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Effect Of Separation Springs On The Design Of A Spacecraft-Launcher Separation System

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Abstract— **The main aim of this paper is to preliminary design a satellite separation system and to show the benefits of using the computer simulation programs; like the MATLAB-SIMULINK; in understanding and analyzing the dynamic behavior of the spacecraft during the satellite separation. So, the study is dedicated to investigate the effect of separation springs of a spacecraft-launcher separation system on the dynamic response of spacecraft (satellite). A mathematical model describing the separation device scheme is deduced. A simulation program was developed, based on the deduced mathematical relations, and used to investigate the dynamic behavior of the system as well as to conduct a parametric study of the system.**

Keywords— Satellite Separation System;; Separation Springs; Simulink

I. INTRODUCTION

When launching a satellite, it is important that the satellite is secured to the launch vehicle during ascent and that the satellite separates safely while in space. A connection device is needed to secure the satellite to the launch vehicle and a release mechanism is needed to separate the satellite. When the satellite has been released it has to be ejected from the launch vehicle and be given the required kinetic energy. The system used to perform these actions is called a separation system, illustrated in Fig. 1

II. SEPARATION SYSTEM DESCRIPTION AND OPERATION

When designing a separation system, it is desirable to have a simple design, because the most important is to make the separation system reliable, i.e., the satellite has to separate every time. A separation system can be designed in various ways to meet the requirements.

A design of a separation system which uses a clamp band with a Clamp Band Opening Device (CBOD) and another design using a Fast-Acting Shock-less Separation Nut (FASSN) are shown in Fig. 2.

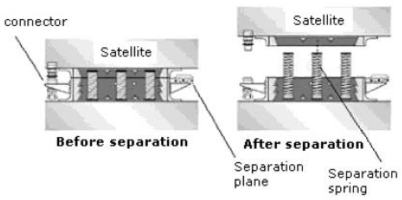

Fig. 1. *A schematic of a satellite separation system during the attachment and separation modes. [1]*

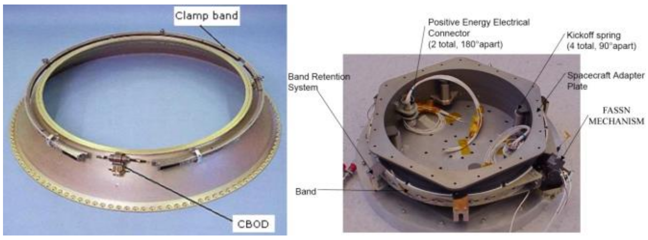

Fig. 2. *Separation system which uses a clamp, showing a FASSN release mechanism. [1] and[4]*

The clamp band is used to secure the satellite to the launch vehicle during ascent. During separation the clamp band releases and makes it possible for the satellite to separate from the launch vehicle. The purpose of the CBOD mechanism is to release the satellite in a controlled way that reduces the clamp band opening shock during separation. The tension in the clamp band is reacted by the CBOD when closed. This device is actuated by an electrical signal from the launch vehicle to release the tension in the clamp band and facilitate the proper release of the clamp band. This release mechanism is used whenever a low clamp band opening shock is recommended.

The CBOD and the FASSN systems are based on a high-lead, back drivable thread and a flywheel. A flywheel with the high-lead thread is held in place for launch. A mating high-lead thread is attached to the deployable portion of the device. When the interface is mated and preloaded, the high-lead thread creates a torque that wants to rotate the flywheel. The trigger of the release system depends on the Ship memory Alloy wire trigger (SMA). When the flywheel is released, the flywheel “spins-up” as the deployable element is extracted. The CBOD, Fig. 3 a, deployable element is the pin puller, while for the FASSN system, the releasing element is the wrap wire.

