The Effect of Payload Weight to Mean Coil Diameter of Helical Compression Spring for Payload Separation System

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Abstract

Helical compression spring is commonly used in the payload separation system of sounding rocket. The purpose of helical compression spring is to jettison the payload when sounding rocket reach at the certain altitude. It is important to determine dimensional parameter of helical compression spring that will be used in the payload separation system, to ensure separation of payload will be done successfully without mechanical failure of spring. The previous study result showed that if the payload weight was 60 kg, the minimum wire diameter of helical compression spring must be 8 mm with mean coil diameter of 80-96 mm to avoid mechanical failure of the spring. In this study, the effect of payload weight to mean coil diameter of helical compression spring was investigated. The analytical method was used in this study. The results showed that maximum shear stress increased with increasing payload weight and mean coil diameter. In order to increase the payload weight, the mean coil diameter must be decreased. The maximum payload weight that can be used was 77 kg with the maximum mean coil diameter of 80 mm, and free length of 0.417 m. A safety factor of 1.65 and energy storing of 81.8 N.m was obtained.

Keywords: *payload; spring; separation, diameter, rocket.*

Nomenclature

d = wire diameter, mm

D_o = outside diameter, mm

D_i = inside diameter, mm

D = mean coil diameter, mm

L_f = free length, m

L_s = solid length, m

k = spring rate, N/m

δ = deflection, m

G = shear modulus of the material, GPa

N_a = number of active coils

1. Introduction

Sounding rocket release payload in the upper atmosphere to take measurements and collect scientific data. Sounding rocket is intended to carry the payload as much as possible. The JAXA sounding rocket of S-310 can reach the altitude up to 200 km with a maximum payload weight of 50 kg (Abe et al., 2009). In addition, the SS-520 sounding rocket has a capability for launching a payload weight of 140 kg to an altitude of 800 km (Inatani, Y., Ishii, N., Nonaka, S., & Abe, 2016). The Indian satellite launch vehicle (SLV-3) is a four-stage, solid-propellant space vehicle capable of putting a 50 to 60 kg payload in Low-Earth Orbit (LEO) (M.K. Abdul Majeed, 1984).

The separation system plays critical role for releasing payload from rocket (Hu et al., 2014). A reliable separation system ensuring the separation is free of collision and minimizing disturbance to the payload (Li et al., 2014). Separation system has two main purposes which are to hold payload and rocket together and to influence payload separation from rocket (Tayefi & Ebrahimi, 2009). The helical compression spring is typically used in separation systems (Hu, X., Chen, X., Tuo, Z., & Zhang, 2012). The Cubesat of 1 kg is separated by using spring with length of 180 mm (Kolawole et al., 2018).

As shown in Figure 1-1, the payload separation system is located in the upper side of rocket. When the payload needs to be separated, release mechanism in the payload separation system unlock payload from rocket and helical compression spring will exert force to the payload. It is important to determine dimensional parameter of helical compression spring that will be used in the payload separation system to ensure separation of payload will be done successfully without failure of spring. The previous study result show that to avoid mechanical failure of the spring, with the payload weight of 60 kg, the minimum wire diameter of helical compression spring was 8 mm with mean coil diameter of 80-96 mm (Laksono, 2021). Based on the previous study resulta, in this study the effect of payload weight to mean coil diameter of helical compression spring design for payload separation system was determined.

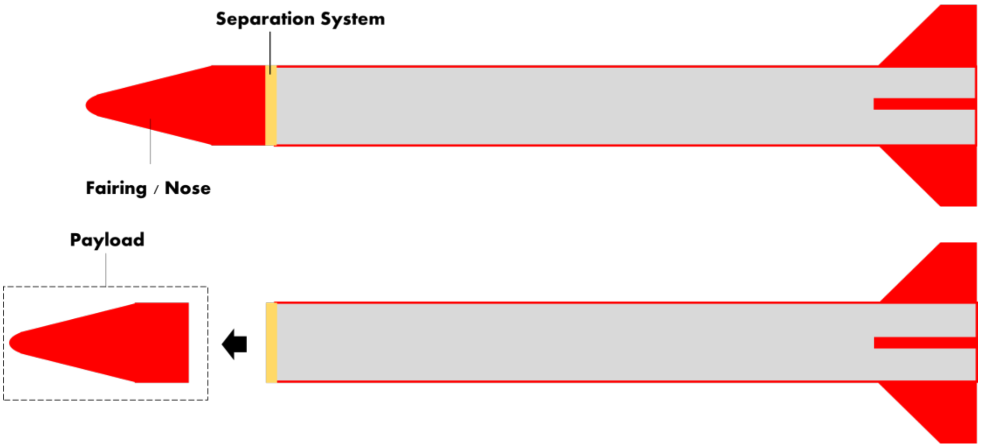

Figure 1-1: Payload Separation

2. Methodology

As shown in Figure 2-1 helical compression spring in the payload separation system, is axially loaded by payload weight, fully compressed and deflected to its solid length. In this study, helical compression spring was assumed to be suffered only static loading from payload weight. The other external forces which exert to the payload are neglected, except spring force.

