Adjustable Counter-Weight for Full Turn Rotary Systems

G. Karakaya, C. Türker, M. Anaklı

***Abstract*—**It is necessary to test to see if optical devices such as camera, night vision devices are working properly. Therefore, a precision biaxial rotary system (gimbal) is required for mounting Unit Under Test, UUT. The Gimbal systems can be utilized for precise positioning of the UUT; hence, optical test can be performed with high accuracy. The weight of UUT, which is placed outside the axis of rotation, causes an off-axis moment to the mounting armature. The off-axis moment can act against the direction of movement for some orientation, thus the electrical motor, which rotates the gimbal axis, has to apply higher level of torque to guide and stabilize the system. Moreover, UUT and its mounting fixture to the gimbal can be changed, which causes change in applied resistance moment to the gimbals electrical motor. In this study, a preloaded spring is added to the gimbal system for minimizing applied off axis moment with the help of four bar mechanism. Two different possible methods for preloading spring are introduced and system optimization is performed to eliminate all moment which is created by off axis weight.

***Keywords*—**Balancing, gimbal, tension, preload, spring.

I. Introduction

A. Balancıng System Importance

In recent years, high precise and accurate motion systems are developed. One of the major problems of these systems is unbalance of the rotary axis, which affects the stabilization and driving motor selection. Therefore, unbalance of the rotary axis needs to be decreased, to design more precise systems with lower driving motor costs.

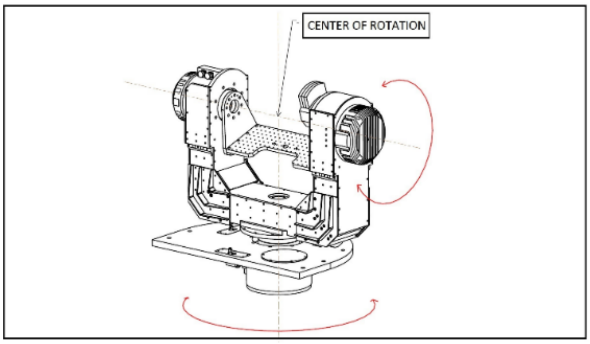

Fig. 1 A Two Axis Gimbal System Balanced by Counterweight [6]

As a solution method, counter weights can be used to eliminate off-axis payloads. However, counter-weights are making the system massive and they are not so useful when the payload is changed. Thus, using spring force as a counter weight is an appropriate solution because the effective spring length (force) can be modified for the varying payloads. The system with the spring mechanism is much more compact than the system with counter-weight. If the system is gigantic then the required power to drive system is also huge. Furthermore, precise control of test system is getting harder when all over the system is getting bigger.

B. Challenges of Study

In literature, there are some studies about balancing robot arms [1], [2]. However, the robot arms are generally balanced on a limited working range. In this study, the systems are tried to balance for full turn, 360^0 degrees. On the other hand, UUT is changed for different kinds of devices, which means that weight and off-axis distance are changeable. The moment, which is acted against the system of motion direction, is modified. Therefore, this study also tries to balance varying off-axis payloads.

C. Counter-Weight Mechanisms in Literature

As Yang and Lan declared, the major challenge of the balancing different payload system against gravity requires the complex designs. In Fig. 2, various types of balancing the system with spring force are showed. As it is seen in Fig. 2, if the system is utilized for different devices, which causes different torques on system, changing the attachment point of spring is not useful because of that extra effort requirement. Generally, the spring length is usually very long, a considerable length change is required to change spring load capacity. Because of this reasons, Yang and Lan designed the system in Fig. 3 [5].

Yang and Lan design is useful and compact that is shown in Fig. 3. However, Yang and Lan balancing system can only be utilized between 26^0 and -26^0 degrees [5].

As Ciupitu states in his article, the adaptive balance of robot arms is not easy to reach when the payload is changing. Therefore, the changing payload and motion spaces complicate the robot arm. Firstly, Ciupitu tries to balance robot arm with a counter-weight. However, when the payload changes there are two options to balance the robot arm, which are changing counter-weights or changing the position of counter weights. Because of the complexity of robot arm, Ciupitu tries to balance system by the help of spring forces. For the purpose of balancing different payloads, Ciupitu placed the springs with moveable connection points [1].