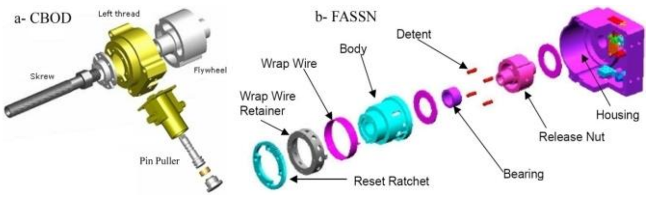

Fig. 3. *3D illustration of the CBOD and FASSN release mechanisms. [1] and [4]*

The separation springs are used to eject the satellite from the launch vehicle, Fig. 1. The ejection velocity depends on the number of springs, their stiffness and their pre-compression. The angular rate of the satellite depends on the design of the separation mechanism. There are two types of separation; symmetric separation, where the separation springs do not contribute to the satellite rotation after separation, and asymmetric separation, where the separation springs give contribution to the satellite rotation after separation. The symmetric separation is preferred if the separation should not cause any satellite rotation. However, if a certain angular rate on the satellite is allowed, the asymmetric separation can be used. The spring sizes and placements decide how the separation will occur and the requirements on the system decide which type of separation will be used. Generally, the separation mechanisms do not require the addition of dampers, since the kinetic energy stays with the parts that separate, causing them to drift apart. [2]

III. MATHEMATICAL MODEL

The separation process consists of two phases; release and ejection. The release phase is the phase when the satellite and the launch vehicle have contact through the separation plane, while the attachment clamps are being released. The duration of this phase normally is within one millisecond. In this phase it is studied how the release mechanism affects the separation.

The ejection phase starts at end of the release phase and extends until the separation springs have lost contact with the satellite surface. The duration of this phase is within few tenths of a second, [4]. In this phase it is studied how the springs affect the separation.

This study will first be focused on the ejection phase of a symmetric separation, then a study of asymmetric separation will be conducted. A free body diagram of the system, Fig. 4, is constructed to show the different forces applied on the system components, assuming launcher body to be fixed and displacement of satellite body is relative to the launcher and there is very small damping effect on the motion of satellite, since the surrounding medium is not completely vacuum.

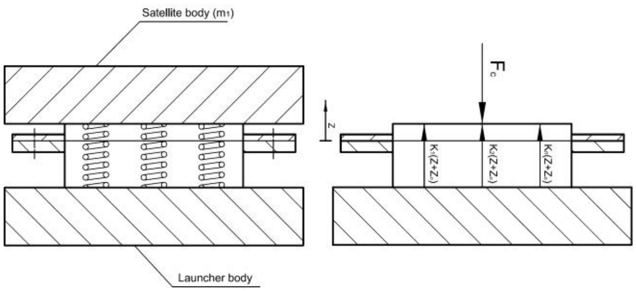

Fig. 4. *Free body diagram of the separation system.*

Assuming uniform distribution of mass of satellite body, motion and rotation are in one plane, CBOD and equivalent non pyro-techniques load drop time (release time), [4], is from 2 to 5 millisecond range, so, it will be assumed to be approaching zero, then

$$m_1\ddot{z} + f\,\dot{z} + m_1\dot{\emptyset}\dot{z} = F_s - F_c \qquad (1)$$

$$F_s = \sum_{i=1}^{n} K_i(z_o - z) \qquad (2)$$

$$\sum_{i=1}^{n} K_i(z_o - z) = \begin{cases} \sum_{i=1}^{n} K_i(z_o - z) & \text{for } z < z_o \\ 0 & \text{for } z \geq z_o \end{cases} \qquad (3)$$

$$F_c = \sum_{i=1}^{n} K_i(z_o) \qquad (4)$$

The clamping force Fc equals the total springs pre-compression force. It is assumed to be fully released instantly, in a step manner.

The displacement z is measured w.r.t the launcher body position at the time of separation. The clamp band main advantage is that it distributes the load uniformly along the perimeter of satellite and launcher fitting, though, the applied force of clamp can be represented by a single resultant force (FS) acting at the center of satellite base. The effect of spring forces are removed as the satellite travels a distance zo, Fig. 5; this is due to the complete extension of springs to its unloaded length.

