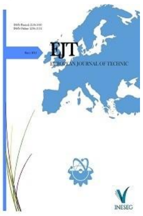
European Journal of Technique

journal homepage: https://dergipark.org.tr/en/pub/ejt

Vol.13, No.2, 2023



Research Article

# Determining the Advantages of a Linear Driven 3-Axis Industrial Robot by Structural and Force Analysis

**Savaş KOÇ[1*], İdris ŞANİ[2]**

[1*]Batman University, Mechanical Engineering Department, Batman, Turkey. (e-mail: savas.koc@batman.edu.tr).
[2] Disaster and Emergency Management Presidency (AFAD), Mardin, Turkey.

ARTICLE INFO

Received: Jan., 06. 2023
Revised: May., 13. 2023
Accepted: Agu., 18. 2023

Keywords:
Linear actuator
Measuring force and torque
Acceleration
Modal Analysis

Corresponding author: *Savas Koc*

ISSN: *2536-5010* | e-ISSN: *2536-5134*

DOI: https://doi.org/10.36222/ejt.1230193

## ABSTRACT

The most important factors affecting the operation of industrial robots are carrying capacity, the weight of the parts of robots, the vibrations in the arms and the manufacturing cost. The manufacturing cost of the robot increases as the weight of the parts and the size of the motors are increased. The forces on the motors and the accelerations at the top axes of the robot, which is driven by the linear movement or rotational moment were measured and compared in this study. In addition, modal analysis, forced vibration analysis and harmonic analysis of the robot were performed in two different drive systems. The structural condition of robot was examined. According to the calculations, smaller motors were used because the torque required for driving the axes using the ball screw system is very small. With the use of the smaller motors, the weights of the arms have been reduced due to the change in size of the motors. Similarly, the manufacturing costs of the robot have also been reduced. Hence, the robot designed in this study has advantages in terms of both structural and manufacturing cost compared to other robot arms. Likewise, it is seen that the robot can be operated using this design according to the accelerations measured at the top axes of the robot arm and the structural analysis.

## 1. INTRODUCTION

With rapid technological progress, innovations have a decisive impact on our lives [1]. Production quality and availability of cheap products have come as an inevitable need in the global industry [2]. Automation automatically controls the system by taking into account observation, decision-making and changes, rather than human interaction using mechanical or electronic devices [3]. Automation technologies are used both in order to accelerate serial production of parts and reduce production costs [4]. In order that a system to be fully automated, machine power must be superior than human power [5]. Manufacturers, who use modern techniques and applications, are provided by industrial automation in their production, have a strategy that will create competition among rival companies [6,7].

As we progress in the era of globalization, developments such as shortened product life cycles, reduced manufacturing cost, increasing innovations, shortage of skilled workers and continuous diversification of product range are observed in the manufacturing sector. Automation systems using industrial robots offer good solutions for productivity and flexibility [8,9]. With the developing technology, industrial robots also have high intelligence and sensitivity [10]. With the developments in robotics and mechatronics, they bring new advantages such as providing convenience for human life, working in risky places instead of human, obtaining autonomy in manufacturing, and using limbs that can serve as prostheses [11]. Robotics is one of the most important technologies that will affect life both in the twenty-first century and in the future [12].

Industrial robots, which are among the most critical elements of industrial automation systems, are widely used in a series of industrial production activities such as spraying, welding and handling and increasing their importance day by day [13,14]. They are also used to protect human life in dangerous conditions such as mechanical vibrations, high temperatures, chemicals and nuclear energy. They perform operations made manually for long periods of time by operators in production sectors in a faster and error-free way [15,16]. By using robots, production is ensured in a way to obtain more products to meet customer expectations in shorter times and does not compromise on quality. The most important features that an industrial robot should have are the repeatability of the process, accuracy and the load capacity it can carry [17]. The load capacity it can carry varies depending on the movement speed of the mechanism used in the robot. As the load carrying capacity increases, the speed of the mechanism decreases. In order to increase the load capacity, different designs have to be obtained for the motors to be used at lower torques. Accuracy is affected by the size and type of load as opposed to repeatability [18].

Industrial manipulators must have six degrees of freedom to reach points in their working environment or space. While the first three axes of the robot that provide the body movement are seen as separate kinematics, the wrist forming the last three axes is defined separately [19]. While the use of actuators has become increasingly important in the field of robotics, their use in industry and scientific research has become popular with the successful advances in actuator technology in recent years. Actuators are often used in robot applications such as mobile humanoid robots, walking mechanisms, and biomedical devices. It is also used in robotic applications with high specific power such as push-pull, rotation, lift-release and positioning [20-22].

As in every system in which movement occurs, vibrations occur in robot arms [23]. Natural vibrations consist of robot manipulators being moved from one point to another and suddenly stop [24]. From an industrial point of view, the residual vibration of robot manipulators is one of the undesirable situations [25]. These vibrations are generally desired for minimizing as much as possible by vibration control methods [26]. In robotic manipulators, good position accuracy is achieved by minimizing vibration of the end-effector. In conducted studies, it is generally preferred to use flexible links [27]. In addition, among the efforts to reduce the unwanted vibrations in the robot arms to low levels, it is preferred to perform the assembly process using bearings suitable for the joint parts [28]. Vibration analysis of a robotic arm with a single flexible link [29] and modal analysis of a robotic arm with a flexible link using the finite element method are examined up to the most dominant vibration modes [30]. A rigid two-degree-of-freedom robot arm forms modal analyzes using the finite element method in the Ansys workbench application [31].

When precision gear systems are used as a drive mechanism in industrial robots, high torque motors should be used to carry the load on the motors. The use of these motors causes weight on the system as well as increases the cost [32]. In order to enable the movement of a robot arm with a lower power motor, actuators that move linearly and can be controlled by stepper motors are used instead of precision gear systems. The use of this drive system, which consists of a ball screw system that delivers the same movement as linear moving systems, provides important advantages [33]. This system is designed at very small powers; and it is calculated to be able to lift more load when operated.

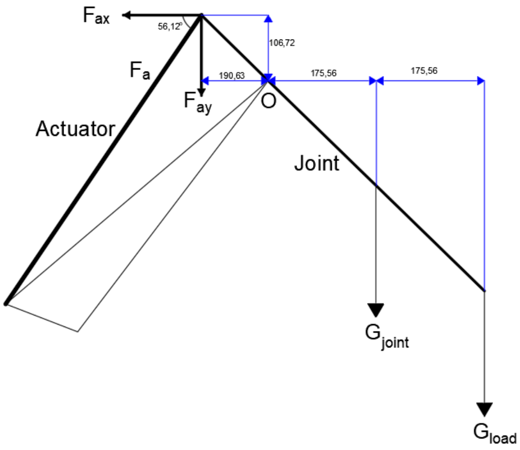


**Figure 1.** Torque calculation on the robot axis [33]

As shown in Fig. 1, at the O point on the 3rd axis, the motor performs movement by rotating the direct arm or by push-pull force of the actuator connected to the end of the arm. In order to calculate the torque on the motor directly connected to the O point, the weight of the bar is to be 4 kg, and the weight of the load and gripper connected to the end of the arm is accepted as 20 kg. To find the torque of the motor, the moment at point O is taken as;

