DESIGN AND OPTIMIZATION OF HYDRAULIC ACTUATOR USED IN JET FIGHTER

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ABSTRACT

DESIGN AND OPTIMIZATION OF HYDRAULIC ACTUATOR USED IN JET FIGHTER

Actuators have been used in many areas from past to present. It is an indispensable equipment in the areas of use in today's technology. They are classified according to their usage areas and drive type. Depending on the type of drive, there are hydraulic, pneumatic and electrical actuators. It also has many uses: construction, manufacturing, automotive, robotics and aerospace industries. Hydraulic actuators are frequently used equipment in the aviation industry. In this thesis, the hydraulic actuator rod used in jet fighters was examined. This actuator is used to move the flight control surfaces in the jet fighter. So hydraulic actuator is vital for jet fighters. First, by conducting a literature search, boundary conditions and parameters were determined for actuator design and analysis. The design of rod was made using the determined parameters and the design parameters were analyzed using the finite element method. Neuro-regression approach was used to model a compact, lightweight and durable actuator. After regression analysis, many scenarios were created to optimize the mass and von Mises stress of the rod. The design and optimization of the hydraulic actuator rod were achieved by using Differential Evolution, Nelder-Mead, Random Search and Simulated Annealing algorithms. It has been concluded that the model and optimization algorithms are reliable and applicable to the problem.

ÖZET

JET UÇAĞINDA KULLANILAN HİDROLİK AKTÜATÖRÜN TASARIMI VE OPTİMİZASYONU

Aktüatörler geçmişten günümüze kadar birçok alanda kullanılmaktadır. Günümüzün teknolojisindeki kullanım alanlarında vazgeçilmez bir ekipmandır. Kullanım alanlarına ve tahrik çeşidine göre sınıflandırılmaktadır. Tahrik çeşidine göre hidrolik, pnömatik ve elektriksel aktüatörler bulunmaktadır. Ayrıca birçok kullanım alanı vardır: inşaat, üretim, otomotiv, robotik ve havacılık sektörleri. Hidrolik aktüatörler havacılık sektöründe sıkça kullanılan bir ekipmandır. Bu tezde jet uçaklarında uçuş kontrol için kullanılan hidrolik aktüatörün rotu incelenecektir. Bu aktüatör jet uçaklarında uçuş kontrol yüzeylerinin hareket ettirilmesinde kullanılmaktadır. Bu yüzden hidrolik aktüatör jet uçakları için hayati öneme sahiptir. İlk olarak literatür araştırılması yapılarak aktüatör tasarımı ve analizi yapılmak için sınır koşulları ve parametreler belirlendi. Belirlenen parametreleri kullanarak deney tasarımı yapılmış ve sonlu elemanlar metodu ile tasarım parametreleri analiz edilmiştir. Kompakt, hafif, dayanıklı bir bir eyleyicinin modellenmesi için Nöro-regresyon yaklaşımı kullanılmıştır. Regresyon analizi yapıldıktan sonra rodun ağırlığını ve von Mises gerilimini optimize etmek için birçok senaryo oluşturulmuştur. Hidrolik aktüatörün rodunun tasarımı ve optimizasyonu Diferansiyel Evrim (Gelişim), Nelder-Mead, Rastgele Arama ve Benzetilmiş Tavlama algoritmaları kullanılarak gerçekleştirilmiştir. Modelin ve optimizasyon algoritmalarının güvenilir ve probleme uygulanabilir olduğu sonucuna varılmıştır.

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CHAPTER 1

INTRODUCTION

In this section, information about actuators will be given. Detailed information about the hydraulic actuators to be examined in this study will be given and the objective of the thesis will be explained.

1.1. Actuator

Actuators are critical equipment used in areas such as engineering, automation and control of mechanical systems. Actuators have been at the forefront of technological developments and have been largely involved in shaping new developments and innovations. Actuators as catalytic agents have led to new developments in many areas of technology. Actuators initially began to develop as simple mechanisms. With the development of the industrial age and technology, actuators have developed hydraulically, pneumatically and electrically. These developments have led to increased efficiency and sensitivity in actuators. The results of the use of actuators combined with advanced control methodologies have ushered in a new era by expanding the boundaries in automation and robotics.[1,2,3]

In theory, actuators cover multiple areas and areas of work, supporting automation and precision control in general with unparalleled effectiveness, apart from the type of drive. It increases production by optimizing machines and processes by providing automation in the field of engineering. In this way, it helps to shorten the production time significantly. When we look at daily life, actuators are frequently present in our lives. For example, it is used in car brakes, transmission systems and steering systems. In addition, the use of the actuator in industry increases performance, efficiency and reliability in production.[2,4,5]

Actuators, in their simplest form, are mechanisms that convert hydraulic energy into mechanical energy to perform a certain task. Different actuators can be used in different industrial areas depending on their intended use. Electric actuators, one of the types of actuators, create linear or rotary motion using electrical energy. For example, solenoids, servo motors and stepper motors are electric actuators. Another type of actuator is the hydraulic actuator. These types of actuators create movement and force using pressurized fluid. Since these actuators can produce high force output, they are generally used in heavy industry. Pneumatic actuators work similar to hydraulic actuators. Pneumatic actuators use pressurized air to create movement. The main reasons for using pneumatic actuators are their simplicity and fast response time. Each actuator has distinct advantages and disadvantages. Therefore, it should be chosen to meet the requirements of the study area. Figure 1.1 shows different types of actuators.[4,6]

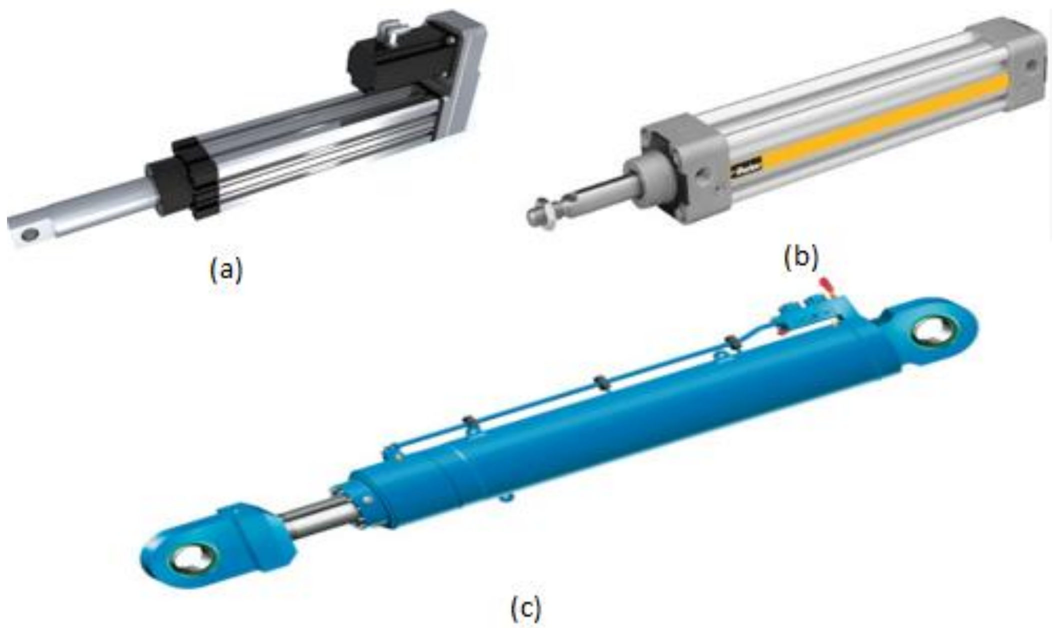


Figure 1.1. (a) Electrical, (b) Pneumatic and (c) Hydraulic Actuator
(Source: Ainla, A.et al[7], Byeong-Sang Kim et al[8])

Thanks to different mechanisms and technologies, actuators offer a wide range of applications for various usage requirements. Hydraulic actuators provide force output and performance suitable for heavy-duty applications and precise control requirements with the help of pressurized fluid. Actuators powered by compressed air are generally preferred for their fast response times and simple control algorithms. The reasons why electric actuators are preferred are that they provide precise silent operation and precise control.[10]

The importance of actuators in today's engineering is an undeniable fact. It serves as the basic building block that increases the productivity and efficiency of production, especially in industry, and also reduces the duration of production. In addition to industry, actuators are frequently used in robotics, transportation, medical fields and aviation. It is an example of how it is an indispensable equipment in defense systems by using it in critical missions such as flight control, weapon systems and landing gear in aviation[9].

In summary, actuators will be a frequent presence today and in the future. Undoubtedly, the biggest reasons for this are precise control, high force capacity and the ability to reach the desired speed. At the same time, with the development of technology, actuator types and places of use are increasing. It stands out with its use in aviation as well as in industry.[8,9,10]

1.2. Hydraulic Actuator

Hydraulic actuators have been used as a critical part of engineering application areas from past to present. Hydraulic actuators create mechanical movement using fluid pressure. Hydraulic actuators are indispensable in many applications by facilitating power generation. Using fundamental engineering disciplines, these actuators are efficient equipment for a variety of applications.[9]

Hydraulic actuators convert hydraulic energy into mechanical energy with the help of fluid pressure. The basis for this is Pascal's Law. With this law, the compressed liquid in a closed volume applies equal pressure to all parts of the volume. It includes cylinder, rod and control valves in a simple hydraulic actuator. Once all these parts are assembled, they are integrated into a hydraulic system. The movement and force requested from the actuator is made with the help of control valves.[9,11]

In the hydraulic system, the liquid pressurized with the help of a pump enters a chamber of the actuator with the help of a control valve and creates force on the rod in the desired direction. This is how hydraulic energy is converted into mechanical energy. At this point, Pascal's Law plays an important role because the pressurized fluid will exert force in all directions. This force can be an extension or retraction force, depending on which chamber of the actuator it enters.[11]

The force generated in the hydraulic actuator can be calculated using the pressure inside the actuator and the effective area of the rod. The resulting force is calculated with the following equation 1.1. It can be adjusted according to the application to be used by changing the hydraulic pressure and the area of the rod.[11]

$$F = P \times A \tag{1.1}$$

In equation 1.1, P represents fluid pressure and A is the piston's effective area.

Hydraulic control valves are used to provide and control movement. Directional control valves regulate the pressurized fluid coming from the hydraulic system and deliver it to the actuator's chamber. Control valves move to different positions so that the actuator can extend or retract. Additionally, control valves control the flow rate by changing the area through which the liquid can pass. In this way, it has the ability to manipulate the speed of the actuator.[10]

Hydraulic actuators can be produced in various configurations by adapting them to specific areas of use and requirements. The most commonly used type of hydraulic actuators are piston actuators that provide linear movement. In this type of actuator, the force occurs on the rod and the rod moves linearly in the cylinder. Another type of actuator is hydraulic motors that provide rotary movement. These actuators are often used in cranes and transport systems.[13] In Figure 1.2. it can be clearly shown parts of hydraulic actuator.

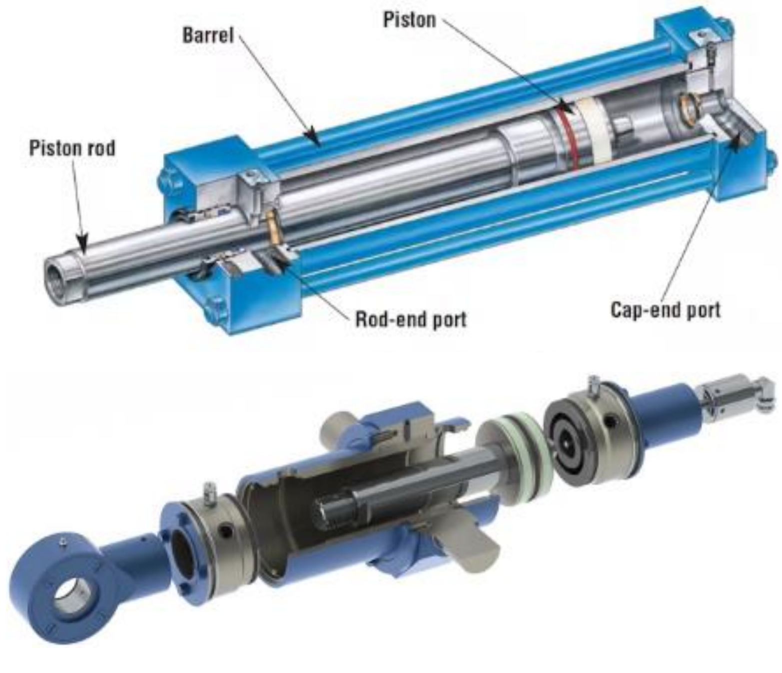


Figure 1.2. Section View of Hydraulic Actuator and Its Parts
(Source: Gomis-Bellmunt, O. et al[11])

Hydraulic actuators are preferred compared to other actuators due to their ability to produce high force, precise control, reliability and low maintenance costs. These actuators can be used in many areas of use. These areas of use are robotics, power transmission systems, industry, maritime, construction, automotive and aviation. The biggest reasons why it is suitable for different areas of use are its ability to work under high loads and its performance in motion control. In addition, the loss occurring when converting hydraulic energy into movement energy in hydraulic actuators is generally below 3%.[3,12]

Aviation, marine, automotive, production and construction sectors are the sectors that frequently use hydraulic actuators today. For example, in automotive applications, hydraulic actuators are used in braking systems, power transmission systems, active suspension, that is, applications where control and uninterrupted performance are required.[5,6]

In manufacturing and machinery, hydraulic systems are an essential equipment. Machines such as presses, injection molding and punchers work with the help of hydraulic actuators. The actuators used here support the system with high force. Because high force output is needed in situations such as metal pressing. In addition, Computer Numerical Control (CNC) increases production performance with precise control in shaping and cutting processes thanks to hydraulic actuators.[15]