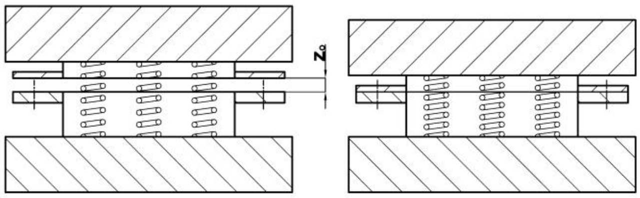

Fig. 5. *Separation mechanism showing satellite adapter last connection point with the launcher.*

The torque produced around the center of separation plane by the spring force distribution along the pitch circle diameter of separation system, Fig.6, can be expressed by the following equation (assuming torque in plane of motion only)

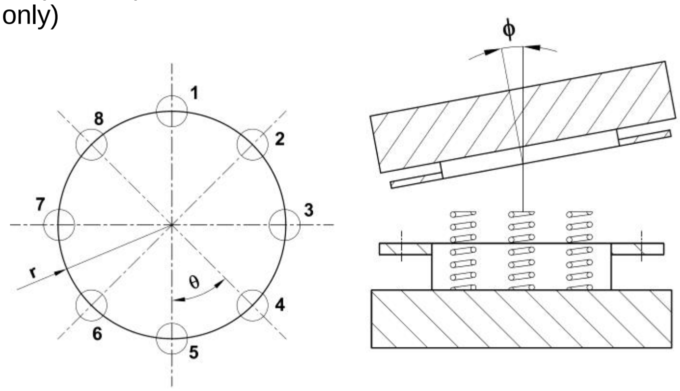

Fig. 6. *Springs distribution along pitch circle diameter of separation system.*

$$T = r\sin\theta\,(F_{s1} + F_{s2}) + F_{s3}\,r - r\sin\theta\,(F_{s6} + F_{s8}) - F_{s7}\,r \qquad (5)$$

$$T = J\,\ddot{\emptyset} + f_r\,\dot{\emptyset} \qquad (6)$$

IV. SIMULATION PROGRAM

The motion of the spacecraft is described by equations (1) thru (6). This mathematical model is used to develop the simulation program, by using the SIMULINK. The program is used to investigate the effect of different design parameters on the spacecraft dynamics, especially the spring stiffness and drag damping coefficient.

The numerical values of the studied systems were obtained from the available literature. They were either directly obtained or calculated from the response values found in references used in these papers

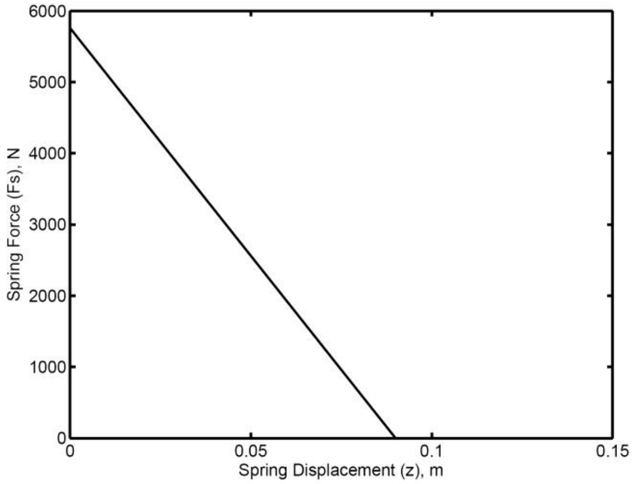

Fig. 7. *Spring force response to its displacement.*

Figure 7 shows the spring force-displacement relation, the spring force reaches zero when the satellite displacement (z) is equal to zo. At displacement z=zo, there would be no contact between the separation spring and satellite body. The time taken for the spring force to change from maximum value to zero, is the duration of the ejection phase.