$$T_{motor} = 4*9.81*0.17556+20*9.81*0.35111=75.78 \text{ Nm} \quad (1)$$

Similarly, the moment is taken at O point to calculate the force drawn by the actuator and how much torque this force creates on the motor over the ball screw (see Equation 2-4):

$$F_{ax}*0.10672+F_{ay}*0.10963 = T_{motor} \quad (2)$$

$$F_a*(\cos 56.12)*0.10672+F_a*(\sin 56.12)*0.10963 = 75.78 \quad (3)$$

$$F_a = 503.5 \text{ N} \quad (4)$$

When the shaft has a pitch of 5 mm and a diameter of 16 mm, the torque to the motor (Equation 5-6):

$$F_t = 0.005*503.5/(pi*0.016) = 50.08 \text{ N} \quad (5)$$

$$T_{motor} = 50.08*0.016/2 = 0.4 \text{ Nm} \quad (6)$$

According to these calculations, the use of smaller motors in the actuator is provided a great advantage in terms of both weight and cost.

In this study, the results are obtained by making a simulation that applies both rotation torque and linear movement in the analysis program to the rotation point that provides the movement of each arm in the robot arm that moves with the ball screw system. The aim of this study is to reveal the advantages provided by the reduction of the size of the motors used in the ball screw actuators, which produce force equivalent to the torque occurring in the arms in the propulsion system used in serial robots. In addition, when the robot is driven by a ball screw and torque, the forces applied to the system and the deformations that occur in the body of the robot are examined with the analyzes made under load. By making a modal analysis, the modes that give the behavior of the system under vibration and the natural frequencies of the system will be determined and the resonance situations will be examined. As a result of these analyses, the displacements caused by the weights on the robot arm while carrying the load and the vibrations that occur at the end of the robot are measured.

## 2. MATERIAL AND METHOD

In order to be efficient and reliable for the robots in the manufacturing industry, the best model is created by analyzing different designs. To optimize and improve the design, design processes such as structural analysis and dynamic simulation are utilized by using the model creation and simulation tools [34]. Modeling and simulation of robot systems using different software programs provide great advantages in design, construction and control processes. With the use of simulation, programmers take the right steps in analyzing behavior, predicting, optimizing and planning.

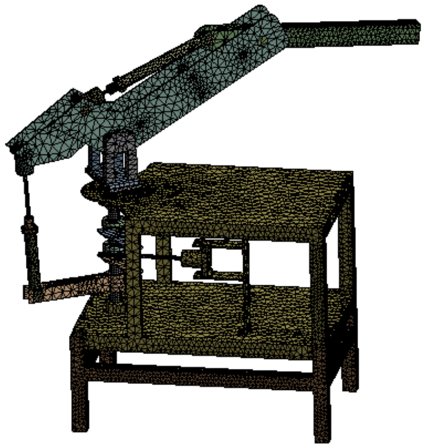


**Figure 2.** Meshing of the robot arm

The 3-axis robot arm is modeled in the Solidworks program as shown in Fig. 2 and moved to the Ansys program to perform the analysis. The mesh operation of the robot manipulator is applied by selecting the default setting in the mesh menu in the workbench interface.

As a result of the size meshing, it is seen that a total of 193754 points are formed on the body and all joints of the robot manipulator are divided into 85831 parts and the distance between the parts is also determined as 15 mm.

## *2.1. Applying Rotational Torque and Linear Force to the Robot*

One of the aims of this study is to compare the torque on the motors by using the rotational torque and linear force. In order to provide three axes rotation, the robot arm is rotated by applying the linear force to the C, G and H points as shown in Fig. 3a. On the same body, torque is defined by applying rotational torque to C, G and A points as shown in Fig. 3b and as in Table 1 for moving the robot arm. When the analysis is performed, the rotation angle for the rotational movement and the progressing distance for the linear movement are defined for the driving parts. The torque applied to the axes of rotation is calculated by applying both linear force and torque to the robot.

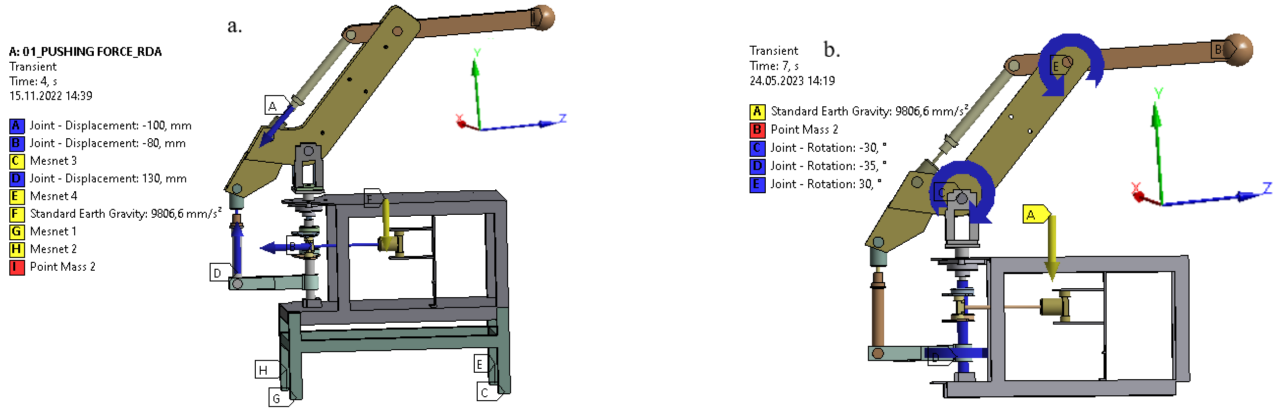


**Figure 3.** Applying linear force and rotational torque to the robot arm

**Table 1.** Angle and progression data for the movement of the robot arm

Rotational Movement Analysis Data

| Motor 1 | | | Motor 2 | | | Motor 3 | | |
|---|---|---|---|---|---|---|---|---|
| Steps | Time (s) | Rotation (°) | Steps | Time (s) | Rotation (°) | Steps | Time (s) | Rotation (°) |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | -10 | 1 | 1 | -10 | 1 | 1 | 10 |
| 2 | 2 | -20 | 2 | 2 | -20 | 2 | 2 | 20 |
| 3 | 3 | -30 | 3 | 3 | -30 | 3 | 3 | 30 |
| 4 | 4 | -35 | 4 | 4 | -35 | 4 | 4 | 35 |
| 5 | 5 | -30 | 5 | 5 | -30 | 5 | 5 | 30 |
| 6 | 6 | -20 | 6 | 6 | -20 | 6 | 6 | 20 |
| 7 | 7 | -10 | 7 | 7 | -10 | 7 | 7 | 10 |