G. Karakaya is with ASELSAN, Ankara, Turkey (corresponding author, phone: +90-312-592-1000 (internal: 5472); fax: +90-312-354-1302; e-mail: gkarakaya@ aselsan.com.tr).

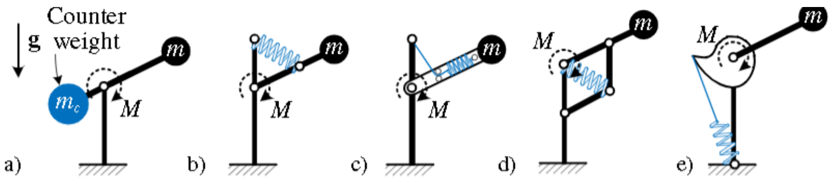

Fig. 2 Different Kinds of Gravity Balancing Systems

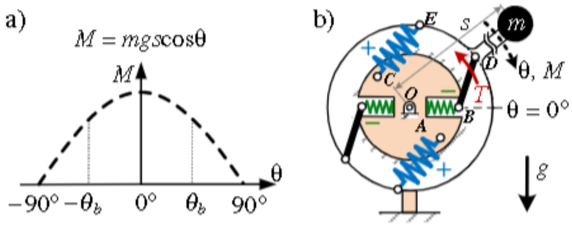

Fig. 3 Yang and Lan Gravity Balancing System Design [5]

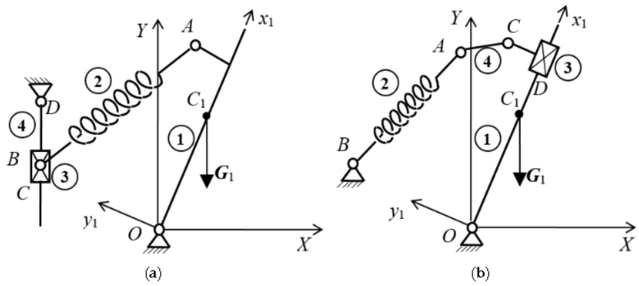

Fig. 4 Ciupitu's Adaptive Balancing (a) Controlled Relocation of Fixed Joint B of Spring (b) Controlled Relocation of Joint A [1]

As Olle declares in his thesis, an adjustable arm-supported table can be balanced for different weights against gravity by using a gas spring because gas springs can produce higher forces in small space. Moreover, gas springs have higher stroke against helical springs, which is very useful for the robot arm application. The gas springs position can be seen in Fig. 5. However, Olle's design has workspace limitation, which means that the design has to be used for the specified working range [3].

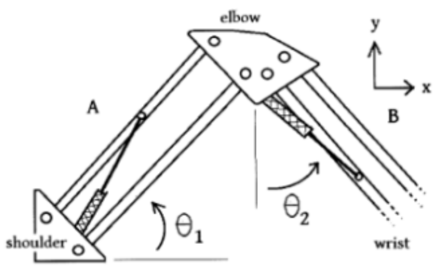

Fig. 5 Olle's Adjustable Arm Supported Table Design [3]

According to Lin et al., robot arms can be balanced by the help of springs. They try to implement springs as a counter weight to achieve higher accuracy and longer battery life on their wheeled desktop robot. The springs are designed and mounted on the proper design to reduce torque created by robot body weight. The robot has 4 DOF (degree of freedom), first and fourth DOF are balanced completely. For the other arm design the springs and their positions can be calculated to reduce dead weight, which effects on rotation axis. In the study, the robot's motion axes operate on limited ranges. Hence, the design only works for particular angles [2].

