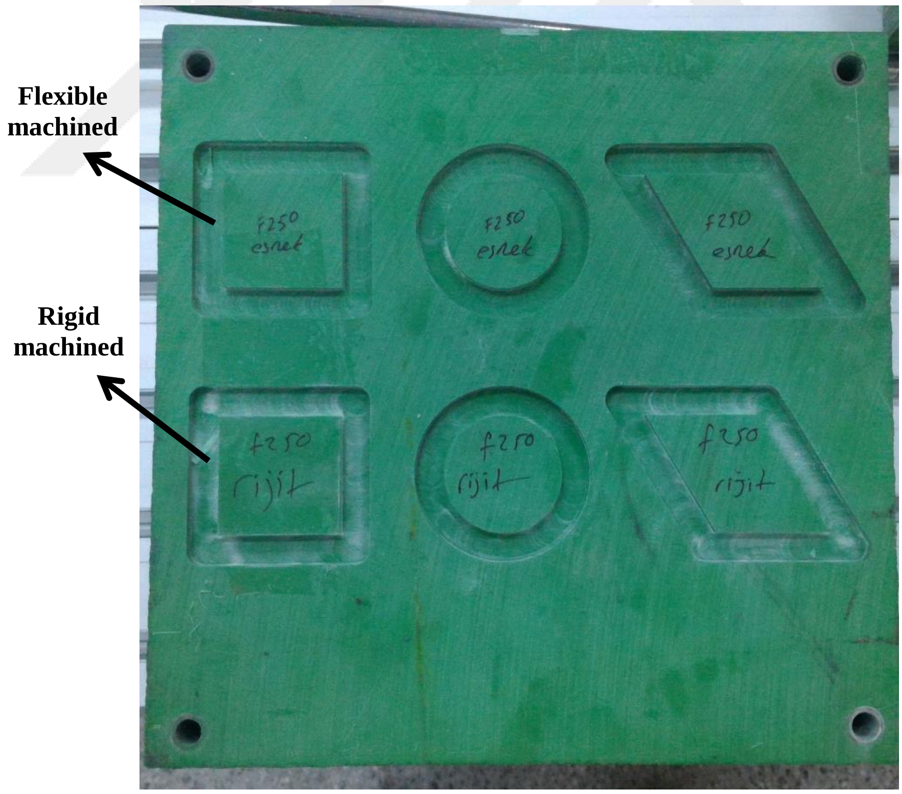


Figure 5.13 Machined sikablock with the CNC machine’s flexible and rigid position (Personal archive, 2017)

5.4 CMM Measurement over the Machined Sikablock

CMM measurements are taken with DEA brand performance series machine. This machine has a measuring distance of 900x1200x800 mm on the X, Y, Z axes respectively. Measurement precision is that 4 μm. Measurement process is shown in following figures. Measurement process is shown in Figure 5.14.

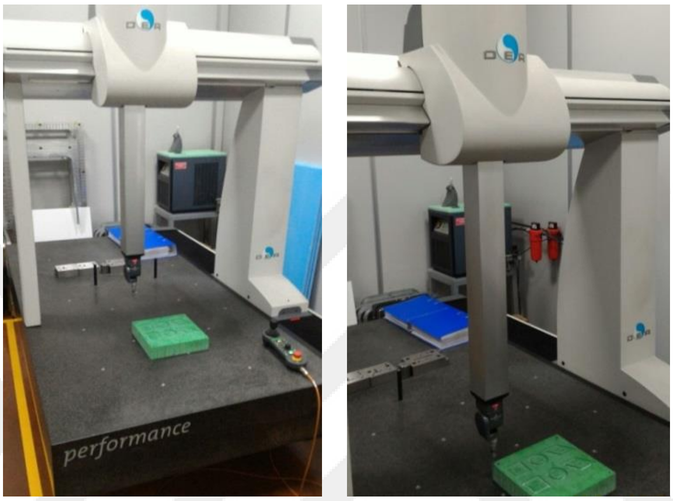


Figure 5.14 CMM measuring process (Personal archive, 2017)

CMM measurement was performed by taking ten point measurements from the circle. In square and parallelogram shapes, measurement was performed by taking two points to determine proper of edges. As known, at least two points are needed to draw a line and at least three points for the circle. For better examine the circularity, ten point measurements is chosen for circle. Schematic view is shown in Figure 5.15.