Linear Movement Analysis Data

| Motor 1 | | | Motor 2 | | | Motor 3 | | |
|---|---|---|---|---|---|---|---|---|
| Steps | Time (s) | Displacement (mm) | Steps | Time (s) | Displacement (mm) | Steps | Time (s) | Displacement (mm) |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | -25 | 1 | 1 | 40 | 1 | 1 | -30 |
| 2 | 2 | -50 | 2 | 2 | 80 | 2 | 2 | -60 |
| 3 | 3 | -75 | 3 | 3 | 120 | 3 | 3 | -90 |
| 4 | 4 | -80 | 4 | 4 | 130 | 4 | 4 | -100 |
| 5 | 5 | -75 | 5 | 5 | 120 | 5 | 5 | -90 |
| 6 | 6 | -50 | 6 | 6 | 80 | 6 | 6 | -60 |
| 7 | 7 | -25 | 7 | 7 | 40 | 7 | 7 | -30 |

## *2.2. Modal analysis*

Free vibration analysis of the system, as shown in Fig. 4, is the analysis without any external force on it. Every structure has a tendency to vibrate at certain natural frequencies. In modal analysis, an input vibration is applied to the structure and the response of the structure to this input is measured in the form of modes. The mode shape is the shape the structure takes as it vibrates at its natural frequency. At the same time, mode shapes are the view of deformation shapes as a result of analysis. In these Modes, natural frequency, damping and mode shapes are determined.

Modal analysis is examined in 6 modes in terms of the deformation of the structure. Thus, the vibration characteristics of the system are obtained. The linear contact group is selected for the analysis. The robot arm is fixed with four legs so that it is contacted to the ground from the bottom. Three stepper motors are placed in the robot arm. The rotational speed of each of these motors is assumed to be 500 rpm and their frequencies are calculated as 8.33 Hz.

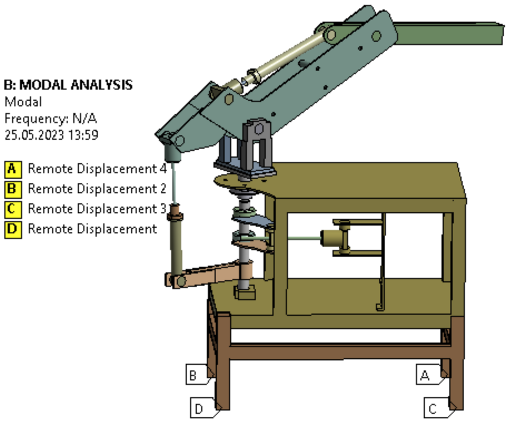


**Figure 4.** Modal analysis of the robot arm

### *2.3. Harmonic response for rotational torque and pushing force*

In the rigid dynamic analysis, the robot arm is moved with a free movement to a coordinate point. In order to compare the harmonic angular motion analysis and harmonic linear motion analysis results, the rigid dynamic analysis is calculated by taking values from both the rotational movement model as shown in Fig. 5a and the linear movement model as shown in Fig. 5b. Thus, results are obtained under the same conditions in the harmonic vibration analysis for both models.

In the harmonic analysis, a force of 200 kg is applied to the top axes of the robot arm as an external force in the direction of gravity, and a force of 4 kg in the direction of gravity is applied as the gripper weight in the same way. A total force of 204 kg at the top axes of the arm, multiplied by the maximum acceleration values obtained in X, Y and Z coordinates of the rigid dynamic analysis, is defined as the outer boundary condition for the harmonic analysis. These external forces are applied respectively in the direction of X, Y and Z coordinates and at the top axes of the arm. These forces are defined as the rotational torque in the rotational movement analysis and the linear force in the linear movement analysis to the shafts to which the motors are connected.

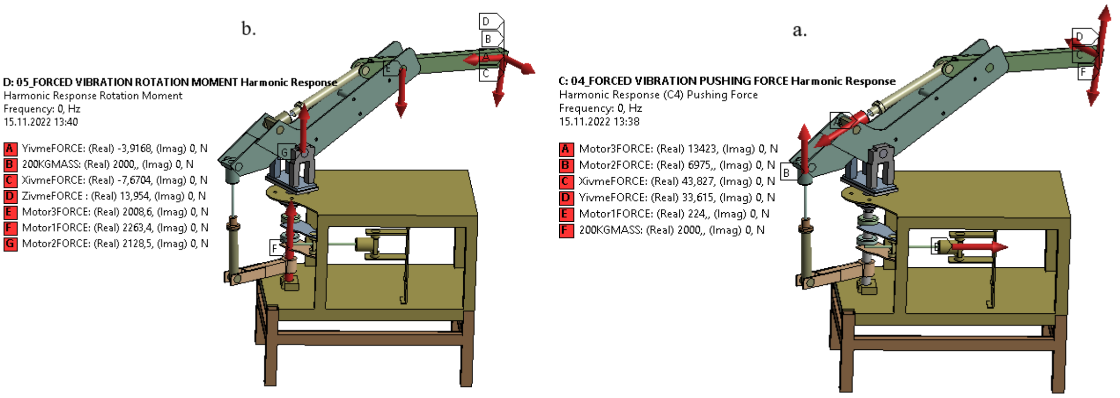
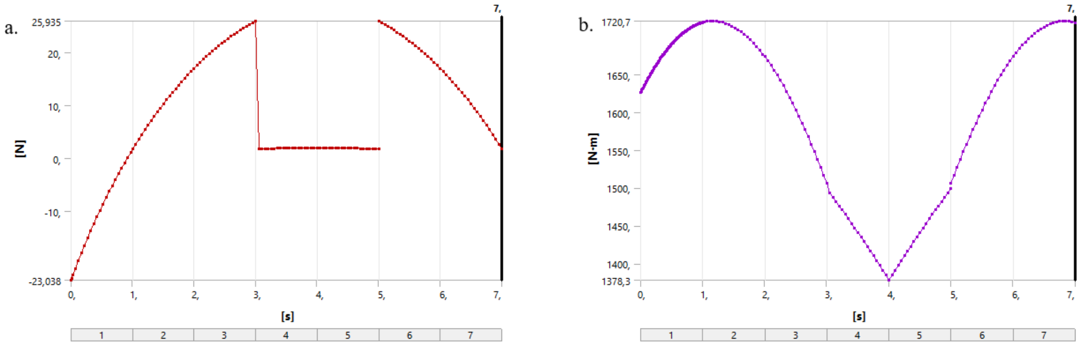


**Figure 5.** Modelling of harmonic analysis and frequency response a) linear b) rotational

## 3. RESULTS AND DISCUSSION

### *3.1. Torque and Force falling on the motor and the actuator*

In the rigid dynamic analysis, the linear force and rotational torque graphs on each motor by moving linearly with the help of the linear force of the motors and by moving the arms with the torque applied to the rotation axes are shown in Fig. 6. When the graphics are examined, it is ensured moving the arms with less force in motor 1. In addition, the forces on the motors are measured to be very small by using the bearings moving the first axis with the linear force. According to these values obtained in motor 1, motor selected very small provides great advantages in both weight of the robot and manufacturing cost. Likewise, when the force graphs on the motor 2 and motor 3 are examined, it is seen that smaller motors can be used to rotate the axes in movements generated with linear force. According to the results of the analysis, larger loads can be carried with smaller linear motors by reducing the manufacturing costs consisting of the torques on the motors and the motor weights.



