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Design Study of Brake Mechanical Control System of UAV

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Abstract

This paper is a study on the mechanical control system design that converts the brake pedal system of a four-seater aircraft to an unmanned aerial vehicle. It is composed of a four-joint link system and a support structure to enable braking and change of direction using a dual redundant electric actuator. A trade-off study was conducted to optimize the support structure and the 4-joint link system.

Keywords: brake system, 4-joint linkage system, kinematic analysis, actuator torque

1. Introduction

This paper is about designing a mechanical control system that converts the brake system of a four-seater aircraft to an unmanned aerial vehicle. The brake system of manned aircraft is composed of a hydraulic system. The hydraulic system can directly control the load, it is possible to control even a very small displacement. Since the UAV uses an electric system rather than a hydraulic system, a mechanism for converting the hydraulic system into an electric system is required. Electric actuators are lightweight and have precise control, but compared to hydraulic actuators, their torque capacity is small and load control is difficult. Therefore, the electric actuator must overcome the pressure of the master cylinder with a small torque. Also, since the stroke of the master cylinder of brake system moves within 1mm during steering and braking, the actuator's operating angle must be large enough to precisely control every small displacement of the master cylinder. In this study, the concept and design parameters were investigated as a trade-off study for the support structure of a four-joint link system and master cylinder. The 4-joint link system is a way to overcome the pressure of the master cylinder with a small torque actuator. Through kinematic analysis, the actuator operating angle and torque amount corresponding to the displacement of the master cylinder according to the geometric design parameters of each link were investigated. And a support structure is important main structure that effectively transmits loads, and a rigid structure to which the support structure is to mounted. The design concept is a rigid structure with little deformation up to the maximum load of the master cylinder, and a light but strong structure. Based on finite element analysis, the design has been changed several times for weight reduction and simplification. And this brake mechanical control system will be tested by ground iron-bird test to verify structural rigidity and load carrying capacity.

2. Design Variables Study

2.1 The Displacement-load Relationship of the Master Cylinder

The brake system of a manned aircraft is generally configured as shown in Figure 1. As for the braking system, a master cylinder with a maximum pressure of 1000 psi is connected to the pilot pedal, and hydraulic pressure is transmitted to the brake pads through the pilot's pedal control, allowing rotation and braking. When the brake pads start to come into contact with the disc wheel, the cylinder stroke becomes very small.

It is first necessary to know the displacement-load relationship of the master cylinder in order to study the design parameters of the linkage. The test data in Figure 2 obtained during the development of a four-seater aircraft was used [1]. After the brake pad contacts the wheel disc, the master cylinder undergoes very little deformation, close to the behavior of a high-rigidity elastomer. Figure 3 shows the relationship between cylinder pressure and rod load. Under the condition that the maximum operating pressure of the master cylinder is 1000psi, the corresponding load is about 2843N, but in this study, assuming the maximum design load is of 300kg, this load corresponds to 2940N and is the rated torque of the actuator. As can be seen from the trend equation in Figure 2, The stiffness modulus of master cylinder is 119 N/mm and 2200 N/mm before and after contacting the brake pads, respectively.