Hydraulic actuators are used in cranes and excavators in construction and heavy industry. These machines perform digging, lifting and material handling operations. It is also used in vehicles such as dump trucks used in earthmoving works.[10]

Hydraulic actuator provides many benefits to the aviation and defense industry. In this industry, actuators are vital in landing gear and flight control surfaces. Likewise, in military vehicles, hydraulic actuators are used in weapon systems, power transmission and ensuring precise and responsive operation in challenging environments.[15]

In the automotive field, hydraulic actuators are integrated into brakes and power transmission systems. Today, these technologies are developed and used to provide easy and comfortable gear shifts in power transmission of transmissions and in driving support, increasing the performance of vehicles.[13]

The use of hydraulic actuators in the maritime field is similar to the aviation industry. In this sector, it is used for anchor handling, steering and opening cargo covers. It can also be used on cranes on the deck of ships.[11]

In the renewable energy sector, hydraulic actuators are used to control turbine blades and control valves in hydroelectric power plants and to regulate fluid flows. Additionally, hydraulic actuators are used in water treatment units and valve controls for piping systems to perform essential functions.[4,6]

It is widely used in tractors, which are an indispensable tool in the field of agriculture. In addition, it takes part in increasing productivity and competence in planting, irrigation and harvesting processes. Due to the versatility of hydraulic actuators and their ability to be shaped according to requirements, they can be used easily in various application areas. It simultaneously promotes innovation in engineering and technology.[9,13]

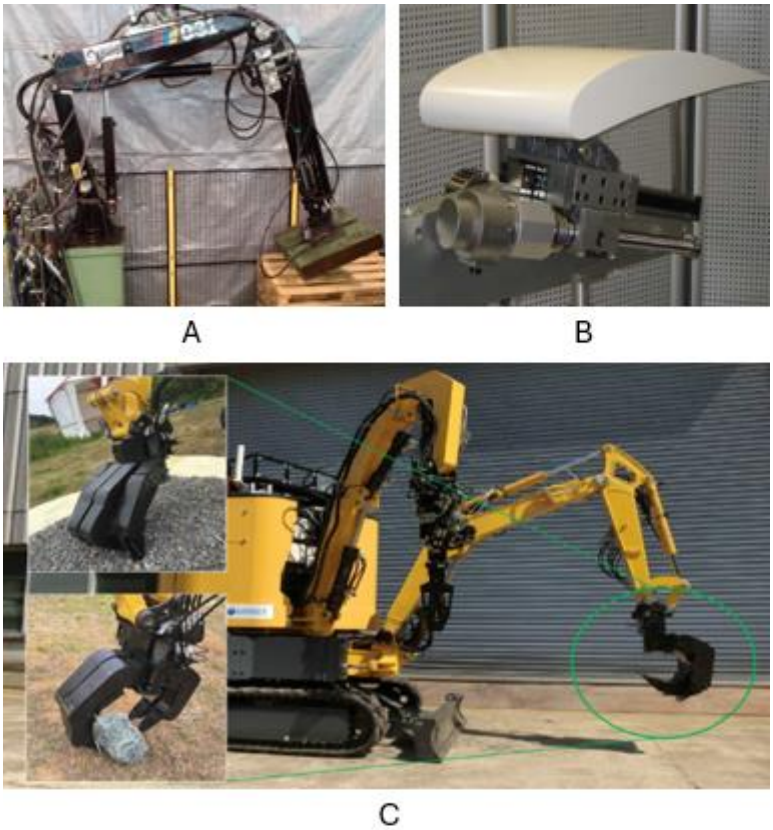


Figure 1.3. Hydraulic Actuator (A) Robotics, (B) Flight Control, (C) Construction (Source: Virtual Aircraft Technology Integration Platform[14])

In summary, the purpose of hydraulic actuators is to create mechanical force and movement using pressurized fluid. There are several types of hydraulic actuators. These actuators can be classified according to their intended use, desired speed and force. Hydraulic actuator types are listed below:

- Linear Actuators
- Rotary Actuators
- Telescopic Actuator

Hydraulic actuators are constantly developing according to usage demands and needs by taking advantage of today's technology. As actuators evolve, it pushes technology forward. As technology continues to advance in control systems, materials and design, the efficiency, reliability and therefore the usage areas of hydraulic actuators will continue to increase.[14]

1.3. Objectives of the Study

The primary features of tandem hydraulic actuators used in jet fighters include redundancy, high stall load capability, and reduced volume occupancy compared to simplex actuators. Through literature studies, it becomes evident that the rod of the actuator plays a pivotal role in imparting these properties to tandem hydraulic actuators. Structural modifications to the rod directly influence the performance of these actuators.[5]

In this thesis, the design, modeling and optimization of the rod of tandem hydraulic actuator for minimum mass and minimum von Mises stress were performed using Random Search (RS), Simulated Annealing (SA), Differential Evolution (DE) and Nelder-Mead (NM).

The objectives of this thesis are outlined as follows:

- To develop structural design parameters within limits and conditions by researching rod structural design development and effective optimization methods using computer programs.
- To determine the important parameters that affect the design and outputs and to create mathematical models between the outputs and design parameters during design.
- Simultaneously minimizing mass, von Mises stress values.
- Comparing the performance of rod designs under varying thickness and radius values using stochastic methods such as Random Search (RS), Simulated Annealing (SA), Differential Evolution (DE) and Nelder-Mead (NM).

CHAPTER 2

JET FIGHTER AND TANDEM HYDRAULIC ACTUATOR FOR FLIGHT CONTROL

In this section, the features of the tandem hydraulic actuator and its relationship with the jet fighter will be explained.

2.1. Hydraulic Actuator in Jet Fighter

In aviation applications such as jet fighters, the hydraulic actuator is vital for the aircraft to perform its functions. The importance of actuators cannot be ignored due to the flight control systems, weapon systems, landing gear and utility actuation they provide to jet fighters.[15]

The indispensable area of use of hydraulic actuators in jet fighters is undoubtedly the jet fighter's control surfaces. These actuators are responsible for carrying out the commands from the pilot. Incoming commands allow the jet fighter to maneuver by moving the control surfaces thanks to the actuator. In dog fight combat situations, the actuators' ability to execute the desired command and react quickly to withstand aerodynamic loads, also it provides to the jet fighter outmaneuvers the opponent and tactical superiority.[15]

Hydraulic actuators are of critical importance in the weapon systems installed on jet fighters. In weapon systems, actuators are used to open and close gun doors and bomb release applications. This actuator is preferred because it provides reliable and precise bomb release. In combat situations, a weapon system designed using hydraulic actuators is critical to successfully completing the jet fighter's mission.[15,16]

In addition, hydraulic actuators are indispensable equipment for the landing gear to perform its function. It facilitates landing gear's doors, retraction/extension of landing gears and steering. Thus, the jet fighter functions safely while taking off and landing. Additionally, using a hydraulic actuator in the landing gear system provides a damper effect to the system.[17]

Flight control surfaces using hydraulic actuators are shown in Figure 2.1. It lies in the ability of jet fighters to deliver precise control, reliable weapons deployment and safe landing operations. These competencies possessed by actuators are integral equipment that contributes to the general functions, mission and overall performance of jet fighters. In line with the demand for increased capabilities of jet fighters and the development of technology, hydraulic actuators will continue to be the basic equipment for jet fighters.

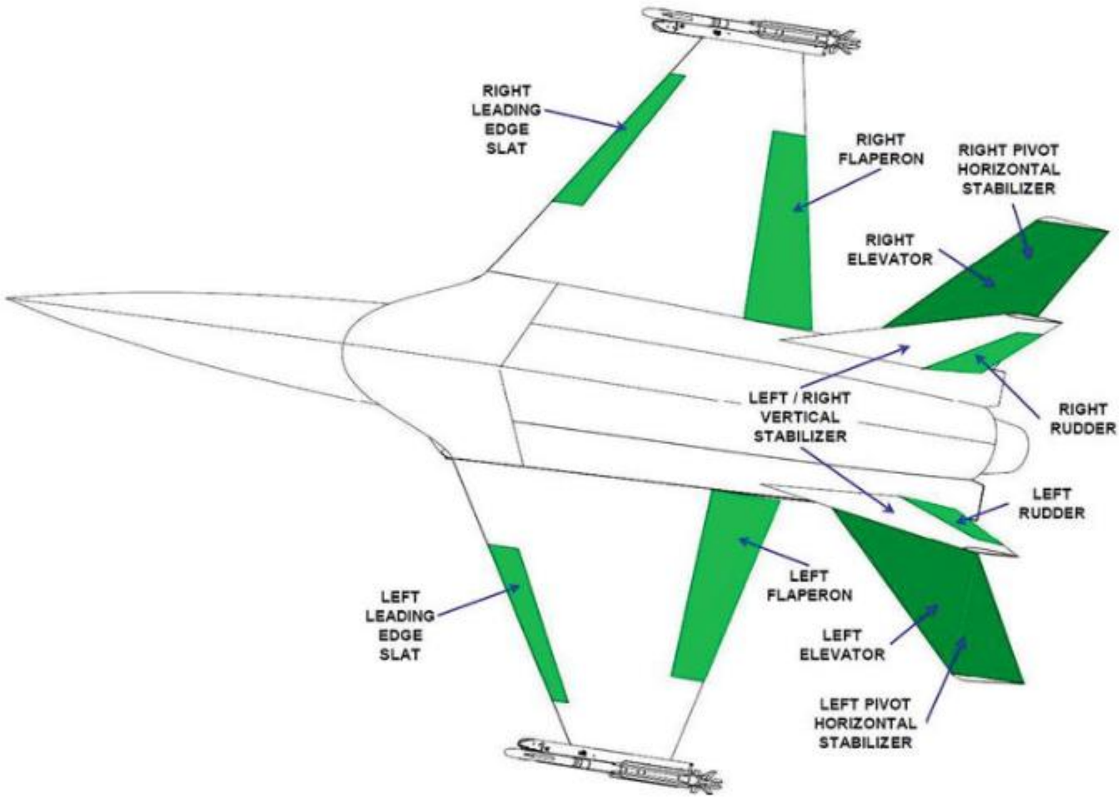


Figure 2.1. Flight Control Hydraulic Actuators in Jet Fighter
(Source: Chaudhuri, A. et al[18])

2.2. Component of Tandem Hydraulic Actuator: Rod

While the hydraulic actuator consists of many parts, as mentioned in the previous sections, one of the most important parts is the rod. Rod is a critical part for hydraulic actuator. It is generally a solid cylindrical shaft and made of stainless steel. Its main function is to withstand loads under operating conditions and is capable of enduring pressures. With the help of this rod, hydraulic energy is converted into force and movement. When the hydraulic fluid enters the actuator chamber, it creates pressure on the surface of the rod, causing the rod to move. In this way, the actuator performs retraction or extension movement according to the desired movement. While performing this movement, the diameter and length of the rod determine the speed of the actuator and the force it can resist. Such parameters are generally selected by calculating the system to meet its requirements and effective parameters are determined.[15]

Tandem hydraulic actuator consists of two cylinders connected in series. A solid rod is mounted on these cylinders. These cylinders are shown in Figure 2.2 and Figure 2.3. The cylinders are designed to work simultaneously to move the rod. In this way, the rod is driven in the same direction by both cylinders. As a result, high strength is obtained.[16]

As with other hydraulic actuators, the rods of tandem hydraulic actuators are used in steel or stainless steel depending on the operating conditions. Material selection is made according to the working pressure of the actuator and the force to which it will be exposed. Sealing elements are integrated around the rods to prevent oil leakage in the actuator. In such a hydraulic actuator, efficiency increases.[3]

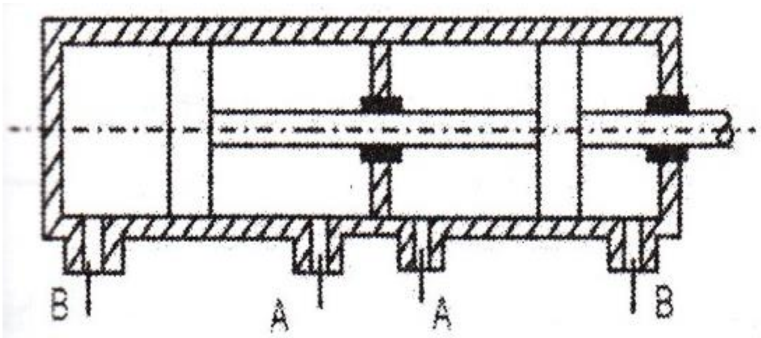


Figure 2.2. Tandem Hydraulic Actuator

(Source: Li, W. et al[17])

Tandem hydraulic actuators are key equipment to realize fast and reliable maneuvers in jet fighters. When combined with the control system, they provide the necessary power, precise and smooth movements to the control surfaces. They have evolved into a compact structure with technology. In this way, it easily meets the requirements of lightness and low volume, which are important criteria for a jet fighter. It contributes to the effective operation of the jet fighter due to its compact structure and to the flight dynamics due to its low weight.[4,15]

As a result, the rod of the tandem hydraulic actuator, which is shown in Figure 2.3, will be the subject of this thesis. The design parameters of the rod, its inner and outer diameter, wall thickness and rod length, vary depending on the requirements of the area where the actuator will be used. Therefore, optimization of the mentioned parameters is critical for the design phase.[4,20]

Figure 2.3. Example of Tandem Hydraulic Actuator

(Source: Aerospace Actuators 2[19])

CHAPTER 3

MODELING

A model is a simplified, reflective, abstract, and conceptual representation of a real-world system or event. In its broadest sense, modeling involves replicating reality and is described as the process of clarifying and understanding an unknown phenomenon by referencing existing information. In this section, the modeling methods used in this study will be explained.