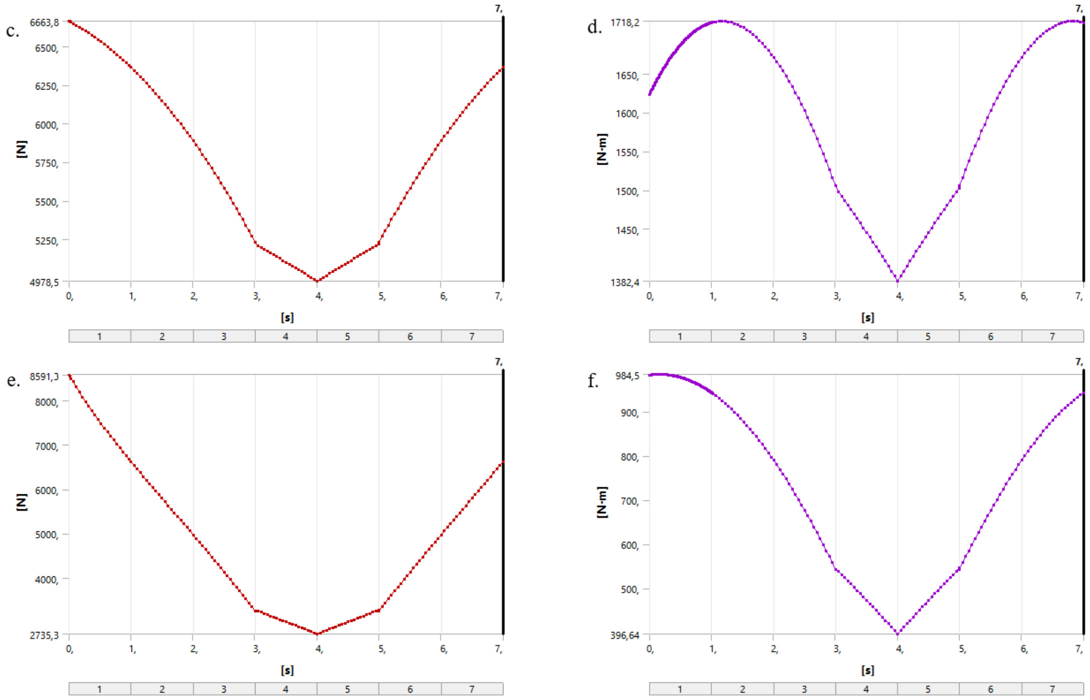
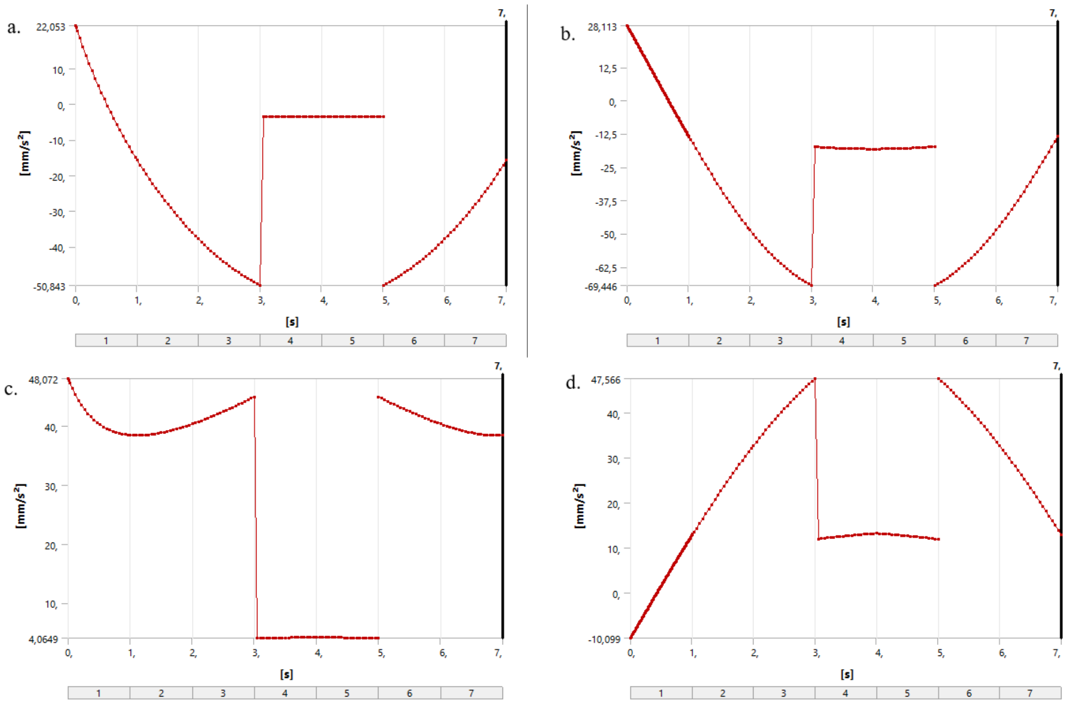


**Figure 6.** Forces falling on motors a) Motor 1, linear force b) Motor 1, rotational torque c) Motor 2, linear force d) Motor 2, rotational torque e) Motor 3, linear force f) Motor 3, rotational torque

## *3.2. Accelerations at the end-point of robot arm*

According to the analysis results, the accelerations in the three-axis directions at the top axes of the robot arm are shown in Fig. 7. By using these accelerations, vibrations at the top axes are determined. The acceleration intervals in the X direction have changed between (22)-(-50) mm/s$^2$ in the linear force and between (28)-(-70) mm/s$^2$ in the rotational torque. The acceleration intervals in the Y direction have changed between (48)-(4) mm/s$^2$ in the linear force and between (48)-(-10) mm/s$^2$ in the rotational torque. The acceleration intervals in the Z direction also have changed between (-2) -(-126) mm/s$^2$ in the linear force and (-5) -(-98) mm/s$^2$ in the rotational torque. The acceleration graphs in X and Z directions are similar to each other, but it is seen that the value range of the linear movement is low in the accelerations in the Y direction. When the accelerations occurring in the axes defined in X, Y and Z directions at the top axes are examined, it is seen that the use of actuators moving with linear force provides an advantage.