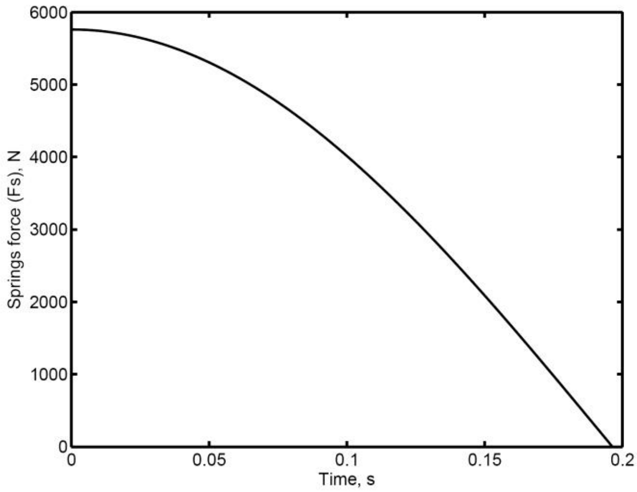

Fig. 8. *Transient response of the spring force to a step release of the clamping force at t = 0s.*

Figure 8 shows the transient response of the spring force to a step release of the clamping force at time t = 0s. This figure shows that the springs are completely released (ejection phase duration) during approximately 0.2 s.

A. SYMMETRIC SEPARATION

A study of the symmetry separation will be discussed in this section, constant spring stiffness along the perimeter was used. This leads to linear displacement of satellite in the direction of spring force vector, with no rotation taking place.

1) EFFECT OF SEPARATION SPRINGS STIFFNESS

The effect of spring stiffness on the displacement response of the satellite was investigated by considering different values of stiffness. At time t= 0 sec, the force Fc representing the clamp force will be removed, simulating the release of strain energy stored in the release mechanism (CBOD or FASNN), the following figure was obtained for constant satellite mass m1 = 1000 kg.

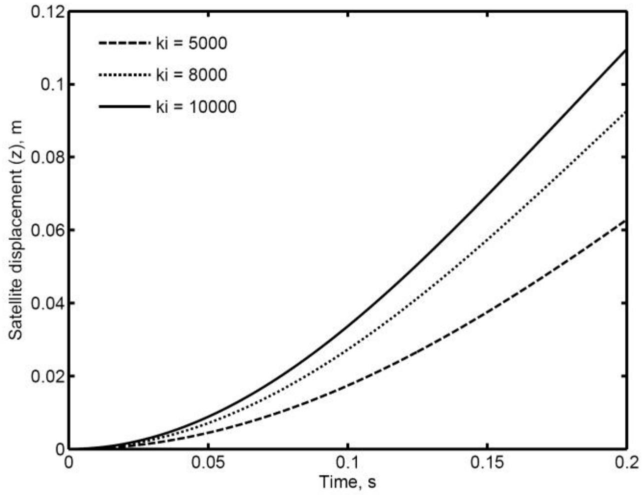

Fig. 9. *Satellite displacement (z) with time, for separation release at t= 0s for different spring stiffness.*

Fig. 9 shows that, the satellite displacement response increases with the increase of separation springs stiffness.