3.1. Design of Experiment (DOE)

Design of experiment (DOE) is a method that efficiently and effectively investigates the cause and effect relationship between inputs and outputs. It is a proactive method that eliminates possible errors by calculating all situations in advance. The cornerstones of this method are replication, blocking and randomization. Replication tries to minimize errors and increase accuracy by repeating testing. Blocking is a method used to prevent the parameters that have the most impact on the result from being hidden. Randomization determines the order in which tests occur.[21]

The experimental design is based on two key parameters. These parameters are factor and level. Factors are input parameters that will affect the output. Level determines the limits of these factors. There are many different DOE methods such as Full Factorial, Randomized Complete Block, Fractional Factorial, Taguchi, Optimal Design (D-Optimal), and Box-Behnken. In this particular study, the D-optimal design method was selected.[22]

3.1.1. Full Factorial Design

Full factorial design takes into account two or more factors of a problem and their levels. This DOE method has been proven to give better results than calculation methods with a different factor each time. Randomization is integrated into Full Factorial Design to eliminate unknown and uncontrollable errors in experiments. It should be repeated three times in order for the results obtained to be analyzed statistically. In addition, this method is also used to find out which parameters affect the outputs.[23]

3.1.2. Randomized Complete Block Design

Randomized Complete Block Design measures one parameter in a test while taking other parameters into account. When examining one parameter, it is necessary to take into account whether the other parameter will have an effect. Testing is carried out by creating appropriate and consistent conditions to reduce the effect of other parameters on the examined values. Thus, errors are tried to be minimized. These suitable conditions are called "blocks" in experimental methodology. Since the created conditions are assigned randomly, this method is called Randomized Complete Block Design. This frequently used experimental design method allows statistical analysis of the results obtained by randomly creating experimental conditions. This leads to the examination of differences between parameters.[24]

Randomized Complete Block Design is preferred in many areas because it directly examines the effect of a parameter to be examined on its output. Additionally, optimizing conditions allows for fewer experiments. Despite its advantages, Randomized Complete Block Design limits the work as it does not have a practical use since it calculates all parameters in a single block. This disadvantage can be eliminated by using a method known as "incomplete random block layout".[24]

3.1.3. Fractional Factorial Design

In a full factorial experiment design, every possible combination of factors and factor levels that affect the result is tested. Since each combination is calculated, this method increases the cost of the tests and takes time to test. In cases where there is time and cost limitation, fractional factorial experimental design is applied, which allows proportional reduction in the number of experiments. This method can be conceptualized as a vertical row arrangement that allows the identification of significant effects while limiting the scope of the study.[25]

3.1.4. Taguchi Design

The purpose of Taguchi design is to reduce the effect of factors that affect the outputs but are outside the controlled factors by creating appropriate combinations during the design phase. Orthogonal arrays are used in Taguchi Design to create these combinations. This method is also called design matrices. While the forming matrices can be simple, they are developed in two or three stages depending on the complexity of the problem. This unique feature allows multiple factors to be tested using a minimum number of experiments while simultaneously varying factor levels.[26]

3.1.5. Optimal Design (D-Optimal)

D-optimal is a computer-aided design method. When developing a method, it complies with the standards, criteria or rules specified by the developer. Thanks to these guidelines, the results usually obtained represent a close approximation of the design that should be produced. Designs created using D-optimal operate as direct optimizations guided by model fit and optimization criteria determined at the beginning of the design. Factorials and fractional factorials, which are traditional methods, work without orthogonality, which is the method used in designs. This results in associated impact estimates.[27]

This DOE method has more advantages in terms of cost and time than other DOE methods. By focusing on specific conditions, fewer combinations occur and optimize time. It facilitates research by creating combinations of factors within themselves. It reduces the number of experiments by creating situations that have a greater impact on the outcome and ignoring those that have less impact. It has been proven advantageous to use the D-optimal method in the following problems:[27]

- When a limited number of design iterations are needed,
- When dealing with factor configurations,
- In the presence of unstable experimental structures,
- When incorporating both operational and mixing variables within the same design.

3.1.6. Box-Behnken Design

The Box-Behnken method was introduced by Box and Behnken in the 1980s. This method is an effective method for modeling second-order response surfaces. It uses incomplete block trials in modeling. For the factors that make up the model to produce effective results, each factor must have three levels.[28]

3.2. Regression Analysis

Regression analysis is a method used when modeling the relationships between variables. This method is a statistical method used to reveal the cause and effect relationship of two or more variables. The purpose of regression is to investigate how the independent variables of the problem affect the dependent variables. Regression is used in many fields such as science, engineering, economics, health sciences, and social sciences to explain and characterize interrelationships within data sets.[29]

In regression models, dependent and independent variables are generally defined as Y and X, respectively. If there is more than one independent variable in the system, it is expressed as (X_1, X_2, ..., X_n). Regression analyzes are also divided into headings. One of the different regression methods (simple linear regression, simple nonlinear regression, multiple linear regression and multiple nonlinear regression) adapted to the different structures of the data structures or the analytical needs of the system can be chosen to be applied.[29]

A classical regression study follows the following steps: collection of data, determination of the model to be applied, estimation of parameters, fitting the model to the system, verification and finally interpretation. Depending on the characteristics of the data set, it can be decided to use different techniques such as linear, polynomial, and time series regression.[29]

The whole purpose is to create a model that accurately captures variable relationships and supports informed decision-making and insight-based predictions. Regression analysis enables evidence-based decisions in various fields to be made by measuring the relationships between parameters.

3.2.1. Simple Linear Regression (SLR)

The method called simple linear regression is a statistical method widely used in scientific research and engineering applications. It is a frequently used method, especially in the field of mechanical design, to understand and model the effect of certain independent variables such as material properties and dimensions on dependent variables such as durability and deformation. For example, in a study examining the durability of steel materials, simple linear regression analysis can be used using tensile test results. Or it is a method that can be used to understand the relationship between the size of the structural material and the load applied to the material. These analyzes provide researchers with valuable information to make design decisions and optimize performance in projects.[30]

SLR; It is a basic statistical technique used to understand the relationship between a dependent variable (Y) and an independent variable (X). Its purpose is to model the relationship between parameters using the following equation:[29,30]

$$Y = \beta_0 + \beta_1 X \epsilon \tag{3.1}$$

where $\beta 0$ and $\beta 1$ are regression coefficients representing the intercept and slope of the line, and ϵ denotes the error term for variability. In this context, Y represents the dependent variable while X represents the independent variable. It is possible to use the terms response variable instead of dependent variable and explanatory variable instead of independent variable. $\beta 0$ directly gives the value of Y when the value of X is equal to zero. and reports the intersection of the regression line with the Y-axis. $\beta 1$ is the quantification of the change in Y per unit change of X. That is, it indicates the slope or rate of change of Y when X changes.

The main purpose of SLR is to estimate the coefficients that will fit the obtained regression line to the observed data points as much as possible. This fitting system involves the process of minimizing the sum of squares of the residuals. The residual represents the difference between the observed Y values and the values predicted by the regression model.[30]

Simple linear regression allows the effect of X on Y to be quantified and modelled. It expresses the relationship in a linear framework and gives the researcher the ability to interpret this relationship. It is a primary aid in hypothesis testing and parameter estimation.[30]

As a result, simple linear regression statistical methodology is an indispensable application. It analyzes the problem by establishing a linear relationship between inputs and outputs. It is used to support and verify empirical analysis in many fields of engineering and social sciences.

3.2.2. Simple Non-Linear Regression (SNLR)

Simple Non-linear regression (SNLR) is one of the statistical methods used to solve problems that have a nonlinear relationship between inputs and outputs. To explain with an example, it can be explained from mechanical engineering: the relationship between stress and strain of a part exposed to different loading conditions can be calculated with this method. Since the mechanical behavior and structural performance of the physical structures formed as in this study are nonlinear, they can be analyzed and predicted with this method.[31]

Applying this method allows us to obtain more logical results, unlike simple linear regression, because most problems have a nonlinear relationship between inputs and outputs. This relationship is expressed by equation 3.1. In this equation, an independent variable, X, and a dependent variable, Y, by making a non-linear equation: [31]

$$Y = f(X, \beta) + \epsilon \tag{3.2}$$

In the equation, Y represents the dependent variable. X is the representation of the independent variable. (X) in this equation represents a nonlinear function with parameters β. ϵ is the term in which possible errors are included in the system. The function can have various mathematical expressions such as exponential, polynomial, logarithmic or sigmoidal, depending on the nature of the relationships being modeled.

The purpose of SNLR is to calculate and statistically analyze the nonlinear relationship of factors to results. This method achieves more reliable and understandable results for complex problems.[31]

SNLR analyzes the problem and examines the effect of inputs on outputs nonlinearly to make it more understandable. Using this method in complex problems allows optimizing design parameters by providing more detailed information about the problem.

3.2.3. Multiple Linear Regression

The multiple linear regression method (MLR) is frequently used in engineering and social sciences. This regression technique is a technique used in engineering systems where multiple independent variables are simultaneously affected by a dependent variable. For example, it is used in engineering methods such as determining the operating life of an equipment. This method is an indispensable method that facilitates obtaining and optimizing information about a complex problem and making accurate and reliable decisions.[32]

In its use in the field of automotive engineering, this method is used to determine engine size, performance and aerodynamic parameters using multiple variables. MLR allows researchers or engineers to make an efficient and safe design in this field.[29,32]
In civil engineering, it is important to calculate the strength of structures such as buildings by taking into account the dimensions or environmental conditions along with the applied load conditions. Engineers use this method to predict the behavior of complex systems, optimizing the problem to meet desired requirements.[32]

Unlike simple linear regression analysis, which performs regression analysis with one input and one output, MLR expands the purpose of regression analysis and examines the effect of more than one input on an output. This relationship is explained in equation 3.4 :[32]

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_p X_p + \epsilon \quad (3.3)$$

In this kind of equation, Y represents the dependent variable, X_1,,…,Xp denote the independent variables, β_0, β_1, β_2,…, β_p are the regression coefficients, and ϵ is the term for error. The purpose of this system is to estimate the coefficients that best fit the given values by minimizing the discrepancies between the predicted and actual Y values[32,33]

To summarize, MLR examines the combined effect of multiple factors on the desired output. Creates insights into dynamic systems and complex problems. Thus, it optimizes problems and makes processes efficient and safe.[32]

3.2.4. Multiple Non-linear Regression

Multiple nonlinear regression (MNLR) is a common method used in engineering to identify complex relationships in problems. The purpose of the technique is to nonlinearly investigate the relationship between a dependent variable and more than one independent variable. This method is suitable for different areas of use due to its approach to the problem. It enables the complex interactions between different factors such as the properties of materials, dimensions, temperatures and loads to be understood and expressed mathematically.[33]

In MNLR, relationships are represented using non-linear functions of the form:[33]

$$Y = f(X_1, X_2, \ldots, X_p; \beta) + \epsilon \tag{3.4}$$

Here, Y denotes the dependent variable, and $X_1, , \ldots, Xp$ are independent variables, f is a non-linear function represented by β, and ϵ represents the error parameters. The purpose of this regression method is to optimize the fit of a nonlinear objective function to observed data and minimize estimation errors by estimating the β parameter.

MNLR is used to calculate and measure the relationship between multiple factors in an objective function. In this way, it helps in determining critical parameters by ensuring the optimization of the processes in the design. It improves design by facilitating the understanding of non-linear dynamic relationships in engineering and makes it easier to find innovative solutions.[33]

To summarize, MNLR is an advantageous statistical method used to investigate and model nonlinear relationships in engineering problems. This method is a suitable method for predicting the results of complex problems and supporting data-based decisions, with its versatility and adaptability to many fields. If this method is included in the research system, the depth and precision of the study increases.

3.3. Coefficient of Determination (R^2)

Coefficient of determination (R^2) is a unitless statistical parameter that tests the suitability of the resulting model to the problem. In other words, it can be expressed as the error rate among the test data of a regression model. The compatibility of the regression model obtained as a result of the studies with the independent variables and the change in the dependent variables is expressed as R^2. The values that Coefficient of determination (R^2) can take are between 0 and 1. The closer R^2 is to 1, the more compatible the data set is with the resulting regression model. If the value is high, it indicates that the independent variables are well integrated into the model. If R^2 is close to 0, the regression needs to be done again.[34]

However, whether the R^2 value is 1 or 0 does not mean that a fully compatible or incompatible regression is performed. External factors and model complexity affect the interpretation of R^2. In other words, it would not be correct to interpret the accuracy of the model by looking only at the R^2 value. The R^2 value gives information about the model's compatibility and predictive ability.[35]

In regression analysis, it gives information about the performance of the model by calculating the model data of the regression analysis with the R^2 value. It is used to ensure the applicability and interpretation of the regression model by using the R^2 value together with other methods.

To calculate R^2 (Coefficient of Determination), which is a statistical measure, the following steps are followed.[34]

To calculate R^2, follow these steps:

1. The total sum of squares (TSS) calculation is made): $TSS = \Sigma(Yi - \bar{Y})^2$. Here, the parameter Yi represents the value of the dependent variable for each observation. $\bar{Y}$ is the average value of the dependent variable.
2. Now the sum of squares (RSS) is calculated: $RSS = \Sigma(Yi - \hat{Y}i)^2$ While the parameter Yi represents the value of the dependent variable for each observation, as in the previous equation, $\bar{Y}$ is the value of the dependent variable predicted by the regression model.
3. In the last stage, the R^2 value is calculated using the parameters calculated in the first two stages: $R^2 = 1 - (RSS / TSS)$.

In this context:

- TSS represents the total variance around the mean of the dependent variable Yi. That is, it is a mathematical expression of the overall variability between different observations of the dependent variable.
- RSS is a mathematical expression of the agreement between the regression model and actual values. In other words, it reflects the total variance of the prediction errors in the regression model.

In summary, R^2 is expressed as the ratio of the variance of the independent variables to the total variance. A higher numerical value indicates that the regression model can describe the objective function better. R^2 is a very important parameter but using it with different methods will lead to the correct result.