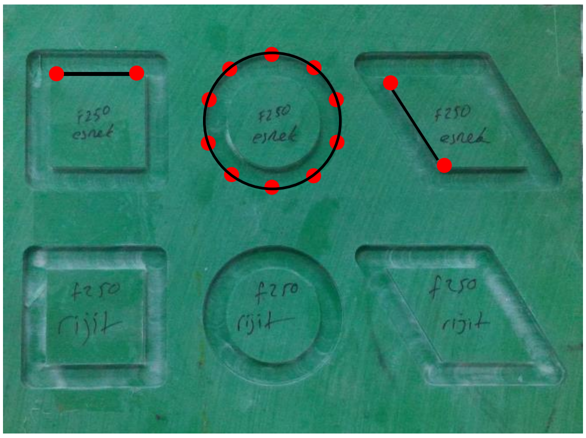


Figure 5.15 CMM measuring process for shapes (Personal archive, 2017)

Measurement results are given in Figure 5.16 and Figure 5.17 and also, deviations are shown in Table 5.7, Table 5.8 and Table 5.9.

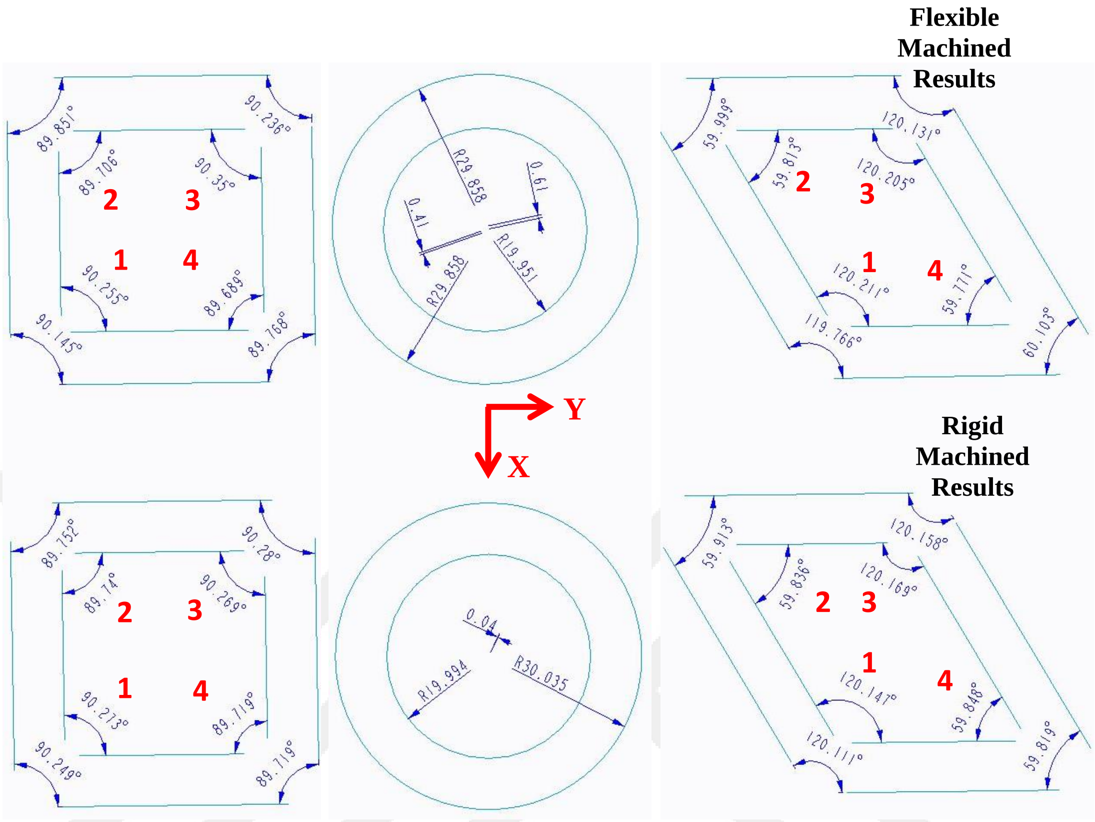


Figure 5.16 Angular measurement results

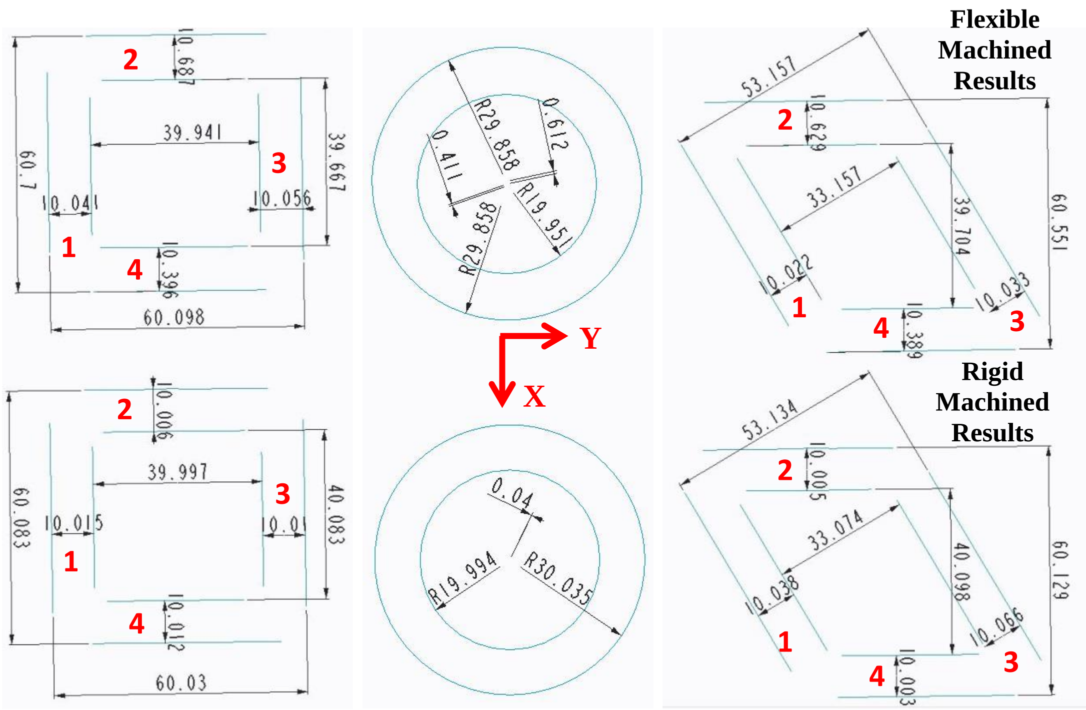


Figure 5.17 Dimensional measurement results

Table 5.7 Angular deviations value after the milling process for square and parallelogram

	Square				Parallelogram			
Angle	Flexible		Rigid		Flexible		Rigid	
(°)	Inside	Outside	Inside	Outside	Inside	Outside	Inside	Outside
α_1	90.255°	90.145°	90.273°	90.249°	120.211°	119.766°	120.147°	120.111°
α_2	89.706°	89.851°	89.740°	89.752°	59.813°	59.999°	59.836°	59.913°
α_3	90.350°	90.236°	90.269°	90.280°	120.205°	120.131°	120.169°	120.158°
α_4	89.689°	89.768°	89.719°	89.719°	59.771°	60.103°	59.848°	59.819°
Differences								
	Square				Parallelogram			
Angle	Flexible		Rigid		Flexible		Rigid	
(°)	Inside	Outside	Inside	Outside	Inside	Outside	Inside	Outside
α_1	+0.255°	+0.145°	+0.273°	+0.249°	+0.211°	-0.234°	+0.147°	+0.111°
α_2	-0.294°	-0.149°	-0.260°	-0.248°	-0.187°	-0.001°	-0.164°	-0.087°
α_3	+0.350°	+0.236°	+0.269°	+0.280°	+0.205°	+0.131°	+0.169°	+0.158°
α_4	-0.311°	-0.232°	-0.281°	-0.281°	-0.229°	+0.103°	-0.152°	-0.181°