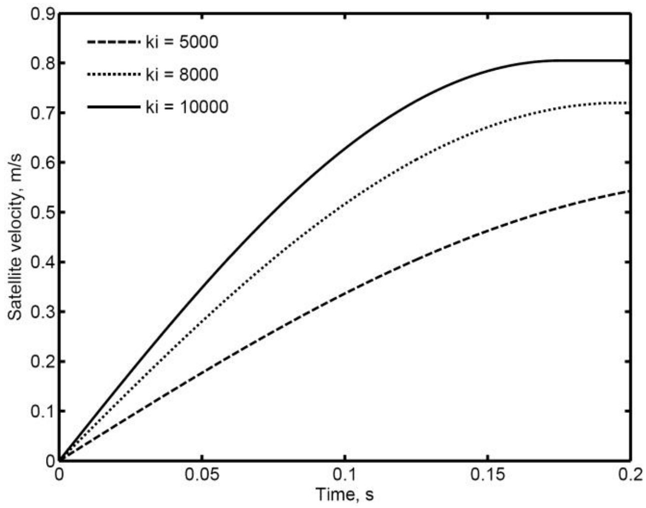

Fig. 10. *Satellite velocity response for different spring stiffness.*

The effect of the separation springs is also shown in Fig. 10, three different stiffnesses values were used, system release time was at t = 0s. for the three shown responses, the three responses stabilizes approximately at the same time (from 0.2 to 0.25s, the slower rate is for the smaller stiffness), the separation velocity stabilizes at v = 0.8 m/s for stiffness Ki = 10000 N/m, while it stabilizes at v = 0.55 m/s for stiffness value Ki = 5000N/m; A matter that clarifies that increasing the spring stiffness increases the separation speed.

2) EFFECT OF SATELLITE MASS

The get the effect of changing satellite mass on the satellite response, three different masses of satellite were introduced in the simulation program at constant spring stiffness Ki = 8000 N/m.

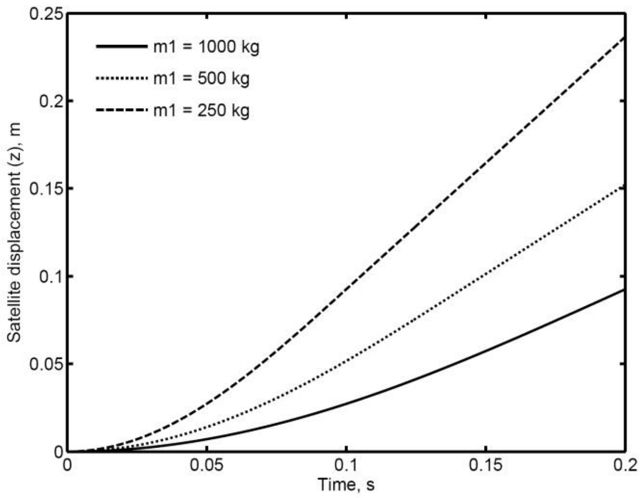

Fig. 11. *Satellite displacement response for different satellite masses after release time t = 0s.*

The satellite displacement response, Fig.11, shows an increase in displacement response with the decrease of satellite mass.

3) EFFECT OF DRAG DAMPING COEFFICIENT

The drag effect on the satellite transient response at the ejection phase has a great effect on the separation speed. To study this effect, a three estimated values of drag damping coefficients were introduced in the model.

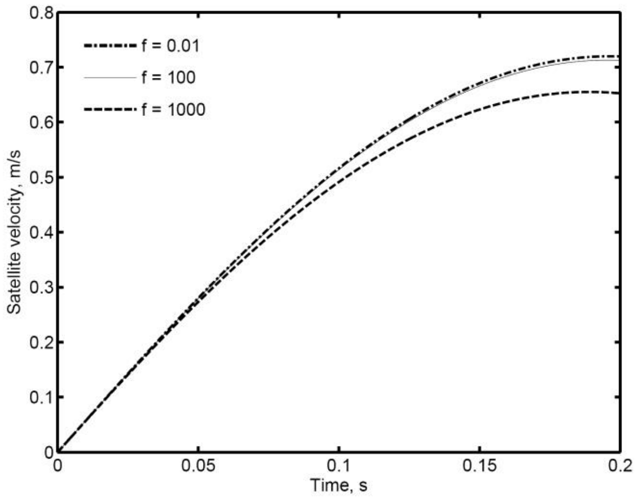

Fig. 12. *Satellite separation velocity for different drag damping coefficients, separation takes place at t= 0s.*

Fig.12, shows how the drag damping coefficients has a very small effect on the separation velocity, at t= 0s separation mechanism operates releasing the satellite, the system transient response time for the three estimated damping values are approximately the same and increasing the drag damping coefficients even with great values (0.01 100, 100) reduces the separation speed, but, with a small value in this very short period of time.