3.4. Neuro Regression Approach

In this method, called Neuro Regression Approach, a hybrid technique was introduced that combines the strengths of regression and artificial neural network to increase the accuracy of predictions at the modeling stage. There are two main data in management, training data and test data. 80% of the data provided to the model is randomly selected as training data, and the remaining 20% becomes test data. The main reason for choosing percentage rates in this way is based on the principle of testing the realism of the model by testing the training data with test data within the presented limits. In this context, after obtaining a suitable model, the maximum and minimum values of the models are calculated within the available range for each design variable. After all the steps are implemented sequentially and carefully, the created model meets many of the criteria necessary for reality.[35]

CHAPTER 4

OPTIMIZATION

Optimization is essentially a complex mathematical process aimed at determining the optimal design. In this process, variables are defined under certain restrictions and the result is achieved by minimizing or maximizing the determined function. The essence of this entire optimization system lies in correctly determining the input values required to obtain the correct outputs. However, finding the solution to the specified problem does not guarantee that the most accurate results will be obtained. The main factor that enables the most advantageous solution to emerge here is the correct use of optimization techniques. The main purpose of engineering is to solve any problem in the most appropriate way, regardless of its complexity level. In the field of engineering, optimization is used to find the most appropriate solutions to problems involving many parameters such as displacement, mass, strength, time and hardness.[35]

Mathematical modeling and analysis are two essential elements of the optimization process. Mathematical modeling is the mathematical expression of the structural features of events in the real world. Analysis is the evaluation of the connection between this mathematical model and reality. This systematic approach to optimization facilitates the interpretation and implementation of the variables in the design and the functions created.[36]

Optimization is a customizable concept that relates to any situation demanded by the problem at hand. If there is a situation where the parameters are restricted, it is called a constrained model. If there is no restriction, it is called an unconstrained model. This unconstrained model gives optimum parameters of problem within predefined conditions. Additionally, optimization problems can be divided into two types, whether the parameters have continuous or discrete values. Whether a created model is time-dependent or not allows that model to be called a static or dynamic model. Additionally, problems subject to optimization can be classified as single or multi-objective depending on the desired results. Single objective optimization means that it optimizes problem according to an output of the problem. Multi-objective optimization optimizes the problem inputs with respect to 2 or more outputs of the problem[35,36]

4.1. Single Objective Optimization

In engineering challenges, after establishing the mathematical framework, determining the parameters that enable the most appropriate result for the specified design is known as single-objective optimization. More simply put, when the goal is the optimization of a single-objective function, this falls within the domain of single-objective optimization. This methodology includes consideration of design variables and function, constraints and all boundaries. General mathematical definition:[35,37]

$$\text{Find } X = \begin{Bmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ x_n \end{Bmatrix} \text{ which minimizes f(x)} \qquad (4.1)$$

depending on the conditions,

$$g_j\ (X) \leq\ 0 \qquad j =\ 1,2, \ldots, m \qquad (4.1)$$

$$h_j\ (X) =\ 0 \qquad k =\ 1,2 \ldots., k \qquad (4.3)$$

In this context, the target parameter of the optimization is called the objective function (f(x)). The parameters that specify the physical or functional properties involved in the design phase of this function are called (x). Predetermined limit values for these parameters are shown as (gi(x) and hj(x)). The optimization problem summarized above is a minimization problem, but it is possible to turn this problem into a maximization problem by changing the sign of the function.

4.2. Multi Objective Optimization

A common approach in many engineering problems is to optimize multiple objectives simultaneously. This approach is found in the literature as multi-objective optimization. Some real-life examples can be seen as balancing the lightness and stiffness required while designing springs, or the need to consider load along with fuel economy and payload in vehicle design. In many cases, the desired properties of the function conflict with each other and cannot result in a single solution that satisfies all requirements simultaneously. In order to solve such multi-objective problems, it is possible to transform them into single-objective problems with weighted linear functions. However, during such a transformation, determining the weights of the objectives is of great importance. Using algorithms designed for single-objective optimizations without determining the correct weights will result in the solution space not being fully explored. This causes optimization to not be fully realized. In the multi-objective optimization process, it is aimed to optimize all objectives at the same time, but if all objectives do not reach the optimum value at the same time, finding a single correct result becomes challenging. For this reason, the scalar best point concept, which is widely used for single-objective optimization, cannot be considered a valid concept for multi-objective optimization.[38]

Multi-objective optimization involves multiple objective functions that need to be minimized or maximized. Similar to single objective functions, such problems generally aim to optimize adaptive and feasible work. The general form of multi-objective optimizations is stated below:[35]

$$\text{Find } X = \begin{Bmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ \\ x_n \end{Bmatrix} \text{ which minimizes } f_1(x), f_2(x), \ldots, f_r(x) \qquad (4.4)$$

depending on the conditions,

$$g_j\,(X) \leq 0 \quad j = 1,2,\ldots,m \qquad (4.5)$$

$$h_j\,(X) = 0 \quad k = 1,2\ldots.,k \qquad (4.6)$$

A solution x represents a set of decision variables, denoted as $x = (x_1, x_2, \ldots, x_n)^T$. The solutions that meet constraints and variable limits form a decision variable space S, also known as the decision space. The biggest difference between single-objective and multi-objective optimization is that a multidimensional solution set is created in multi-objective optimization. This additional space is referred to as the objective space. For every solution x in the decision variable space, there corresponds a point in the objective space, indicated as $f(x) = z = (z_1, z_2, \dots, z_M)$. This mapping occurs between an n-dimensional solution vector and an m-dimensional objective vector".[35,38]

In reality, most research and optimization processes have more than one parameter to consider. Searching for the most appropriate solution for a single objective is not sufficient in such problems because other objectives are also important for solving the problem. Multiple objectives can result in a type of trade-off optimal solutions, also called pareto-optimal solutions. This solution type actually enables a compromise between conflicting objects. And in the optimization process, providing the best value for one objective generally results in a performance sacrifice for the other objective. Solutions in this type of multi-objective optimization types are generally examined under two main headings:[35]

1. Identifying a set of solutions that approximate Pareto-optimal solutions.
2. Determining a set of solutions that can represent all elements of the Pareto-optimal front.

4.3. Deterministic and Stochastic Optimization

Deterministic and stochastic types of optimizations are two basic methodologies, each representing different characteristics and practical applications.

This method, called deterministic optimization, is used to find the best possible solution to a given problem set, taking into account fixed and precisely known inputs and constraints. Similar to other methods, the method works to find the most appropriate solution that gives the maximum or minimum value for a particular objective, taking into account all defined constraints. The most commonly used techniques during the implementation of this method are linear programming, integer programming and dynamic programming. These methods become ideal methods for data-based decision-making with well-defined parameters in scenarios where there is no uncertainty or randomness.[35,39]

In contrast to the first method, stochastic optimization is preferred to cope with difficulties in environments where randomness or randomness exists in the input parameters. Apart from deterministic optimization, which has some limits and considers some parameters as constant, it also deals with probabilistic distributions and probability scenarios among the parameters. The aim of this method is to provide satisfactory performance in various probabilistic realizations of undetermined parameters and to achieve realistic results. Stochastic optimization strategies enable modeling the probabilistic distributions of uncertainties and integrating this uncertainty into the function throughout the optimization process. In the field of stochastic programming, it is possible to use techniques such as Monte Carlo simulation and evolutionary algorithms. It is a particularly valuable technique for decision-making in finance, supply chain or engineering fields where uncertainties are high and outcomes remain uncertain.[35]

Basically, while deterministic optimization focuses on finding optimal solutions in environments with known and fixed parameters, stochastic optimization is a method that can provide satisfactory performances in environments with problems or potential scenarios with random parameters. Both methods are very powerful methods when used under appropriate conditions and are used in many different areas to address optimization challenges in a wide variety of areas. As a matter of fact, Genetic Algorithm (GA), Simulated Annealing (SA), Random Search (RS), Differential Evolution (DE), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Tabu Search (TS), Artificial Bee Colony (ABC), Markov Chain Monte Carlo (MCMC), Harmony Search (HS), Covariance Matrix Adaptation (CMA) and Grenade Explosion Method (GEM) are considered stochastic optimization techniques. Using biological, mathematical and physical principles as a basis, these methods are used as powerful tools to solve optimization challenges in many fields. Researchers have improved these optimization methods over time and introduced new optimization variations to the scientific world that allow more efficient results to be obtained. Continuing with developments, these optimization methods have become improved, scalable and suitable research methods for different types of problems.[35]

4.3.1. Random Search

The process called random search optimization is applied to find the best solution within a specific search space, a method used in multiple fields such as statistics and engineering. Unlike systematic approaches that follow predetermined paths, random searches perform operations by randomly selecting configurations or points in space. In other words, it means that different points in space are investigated without adhering to any set pattern. Each of these different points compares how compatible the solution is with the desired result against the established objective function. This is a completely iterative process and continues until a satisfactory result is achieved.[35]

The most advantageous aspect of this method is that it is simple and easily applicable. Since it does not have a complex mathematical basis, it is a method that does not require specific knowledge and thus can be easily applied at many different points. In addition, random search is especially useful in scenarios involving high-dimensional search spaces or non-convex functions where traditional methods cannot be practically used. It is a very useful tool in discovering promising regions in cases where systematic approaches may be overlooked by randomly exploring the search area.[35,40]

However, random search also has certain limits. Since the points are chosen randomly, it does not guarantee convergence to a global optimum value in irregular or multimodal search spaces. Additionally, it may require more computational effort than other methods. Especially in multidimensional spaces, it often requires a large number of samples to find the desired correct solution. However, despite these disadvantages, random search is often used as a baseline in optimization. Or, to increase performance and robustness, maximum benefit is tried to be achieved by combining techniques such as gradient descent or genetic algorithms as shown in Figure 4.1. The fact that it has a simple structure and is managed with a versatile structure enables it to be widely used in solving problems that require optimization.[35]

4.3.2. Simulated Annealing

Simulated annealing (SA) method is considered one of the most effective versatile optimization algorithms among stochastic approaches. It is a proven fact that this method is very useful in determining the global minimum values of functions containing a significant number of independent variables. The simulated annealing method exploits the analogy between physical annealing and the search for minimum function values through mixed integer, discrete, or continuous minimization. In condensed matter physics, this process is seen as the expression of a thermal phenomenon in which a solid in a heat bath aims to reach low energy states.[35]

At the heart of the simulated annealing system is the use of random search within the framework of a Markov chain. All changes that improve the main objective function are adopted with the preservation of certain non-ideal arrangements. At each iteration in the SA algorithm, a new point is randomly generated, and the algorithm run is terminated upon the satisfaction of any predetermined stopping criteria. An example can be seen in Figure 4.2. The extent of searches and the distance between the new result point and the old result point are scaled according to temperature and obey the Boltzmann probability distribution.

The Boltzmann Probability Distribution is formally expressed as:[35]

$$P(E) = e^{-E/kT} \tag{4.7}$$

In the equation, the P(E) represents the probability of achieving the energy level (E), K represents the constant of Boltzmann and T represents the temperature of environment.

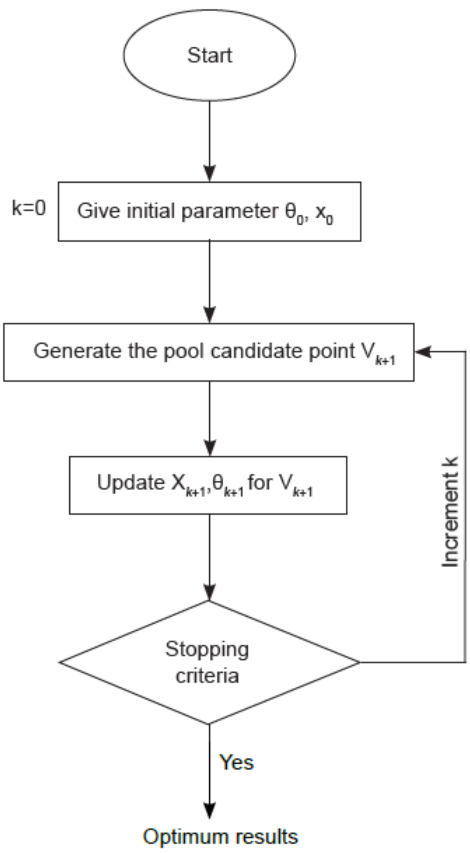


Figure 4.1. Flowchart of Random Search
(Source: Aydin, L.et al[35])

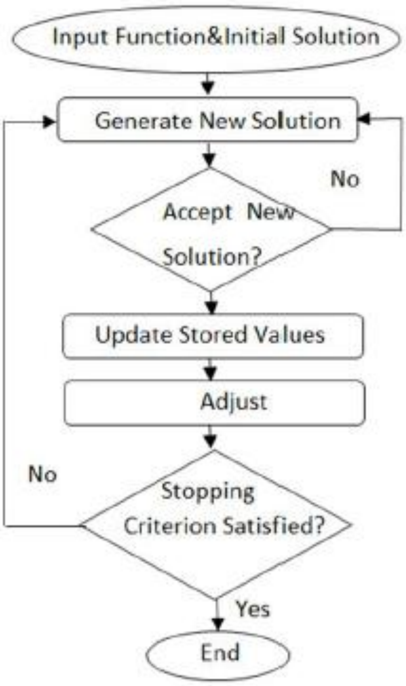


Figure 4.2. Flowchart of Simulated Annealing
(Source: Aydin, L.et al[35])

4.3.3. Differential Evolution

The differential evolution (DE) algorithm was proposed by Price and Storn in 1995. This algorithm is considered a versatile meta-heuristic approach characterized by versatile variables. It is a population-based approach and is based on genetic algorithms. Due to its operational framework, it is included in the literature as an important tool in the optimization of problems involving continuous data. It is traditionally used in scenarios involving continuous variables, but it can also be applied in scenarios involving discrete or hybrid continuous-discrete variables. In the areas of problems where DE is used, objective functions are prioritized over fitness functions and generally include alternative solutions.[35,42]

DE works without restrictions, more precisely, it is suitable for solving problems where these restrictions are embedded in the objective function. Compared to other alternative algorithms, this method stands out as a very tough competitor compared to other methods where real parameters are optimized. There are three basic control parameters that are essential for the correct functioning of this method: differentiation/mutation constant, crossover constant, and population size. Other control parameters that can be considered complementary include: (i) the size of the problem, which defines the level of complexity of the optimization situation, (ii) the maximum number of cycles set as stopping criteria during the iteration, and (iii) boundary constraints. The universal order shaped by all of these parameters aims to reach the optimal result by continuing until the stopping criterion.[35]

Figure 4.3 depicts a flowchart outlining the procedural steps of the DE algorithm.