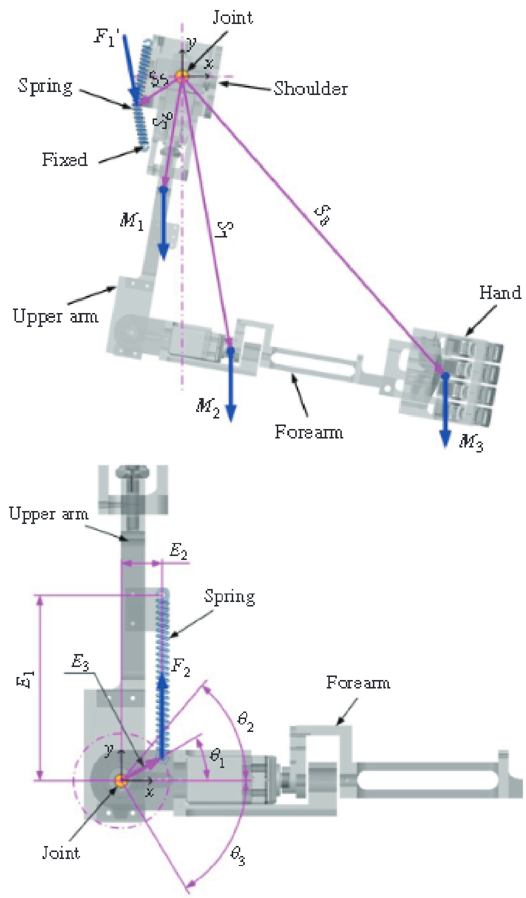

Fig. 6 Lin et al.'s Design [2]

II. Detailed Review of the Counter Balancing Mechanism

Cosine theorem can be used to find out value of a. Theorem can be expressed as;

$$A^2 = R^2 + L^2 - 2RLcos(90 + \alpha) \quad (1)$$

Cosine theorem can also be utilized to determine value of θ. θ can be represented as;

$$L^2 = R^2 + A^2 - 2RAcos(\theta) \quad (2)$$

$$\cos^{-1}\left(\frac{L^2-R^2-A^2}{-2RA}\right) = \theta \qquad (3)$$

TABLE I
CONSTANTS FOR MATHEMATICAL EQUATIONS

Symbol	Meaning
L	Difference between the Spring Connection Point and Center of the Shaft
A	Deformed Spring Length
C	Spring Length without the Load
k	Spring Coefficient
g	Acceleration of the Gravity
m	Mass of the UUT
B	Difference between Center of Mass of UUT and Center of the Shaft
R	Radius of Balancing Disk
α	The Angle Between Shaft Position and Zero Position of Shaft
θ	The Angle Between a and x Length
Δx	Linear Actuator Position

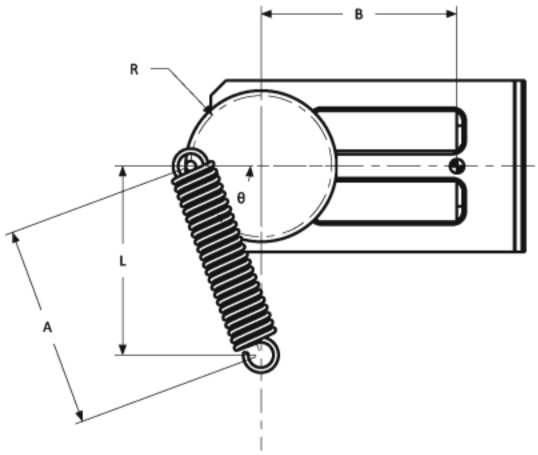

Fig. 7 Spring Balancing System Coefficients [4]

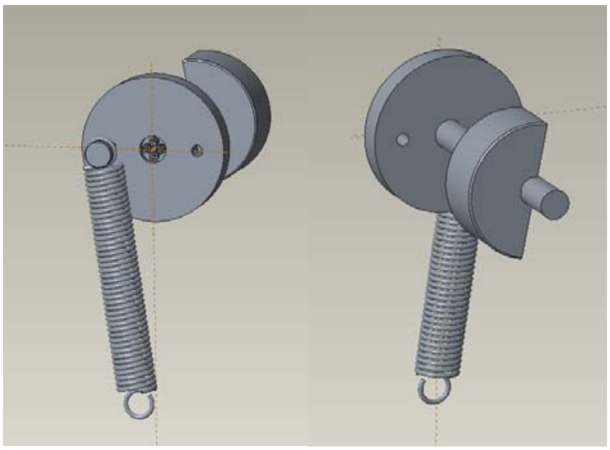

Fig. 8 Only Spring as a Counter-Weight

The force, which is acted by spring, can be calculated from (4). It can be written as;