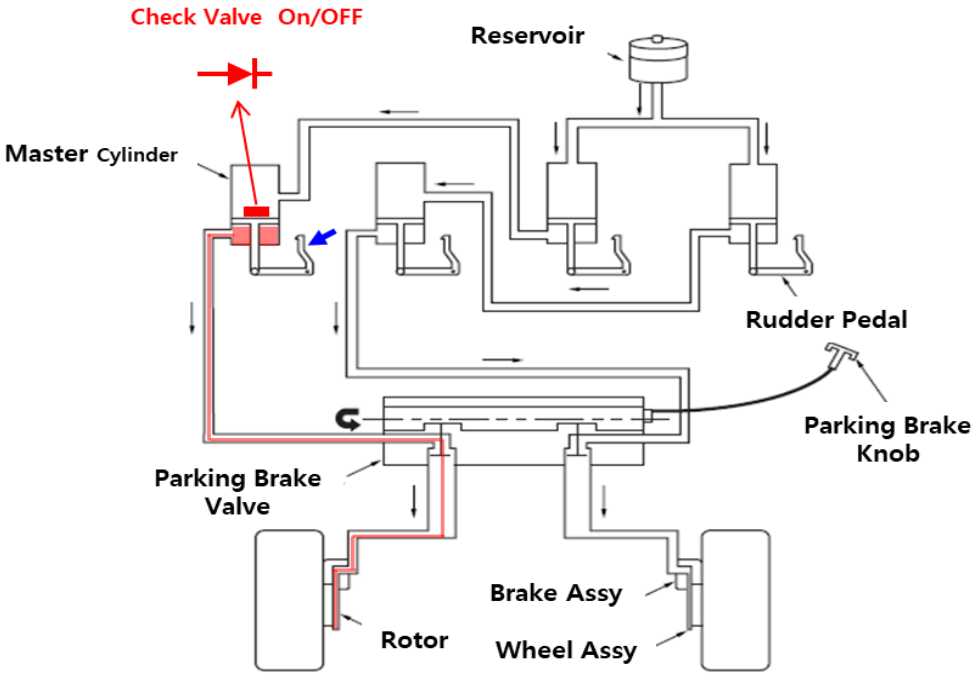

Figure 1 – Configuration of Brake System

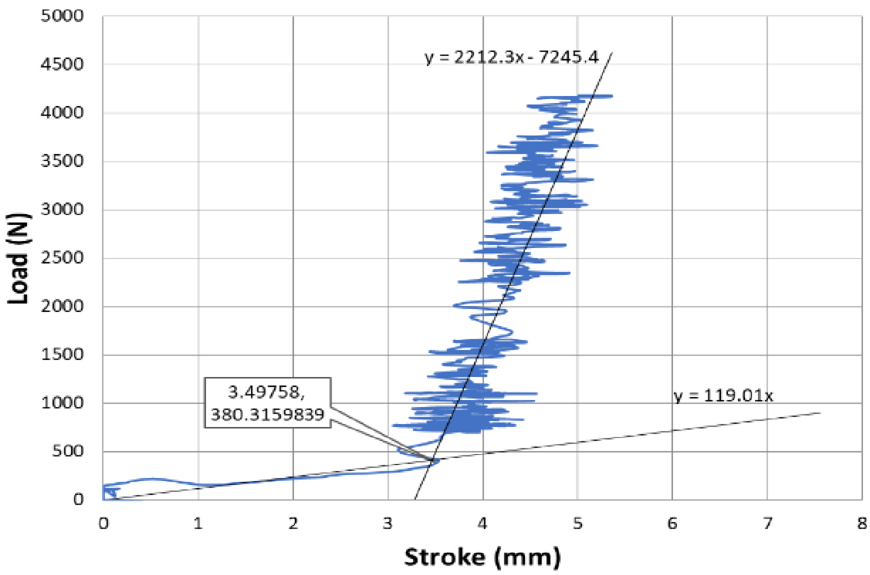

Figure 2 – Load and Displacement Relationship for Master Cylinder

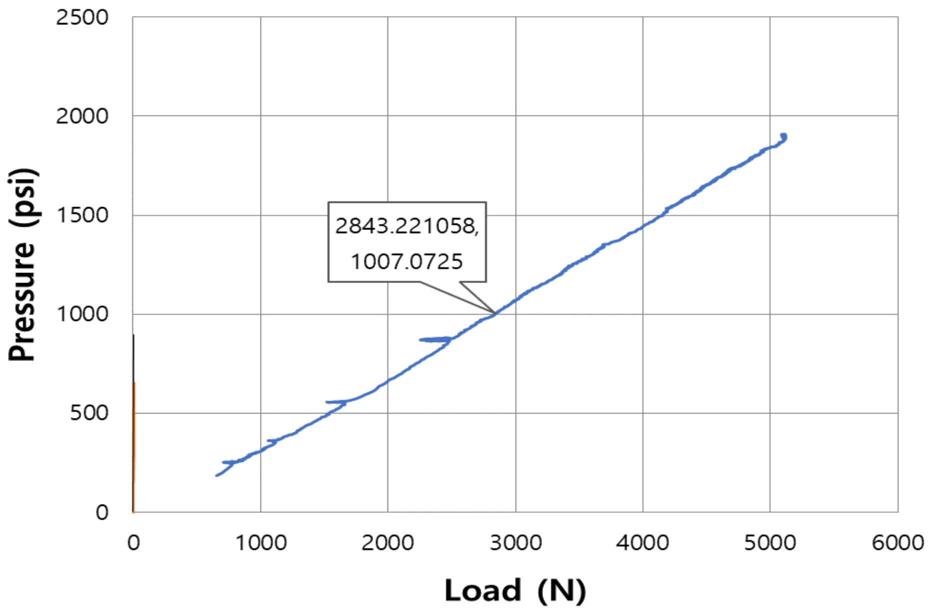

Figure 3 – Pressure and Load Relationship for Master Cylinder.

2.2 Linkage Types Study

The actuator shall be set to withstand the design maximum load. As results of surveying the dual redundant actuators based on the rated torque, the 12Nm actuator is the first one, and the 20Nm actuator is being considered as another candidate.

First, in order to check the validity of the actuator torque, the moment arm ratio is assumed to be 6, and the load on acting on the actuator is 490N and the length of actuator arm is 24.5 mm for torque 12Nm.