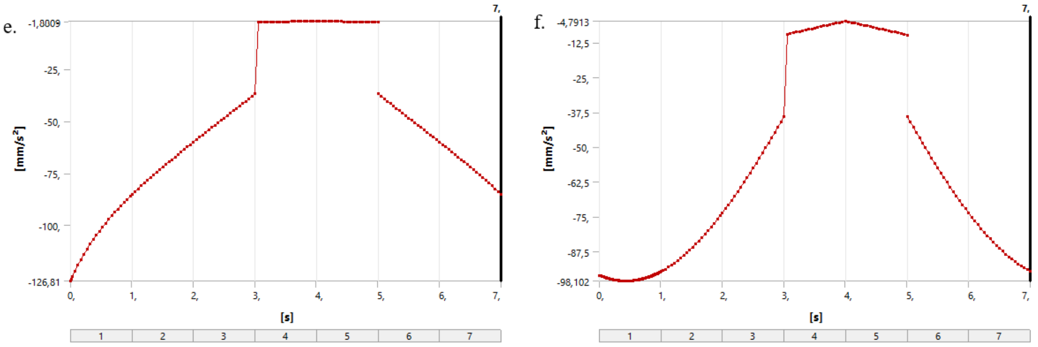


**Figure 7.** Accelerations at the robot end-point a) linear, in the X direction b) rotational, in X direction c) linear, in Y direction d) rotational, in Y direction e) linear, in Z direction f) rotational, in Z direction

### *3.3. Results of modal analysis*

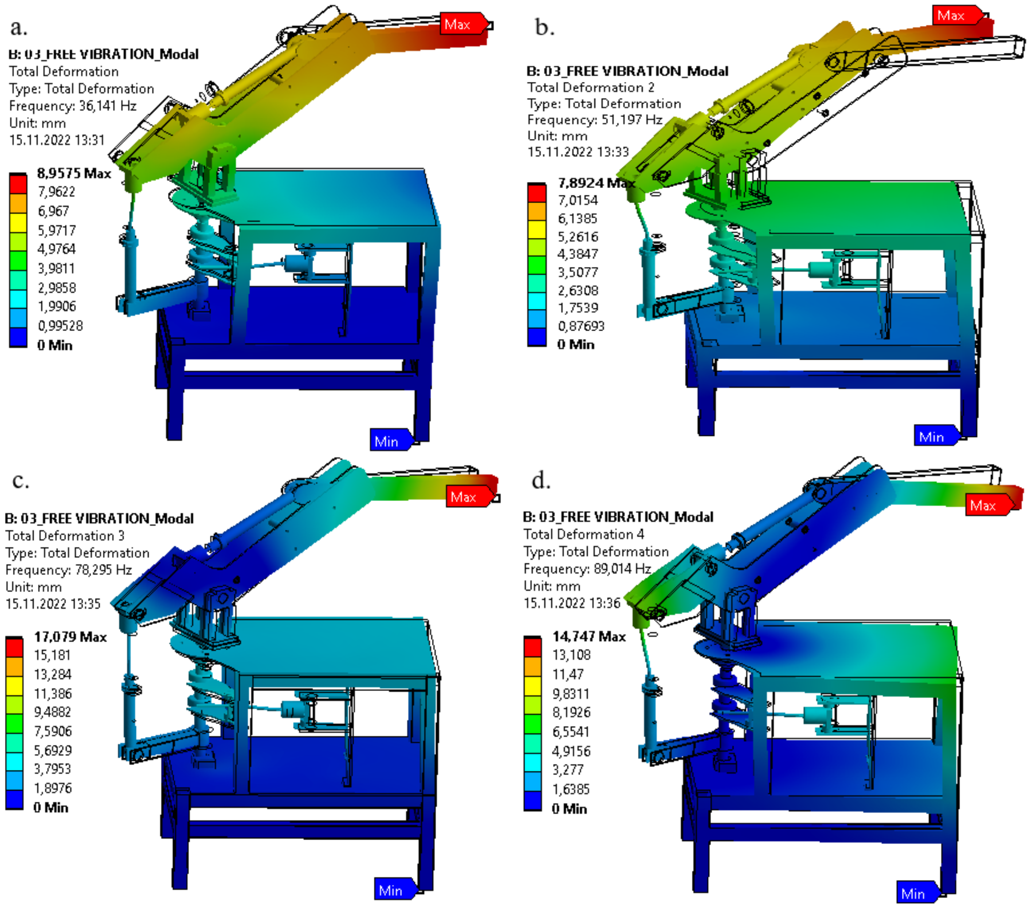
Modal analyzes of the three-axis robot arm are measured in 6 modes as shown in Table 2. The 1st mode is the vibration caused by the robot's movement to the right and left. The 2 st mode is the vibration caused by the robot pulling backwards in the Y direction. The 3rd and 5th mode is the vibration caused by the movement of the 2nd and 3rd axis to the right and left. The 4th and 6th modes are vibrations caused by the robot's rotation around itself.

In the analyzes made considering the operating frequency of the motors, as shown in Fig. 8, a total deformation of 8.95 mm has occurred at the 1st mode 36.141 Hz frequency. Similarly, respectively, the 2nd Mode is 7.89 mm at 51.197 Hz, the 3rd Mode is 17.079 mm at 78.295 Hz, the 4th Mode is 14.747 mm at 89.014 Hz, the 5th mode is 17.85mm at 100.86 Hz, and the 6th mode is 15.372 mm at 115.56 Hz.

By comparing the natural frequencies of the motors and the frequencies measured as a result of the modal analysis, the state of the system in resonance is examined. The purpose of the modal analysis of moving systems is to measure whether the system has come to its resonance value. While the natural frequency of the motors used in the three-axis robot is calculated as 8.33 Hz, the frequency values measured as the result of the modal analysis have changed between 36.141-115.56 Hz.

**Table 2.** Modes and frequencies formed as a result of analyzes.

| Mod | Frekans (Hz) |
|---|---|
| 1. Mod | 36,141 |
| 2. Mod | 51,197 |
| 3. Mod | 78,295 |
| 4. Mod | 89,014 |
| 5. Mod | 100,86 |
| 6. Mod | 115,56 |



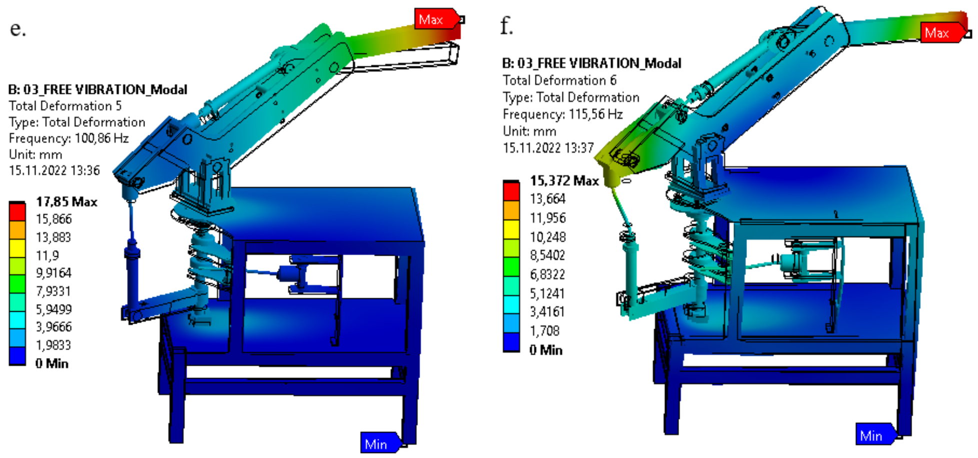


**Figure 8.** Total deformation in 6 modes a) mod 1 b) mod 2 c) mod 3 d) mod 4 e) mod 5 f) mod 6

### *3.3. Results of forced vibration analysis*

In the harmonic analysis of the middle arm, which forms the 2nd axis of the robot, the maximum and minimum points, at which the total deformation and von-Mises stress have occurred in the arm, are shown in Fig. 9. When the harmonic analysis results of this arm are examined, it is observed that the maximum total deformation in linear movement in the middle arm is measured as 3.55 mm and von-Mises stress as maximum 64.825 MPa. Likewise, the maximum total deformation in rotational movement is measured at 1.5 mm and von-Mises stress as 50.63 MPa maximum. According to these results, it is determined that the values of deformation and von-Mises stress are greater in linear movement. It is seen that it is more advantageous to drive this arm with the rotational movement since the small deformation and von-Mises stress of the structure is considered to be a better design.