$$F_s = (A - C) * k \qquad (4)$$

The effective spring force can be retrieved from (5) as;

$$F_{s_{effective}} = F_s * \cos(90 - \theta) \qquad (5)$$

The moment that is created by spring can be identified from (6), which is represented as:

$$M_s = F_{s_{effective}} * R \qquad (6)$$

The moment that is created by the UUT can be calculated from (7):

$$M_{uut} = m * g * B * \cos(\alpha) \qquad (7)$$

The moment difference between spring moment and UUT moment must be zero in order to say the system is balanced. Then, the equality can be written as;

$$M_{uut} = M_s \qquad (8)$$

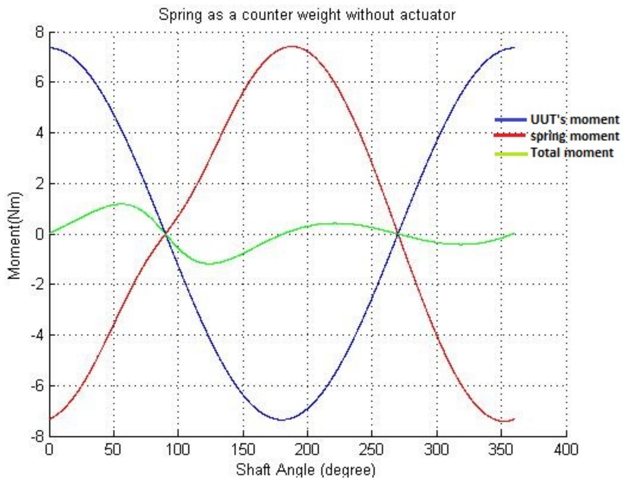

Fig. 9 Spring, UUT's and Total Moment Graph [4]

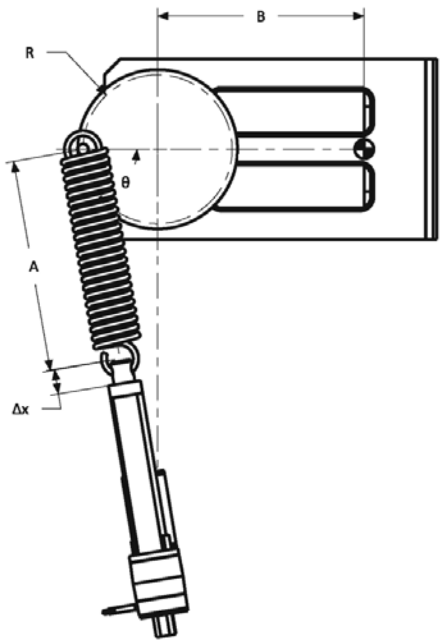

Fig. 10 Coefficients for Balancing System with Actuator [4]

All these equations and coefficients are written in MATLAB to visualize the graph on Fig. 9. As it can be seen from Fig. 9 the acting moment by UUT can be reduced by the help of spring force. However, it is not easy to eliminate all UUT moment completely. For instance, the moment created by UUT is equal when the shaft rotation angles are 110^0 and 250^0 in Fig. 11. On the other hand, the moment values that are created by spring are not equal at the 110^0 and 250^0 shaft rotation angles because of the effective length of the spring. Furthermore, the spring coefficient is linear for a limited range. In addition, it is hard to decide spring and its coefficient. A linear actuator can be utilized to ignore these spring problems and to balance system totally. As it is shown in Fig. 14, the system can be balanced completely when the spring and linear actuator are used together. The linear actuator position can be calculated from (9):