The master cylinder shall be mounted on a rigid structure. The seat rail is the suitable place for installing the brake control system. The configuration is shown in the figure 4 so that the master cylinder could be located in the middle of the seat rail if possible.

Although linkages and support structures are based on a rigid body design, the rotation angle of the actuator is operated larger than the design value due to the deformation of support structures, and interference with other members may occur. As shown in Figure 5, the deformations of master cylinder support structure and the moment arm were considered.

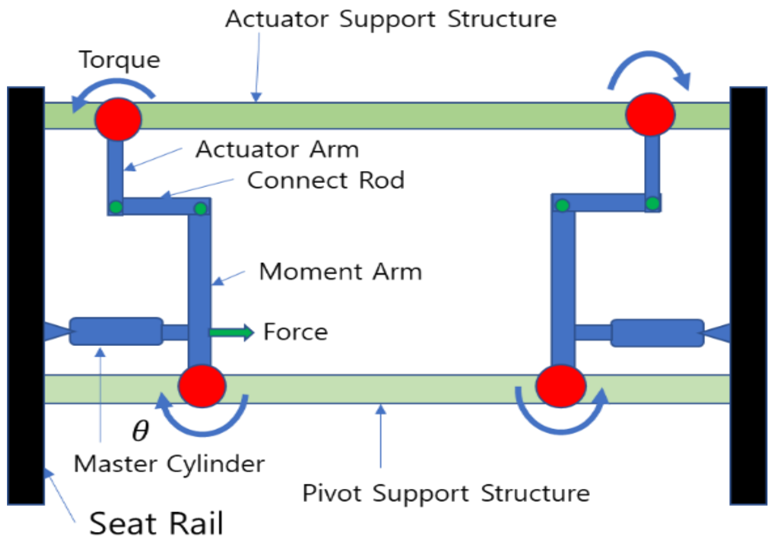

Figure 4 – Initial Design Concept of Brake System

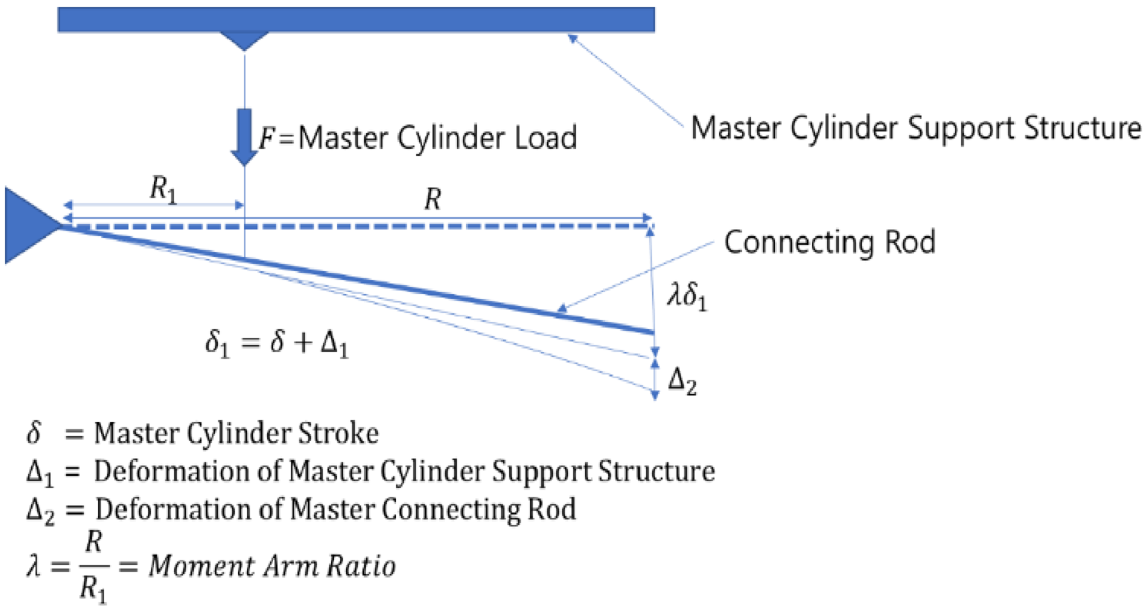

Figure 5 – Linkage Behavior by Deformation

Assuming that $\Delta_1 \leq 0.15\delta$, $\Delta_2 \leq 1$mm, δ=1.4mm where Δ_1 is the deformation the support structure of master cylinder and Δ_2 is the deformation of the moment arm and δ is the displacement of the master cylinder after the brake pad contacts. And the allowance for the rotation angle of the actuator is defined as $\Delta\varphi \leq 5°$ in consideration of the deformation of the support structures and the clearance between bolt joints.