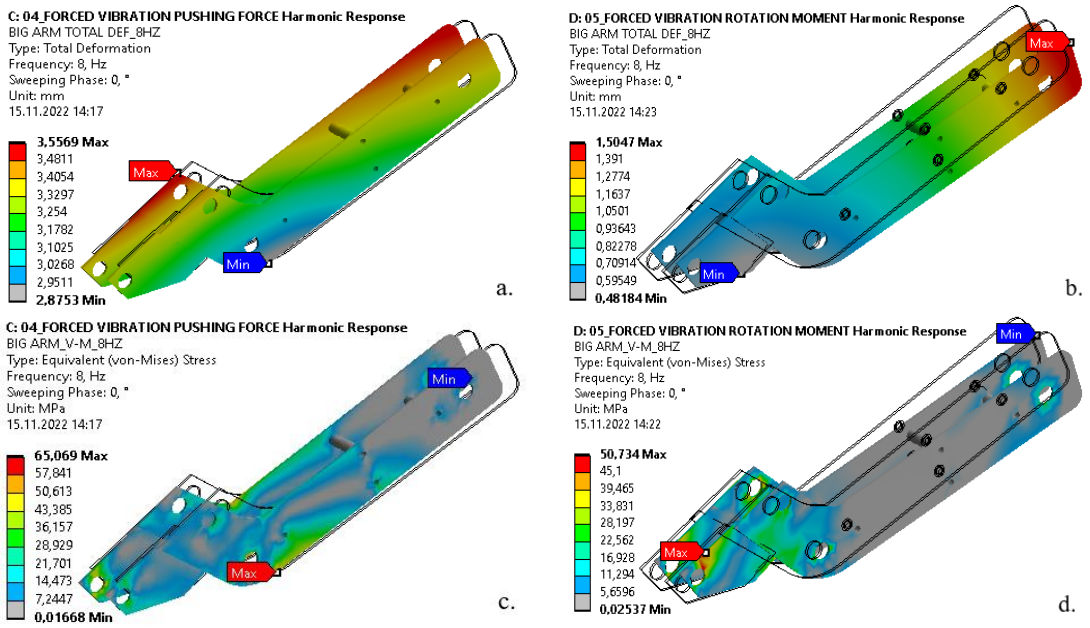


**Figure 9.** Results of 2nd arm harmonic analysis a) linear, total deformation (mm) b) rotational, total deformation (mm) c) linear, von-Mises stress (Mpa) d) rotational, von-Mises stress (Mpa

In the harmonic analysis of the arm, which forms the 3rd axis of the robot, the maximum and minimum points where the total deformation and von-Misses stress have occurred in the arm are shown in Fig. 10. When the results of the harmonic analysis of this arm are examined, it is seen that the linear movement is measured the maximum total deformation as 3.52 mm and von-Mises stress as maximum 50.42 MPa. Likewise, the rotational movement is measured the maximum total deformations as 2.8 mm and von-Mises stress as a maximum of 76.48 MPa. According to these results, it is determined that the deformation is greater in linear movement, and von Mises stress is greater in rotational movement. Since von-Mises stress is small in linear movement, moving the arm with the linear force is seen as a better design.

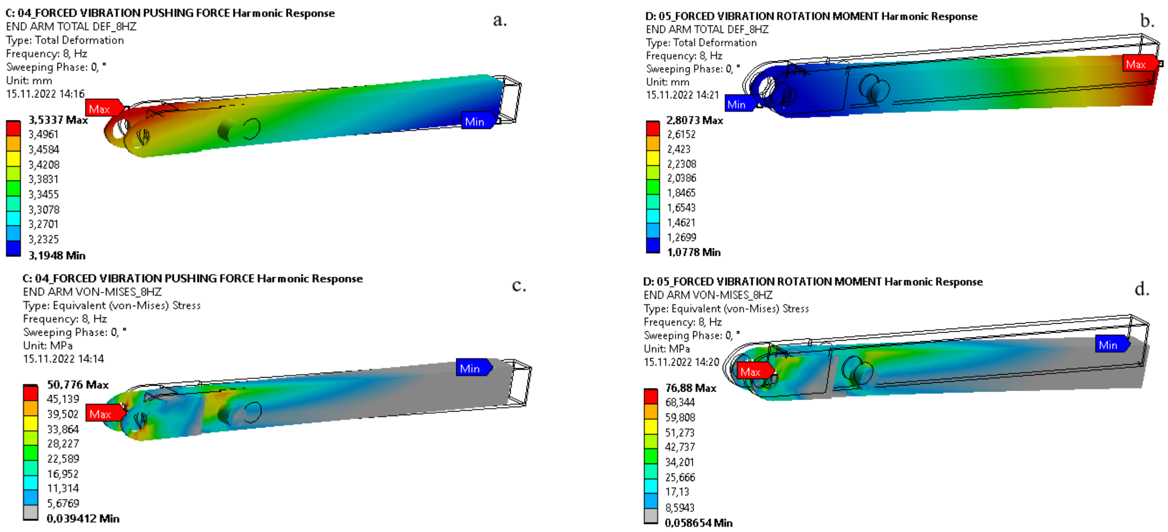


**Figure 10.** Harmonic analysis results of the 3rd arm a) linear, total deformation (mm) b) rotational, total deformation (mm) c) linear, von-misses (Mpa) d) rotational, von-misses (Mpa)

The maximum and minimum points of the total von-Mises stress on the body in the harmonic analysis for the robot's body are shown in Fig. 11. According to the results of the harmonic analysis, the maximum von-Mises is measured in linear movement as 460.89 MPa and in rotational movement as 474.38 MPa. Although von-Mises stress has not changed much in the two different movements, it is more advantageous in linear movement as it is measured less. Thus, according to the results of all harmonic analyses, it is accepted that the robot driven by linear movement can be chosen as a better design model.