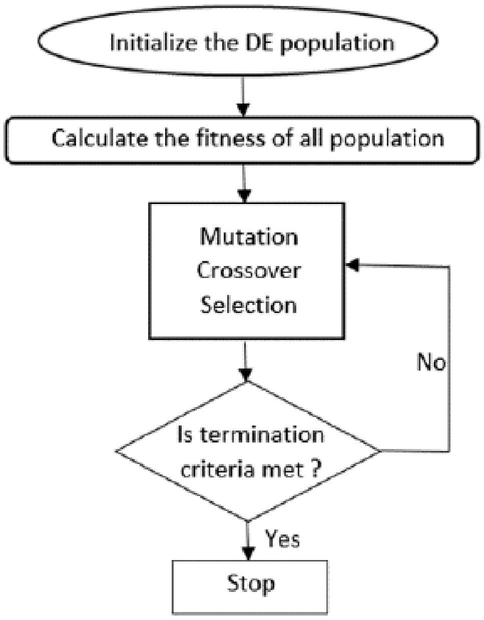


Figure 4.3. Flowchart of Differential Evolution
(Source: Aydin, L.et al[35])

4.3.4. Nelder Mead

Nelder-Mead optimization is also an iterative method, another name is the simplex method. It is a tool used when finding the minimum or maximum value of an objective function in a multidimensional space. Introduced to the literature by John Nelder and Roger Mead in 1965, this method is a method in which functions are optimized without relying on gradient information. For this reason, it is simple, but despite its simplicity, it is accepted for its effectiveness. These features make the method suitable for use in scenarios where the objective function is not linear or convex, such as engineering, economics, or machine learning, where derivatives are not involved.[35]

A simplex can be named in many different ways, such as a geometric shape resembling a triangle in two dimensions or a tetrahedron in three dimensions. The algorithm works by creating a simplex iteration within the search space. In each iteration, the algorithm evaluates the objective function at the vertices of the simplex and updates the simplex according to the result of the evaluation. These updates may include reflection, expansion, contraction, or collapse. These moves are decided entirely by taking into account the values at the simplex's vertices.[43]

The initially created simplex can be thought of as a set of points in the search space. The initial occurrence is set by more random methods. As successive iterations are created, the simplex evolves to approach the maximum or minimum in the objective function as desired. In other words, this algorithm decides the behavior of the objective function according to the given simplex and lengthens, thins, enlarges or changes the shape of the simplex to fit the objective function. This makes it possible to scan results in complex shapes and planes.[35,43]

Despite all these advantages, the Nelder-Mead method also has certain limitations. In high-dimensional space planes, if the objective function has narrow valleys or a very flat structure, it may be very slow to approach accurate results for these regions. Two important criteria that determine performance are sensitive to the choice of starting points and other parameters. With all its positive and negative aspects, with optimal consideration of all factors involved in the objective function, Nelder-Mead remains a widely used optimization technique thanks to its simplicity, versatility and effectiveness. Figure 4.4 explains the algorithm.[35]

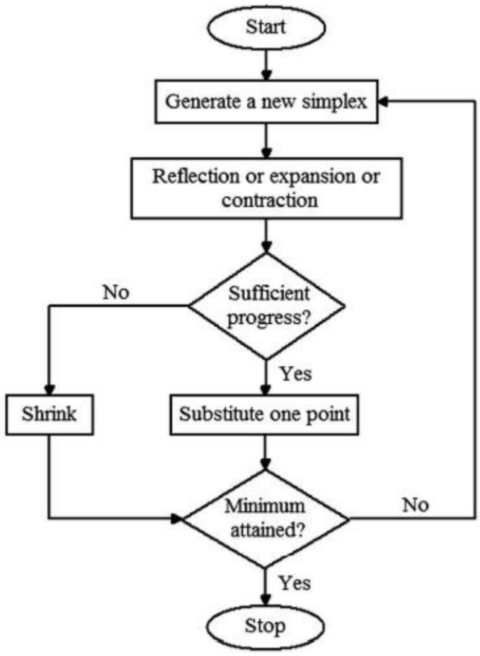


Figure 4.4. Flowchart of Nelder-Mead

(Source: Aydin, L.et al[35])

CHAPTER 5

RESULT AND DISCUSSION

This section includes the problem definition, regression modeling results and optimization results.

5.1. Problem Definition

The tandem hydraulic actuator design used in the flight control system of jet fighter aircraft is discussed. The design, modeling and optimization of the rod, which is one of the most important parts of the tandem hydraulic actuator, is subjected to tension and compression loads when the jet fighter is in operation, buckling analysis was investigated. It provides to the system redundancy and higher force.[15]

In this thesis, the actuator should meet force of 55.6 kN of both pushing and retractive force[45]. The physical parameters, material and operating conditions of the equipment required for the research were taken from the literature. Figure 5.1 show where the forces and pressures act on the rod.

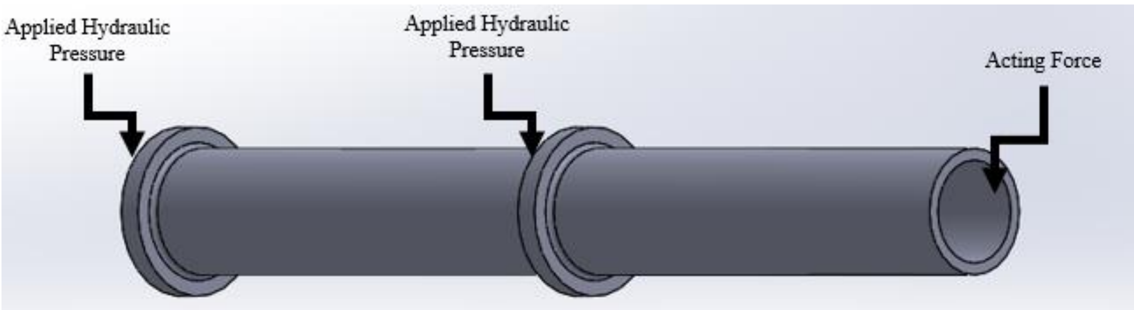


Figure 5.1. Illustration of Acting Force and Hydraulic Pressure on the Rod

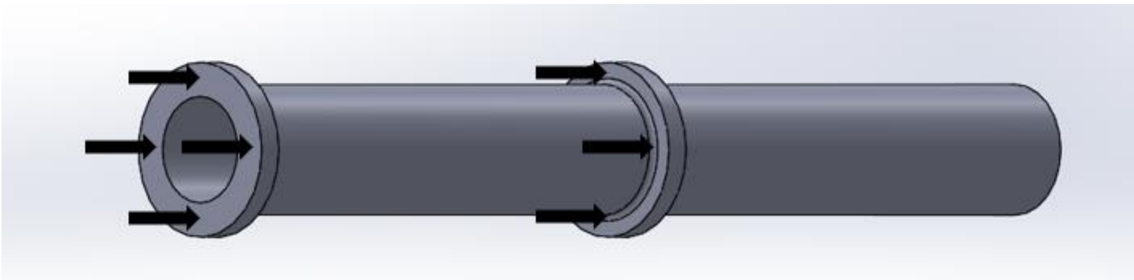


Figure 5.2. Applied Hydraulic Pressure on the Rod

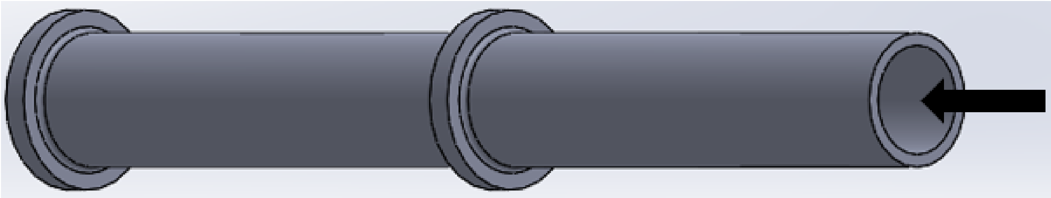


Figure 5.3. Applied Force on the Rod

As a result of the literature research, it was concluded that the force resisted by the rod designed for hydraulic tandem actuators must resist can take values in the range of 40-300 kN.[46]. Parameters of hydraulic tandem actuator rod are indicated in Figure 5.4.

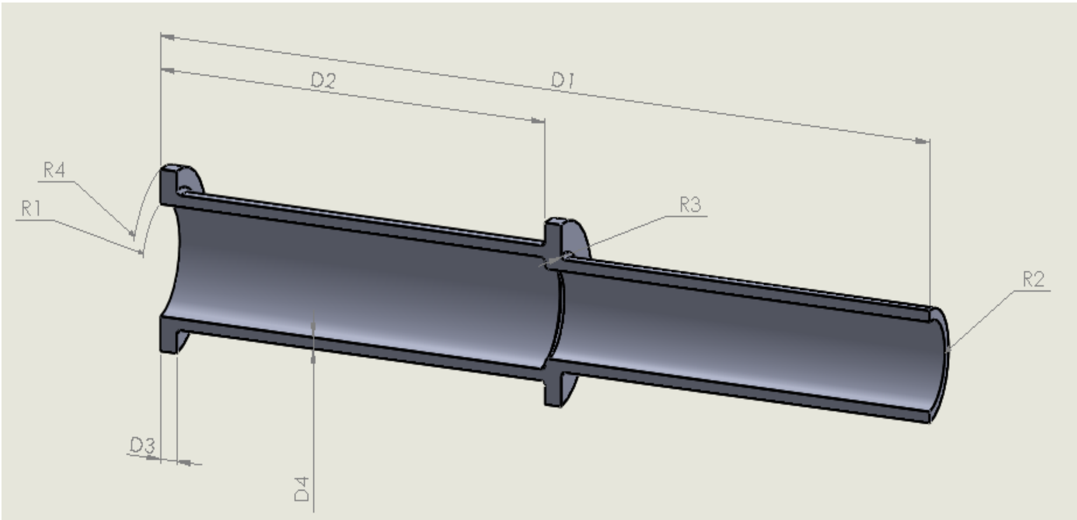


Figure 5.4. Rod of Hydraulic Tandem Actuators Parameters

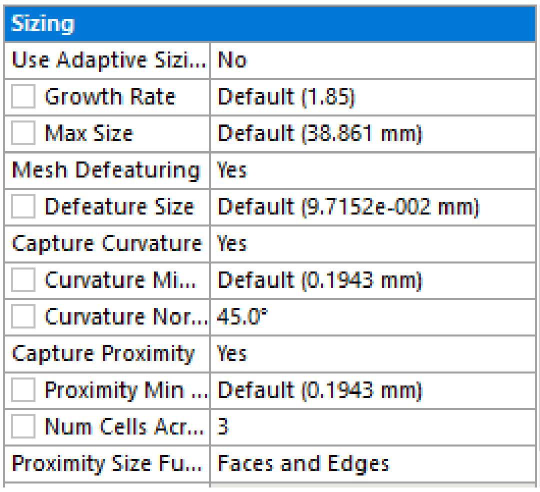
To find the minimum buckling stress value for the rod, the radius R1 varied from 12.7 to 38.1 mm with an increment of 8.45 mm, radius R2 varied from 15 to 20 mm with a decrement of 1.25 mm and dimension D4 varied from 2 to 5 mm with a decrement of 1 mm. In order not to change the designed geometry, R4 values were changed with R1 to keep constant tail stock area, while D1, D2, D3 and R3 values were kept constant.

Rod material was selected as 17-4PH, an alloy of primarily tooling steel and stainless steel, in which stainless steel is for corrosion resistance and tool steel is mainly for machining and hardening. 17-4PH mechanical properties are given in Table 5.2. It is always preferable to build these parts from the material that come from the same batch[47]. This is to avoid any danger of corrosion due to internal electrolysis. These parts will be harder than any potential contaminants to have less chances of radial clearance increment due to wear, which ultimately increases the leakage as discussed in previous section.[47]

Table 5. 1. Mechanical Properties of AISI 410

Elastic Modulus	200 GPa
Shear Modulus	83.9 GPa
Ultimate Tensile Strength	1100 MPa
Yield Strength	1000 MPa
Poisson's Ratio	0.28
Density	7800 kg/m^3

Meshing holds significant importance in finite element analysis. The process involves dividing the design into smaller parts called elements, where the number of elements, their shapes, and the number of nodes greatly influence the analysis outcome. Consequently, meshing is a critical step to consider in finite element modeling. In this study, the rod's meshing was conducted using the "automatic method" in ANSYS, employing "mesh defeaturing" and "capture curvature" within the sizing tool. Mesh parameters are shown in Figure 5.5.