For the kinematic analysis of 4 joint link system, a linkage type 1 as shown in Figure 6 was constructed. If the rotating arms are same length, each rotation arm's angle is same. Since the moment arm is longer than the arm of actuator, the distance of the moment arm by rotation angle is not proportional to the length ratio. And the connecting rod also affects the rotation angle of the actuator arm. Kinematic analysis was performed by sequentially increasing the angle of the actuator arm until the length of the connecting rod become the same.

The force and moment in the converged configuration are calculated by the following equation:

$$F_{rod} = \frac{F_{act}}{\lambda\, cos(\theta+\theta_0+\alpha)} \tag{1}$$

$$T = F_{rod} r\, cos(\varphi + \varphi_0 - \alpha) \tag{2}$$

The α gradually increases in the counterclockwise direction as the inclination angle.

Considering the geometrical constraints, the geometry in Figure 4 is defined as follows:

R=180mm, R_1=30mm, L=58 mm, r=24.5mm

In rigid body motion condition, the kinematic analysis result is as follows:

φ=80.3 deg, T=9.37Nm

Considering the allowance angle of Δφ=5° the rotating angle of the actuator is very close to 90 degrees. The actuator arm should be longer.

As a parametric study, the effects of rotation angle and moment of the actuator were examined using the arm length as a variable, and the results are shown in Table 1. It can be seen that the shorter the arm length, the greater the rotation angle is affected.

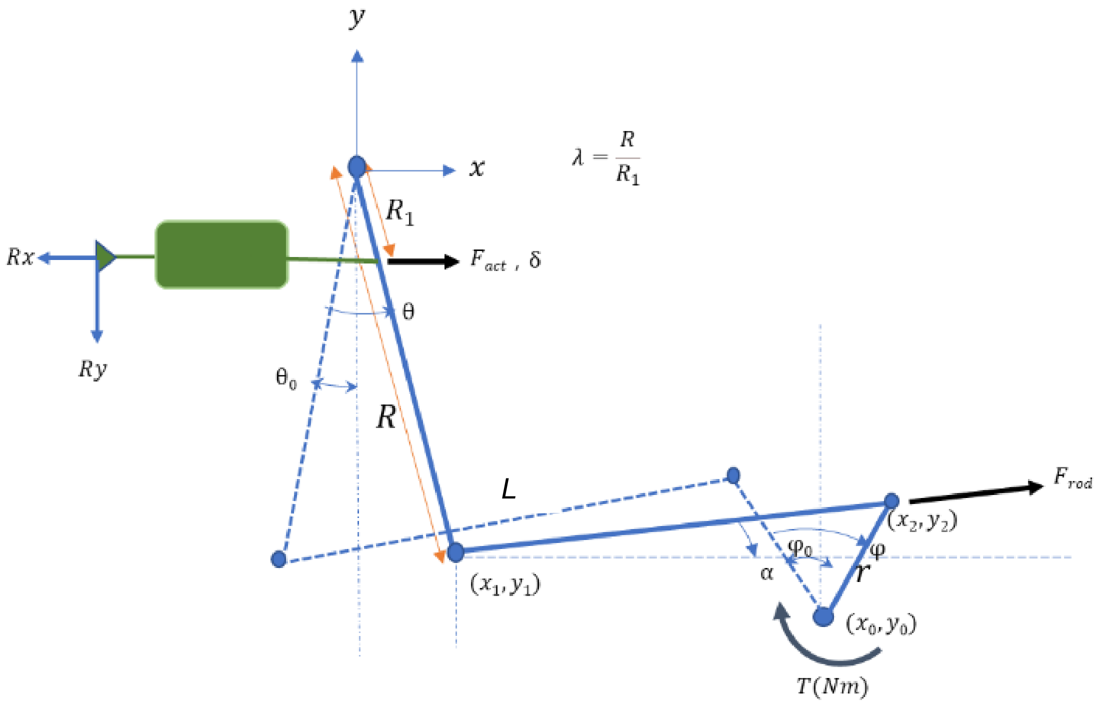

Figure 6 – Linkage Type 1

Table 1 Torque and Rotation Angle for Actuator Arm

r(mm)	φ (deg)	Torque (Nm)
25	77.80	9.75
30	60.43	12.04
35	50.13	13.12
40	43.05	13.73

Another linkage type 2 as shown in Figure 7 was considered. The α gradually increases in the clockwise direction as the inclination angle. In this case, the moment equation is the same as the previous linkage type, but the force is expressed differently as follows;

$$F_{rod} = \frac{F_{act}}{\lambda \cos(\theta + \theta_0 - \alpha)} \quad (3)$$

The calculation results for the geometry considered in Table 1 are shown in Table 2. It can be seen that rotation angles of arm are slightly larger than the type in Table 1, but torques are significantly lowered. This is because the acting force of the actuator decreases as α increases.