$$\Delta x = \left(\frac{M_{UUT}}{k * \sin(\theta) * R}\right) - A + C \tag{9}$$

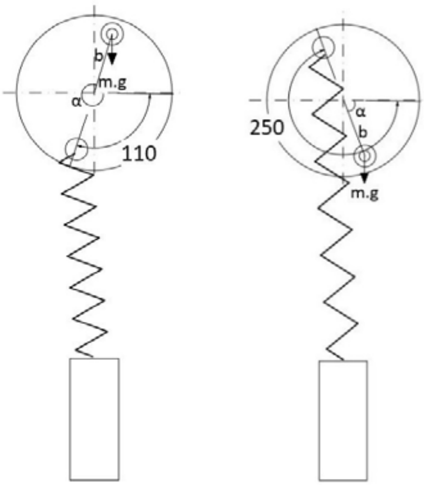

Fig. 11 Shaft Angle Positions at 110^0 and 250^0

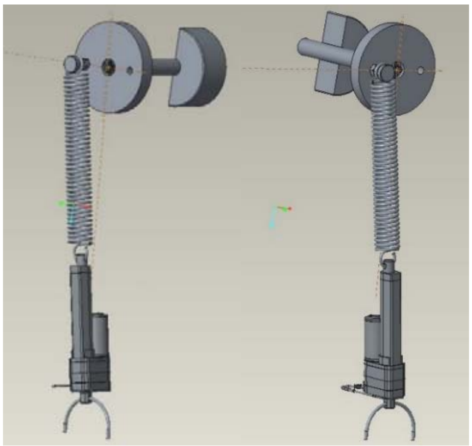

Fig. 12 Spring and Actuator Together and Adjustable Pin Position

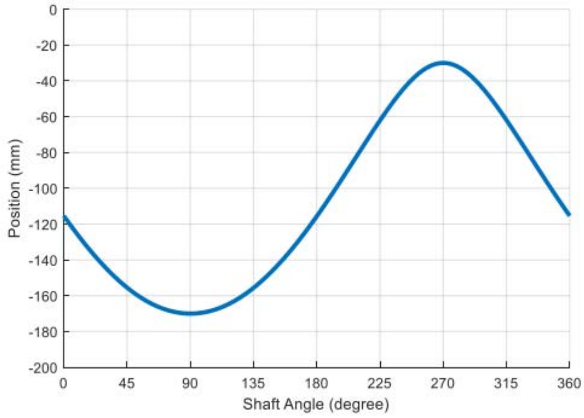

Fig. 13 Actuator position for every angular position of system [4]

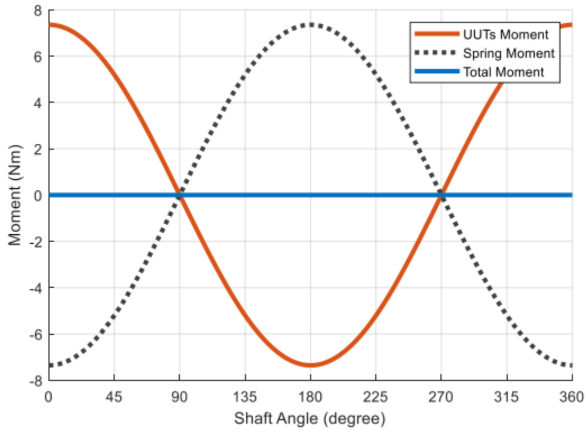

Fig. 14 Required Spring Moment and Total Moment [4]

III. Balancing System Analysis on Adams/View

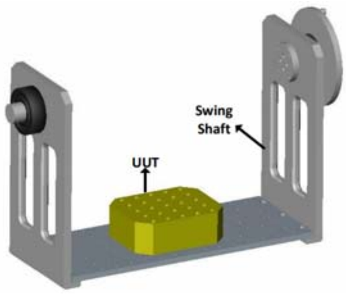

Fig. 15 Unbalanced System Model on Adams/VIEW [4]

Unbalanced system can be seen from Fig. 15. The center of mass of gimbal system with UUT is placed out of rotation axis, which causes extra moment for electrical motor. The created moment on rotation axis can be seen from graph on Fig. 16.