Table 5.8 Dimensional deviations value after the milling process for square and parallelogram

	Square				Parallelogram			
Dimensions	Flexible		Rigid		Flexible		Rigid	
(mm)	Inside	Outside	Inside	Outside	Inside	Outside	Inside	Outside
width	39.941	60.098	39.997	60.030	33.157	53.157	33.074	53.134
height	39.667	60.700	40.083	60.083	39.704	60.551	40.098	60.129
t_1	10.041		10.015		10.022		10.038	
t_2	10.687		10.006		10.629		10.005	
t_3	10.056		10.010		10.033		10.066	
t_4	10.396		10.012		10.389		10.003	
Differences								
	Square				Parallelogram			
Dimensions	Flexible		Rigid		Flexible		Rigid	
(mm)	Inside	Outside	Inside	Outside	Inside	Outside	Inside	Outside
width	-0.059	+0.098	-0.003	+0.030	+0.157	+0.157	+0.074	+0.134
height	-0.333	+0.700	+0.083	+0.083	-0.296	+0.551	+0.098	+0.129
t_1	+0.041		+0.015		+0.022		+0.038	
t_2	+0.687		+0.006		+0.629		+0.005	
t_3	+0.056		+0.010		+0.033		+0.066	
t_4	+0.396		+0.012		+0.389		+0.003	

Table 5.9 Dimensional deviations value after the milling process for circle

Circle				
Radius	Flexible		Rigid	
(mm)	Inside	Outside	Inside	Outside
r_1	19.951	29.858	19.994	30.035
r_2	-	29.858	-	-
Concentricity difference	0.612 0.411		0.040	
Differences				
Radius	Flexible		Rigid	
(mm)	Inside	Outside	Inside	Outside
r_1	-0.049	-0.142	-0.006	+0.035
r_2	-	-0.142	-	-
Concentricity difference	+0.612 +0.411		+0.040	

As seen in the tables above, dimensional and angular differences between flexible and rigid position of the CNC machine are presented. According to these results, especially in the X direction corresponding to the local natural frequency (freq. 9), maximum deflections are observed from all shapes.

In circle measurements, circle, which is machined with flexible position, was measured an ellipse. Therefore, two different circle centers, which are 0.612 and 0.411 mm distance away to each other, were measured. Besides, inner and outer radius values were measured deficient 0.049 mm and 0.142 mm, respectively.

On the other hand, the circle, which is machined with rigid position, was measured a circle. Therefore, there is a single circle center corresponding to the inner and outer circle. But these two centers are not concentric, and concentricity distance between inner and outer circle was measured as 0.04 mm. Besides, inner and outer radius values were measured negative 0.006 mm and positive 0.035 mm, respectively.

In square and parallelogram measurements, while angular differences are not observed distinctly, dimensional differences are observed clearly. The reason of this, CNC machine rigidity is quite high to observe angular deviation according to machined sikablock. But, especially for the flexible position, mode shape behavior of ninth natural frequency has effect to dimensional deviation. In particular, for the width and height dimensions, the deviations between the flexible and rigid position were measured up to 129 times.

When the end point vibrations are ignored, the way the cutting tool has followed, must be measured as a cutting tool diameter and this value for this study is 10 mm. So, the distance between the inner and outer edges for square and parallelogram are to be 10 mm or higher. However, this value will deviate in greater value due to the vibration of the cutting tool. Dimensional differences are presented in Table 5.10.

Table 5.10 Dimensional differences for machined shapes

Dimension	Square			Circle			Parallelogram		
(mm)	Flexible	Rigid	Difference (times)	Flexible	Rigid	Difference (times)	Flexible	Rigid	Difference (times)
width (inside)	-0.059	-0.003	19.666	-	-	-	+0.157	+0.074	2.121
width (outside)	+0.098	+0.030	3.266	-	-	-	+0.157	+0.134	1.171
height (inside)	-0.333	+0.083	5.012	-	-	-	-0.296	+0.098	4.020
height (outside)	+0.700	+0.083	8.433	-	-	-	+0.551	+0.129	4.271
t_1	+0.041	+0.015	2.733	-	-	-	+0.022	+0.038	0.579
t_2	+0.687	+0.006	114.5	-	-	-	+0.629	+0.005	125.8
t_3	+0.056	+0.010	5.600	-	-	-	+0.033	+0.066	0.500
t_4	+0.396	+0.012	33.000	-	-	-	+0.389	+0.003	129.666
r_1 (inside)	-	-	-	-0.049	-0.006	8.166	-	-	-
r_1 (outside)	-	-	-	-0.142	+0.035	5.057	-	-	-
concentricity	-	-	-	+0.612	+0.040	15.300	-	-	-