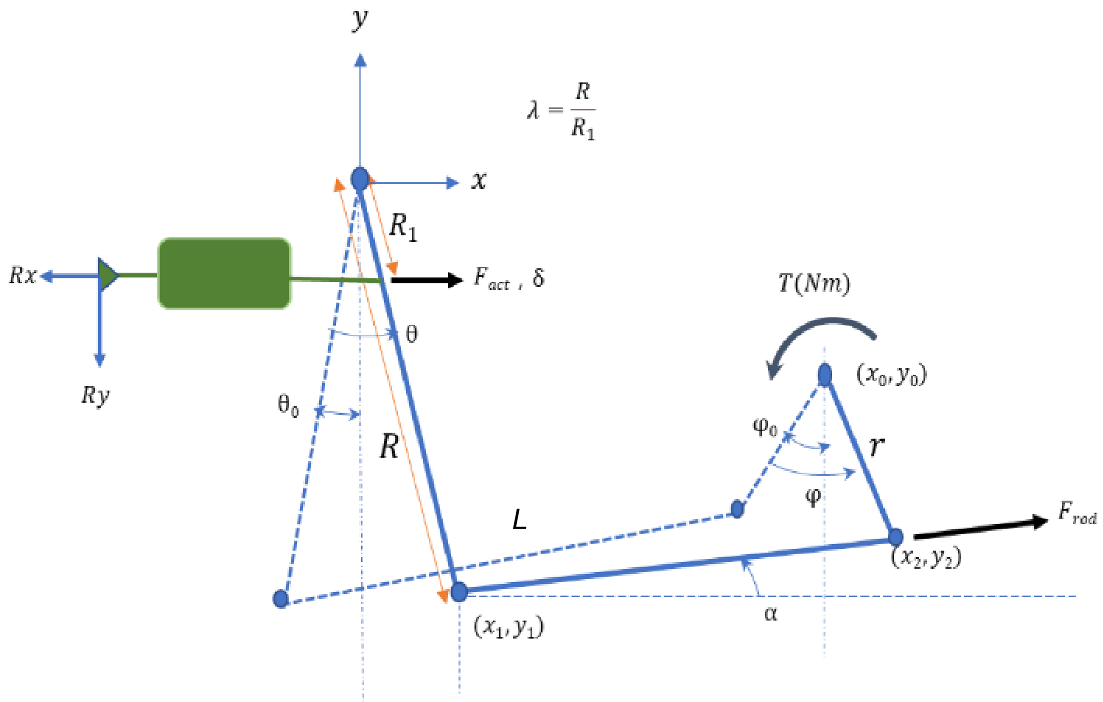

Figure 7 – Linkage Type 2

Table 2 Results of Linkage Type 2

r(mm)	φ (deg)	Torque (Nm)
25	81.21	7.00
30	61.53	9.86
35	50.49	11.26
40	43.10	12.11

2.3 Linkage Design Freezing

The linkage was determined in the type shown in Figure 8, and the length of the actuator arm was decided to be 32mm in consideration of the additional rotation angle of 10 degrees and surplus torque of at least 10%. The conceptual design is set as the layout shown in Figure 10, and the rotation angle and torque were analyzed.

The design values of geometry are as follows:

$$R=180mm,\ \lambda=R/R_1=6,\ r=32mm,\ L=58mm,\ \theta_0=\varphi_0=0$$

Kinematic analysis results are shown in Figure 9 and Table 3. The margin of safety is 15% based on the actuator's rated torque 12Nm, and the control angle ranges that can be operated during direction change and braking are 40~ 60 degrees.