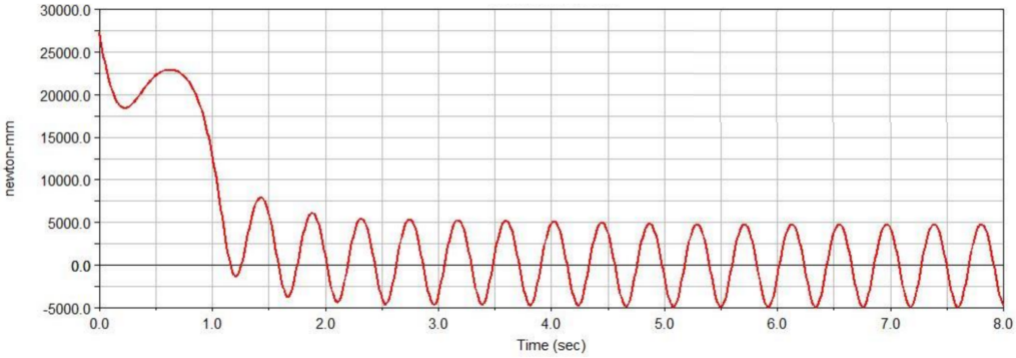

Fig. 16 Required Moment to Drive Unbalanced System [4]

In the first concept the spring is utilized for balancing the gimbal system with UUT. Therefore, Adams/View model can be seen from Fig. 17. The generated moment by unbalanced mass on system is decreased with the help of balancing disk and spring. Hence, the overall required moment to drive gimbal system can be seen from graph on Fig. 18.

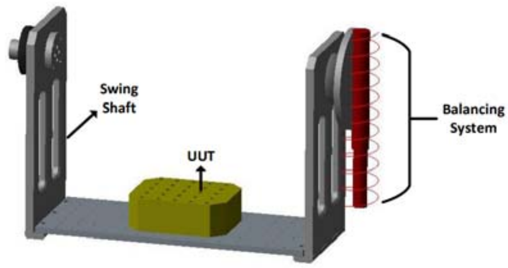

Fig. 17 Spring Balanced System Model [4]

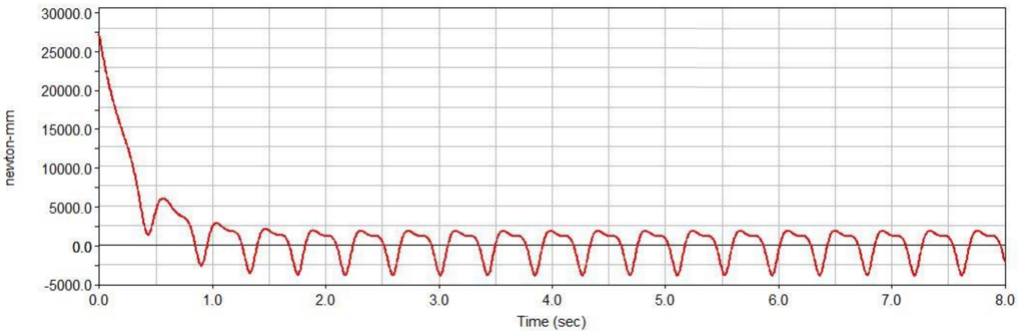

Fig. 18 Required Moment to Drive Spring Balanced System [4]

To get better balance concept two with actuator, spring and balancing disk are utilized to reduce unbalance moment from the gimbal. The analysis model can be seen from Fig. 19. When the solution is investigated the system is balanced much more effectively than the only spring balanced system, which can be seen from graph on Fig. 20.

IV. Modal Analysis on Ansys

The whole system is getting more sensitive to vibration with adding balancing system. Therefore, vibration may affect the system performance. In fact, the balancing system creates extra moment on system. Hence, the modal analysis has to be investigated. In Fig. 21, the whole system model can be seen on for modal analysis. The spring features can be seen on Table II.