As seen in Table 5.10, except for parallelogram t_1 and t_3, all deviation of flexible dimensions are higher than the deviation of rigid dimensions. This deviation can be reached up to 129 times. Especially for t_2 and t_4 dimensions, dimensional differences are reached to maximum value due to effect of machine flexibility on the X direction. Comparison of flexible and rigid position in terms of analysis and experimental is shown in Table 5.11.

Table 5.11 Comparison of flexible and rigid position in terms of analysis and experimental

Data	Flexible position	Rigid position
Static Analysis Results (end-point deformation)	1.18215 mm	0.40838 mm
Modal Analysis (directly related of cutter tool)	Freq. 1 – 15.115 Freq. 5 – 52.451 Freq. 9 – 85.079	Freq. 5 – 15.218 Freq. 5 – 53.968 Freq. 8 – 75.085
Experimental Results	Freq. 1 – 13.18 Freq. 5 – 51.22 Freq. 9 – 84.57	Freq. 1 – 13.56 Freq. 5 – 45.49 Freq. 8 – 74.71
CMM Measurement	Square t_2 = +0.687 t_4 = +0.396 Parallelogram t_2 = +0.629 t_4 = +0.389 Circle r_{in}=0.049 r_{out} =0.142 concentricity = 0.612	Square t_2 = +0.006 t_4 = +0.012 Parallelogram t_2 = +0.005 t_4 = +0.003 Circle r_{in}=0.006 r_{out} =0.035 concentricity = 0.040

CHAPTER SIX
CONCLUSIONS

In this study, a CNC machine, which is designed to machine orthotic prosthetic socket mold, personalized insole and waist corset, was presented. History and progress of the Computer Numerical Control machined were researched. Advantages and disadvantages, construction types, control systems and mechanical components of CNC machines were presented. Besides, types of machines, which using in healthcare area, were expressed detailed.

The CNC machine was built based on the previous design, and it was improved from 2.5 axis milling to four axis milling capacity with the new design. CNC machine, which is developed with this study, have 8 pair insole milling capacity at a time, and also CNC machine have machining capacity for waist corset up to diameter Ø650 mm and length 1000 mm. CNC machine have 3-Axis milling capacity with the fixing table, and also 4-Axis milling capacity when the fixing table disassembled. However, previous CNC machine have only 2.5-Axis milling, that mean is machine have linear X and Z axis and also a rotary axis. While new CNC machine has 1350x910x400 mm working space when using 3-Axis milling and 1110x400xØ600 mm working space with 4-Axis milling, previous CNC machine has 1350x450xØ450 mm working space with 2.5-Axis milling. With new design construction is changed from aluminum sigma profiles to steel profiles, and total weight is raised from 315 kg to 450 kg. 750 Watt Estun AC Servo motors were used into new CNC machine. As for control unit of CNC machine, Fagor 8055-M closed loop CNC control unit was used. Moreover, dedusting system was added to CNC machine. Besides, design parameters of each axis are presented detailed.

Cutting force was calculated for the aluminum material and engineering calculations were presented for each axis. Axis and spindle motors calculations were given as comparatively.

Mach 3 control unit and Fagor 8055-M control unit features and connections were presented and manufactured stages of CNC machine were shown.

Analysis model of the CNC machine was created in SolidWorks to perform finite element analysis. Analysis model consists of four parts called member. These members were connected to each other by connectors. For the CNC machine analysis model two different analysis models was created. One of them is Solid model the other one is Solid-Shell mixed model. Static and Modal analysis were performed with this models. Although the results of analyzes were very similar to each other, it was seen that there was a time difference about three hours between the solution times. Static and modal analyses were performed in order to make sure the design of machine was adequate to serve. Analysis results were found acceptable.