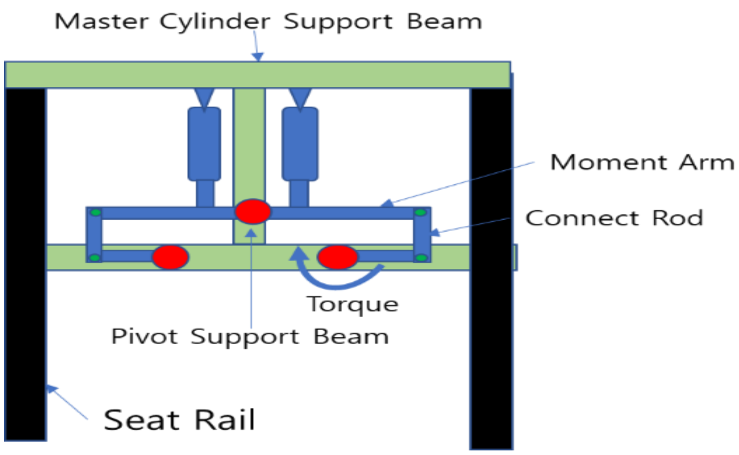

Figure 8 – 2nd Brake System Concept

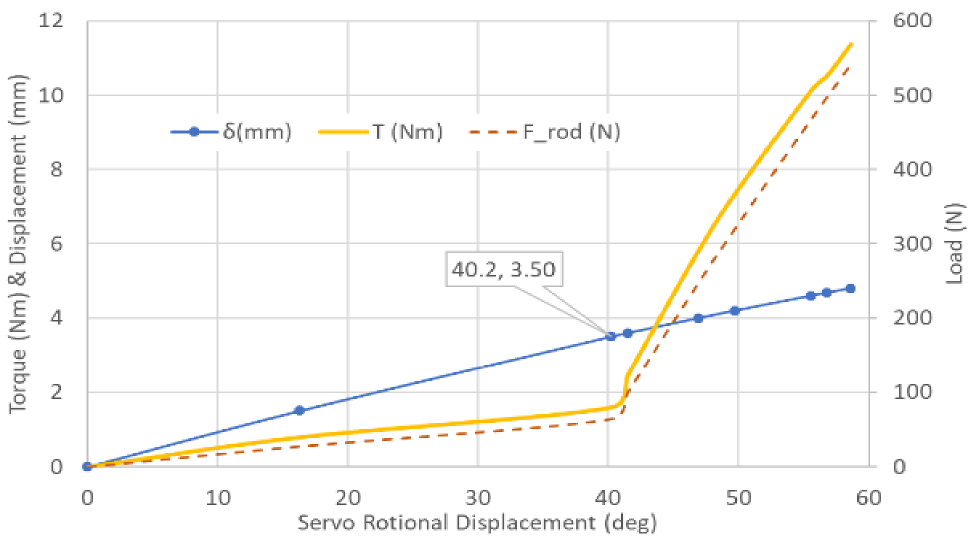

Figure 9 –Torque and Force, and Displacement by Rotation Angle

Table 3 Summary of Results for Present Design

F_act (N)	δ(mm)	ϕ(deg)	F_rod (N)	T (Nm)	M.S
0	0.00	0.0	0	0.00	0.00
165	1.50	16.3	28	0.80	14.07
385	3.50	40.2	64	1.60	6.51
605	3.60	41.5	101	2.48	3.83
1485	4.00	46.9	248	5.82	1.06
1925	4.20	49.7	321	7.35	0.63
2805	4.60	55.6	468	10.13	0.18
2940	4.68	56.8	498	10.52	0.14
3245	4.80	58.6	542	11.37	0.06

2.4 Parametric study

In the current design, the length of the connecting rod can be adjusted because the rod-end bearings are fastened to both ends. Without changing the hard point, changes in torque and rotational angle were examined as the length of rod was adjusted.

Figure 11 shows the results of adjusting only the length of the rod without changing the position of the moment arm. If the length of the rod is increased, the initial position of the actuator arm changes, and accordingly, the inclination of rod changes and torque changes. As the rod increases by 2mm, the torque gains a 5%.

Figure 12 is another example, showing the results of changing the rod length when the moment arm is tilted by 1 degree. Compared to θ_0=0, the torque decreases, while the rotation angle increases. Since the torque decreases as the rotation angle increases, it is desirable whether the rotation angle widens the range. However, when the operating angle is large, the operating speed of the actuator must be fast, so it is necessary to select an appropriate operating range of the actuator in consideration of the characteristics of the actuator.

Therefore, the results of the study provide information for design and fabrication guidelines as the torque can be changed more than 5% through fine adjustment of the angle or length in linkage system.

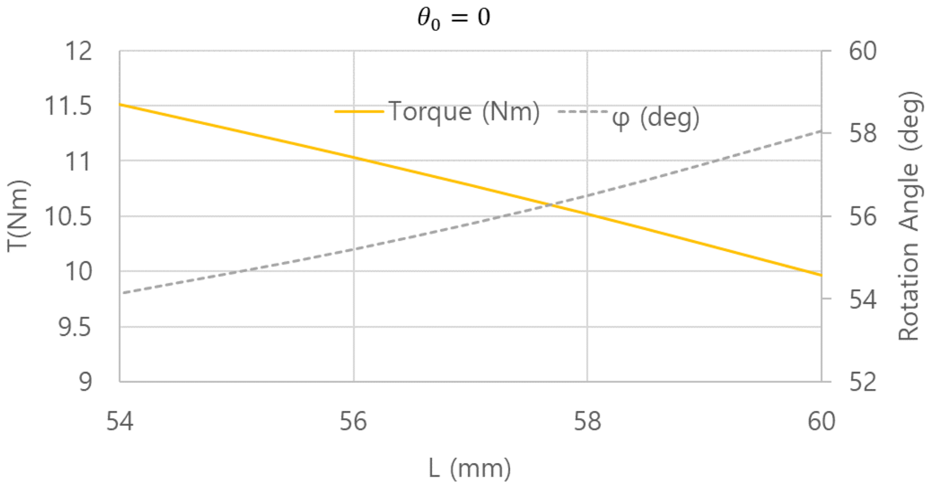

Figure 10 – Torque and Rotation Angle of Variable L ($\theta_0 = 0°$)