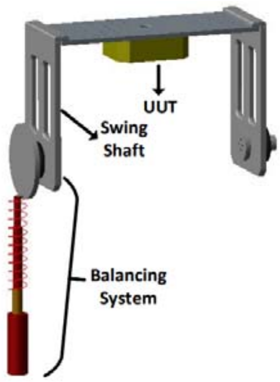

Fig. 19 Spring& Linear Actuator Balanced System Model [4]

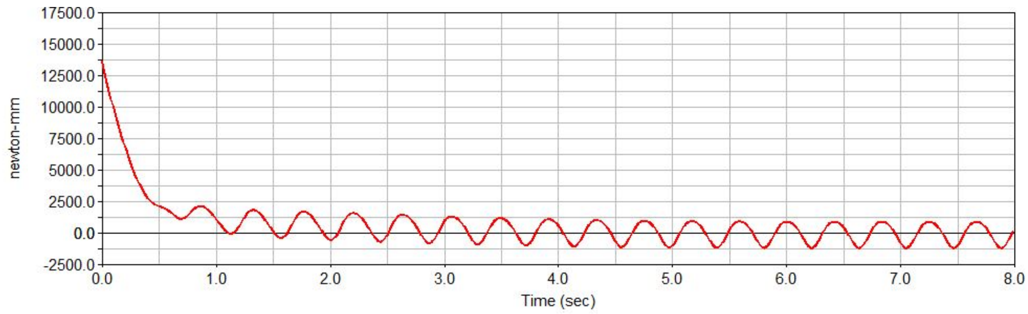

Fig. 20 Required Moment to Drive Spring& Linear Actuator Balanced System [4]

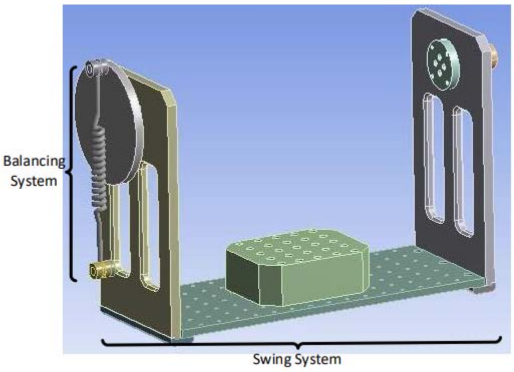

Fig. 21 System Model on Ansys [4]

TABLE II
INPUT FOR MODAL ANALYSIS

Coefficient	Meaning
Spring Stiffness	1.8 N/mm
Damping	0 N/mm
Free Length	200mm
Deformed Spring Length	250mm
UUT Mass	8 kg
Rotating Radius	150mm
Applied Moment	11.772 Nm

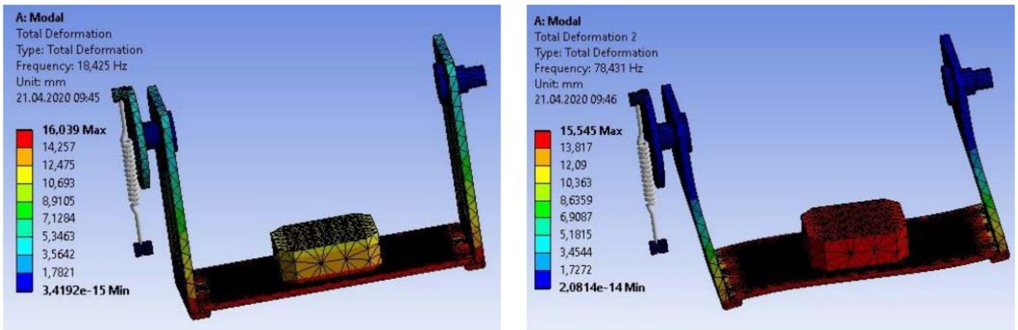

Fig. 22 First Two Modes of System [4]