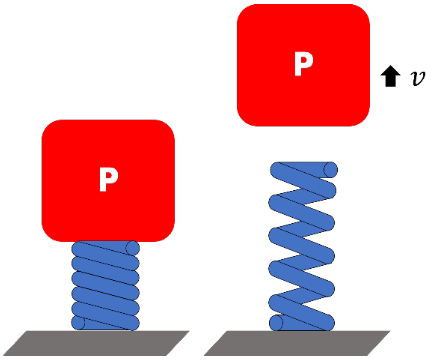

Figure 2-1: Payload and Spring.

Some parameters of helical compression spring such as maximum shear stress, yield shear strength, safety factor, deflection, free length, and energy storing were calculated in this study. Calculation of the helical compression spring parameters are constrained by the following conditions:

- Wire Diameter: 8 mm
- Number of springs used: 1
- Cross-section of wire: round
- Solid length of spring: 200 mm
- Material of spring: Hard drawn wire (ASTM A227)
- Shear modulus of spring: 80 GPa
- Payload Weight: 60 ≤ F ≤ 100 kg
- Type of ends: squared and grounds

2.1. Helical Compression Spring

Helical compression spring is spring with capability to resist compressive force. It is one of the most important spring in mechanical design (Wahl, 1944). They usually used in machinery or equipment for controlling vibration, reducing forces, applying forces, and storing energy (Sawanobori, T., Akiyama, Y., Tsukaharat, T., & Nakamura, 1985). Without an applied load, the spring length is called the free length. When a compressive force is applied, the coils are touch each other until the minimum length of spring achieved and this length is called the solid length (Pattar, S., Sanjay, S.J., & Math, 2014). Figure 2-2 shows a dimensional parameter of round-wire helical compression spring.

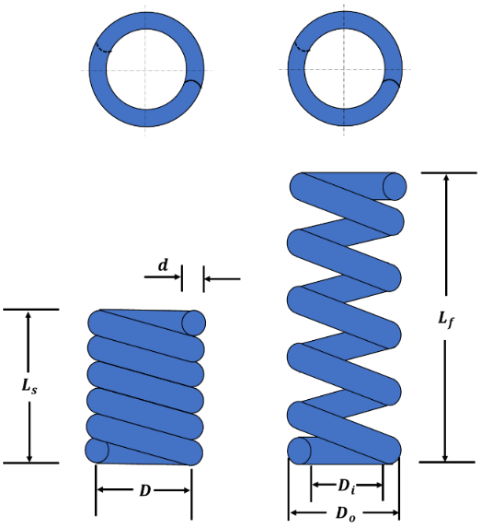

Figure 2-2: Dimensional Parameters of Helical Compression Spring.

Spring index is the ratio of the mean diameter of the coil to the diameter of the wire as expressed by equation below:

$$C = \frac{D}{d} \tag{2-1}$$

Spring rate (stiffness) is the load required per unit deflection of the spring as expressed by equation below:

$$k = \frac{F}{\delta} = \frac{d^4 G}{8\, D^3 N_a} \tag{2-2}$$

$$\delta = \frac{8 F D^3 N_a}{d^4 G} \tag{2-3}$$

2.2. Stress in Helical Compression Spring

The major stress generated in helical compression spring is shear stresses due to torsional moment (Chary & Reddy, 2016). As shown in Figure 2-3, round-wire helical compression spring, loaded by the axial compressive force.