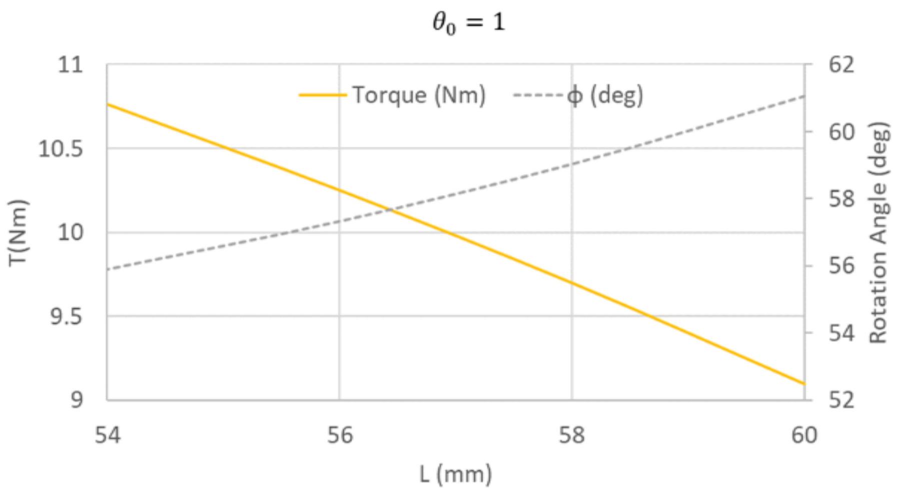

Figure 11 – Torque and Rotation Angle of Variable L ($\theta_0 = 1°$)

3. Support Structures Design

The key deign requirement of the support structure is rigid member whose deformation is within 0.2mm under the maximum operation pressure of master cylinder of 1000psi. And it should be light and simple. Aluminum is used as a material, and it is designed as one body simple frame. Three major design change were made based on the finite element analysis in terms of weight reduction and load path, and the process is briefly introduced.

Figure 12 to Figure 14 show the design change configurations and deformation results. The design of Figure 12 is first one. The master cylinder is mounted on the middle of frame. The key deign requirement of the support structure is rigid member whose deformation is within 0.2mm under the maximum operation pressure of master cylinder of 1,000psi. And it should be light and simple. Aluminum is used as a material, and it is designed as one body simple frame.

Three major design change were made based on the finite element analysis in terms of weight reduction and load path, and the process is briefly introduced.

The configuration in Figure 12 is the results of the first design, and the deformation occurs about 0.18mm, which satisfies the design requirements. However, the load supporting points are located on the middle of the upper frame, so some deformation occurs, and the weight is about 1.6kg, which is relatively heavy.

The second design is shown as Figure 13. Same concept is applied as the first one, but in the case where the support point is at the edge direction rather than the middle. The deformation is 0.07mm. It has been reduced by more than 2.5 times compared to the first design, and the weight was also reduced to about 1.3kg. Examining the displacement distributions, it can be seen that almost no deformation occurs in middle area, and there is relatively small deformation at the edge region.

By adopting the concept of separating the left and right as a cantilevered type, the final design was as shown in Figure 14. The deformation is 0.1mm, and the total weight of the left and right sides is 0.46 kg. The structures have been fabricated and is scheduled for ground iron-bird testing.