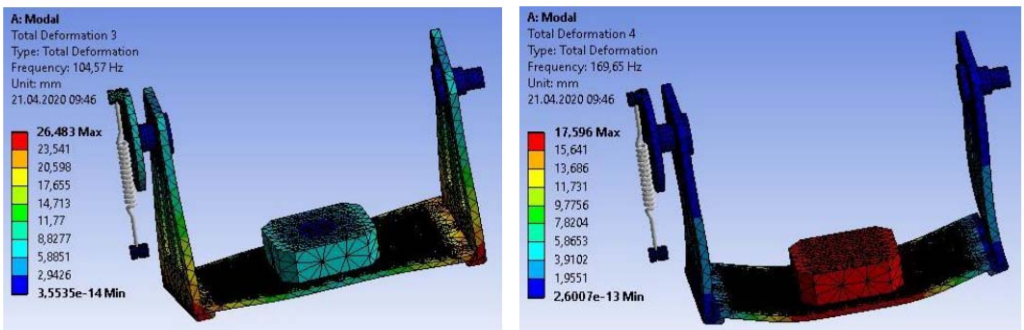

Fig. 23 Third and Fourth Modes of System [4]

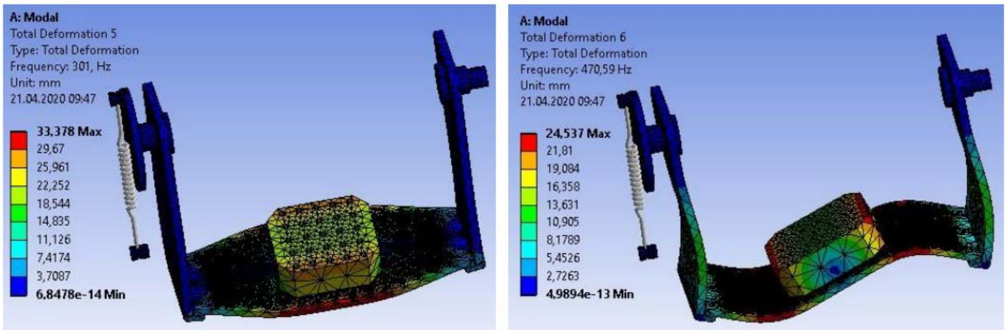

Fig. 24 Fifth and Sixth Modes of System [4]

The first six modes can be seen from Figs. 22-24. Resonance frequencies are 18, 78, 104, 169, 301 and 407 Hz for whole system with balancing. However, the gimbal systems working speeds are far below from the first critical speed. Therefore, the balancing system can be utilized for kind of low speed rotating systems. Also, FRF (frequency response function) graph can be seen from Fig. 25. The peak points on graph show the critical speed for system.

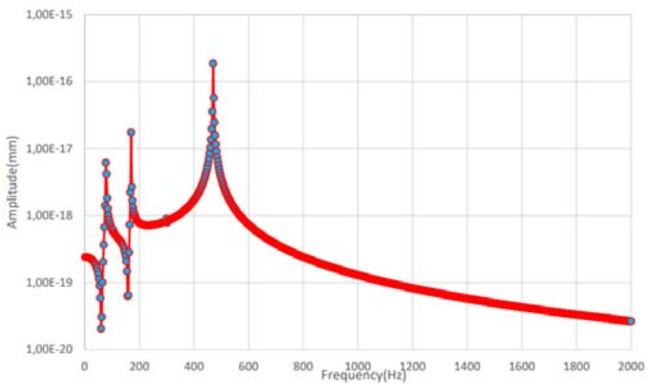

Fig. 25 Frequency Response Function Graph [4]

V. Conclusion

In order to balance off-axis weight of a rotary system, two solutions are proposed to be used in precision mechanical system. One of the solutions uses only spring as a counter weight, which is shown on Fig. 8. The other solution utilizes spring and linear actuator together as it can be seen from Fig. 9.

The first method, which uses only a spring, is called passive solution. The system compensates the unbalancing weight for 360^0 degree but the unbalanced weight cannot be eliminated totally on motor shaft by using only the spring. Moreover, the spring coefficient behaves linear for the limited range. If the system deviates from the limit of the spring, it cannot eliminate the off-axis weight exactly. Therefore, the second method is developed, which is called the active solution because of linear actuator. The second solution is also used to remove unbalancing for the range of 0^0 to 360^0. Furthermore, the second system eliminates unbalancing on the motor shaft completely by the help of linear actuator. The total unbalanced moment can be seen on Fig. 20.

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