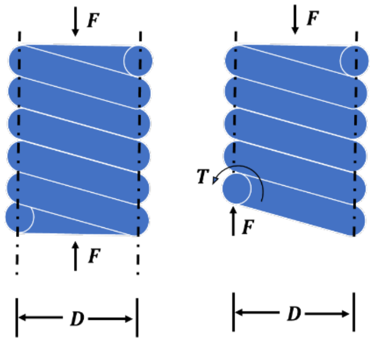

Figure 2-3: Free Body Diagram of Helical Compression Spring

The maximum stress in the wire may be calculated by superposition of the torsional shear stress $\tau_1$and direct shear stress τ_2 given by the equation below.

$$\tau_{max} = \tau_1 + \tau_2 \tag{2-4}$$

the torsional shear stress in a bar subjected to a torsional moment T is given by the equation below:

$$\tau_1 = \frac{8FD}{\pi d^3} \tag{2-5}$$

direct shear stress is given by the equation below:

$$\tau_2 = \frac{4F}{\pi d^2} \tag{2-6}$$

combining equation (2-5) and (2-6) we obtain:

$$\tau_{max} = \frac{8FD}{\pi d^3}\left(1 + \frac{0.5}{C}\right) \tag{2-7}$$

then the maximum shear stress is given by the equation below:

$$\tau_{max} = K_s \frac{8FD}{\pi d^3} \tag{2-8}$$

where K_s a shear-stress correction factor and is defined by the equation below:

$$K_s = 1 + \frac{0.5}{C} \tag{2-9}$$

The ultimate tensile strength is given by the equation below:

$$S_{ut} \cong Ad^{b} \tag{2-10}$$

where

$$A = 1753{,}3\ MPa$$

$$b = -0.182$$

The yield shear strength is given by the equation below:

$$S_{sy} = 0.577\ (0.75)\ S_{ut} \tag{2-11}$$

2.3. Buckling in Helical Compression Spring

Buckling of steel helical compression spring with squared and ground ends is given by the equation below:

$$L_f < 2.63\frac{D}{\alpha} \tag{2-12}$$

where α is a constant related to end condition and α values for end conditions can be seen in the table 2-1.

Table 2-1: End Condition Constants (Budynas, R.G., Nisbett, J.K, & Shigley, 2008)

End Condition	α
Spring supported between flat parallel surfaces (fixed ends)	0.5
One end supported by flat surface perpendicular to spring axis (fixed); other end pivoted (hinged)	0.707
Both ends pivoted (hinged)	1
One end clamped; other end free	2

3. Result and Analysis

Figure 3-1 shows the relationship between payload weight and maximum shear stress with mean coil diameter of 80, 88, and 96 mm. As shown in the figure, maximum shear stress increased with increasing payload weight and mean coil diameter. The combination between mean coil diameter of 80 mm with payload weight of 60 and 100 kg resulted in maximum shear stress of 245.7 MPa and 409.4 MPa, respectively. In addition, the combination between mean coil diameter of 88 mm with payload weight of 60 and 100 kg resulted in maximum shear stress of 269.1 MPa and 448.4 MPa, respectively. The combination between mean coil diameter of 96 mm with payload weight of 60 and 100 kg resulted in maximum shear stress of 292.6 MPa and 487.7 MPa, respectively. Meanwhile, the yield shear strength was 519.8 MPa.

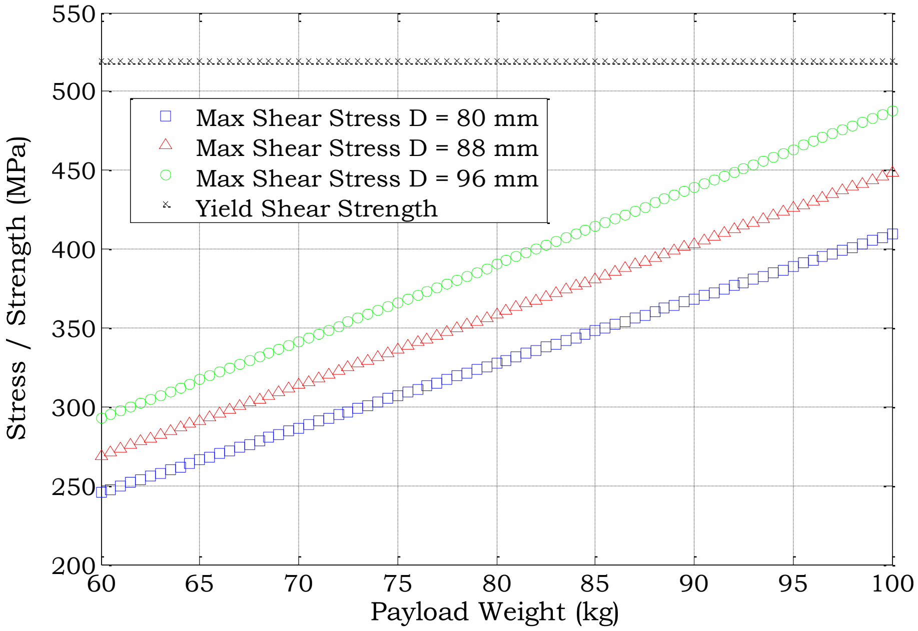

Figure 3-1 : Payload Weight vs Maximum Shear Stress.