Sizing	
Use Adaptive Sizi...	No
Growth Rate	Default (1.85)
Max Size	Default (38.861 mm)
Mesh Defeaturing	Yes
Defeature Size	Default (9.7152e-002 mm)
Capture Curvature	Yes
Curvature Mi...	Default (0.1943 mm)
Curvature Nor...	45.0°
Capture Proximity	Yes
Proximity Min ...	Default (0.1943 mm)
Num Cells Acr...	3
Proximity Size Fu...	Faces and Edges

Figure 5.5. Meshing Parameters

Additionally, quality control for meshing was performed prior to analysis, considering skewness and orthogonal quality criteria. Lower skewness values, ranging from 0 to 1 and indicating the ratio between the current and optimal mesh structures, signify better mesh quality. Orthogonal quality, another determinant of mesh quality, is calculated using vector mechanics, where a value of 0 represents the worst and 1 the best quality. Furthermore, element quality serves as an indicator of overall mesh structure, with values closer to 1 denoting better mesh quality[48]. Upon completion of the meshing process, the skewness, orthogonal quality, and element quality values for the design were determined to be 0.228, 0.768, and 0.837, respectively, based on the criteria. Moreover, Figure 5.6, Figure 5.7 and Figure 5.8 visually depict these metrics, which serve as benchmarks for assessing the mesh quality implemented in the design.

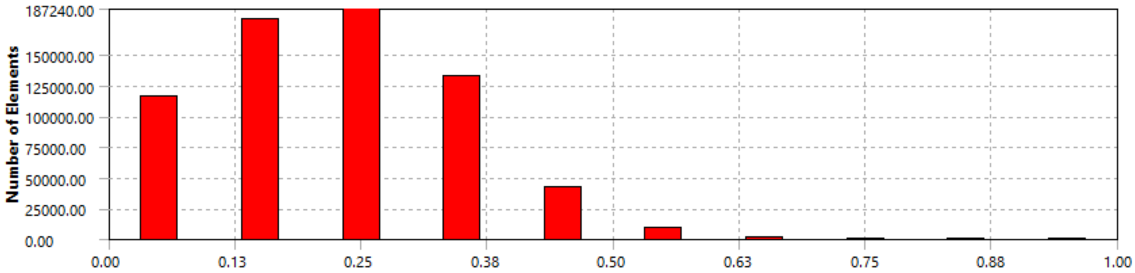


Figure 5.6. Meshing Quality Parameter: Skewness

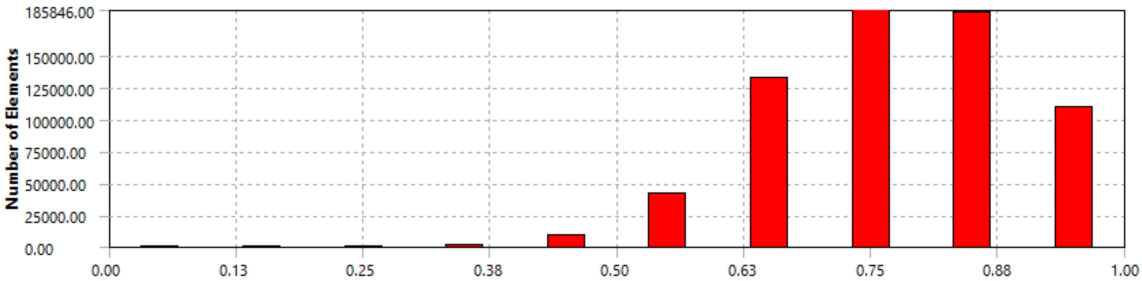


Figure 5.7. Meshing Quality Parameter: Orthogonal Quality

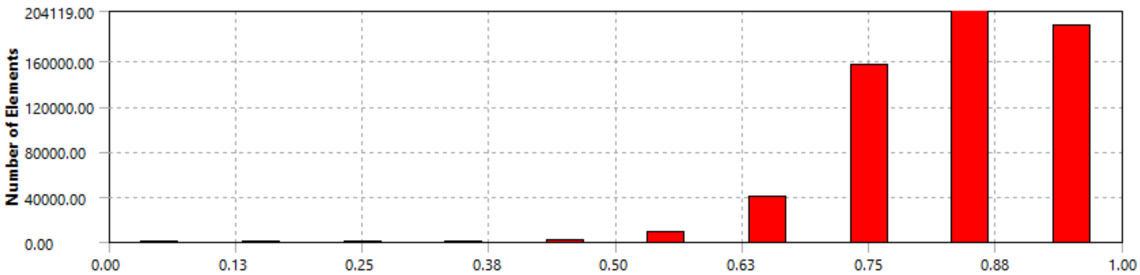


Figure 5.8. Meshing Quality Parameter: Element Quality

Mesh sensitivity analysis plays a crucial role in the validation and optimization of numerical simulations, ensuring the reliability and accuracy of the results against the physical system in question. Mesh sensitivity analysis results are given in Table 5.3. By examining the impact of network parameters on simulation results, engineers gain valuable insight into the suitability of networking strategies and the allocation of computational resources. This analytical process empowers engineers to make informed decisions, thereby increasing confidence in the accuracy and representativeness of simulation results. Mesh sensitivity analysis results are shown in Table 5.3. After that 3D models are created in SolidWorks software.

Table 5. 2. Mesh Sensitivity Analysis Results

Test Number	Von misses (Mpa)	Nodes	Element	Error (%)
1	471.3	3211453	2265421	0.74
2	467.83	2489651	1613672	2.03
3	458.48	1654839	895113	4.25
4	439.76	785762	472526	8.48
5	405.35	220134	124320	-

Following the completion of the verification study, regression models tailored to the specific problem were developed utilizing Design of Experiments (DOE) and Finite Element Method (FEM). Subsequently, various optimization algorithms were employed to conduct the optimization process, culminating in the attainment of the optimal design. These processes are elaborated upon in the subsequent subsections.

5.2. Design of Experiment and Finite Element Analysis Results

The exploration of the effects of multiple factors on a system's output is facilitated by the use of design of experiments, aiming for efficient analysis. By systematically varying these factors and analyzing their impact, DOE helps optimize processes, improve product quality, and enhance understanding, all while minimizing the number of experiments needed. In our problem, the desired von Mises stress and mass values of the rod are initially specified. Subsequently, the design of experiment method is employed to comprehend and optimize the effects by varying the levels of the design variables[21]. Through the utilization of experimental design, more precise information about the studied system can be obtained, as it allows for the evaluation of the combined effect of all parameters. The levelling process forward parameters affecting the mechanical properties of the design was conducted to apply the experimental design method. Specifically, there are 5 levels for R1 and R2, and 4 levels for D4, as indicated. These levels were chosen considering the real product.

After material selection, meshing and mash sensitivity for analysis, analysis was run by changing only geometry. As a result of the preliminary static analysis, it was observed that the stress concentration occurred at the center of the rod, as shown in Figure 5.9.

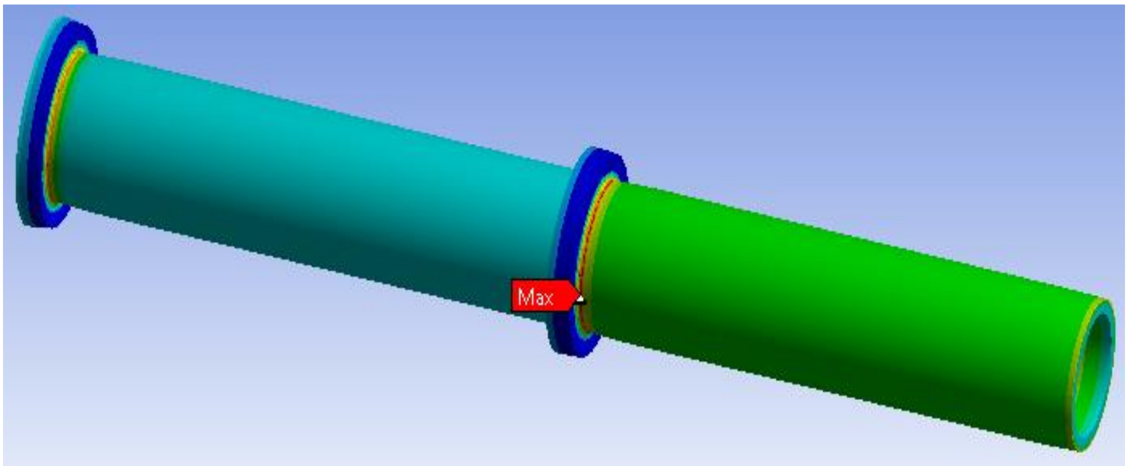


Figure 5.9. FEA Analysis of the Rod

Following the determination of factors and levels, the appropriate DOE method for the problem is chosen. In this case, the D-optimal method, known for its optimization-based approach among the DOE methods mentioned in Chapter 3, was selected. DOE has significance in the literature for understanding the impact of each factor. In this study, the DOE method was used to examine the effects of 3 factors on mass and stress outputs. An experimental design was carried out using the Design Expert program, with 52 simulations formulated based on the main and combined effects (2F1) of the factors in Table 5.4. The data set contains 52 different design suggestions. Therefore, the results of the analyzes will be different from each other.

5.3.Neuro Regression Results

In this thesis, the first step for the optimization of the hydraulic tandem actuator rod is to create the mathematical model. For this, regression must be done using the results. In this step, we will try to increase the accuracy, reliability and robustness of the results by using Neuro Regression. In regression, the effects of variables on mass and von Misses stress will be examined and mathematical models will be created.

As stated in the previous sections, the results were divided into two parts randomly, 80% training data and 20% testing data respectively. 42 out of 52 data are shown in Table 5.5. Table 5.6 shows 10 data sets as test data.

Table 5.3. Results of DOE and FEA

Run	R1 [mm]	R2 [mm]	D4 [mm]	Mass [kg]	von Misses [MPa]	Deformation [mm]
1	25	17.5	5	2.346	386.68	0.139
2	32.5	20	5	2.807	379.21	0.138
3	17.5	16.25	4	1.551	241.35	0.177
4	25	18.75	2	1.010	838.12	0.341
5	25	18.75	4	1.920	395.02	0.162
6	25	16.25	4	1.830	550.99	0.192
7	40	15	2	1.223	1582.7	0.63
8	40	17.5	4	2.434	820.72	0.274
9	10	18.75	3	1.037	545.12	0.314
10	17.5	18.75	2	0.870	400.39	0.351
11	25	20	2	1.032	720.43	0.323
12	40	15	5	2.933	747.73	0.249
13	17.5	15	3	1.146	441.15	0.267
14	32.5	20	3	1.699	716.42	0.246
15	40	17.5	2	1.267	1410.3	0.55
16	25	17.5	2	0.988	939.54	0.375
17	17.5	20	4	1.685	206.94	0.167
18	40	20	3	1.908	957.38	0.324
19	25	15	4	1.786	642.16	0.21
20	40	17.5	3	1.841	1057.5	0.375
21	25	15	3	1.355	874.58	0.291
22	32.5	16.25	5	2.639	536.78	0.176
23	10	15	4	1.227	328.08	0.238
24	25	20	3	1.489	467.66	0.211
25	17.5	17.5	5	1.997	163.38	0.141
26	25	20	5	2.457	236.96	0.123
27	10	15	2	0.664	556.5	0.49
28	32.5	17.5	2	1.128	1132	0.436
29	32.5	16.25	2	1.105	801.32	0.314
30	32.5	18.75	2	1.150	1043.21	0.3637
31	10	17.5	5	1.648	271.18	0.181
32	40	18.75	5	3.100	631.59	0.195
33	17.5	16.25	5	1.941	196.16	0.147
34	10	17.5	4	1.316	347.4	0.231
35	40	20	4	2.523	705	0.235
36	17.5	17.5	4	1.596	213.43	0.178
37	40	15	4	2.344	922.51	0.32
38	40	18.75	2	1.289	1360.2	0.523
39	17.5	15	4	1.506	312.88	0.197
40	25	18.75	3	1.456	553.13	0.227
41	10	20	2	0.753	885.13	0.482

(Cont. on next page)

Table 5.3 (Cont.)

42	32.5	15	4	2.065	748.63	0.247
43	32.5	17.5	4	2.154	635.93	0.21
44	32.5	15	3	1.565	988.72	0.337
45	10	16.25	3	0.970	410.87	0.317
46	17.5	16.25	3	1.179	363.33	0.252
47	25	16.25	2	0.966	642.12	0.198
48	17.5	17.5	2	0.848	467.83	0.364
49	25	18.75	5	2.402	282.3	0.131
50	10	15	3	0.936	415.83	0.324
51	40	16.25	2	1.245	1521.5	0.593
52	32.5	17.5	3	1.632	836.2	0.288

After the training and test data groups are created, the next step is to determine the models to be used for regression. For the models, 12 different regression models taken from the literature were used. These models are given in Table 5.7. "Wolfram Mathematica 11.3" was used to create models, determine coefficients, coefficient of determination and optimization. It is an important part of model selection that the lower and upper limits of the output, in desired physical range, additionally must be taken into consideration. In this way, the mathematical models developed for the optimization process enabled the estimation of stress and mass and and the optimum value of the process parameters to obtain the desired values. The coefficient of determination values for all data groups of the model to be selected from Neuro-Regression results produced with 12 different models should be greater than 0.90 and the maximum-minimum values should be in an acceptable range in line with the physical requirements of the problem

Table 5.4. Testing Data Set

Run	R1 [mm]	R2 [mm]	D4 [mm]	Mass [kg]	von Misses [MPa]	Deformation [mm]
4	25	18.75	2	1.010	838.12	0.341
15	40	17.5	2	1.267	1410.3	0.55
23	10	15	4	1.227	328.08	0.238
27	10	15	2	0.664	556.5	0.49
29	32.5	16.25	2	1.105	801.32	0.314
37	40	15	4	2.344	922.51	0.32
40	25	18.75	3	1.456	553.13	0.227
44	32.5	15	3	1.565	988.72	0.337
46	17.5	16.25	3	1.179	363.33	0.252
52	32.5	17.5	3	1.632	836.2	0.288