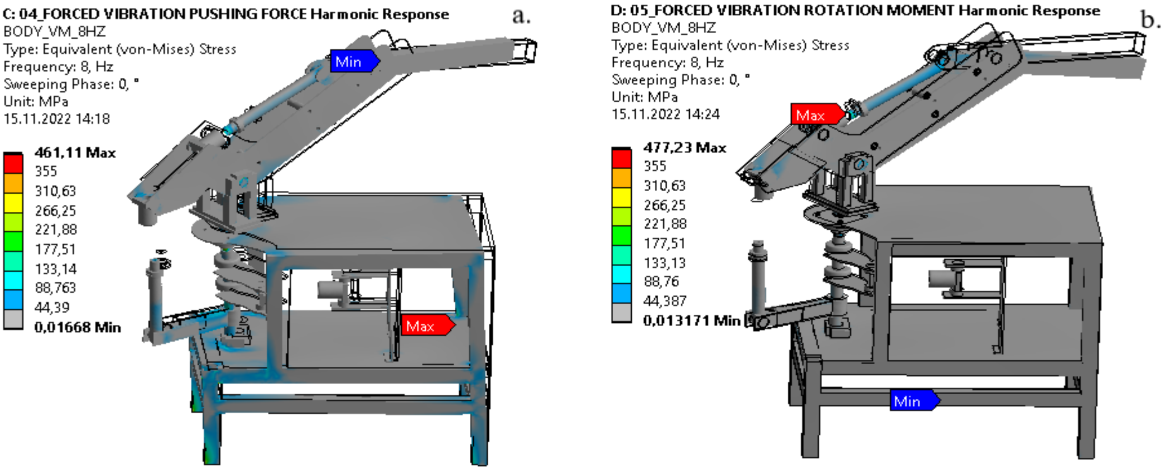


**Figure 11.** Body results of harmonic analysis a) linear, von-Mises stress (Mpa) b) rotational, von-Mises stress (Mpa)

In the forced vibration analysis of the system, the normal stress graph in linear movement and the normal stress graph in rotational movement are shown in Fig. 12. When the graphs are examined, in linear motion the maximum stress occurred at 100 Hz and the minimum stress at 35 Hz. In the rotational movement, the maximum stress occurred at 100 Hz and the minimum stress at 112.5 Hz. In addition, the normal stress amplitude has increased up to 6 MPa in linear movement and up to 6.3 MPa in rotational movement.

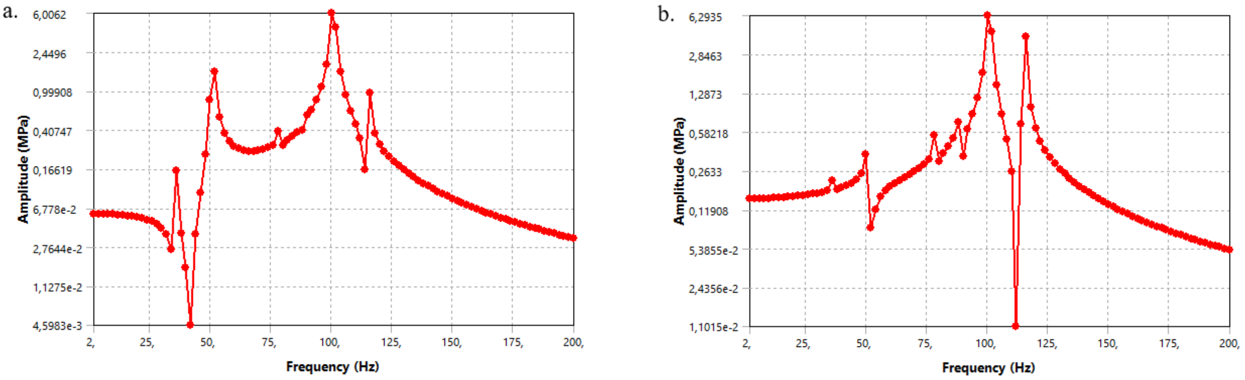


**Figure 12.** Graph of normal stress in a) linear movement and b) rotational movement

## 4. CONCLUSIONS

From past to present, the use of robots in developed industrial areas has gained importance day by day. The most important features of working robots in the industrial field have possessed the weight and the vibrations that have occurred at the endpoint. In robot arms used in industry, the parts used in drive and control should be chosen from quite light materials, since the weights of the parts are added to the weight on the previous arm. Since the size of the motors is increased in parallel with the magnitude of the force on the motor, the weight on each arm is also increased. In this study, the forces on the motors in the movements of the three axes industrial robot in two different drives and the torques created by these forces on the motor are examined. The robot is operated by applying torque to the rotation point of the arms with the linear force in the ball screw system. In the other system, it is also operated by applying a direct torque to the rotation point of the arms. The aim of this study is to determine which drive system is advantageous by comparing the torque created on the motor shaft by the forces falling on each motor in the linear drive system and the torque values applied to the rotation axis. In addition, the accelerations occurring at the endpoint of the robot during the operation of the motors in two different drive systems are measured, and the vibrations occurring at the endpoint of the system from these accelerations are compared.

As a result of the calculations, the torque value calculated for the 3rd motor in the drive system made with linear actuator was 0.4 Nm, while it was 75.78 Nm in the drive system made by applying rotation torque. The weight and cost of stepper motors increase in parallel with the torque they produce. The costs of the motors can be calculated by looking at the dimensions of the motors that must be used to meet these torques. In addition, as the dimensions of the engines increase, their weight will also increase, so the mass of the system and, accordingly, inertia will increase. As a result, it causes more weight on the system and increases its manufacturing cost.

As a result of the analyses, considering the torque on the motors and the vibrations at the endpoint, it is seen that the design created by applying linear force is more advantageous. In the modal analysis of the system, the natural frequencies and deformations occurring in 6 different modes and the resonance state of the stepper motors used in the robot arm at certain revolutions were examined. In addition, forced vibration and harmonic analysis of the system are made and total deformation, von Mises stress and normal stress graphs are obtained in each part and in all system. It has been calculated that this drive system can carry the same weight by applying approximately 1/20 of the torque value required to be applied according to the drive system used to move conventional robots. Thus, since the weights and costs of the motors will decrease at the same rate, the total weight of the robot arm, the weights of the arms forming each axis and the total cost will decrease.

## REFERENCES

[1] Ertuğrul Ş, Kaya O, Eraslan H, et al. Humanoid robot arm design, simulation, kinesthetic learning, impedance control and suggestions. Journal of the Faculty of Engineering and Architecture of Gazi University. Vol. 37, No. 2, pp. 1139-1154, 2022.

[2] Mehrpouya M, Dehghanghadikolaei A, Fotovvati B, et al. The potential of additive manufacturing in the smart factory industrial 4.0: A review. Applied Sciences. Vol. 9, No. 18, pp. 3865, 2019.

[3] Lu Y, Xu X and Wang L. Smart manufacturing process and system automation–a critical review of the standards and envisioned scenarios. Journal of Manufacturing Systems. Vol. *56*, pp. 312-325, 2020.

[4] Almurib HA, Al-Qrimli HF and Kumar N. A review of application industrial robotic design. In: 2011 Ninth International Conference on ICT and Knowledge Engineering. Bangkok, Thailand, 12-13 January 2012; pp. 105-112. IEEE.

[5] Evjemo LD, Gjerstad T, Grøtli EI, et al. Trends in smart manufacturing: Role of humans and industrial robots in smart factories. Current Robotics Reports. Vol. 1, No. 2, pp. 35-41, 2020.