After the CNC machine was produced, experimental measurements were taken from the machine. Difference between the experimental results and the finite elements analysis results were acceptable.

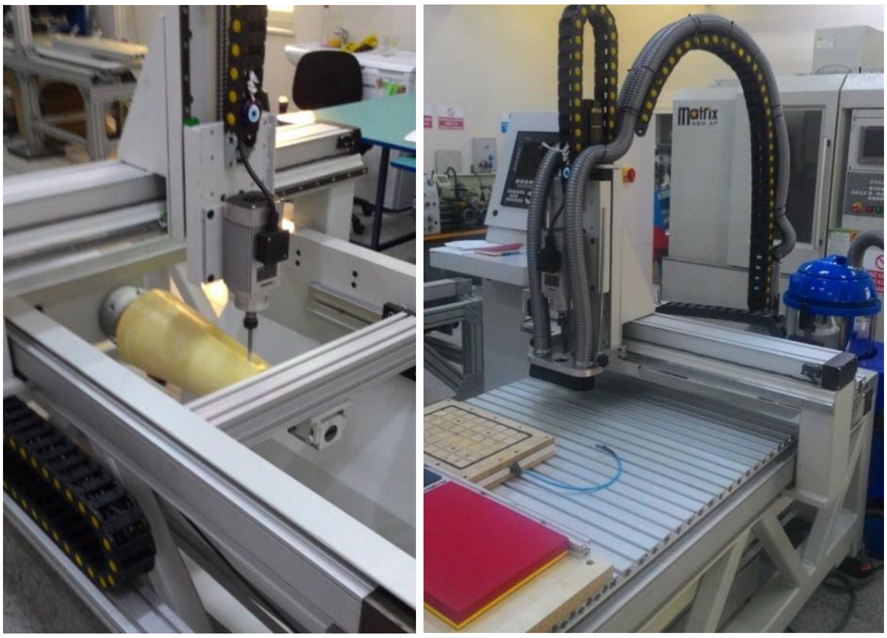
Stiffness reduction studies were performed in order to present the effect of the flexibility of machine. Appropriate design was produced and experimental measurements were taken over the CNC machine.

Geometric shapes were determined in order to present deviation between the flexible and rigid position of CNC machine and then CAM program of determined shapes was generated. After that, machining process was carried out with sikablock work piece.

CMM measurements were taken with DEA Coordinate Measurement Machine over the machined sikablock. The effect of the flexibility of CNC machine over the milling parts was presented detailed. According to the results, in the static analysis for the flexible and rigid position of machine, end-point tool deformation is 1.18215 and 0.40838, respectively. In the CMM measurements, maximum deviation for the flexible and rigid position of machine is 0.687 and 0.035 respectively. While maximum deviation of flexible position occurred in square shape, maximum deviation of rigid position occurred in circle shape.

When considered the angular results of CMM measurements, there have not clear results to understand difference of rigid and flexible position of CNC machine. Although some angular results in geometric shapes are similar with expectations for a flexible and rigid position, this has not been observed in all the results. When it comes to dimensional tolerance, the results are in accordance with expectations. In dimensional tolerances, parallel with machine axis direction such as X and Y, deviations between the flexible and rigid machining were observed clearly for square and circle shapes. Eventual comparison table were given in Section 5.4.

At the end of this thesis, a CNC machine, which have capable of 3-Axis and 4-Axis milling capacity optionally, was produced and has been successfully run. Also in this thesis, machining process for two different position of machine, which is flexible and rigid position, was carried out and results were measured with CMM. The differences between the two positions were presented with comparative tables. The CNC machine developed with this study is shown in Figure 6.1.



(a) (b)

Figure 6.1 CNC machine (a) four axis milling, (b) three axis milling (Personal archive, 2017)

The future works in order to extend this study can be summarized as follows,

- The numerical relationship between machine rigidity and machining precision can be established. For this purpose, the dimensional, positional and geometric tolerances obtained under different machining parameters should be evaluated. Work on this assessment should be done taking into account both the analysis and the experimental data.
- Computer programs can be developed that determine the machining parameters according to the tolerances that the parts to be produced must have.

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