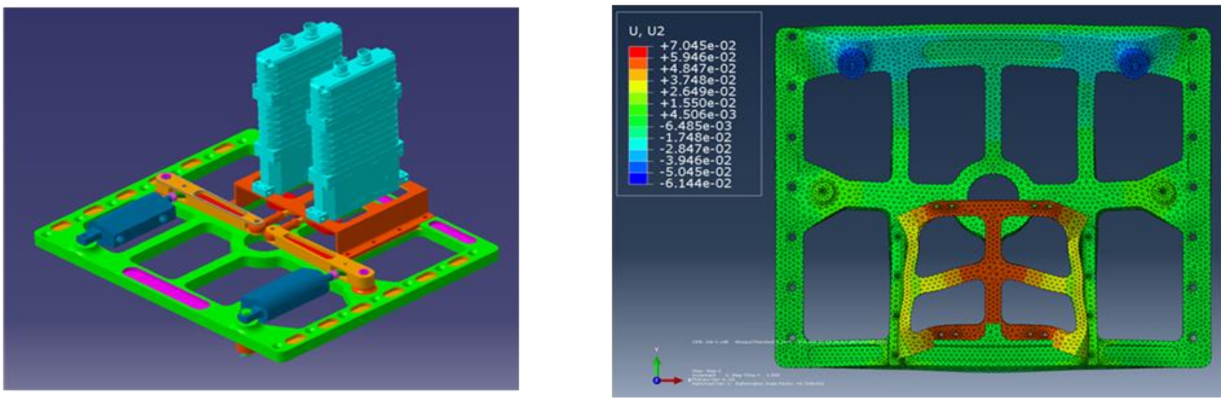

Figure 12 – 1st Design Results

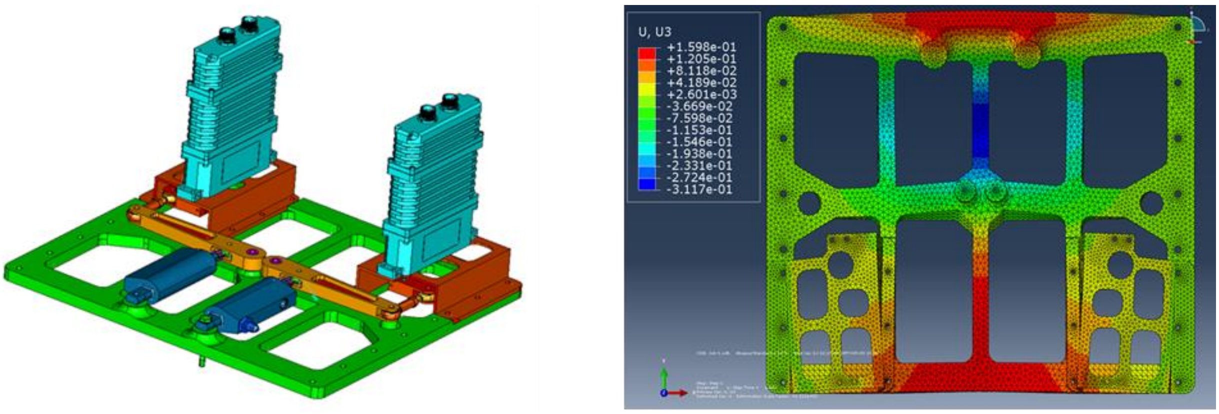

Figure 13 – 2nd Design Results

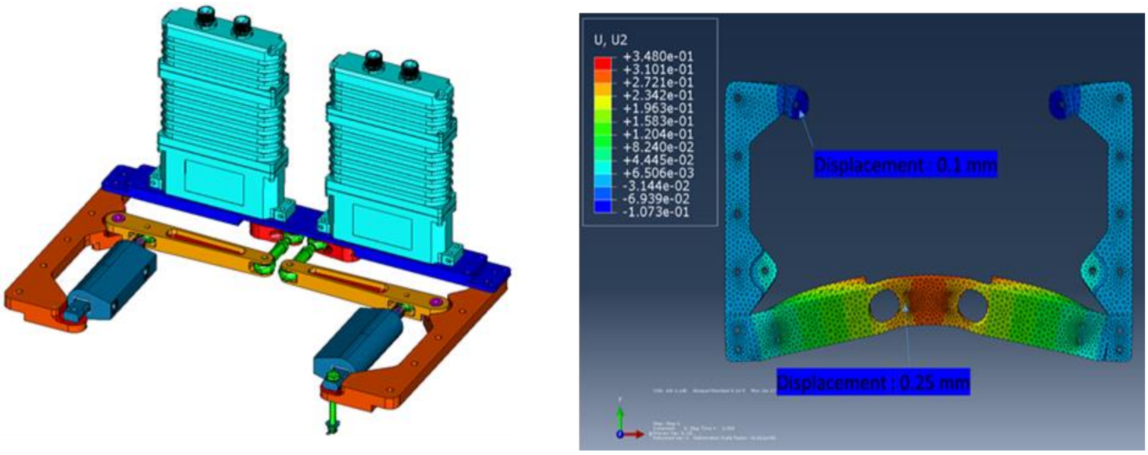

Figure 14 – Final Design Results

4. Conclusion

The design study of the link system of the brake mechanical control system was conducted through kinematic analysis and parametric study. In addition, examples of rigid body design for support structures were introduced. In linkage design, the main design factor is the length of moment arm and torque arm, which transmits a large load to a small load, but it was found that the connecting rod between moment arm to torque arm had also a large effect on the torque. Also, since the rotation angle and torque are different depending on the linkage types, a type suitable for the characteristics of the structures should be selected. The support structures and link members should be designed as a rigid body fundamentally, but allowance for rotation range should be allowed in consideration of the increase in weight and the fact that the base structure to which the support structure is installed is an elastic body. This structure intends to verify the design requirements through the ground iron bird test, and the results of parametric study will be tested. In addition, an in-depth study will be conducted on the effect elastic deformation by analysis and testing.

5. Acknowledgement

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7. Copyright Statement

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