[6] Hedelind M. and Jackson M. "How to improve the use of industrial robots in lean manufacturing systems", Journal of Manufacturing Technology Management. Vol. 22, No. 7, pp. 891-905, 2011.

[7] Acharya V, Sharma SK and Gupta SK. Analyzing the factors in industrial automation using analytic hierarchy process. Computers & Electrical Engineering. Vol. 71, pp. 877-886, 2018.

[8] Pan Z, Polden J, Larkin N, et al. Recent progress on programming methods for industrial robots. Robotics and Computer-Integrated Manufacturing. Vol. 28, No. 2, pp. 87-94, 2012.

[9] Bal HÇ and Erkan Ç. Industry 4.0 and competitiveness. Procedia computer science. Vol. 158, pp. 625-631, 2019.

[10] Li Z, Li S and Luo X. An overview of calibration technology of industrial robots. IEEE/CAA Journal of Automatica Sinica. Vol. 8, No. 1, pp. 23-36, 2021.

[11] Tezel C, Günay O and Kayisli K. Implementation of a Robot Hand Controlled with Android Software. International Journal of Engineering Science and Application. Vol. 1, No. 4, pp. 137-141, 2017.

[12] Luo X, Liu S, Xu M, et al. On research progress and development trend for motion control problems of industrial robots. In: 2018 8th International Conference on Manufacturing Science and Engineering (ICMSE 2018). Shenzhen, China, 30-31 March 2018, pp. 241-246. Atlantis Press.

[13] 13. Garcia E, Jimenez MA, De Santos PG, et al. The evolution of robotics research. IEEE Robotics & Automation Magazine. Vol. 14, No. 1, pp. 90-103, 2017.

[14] Swevers J, Verdonck W and De Schutter J. Dynamic model identification for industrial robots. IEEE control systems magazine. Vol. 27, No. 5, pp. 58-71, 2007.

[15] Tsitsimpelis I, Taylor CJ, Lennox B, et al. A review of ground-based robotic systems for the characterization of nuclear environments. Progress in nuclear energy. Vol. 111, pp. 109-124, 2019.

[16] Pogliani M, Quarta D, Polino M, et al. Security of controlled manufacturing systems in the connected factory: the case of industrial robots. J Comput Virol Hack Tech. Vol. 15, pp. 161–175, 2019.

[17] Lu Z, Chauhan A, Silva F, et al. A brief survey of commercial robotic arms for research on manipulation. In: 2012 IEEE Symposium on Robotics and Applications (ISRA). Kuala Lumpur, Malaysia, 3-5 June 2012. pp. 986-991. IEEE.

[18] Ayyıldız M and Aşkar Ayyıldız E. Accuracy and Repeatability Performance of Prototype Linear Delta Robot. Duzce University Journal of Science and Technology. Vol. 8, No. 1, pp. 869-879, 2020.

[19] Almurib HA, Al-Qrimli HF and Kumar N. A review of application industrial robotic design. In: 2011 Ninth International Conference on ICT and Knowledge Engineering. Bangkok, Thailand,12-13 January 2012. pp. 105-112. IEEE.

[20] Ehsani M, Gao Y and Gay S. Characterization of electric motor drives for traction applications. In: Proceedings of the IECON'03: 29th annual conference of the IEEE industrial electronics society (IEEE Cat. No. 03CH37468). Roanoke, VA, 2–6 November 2003, pp.891–896. New York: IEEE.

[21] Madden JDW. Mobile robots: motor challenges and materials solutions. Science. Vol. 318, pp. 1094–1097, 2007.

[22] Liang W, Liu H, Wang K, et al. Comparative study of robotic artificial actuators and biological muscle. Advances in Mechanical Engineering. Vol. 12, No. 6, pp. 1-25, 2020.

**[23]** Kapsalas CN, Sakellariou JS, Koustoumpardis PN, et al. An ARX-based method for the vibration control of flexible beams manipulated by industrial robots. Robotics and Computer-Integrated Manufacturing. Vol. 52, pp. 76-91, 2018.

**[24]** Thomsen DK, Søe-Knudsen R, Balling O, et al. Vibration control of industrial robot arms by multi-mode time-varying input shaping. Mechanism and Machine Theory. Vol. 155, pp. 1-32, 2021.

**[25]** Chang PH and Park HS. Time-varying input shaping technique applied to vibration reduction of an industrial robot. Control Engineering Practice. Vol. 13, No. 1, pp. 121-130, 2005.

**[26]** Mohamed Z, Chee AK, Hashim AM, et al. Techniques for vibration control of a flexible robot manipulator. Robotica. Vol. 24, No. 4, pp. 499-511, 2006.

**[27]** Dwivedy SK and Eberhard P. Dynamic analysis of flexible manipulators, a literature review. Mechanism and machine theory. Vol. 41, No. 7, pp. 749-777, 2006.

**[28]** Telli S and Kopmaz O. Two Different Methods to Investigate Dynamic Motion of Flexible Link That Rotates About Fixed Axes. Turkish Journal of Engineering and Environmental Sciences. Vol. 24, No. 3, pp. 127-134, 2000.

**[29]** Tso SK, Yang TW, Xu WL, et al. Vibration control for a flexible-link robot arm with deflection feedback. International journal of non-linear mechanics. Vol. 38, No.1, pp. 51-62, 2003.

**[30]** Garcia-Perez OA, Silva-Navarro G and Peza-Solis JF. Flexible-link robots with combined trajectory tracking and vibration control. Applied Mathematical Modelling. Vol. 70, pp. 285- 298, 2019.

**[31]** Sahu S, Choudhury BB and Biswal BB. A vibration analysis of a 6 axis industrial robot using FEA. Materials Today: Proceedings. Vol. 4, No. 2, pp. 2403-2410, 2017.

**[32]** Pham AD and Ahn HJ. High precision reducers for industrial robots driving 4th industrial revolution: state of arts, analysis, design, performance evaluation and perspective. International journal of precision engineering and manufacturing-green technology. Vol. 5, No. 4, pp. 519-533, 2018.

**[33]** Koç S and Doğan C. Manufacturing and controlling 5-axis ball screw driven industrial robot moving through G codes, Gümüşhane University Journal of Science and Technology. Vol. 12, No. 2, pp. 454-465, 2022.

**[34]** Raza K, Khan T and Abbas N. Kinematic analysis and geometrical improvement of an industrial robotic arm. Journal of King Saud University-Engineering Sciences. Vol. 30, No. 3, pp. 218-223, 2018.

## BIOGRAPHIES

**Savaş KOÇ** obtained his M.Sc degree in electrical Teaching from Firat University, Institute of Science and Technology and Ph.D degree in Mechanical Engineering from Harran University, Institute of Science and Technology. He is working as Assistant Professor at Department of Mechanical Engineering, Batman University. His main research fields are industrial robot and artificial intellegente..

**Idris ŞANİ** obtained his M.Sc. degree in Mechanical Engineering from Batman University, Institute of Science and Technology. He is working as Technician at Mardin Disaster and Emergency Management Presidency (AFAD).