Table 5.5. Training Data Set

Run	R1 [mm]	R2 [mm]	D4 [mm]	Mass [kg]	von Misses [MPa]	Deformation [mm]
1	25	17.5	5	2.346	386.68	0.139
2	32.5	20	5	2.807	379.21	0.138
3	17.5	16.25	4	1.551	241.35	0.177
5	25	18.75	4	1.920	395.02	0.162
6	25	16.25	4	1.830	550.99	0.192
7	40	15	2	1.223	1522.7	0.63
8	40	17.5	4	2.434	820.72	0.274
9	10	18.75	3	1.037	545.12	0.314
10	17.5	18.75	2	0.870	400.39	0.351
11	25	20	2	1.032	720.43	0.323
12	40	15	5	2.933	747.73	0.249
13	17.5	15	3	1.146	441.15	0.267
14	32.5	20	3	1.699	716.42	0.246
16	25	17.5	2	0.988	939.54	0.375
17	17.5	20	4	1.685	206.94	0.167
18	40	20	3	1.908	957.38	0.324
19	25	15	4	1.786	642.16	0.21
20	40	17.5	3	1.841	1057.5	0.375
21	25	15	3	1.355	874.58	0.291
22	32.5	16.25	5	2.639	536.78	0.176
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25	17.5	17.5	5	1.997	163.38	0.141
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28	32.5	17.5	2	1.128	1132	0.436
30	32.5	18.75	2	1.150	1043.21	0.3637
31	10	17.5	5	1.648	271.18	0.181
32	40	18.75	5	3.100	631.59	0.195
33	17.5	16.25	5	1.941	196.16	0.147
34	10	17.5	4	1.316	347.4	0.231
35	40	20	4	2.523	705	0.235
36	17.5	17.5	4	1.596	213.43	0.178
38	40	18.75	2	1.289	1360.2	0.523
39	17.5	15	4	1.506	312.88	0.197
41	10	20	2	0.753	885.13	0.482
42	32.5	15	4	2.065	748.63	0.247
43	32.5	17.5	4	2.154	635.93	0.21
45	10	16.25	3	0.970	410.87	0.317
47	25	16.25	2	0.966	642.12	0.198
48	17.5	17.5	2	0.848	467.83	0.364
49	25	18.75	5	2.402	282.3	0.131
50	10	15	3	0.936	415.83	0.324
51	40	16.25	2	1.245	1521.5	0.593

Table 5.6. Regression Model Taken From Literature

(Source: Aydin, L.et al[35])

Model Name	Nomenclature	Formula
Multiple linear	L	$Y = \sum_{i=1}^{2}(a_i x_i) + c$
Multiple linear rational	LR	$Y = \frac{\sum_{i=1}^{2}(a_i x_i) + c_1}{\sum_{j=1}^{2}(b_j x_j)} + c_2$
Second order multiple non-linear	SON	$Y = \sum_{k=1}^{2}\sum_{j=1}^{2}(a_j x_j x_k) + \sum_{i=1}^{2}(a_i x_i) + c$
Second order multiple non-linear rational	SONR	$Y = \frac{\sum_{k=1}^{2}\sum_{j=1}^{2}(a_j x_j x_k) + \sum_{i=1}^{2}(a_i x_i) + c_1}{\sum_{l=1}^{2}\sum_{m=1}^{2}(a_m x_m x_l) + \sum_{n=1}^{2}(a_n x_n)} + c_2$
First order trigonometric multiple non-linear	FOTN	$Y = \sum_{i=1}^{2}(a_i \sin[x_i] + a_i \cos[x_i]) + c$
First order trigonometric multiple non-linear rational	FOTNR	$Y = \frac{\sum_{i=1}^{2}(a_i \sin[x_i] + a_i \cos[x_i]) + c_1}{\sum_{j=1}^{2}(a_j \sin[x_j] + a_j \cos[x_j])} + c_2$
Second order trigonometric multiple non-linear	SOTN	$Y = \sum_{i=1}^{2}(a_i \sin[x_i] + a_i \cos[x_i]) + \sum_{j=1}^{2}(a_j \sin^2[x_j] + a_j \cos^2[x_j]) + c$
Second order trigonometric multiple non-linear rational	SOTNR	$= \frac{\sum_{i=1}^{2}(a_i \sin[x_i] + a_i \cos[x_i]) + \sum_{j=1}^{2}(a_j \sin^2[x_j] + a_j \cos^2[x_j]) +}{\sum_{k=1}^{2}(a_k \sin[x_k] + a_k \cos[x_k]) + \sum_{l=1}^{2}(a_l \sin^2[x_l] + a_l \cos^2[x_l}$ $+ c_2$
First order logarithmic multiple non-linear	FOLN	$Y = \sum_{i=1}^{2}(a_i Log[x_i]) + c$
First order logarithmic multiple non-linear rational	FOLNR	$Y = \frac{\sum_{i=1}^{2}(a_i Log[x_i]) + c_1}{\sum_{j=1}^{2}(a_j Log[x_j])} + c_2$
Second order logarithmic multiple non-linear	SOLN	$Y = \sum_{k=1}^{2}\sum_{j=1}^{2}(a_j Log[x_j x_k]) + \sum_{i=1}^{2}(a_i Log[x_i]) + c$
Second order logarithmic multiple non-linear rational	SOLNR	$Y = \frac{\sum_{k=1}^{2}\sum_{j=1}^{2}(a_j Log[x_j x_k]) + \sum_{i=1}^{2}(a_i Log[x_i]) + c_1}{\sum_{m=1}^{2}\sum_{l=1}^{2}(a_l Log[x_l x_m]) + \sum_{n=1}^{2}(a_n Log[x_n])} + c_2$

The results of the regressions for stress are as in the table 5.7. First, the coefficient of determination was checked from the results. In all results, it was seen that R-square was greater than 0.9. Looking at the maximum and minimum values of the next stage, 6 regressions are not within physical limits. These regressions are highlighted in the table 5.7. When other regression models were examined, it was seen that the "Second Order Non-linear" model met the necessary conditions for von Mises stress. Therefore, the von Mises stress regression for this study is stated in the equation 5.1.

$$von\ Mises\ Stress = -2010.19 + 50.2994 * D4 + 0.816142 * D4^2 + 223.119 * E4 - 3.12547 * D4 * E4 - 3.94161 * E4^2 + 126.554 * F4 - 4.22683 * D4 * F4 - 8.98458 * E4 * F4 - 5.04297 * F4^2 \quad (5.1)$$

Table 5.7. Neuro Regression Models For von Mises Stress

Model	$R^2_{Training}$	$R^2_{Testing}$	Maximum	Minimum
L	0.976	0.967	1464.502	167.180
RL	0.955	0.945	1436.078	296.938
SON	0.998	0.984	1517.506	160.269
~~SONR~~	~~0.937~~	~~0.925~~	~~5232.964~~	~~-28.309~~
FOTN	0.940	0.916	1462.607	164.118
~~FOTNR~~	~~0.983~~	~~0.978~~	~~1544.819~~	~~224.907~~
SOTN	0.974	0.962	1445.904	162.203
~~SOTNR~~	~~0.985~~	~~0.967~~	~~1591.600~~	~~150.727~~
FOLN	0.941	0.931	1477.520	175.141
~~FOLNR~~	~~0.939~~	~~0.927~~	~~878.040~~	~~204.186~~
~~SOLN~~	~~0.967~~	~~0.942~~	~~1277.519~~	~~-24.860~~
~~SOLNR~~	~~0.981~~	~~0.947~~	~~878.034~~	~~204.173~~

The results of the regressions for Mass are as in the table 5.8 . First of all, the coefficient of determination was checked from the results. In all results, it was seen that R-square was greater than 0.9. Looking at the maximum and minimum values of the next stage, 4 regressions are not within physical limits. These regressions are highlighted in the table 5.8. When other regression models were examined, it was seen that the “Second

Order Non-linear” model met the necessary conditions for von Mises stress. Therefore, the mass regression for this study is specified in the equation 5.2.

$$Mass\ (kg) = 0.191957 + 0.000132636 * D4 + 6.13437 * (10^\wedge - 7) * D4^2 - 0.000724816 * E4 - 9.28551 * (10^\wedge - 6) * D4 * E4 - 9.89895 * (10^\wedge - 6) * E4^2 - 0.00793788 * F4 + 0.00930877 * D4 * F4 + 0.00929826 * E4 * F4 + 0.00930815 * F4^2 \quad (5.2)$$

Table 5.8. Neuro Regression Models For Mass

Model	$R^2_{Training}$	$R^2_{Testing}$	Maximum	Minimum
~~L~~	~~0.997~~	~~0.987~~	~~2.899~~	~~0.565~~
RL	0.997	0.986	3.095	0.749
SON	0.998	0.984	3.101	0.752
SONR	0.998	0.987	3.109	0.758
~~FOTN~~	~~0.995~~	~~0.970~~	~~2.772~~	~~0.480~~
FOTNR	0.984	0.995	3.108	0.731
~~SOTN~~	~~0.997~~	~~0.985~~	~~2.882~~	~~0.607~~
SOTNR	0.992	0.981	3.100	0.738
FOLN	0.994	0.984	3.083	0.761
FOLNR	0.999	0.986	3.035	0.775
~~SOLN~~	~~0.994~~	~~0.968~~	~~2.733~~	~~0.411~~
SOLNR	0.999	0.965	3.035	0.775

5.4. Results of Optimization

Optimization is a concept used to optimize a system or process. In general, it ensures the most effective and efficient use of resources. In this section, optimization will be made according to the two outputs of the problem, stress and mass. Regression was performed for each outcome. As a result, the most reliable and suitable mathematical models were selected. Scenarios for optimization of these mathematical models were created for each output. These outputs play a very critical role in the design. Stochastic methods were chosen for their optimization. These methods are “Differential Evolution”, “Simulated Annealing”, “Random Search” and “Nelder-Mead” algorithms. “Wolfram

Mathematica 11.3" program was used for optimization. In this program, "Nminimize" command and "MaxIteration" command are used for optimization. The "Nminimize" command was used to find the smallest value in the created mathematical model. The "MaxIteration" command was used to increase the accuracy of the result.

Table 5.9. Scenarios of Optimization

Scenario	**Optimization 1 (von Mises Stress)**	**Scenario**	**Optimization 2 (Mass)**
1a	$10 \leq R1 \leq 40$ $15 \leq R2 \leq 20$ $2 \leq D4 \leq 5$	2a	$10 \leq R1 \leq 40$ $15 \leq R2 \leq 20$ $2 \leq D4 \leq 5$
1b	$10 \leq R1 \leq 40$ $15 \leq R2 \leq 20$ $23.765 \leq R4 \leq 47.489$ $2 \leq D4 \leq 5$	2b	$10 \leq R1 \leq 40$ $15 \leq R2 \leq 20$ $23.765 \leq R4 \leq 47.489$ $2 \leq D4 \leq 5$
1c	$Mass \leq 1.5$ $10 \leq R1 \leq 40$ $15 \leq R2 \leq 20$ $2 \leq D4 \leq 5$	2c	$Stress \leq 500$ $10 \leq R1 \leq 40$ $15 \leq R2 \leq 20$ $2 \leq D4 \leq 5$
1d	$Mass \leq 1.5$ $R1 = 25$ $15 \leq R2 \leq 20$ $2 \leq D4 \leq 5$	2d	$Stress \leq 500$ $R1 = 25$ $15 \leq R2 \leq 20$ $2 \leq D4 \leq 5$

In the optimization condition in Scenarios 1a and 2a, the physical limitation mentioned in the Problem Definition section, as well as the production limitation of the part and finite element analysis limitations, were taken into account for the parameters. That is, R1, R2 and D4 values will increase in a determined way. Considering the restrictions, the increase levels of R1, R2 and D4 values are 1, 0.25, 0.25, respectively. Optimization was made according to these increase rates and physical limits. Under this optimization condition, safer design parameters for production are obtained.

In the optimization condition in Scenarios 1b and 2b, the parameters were subjected to only the physical limitation mentioned in the Problem Definition section. The aim here is to obtain the minimum stress and mass values within physical limits. With this restriction, there is no restriction for the stress and mass values within the limits specified in the parameters.

In the optimization condition in Scenario 1c, mass is limited for the parameters in addition to the physical limitation mentioned in the Problem Definition section. In this condition, the mass value is expected to be less than or equal to 1.5 kg. In this way, the part has the desired mass value and parameters have been determined to make it more durable.

In the optimization condition in Scenario 2c, mass is limited for the parameters in addition to the physical limitation mentioned in the Problem Definition section. In this condition, the stress value is expected to be less than or equal to 500 MPa. In this way, the part has the desired mass value and parameters have been determined to make it more durable.

In the optimization condition in Scenario 1d, the physical parameters R2 and D4, which are mentioned in the Problem Definition section, vary within physical limits, while the mass value is limited. In addition to these limitations, the R1 parameter was kept constant. The reason why the R1 parameter is kept constant is that the part on which the equipment will be mounted is clear. In this condition, the mass value is expected to be less than or equal to 1.5 kg. In this way, the part can be designed most appropriately according to the system to be assembled.

In the optimization condition in Scenario 2d, the stress value is limited while the physical parameters R2 and D4, which are mentioned in the Problem Definition section, vary within physical limits. In addition to these limitations, the R1 parameter was kept constant. The reason why the R1 parameter is kept constant is that the part on which the equipment will be mounted is clear. In this condition, the mass value is expected to be less than or equal to 500 MPa. In this way, the part can be designed most appropriately according to the system to be assembled.

5.4.1. Optimization Results for Stress Output

Table 5.10 lists the results of the optimization studies for von Mises stresses. In the first optimization problem, 1a, optimization algorithms gave different results. This is due to fundamental differences in the algorithms' search strategies, their degree of randomness, and the nature of the algorithms. Differential Evolution and Simulated Annealing optimizations give the most optimum results in this problem. The values given by these optimization algorithms for stress and mass are 143.358 MPa and 2.226kg, respectively.