B. ASYMMETRIC SEPARATION

Asymmetric separation is another requirement that can be achieved from the separation system, this kind of separation is accompanied by rotation of satellite, this action can be achieved by varying the springs stiffness at one side of the separation pitch circle diameter.

By using fixed spring stiffness of 8000N/m for all spring except for springs 2, 3 and 4, the value of stiffness is 10000N/m. for satellite mass of 1000kg, zo = 0.09m, angle between springs are constant and equal to θ = 45o and finally a pitch circle radius of r = 0.25 m. the system shows the same dynamic behavior for the different changes shown in the symmetric system, but there occurs a rotation shown below.

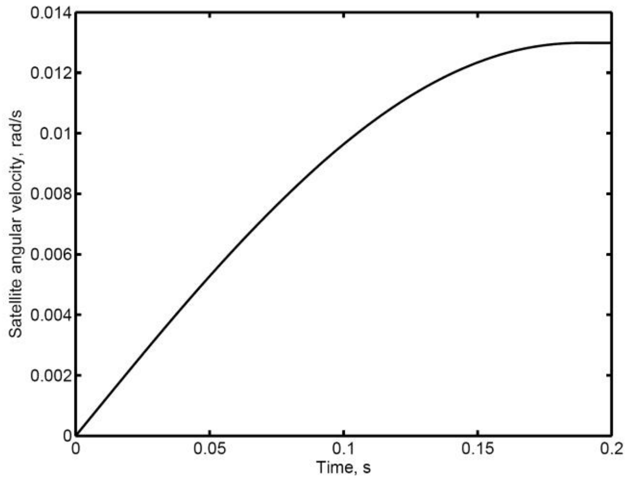

Fig. 13. *Satellite angular velocity response for release taking place at t=0s, rotational damping coefficient f_r= 0.01N ms/rad.*

Without any artificial damping to the satellite, just the same damping coefficient used for linear translation, the satellite angular velocity, Fig.13, shows a steady state of 0.013 rad/s after 0.2s.

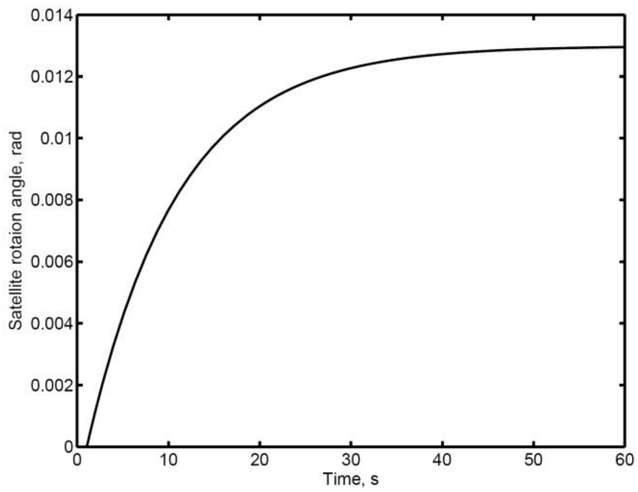

Fig. 14. *Satellite separation angle (Φ) using k2=k3=k4= 10000N/m, rest of springs stiffness = 8000N/m, m1=1000, zo=0.09m,r= 0. 25m, θ=45o.*

If the rotational angle of the released satellite needs to be fixed at any required value, an extra rotational damping (fr) is required. Using a rotational damping coefficient fr = 1000N ms/rad (by using an artificial damper) results in an over-damped response of satellite rotation that starts at t= 1s and settles at t= 60s, Fig.14, at an angle Φ=0.013rad=0.74o. To see the equivalent revolution per minute of this revolutionary motion, another relation between satellite rpm and time is shown in Fig.15.