Figure 3-2 shows the relationship between payload weight and safety factor. As shown in the figure, safety factor decreased with increasing payload weight. Also, smaller mean coil diameter has higher safety factor.

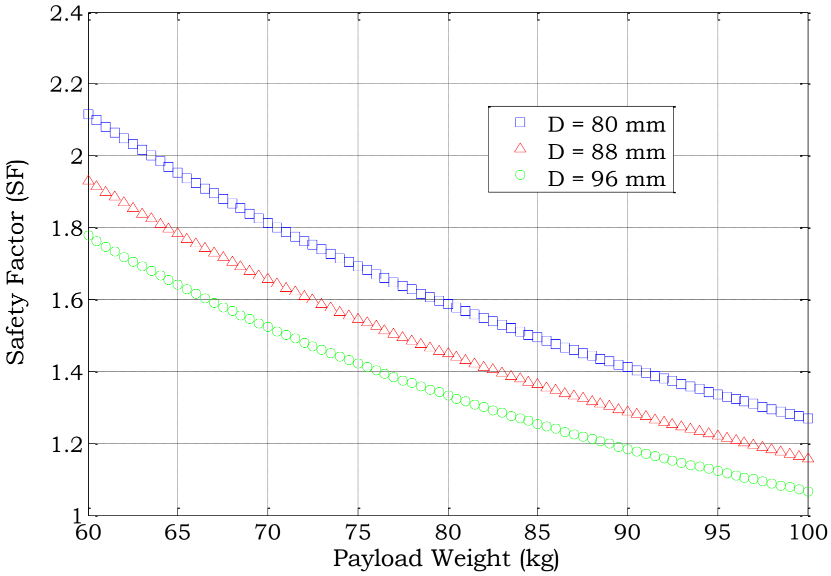

Figure 3-2 : Payload Weight vs Safety Factor.

Figure 3-3 shows the relationship between payload weight and spring deflection. As shown in the figure, deflection increased with increasing payload weight. The deflection of 0.169 m was obtained with the combination of payload weight of 60 kg and mean coil diameter of 80 mm. Meanwhile, the combination between payload weight of 60 kg with mean coil diameter of 88 mm and 96 mm, resulted in deflection of 0.225 m and 0.292 m, respectively. In addition, the deflection of 0.282 m was obtained with the combination of payload weight of 100 kg and mean coil diameter of 80 mm. Meanwhile, the combination between payload weight of 100 kg with mean coil diameter of 88 mm and 96 mm, resulted in deflection of 0.375 m and 0.487 m, respectively.

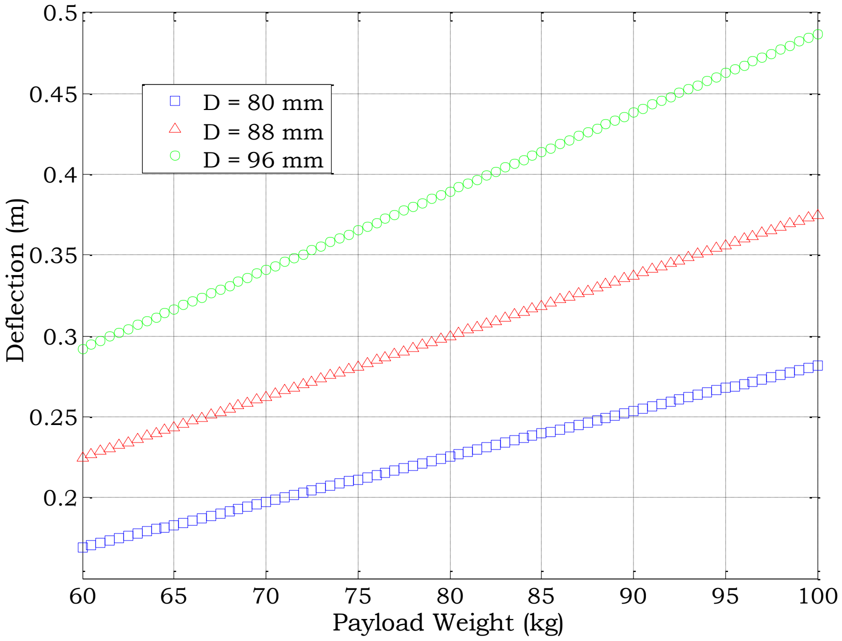

Figure 3-3 : Payload Weight vs Deflection.