In optimization problem 1b, all optimization algorithms reached the same result. The optimum stress value is 143.208 MPa, as in 1a. In this scenario, the values given by the program for the parameters are 20.428 mm, 20 mm, 29.24 mm and 5 mm, R1, R2, R4 and D4, respectively. With these parameters, the mass value was found to be 2.246.

For scenario 1c, the stress value was found to be the same with the optimization methods used. For a rod design weighing less than 1.5 kilograms, the stress value was found to be 198.020 MPa and the mass was 1.5 kilograms.

In scenario 1d, unlike 1c, the R1 value is kept constant. The stress value and parameters were found to be the same in different optimizations made for this condition. As a result, when we kept the R1 value constant, an increase in the stress value was observed von Mises stress and the mass value was found to be 553.941 MPa and 1.5 kilograms.

5.4.2.Optimization Results for Mass Output

Table 5.11 shows the optimization results of the scenarios created for mass.

In the first optimization problem, 2a, other optimization algorithms except Random Search reached the same result. This is due to fundamental differences in the algorithms' search strategies, their degree of randomness, and the nature of the algorithms. For this scenario, the values given by the optimizations for stress and optimization are 445.241 MPa and 0.674kg, respectively.

In the 2d optimization problem, all optimization algorithms reached the same result. The optimum mass value was found to be close to 1a. The optimum mass value was found to be 0.665 for this scenario. In this scenario, the values given by the program for the parameters are 10 mm, 15 mm, 23.765 mm and 2 mm, R1, R2, R4 and D4, respectively. With these parameters, the von Mises stress value was found to be 444.383 MPa.

For scenario 2c, the stress value was found to be the same with the optimization methods used. For a rod design with a von Mises stress value of less than 500 MPa, the mass value was found to be 0.826 and the von Mises stress value was 400.020 MPa.

In scenario 2d, unlike 2c, the R1 value is kept constant. In different optimizations made for this condition, the mass value and parameters were found to be the same. For this scenario, the mass value was found to be 1,878 kilograms, while the von Mises value was found to be 399,950.

Figures 5.10 and 5.11 show the convergence graphs of minimization results obtained with four different search algorithms for von Mises and mass objective functions. The number of iterations indicates when the algorithms will stop and has different values for each design. In addition, it is seen that there is stability after 40 iterations for MDE and MNM optimization algorithms. On the other hand, in the solutions of the MSA algorithm, the reason for jumping after about 100 iterations and coming back to the same value is that there is no improvement in successive iterations.

Table 5.10. Optimization Results For von Mises Stress

Scenario No	Constraints	Optimization Algorithms	von Mises Stress (MPa)	Weight (kg)	Suggested Design
1a	10 ≤ R1 ≤ 40 15 ≤ R2 ≤ 20 2 ≤ D4 ≤ 5	NM	164.897	2.111	R1 = 18, R2 = 19.5, D4 = 5
		DE	143.358	2.226	R1 = 20, R2 = 20, D4 = 5
		SA	143.358	2.226	R1 = 20, R2 = 20, D4 = 5
		RS	215.563	2.356	R1 = 24, R2 = 19, D4 = 5
1b	10 ≤ R1 ≤ 40 15 ≤ R2 ≤ 20 23.765 ≤ R4 ≤ 47.489 2 ≤ D4 ≤ 5	NM	143.208	2.246	R1 = 20.428, R2 = 20, R4 = 29.24, D4 = 5
		DE	143.208	2.246	R1 = 20.428, R2 = 20, R4 = 29.24, D4 = 5
		SA	143.208	2.246	R1 = 20.428, R2 = 20, R4 = 29.24, D4 = 5
		RS	143.208	2.246	R1 = 20.428, R2 = 20, R4 = 29.24, D4 = 5
1c	Mass ≤ 1.5 10 ≤ R1 ≤ 40 15 ≤ R2 ≤ 20 2 ≤ D4 ≤ 5	NM	198.020	1.500	R1 = 10, R2 = 15, D4 = 4.891
		DE	198.020	1.500	R1 = 10, R2 = 15, D4 = 4.891
		SA	198.020	1.500	R1 = 10, R2 = 15, D4 = 4.891
		RS	198.020	1.500	R1 = 10, R2 = 15, D4 = 4.891
1d	Mass ≤ 1.5 R1 = 25 15 ≤ R2 ≤ 20 2 ≤ D4 ≤ 5	NM	553.941	1.500	R1 = 25, R2 = 20, D4 = 3.025
		DE	553.941	1.500	R1 = 25, R2 = 20, D4 = 3.025
		SA	553.941	1.500	R1 = 25, R2 = 20, D4 = 3.025
		RS	553.941	1.500	R1 = 25, R2 = 20, D4 = 3.025

Table 5.11. Optimization Results For Mass

Scenario No	Constraints	Optimization Algorithms	von Mises Stress (MPa)	Mass (kg)	Suggested Design
2a	10 ≤ R1 ≤ 40 15 ≤ R2 ≤ 20 2 ≤ D4 ≤ 5	NM	445.241	0.674	R1 = 10, R2 = 15, D4 = 2
		DE	445.241	0.674	R1 = 10, R2 = 15, D4 = 2
		SA	445.241	0.674	R1 = 10, R2 = 15, D4 = 2
		RS	601.503	0.938	R1 = 18, R2 = 17, D4 = 2.25
2b	10 ≤ R1 ≤ 40 15 ≤ R2 ≤ 20 2 ≤ D4 ≤ 5	NM	444.383	0.665	R1 = 10, R2 = 15, R4=23.765, D4 = 2
		DE	444.383	0.665	R1 = 10, R2 = 15, R4=23.765, D4 = 2
		SA	444.383	0.665	R1 = 10, R2 = 15, R4=23.765, D4 = 2
		RS	444.383	0.665	R1 = 10, R2 = 15, R4=23.765, D4 = 2
2c	Stress ≤ 500 10 ≤ R1 ≤ 40 15 ≤ R2 ≤ 20 2 ≤ D4 ≤ 5	NM	400.020	0.826	R1 = 10, R2 = 15, D4 = 2.602
		DE	400.020	0.826	R1 = 10, R2 = 15, D4 = 2.602
		SA	400.020	0.826	R1 = 10, R2 = 15, D4 = 2.602
		RS	400.020	0.826	R1 = 10, R2 = 15, D4 = 2.602
2d	Stress ≤ 500 R1 = 25 15 ≤ R2 ≤ 20 2 ≤ D4 ≤ 5	NM	399.950	1.878	R1 = 25, R2 = 20, D4 = 3.821
		DE	399.950	1.878	R1 = 25, R2 = 20, D4 = 3.821
		SA	399.950	1.878	R1 = 25, R2 = 20, D4 = 3.821
		RS	399.950	1.878	R1 = 25, R2 = 20, D4 = 3.821

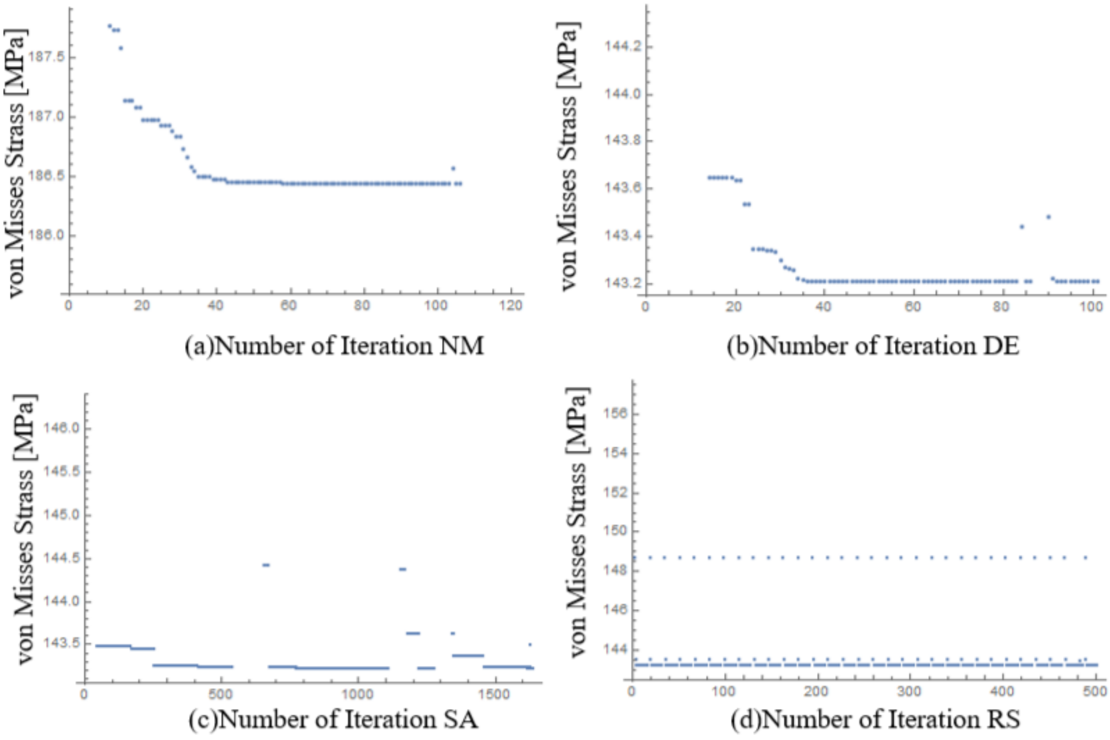

Figure 5.90. Convergence Graphic Optimization for von Misses Stress

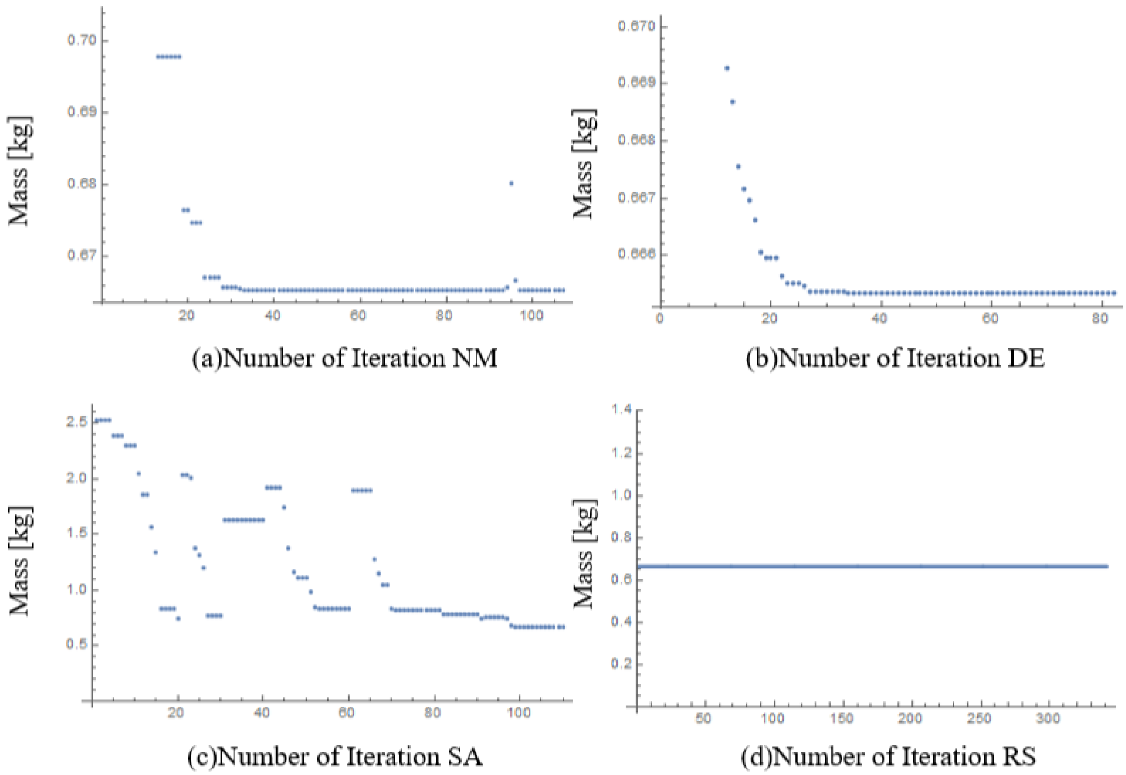

Figure 5.101. Convergence Graphic Optimization for Mass

CHAPTER 6

CONCLUSION

In this thesis study, the design and optimization study of the rod, which is one of the most important parts of the hydraulic tandem actuator used in jet fighters, was carried out. The first step of the thesis was to research the literature and find the requirements for a suitable actuator. The force and material that the actuator must support were determined from the values found. After determining the inputs and outputs for the problem, the D-optimal method, which is one of the design of experiment methods, was used to create data sets. As a result of DOE, a total of 52 data sets were obtained. Then, SolidWorks 2018 program was used to create solid models according to DOE data. After solid models were created, ANSYS 19.2 was used to perform finite element analysis. Neuro-Regression approach was used to move on to the next stage. In this way, 80% of the data was used as training data and the remaining 20% was used as test data. Thus, an attempt was made to increase the accuracy of the regression. Wolfram Mathematica 11.3 program was used for regression. Research has been conducted for optimization, which is the next step after regression. The methods to be used for optimization were Nelder Mead, Differential Evolution, Random Search and Simulated Annealing. These methods were used to optimize the von Mises stress and mass values, which are the output of the thesis problem, and to determine the most appropriate parameters.

As a conclusion, the results of different optimization methods in the created scenarios were found to be the same for stress and mass values. In the optimization methods, it was seen that Nelder Mead and Differential Evolution methods reached the optimum result with fewer iterations. It has been shown that this study can reach the result quickly and reliably by determining the desired conditions with mathematical models and optimization. This study will undoubtedly be useful to those who are interested in and will work on hydraulic actuator rod design.

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