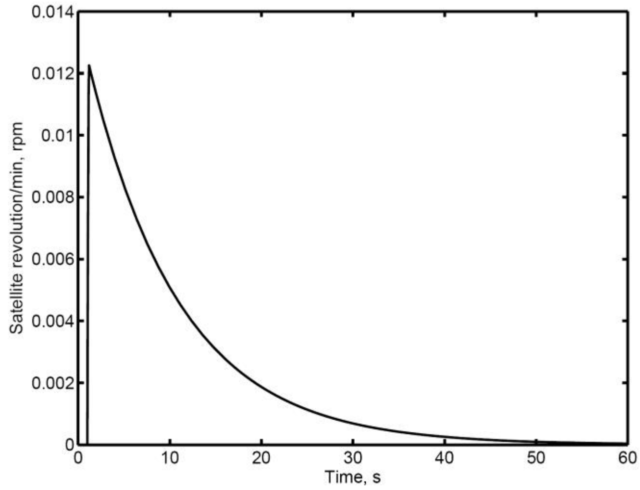

Fig. 15. *Satellite rotation speed response.*

The satellite speed response shows, Fig.15, a peak value of 0.0121 rpm at t=1s, which is at the time of release. The speed decreases after the ejection phase was finished, the speed reaches zero at approximately t=60s.

V. CONCLUSIONS

This paper deals with the dynamic behavior of the satellite separation system with no pyro-technique release mechanism used. System shows an ejection transient response time of 0.2 s; A value that agrees with the statement (The duration of ejection phase normally is in the magnitude of a few tenths of a second, [4].). The spring force response with the satellite displacement shows a cut-off force at 0 N, because the spring precompression distance is actually the distance travelled by the spring-satellite in contact after the separation mechanism was released.

The satellite displacement response showed a direct proportional relation with spring stiffness and an inversely proportion with the satellite mass and drag damping coefficient.

The separation linear speed (z), rotational angle (Φ), pitch circle radius, springs precompression, satellite mass and number of springs can be altered during an iteration design to achieve the specific technical requirements according to the available budgets. The SIMULINK simulation program is a powerful tool in design, which reduces experimental cost and time when trying to get a more tuned response of the implemented system.

A preliminary design of a separation system is produced, which needs to go through the iterative process between the spacecraft analysis, mathematical model and the structure scheme to produce the detailed design.

VI. RECOMMENDATIONS AND FUTURE WORK

The complete study was deduced from a simplified separation model, where assumptions need to be more refined. The data used in calculation is to be taken from an actual system.

Three dimensional studies (along 3 planes) should be completed to the introduced design, including the six degree of freedom movements along the three axes. After verification of this model, the detail design should start producing the material, design drawings and the critical load analysis should be carried out to be used for test procedures production.

VII. REFERENCES

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[4] David Dowen, Scott Christiansen, Development of a Reusable, Low-Shock Clamp Band Separation System for Small Spacecraft Release Applications, Starsys Research Corporation, Colorado, USA, 2001

[5] Matlab Reference Guide - The Math Works Inc, 1997

VIII. NOMENCLATURE

f	= 0.01	drag damping coefficient, N ms/rad.
F_c	--	Clamp band reaction force, N.
f_r	= 0.01	Rotational damping coefficient, N ms/rad.
F_s	--	Spring force, N.
J	= 1000	Polar mass moment of inertia, kg m^2
K_i	= 8000	Spring stiffness, N/m.
m_1	= 1000	Satellite mass, kg.
n	= 8	Number of evenly distributed springs.
r	= 0.25	Pitch circle radius of satellite separation fitting, m.
T	--	Torque applies around separation plane, Nm
Z	--	Satellite displacement, m.
Z_o	= 0.09	Spring precompression, m.
θ	= 45^o	Angle between springs along the pitch circle diameter, rad.
Φ	--	Rotation separation angle of satellite, rad.

APPENDIX A
MATLAB-SIMULINK SIMULATION PROGRAM

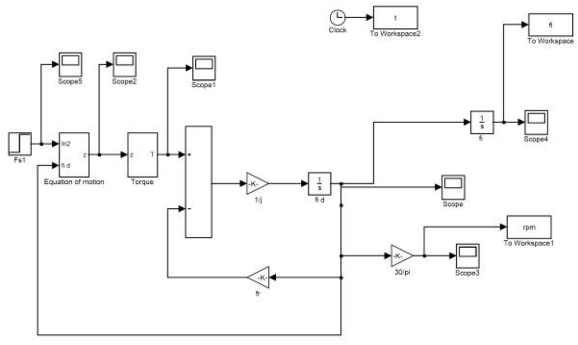

Fig. 16. *A1 Matlab-Simulink main block diagram.*

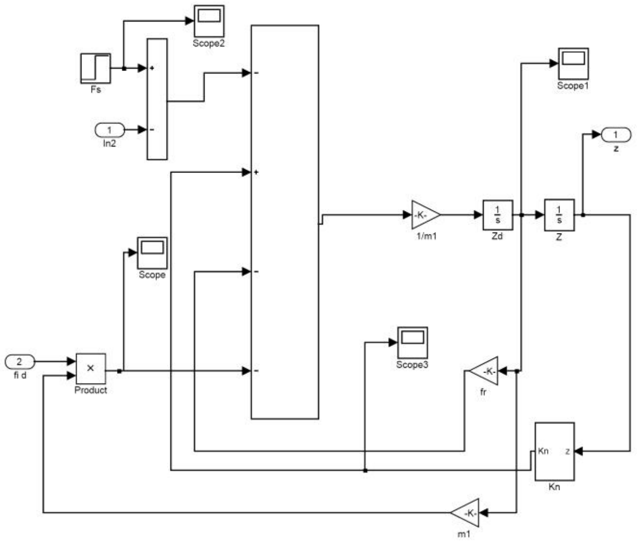

Fig. 17. *A2 Spring force Block diagram.*

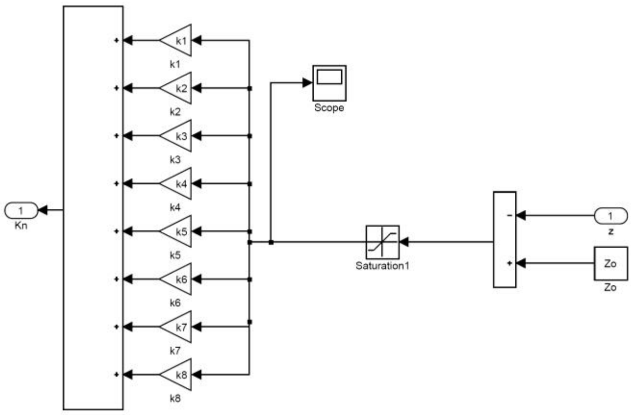

Fig. 18. *A3 Spring force Block diagram.*

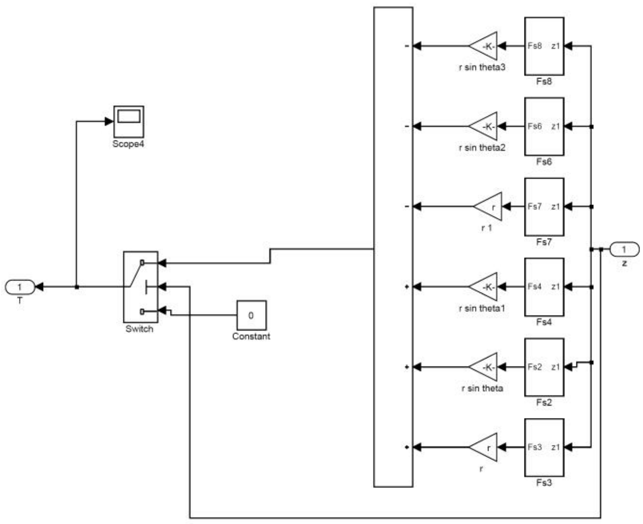

Fig. 19. *A4 Torque Block diagram.*