Figure 3-4 shows the relationship between payload weight and free length with mean coil diameter of 80 mm. As shown in the figure, free length linearly increased with increasing payload weight. The free length of 0.369 m and 0.482 m were obtained with payload weight of 60 kg and 100 kg, respectively. The buckling criteria suggested that the free length shouldn't more than 0.42 m. The payload weight must be lower than 78 kg in order to avoid buckling problem.

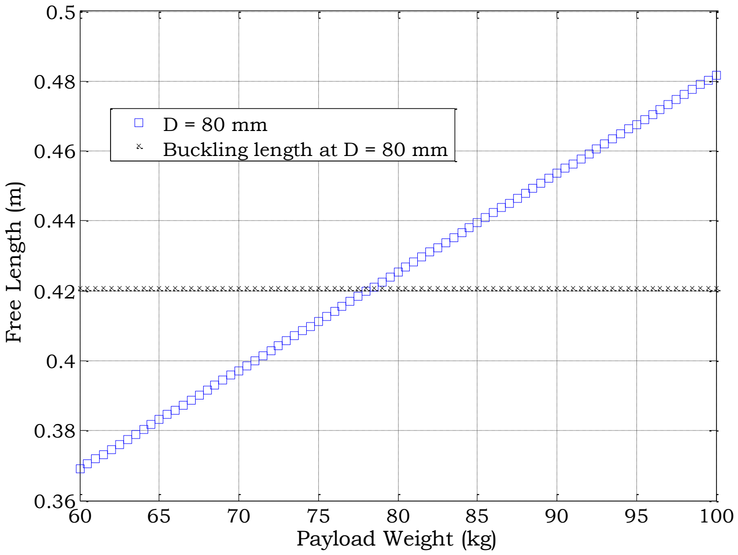

Figure 3-4 : Payload Weight Vs Free Length with D = 80 mm.

Figure 3-5 shows the relationship between payload weight and free length with mean coil diameter of 88 mm. As shown in the figure, free length linearly increased with increasing payload weight. The free length of 0.425 m and 0.575 m were obtained with payload weight of 60 kg and 100 kg, respectively. The buckling criteria suggested that the free length shouldn’t more than 0.463 m. The payload weight must be lower than 70 kg in order to avoid buckling problem.

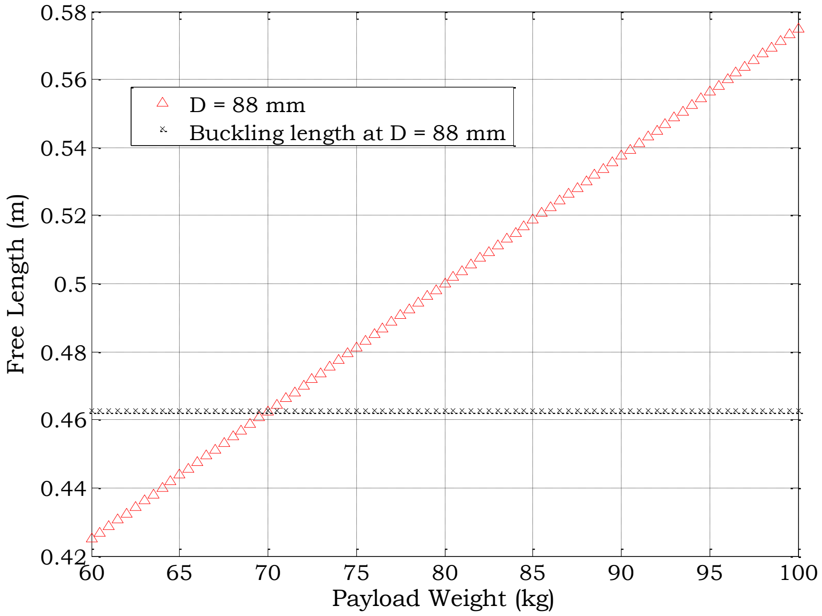

Figure 3-5 : Payload Weight Vs Free Length with D = 88 mm.

Figure 3-6 shows the relationship between payload weight and free length with mean coil diameter of 96 mm. As shown in the figure, free length linearly increased with increasing payload weight. The free length of 0.492 m and 0.687 m were obtained with payload weight of 60 kg and 100 kg, respectively. The buckling criteria suggested that the free length shouldn’t more than 0.505 m. The payload weight must be lower than 62.5 kg in order to avoid buckling problem.

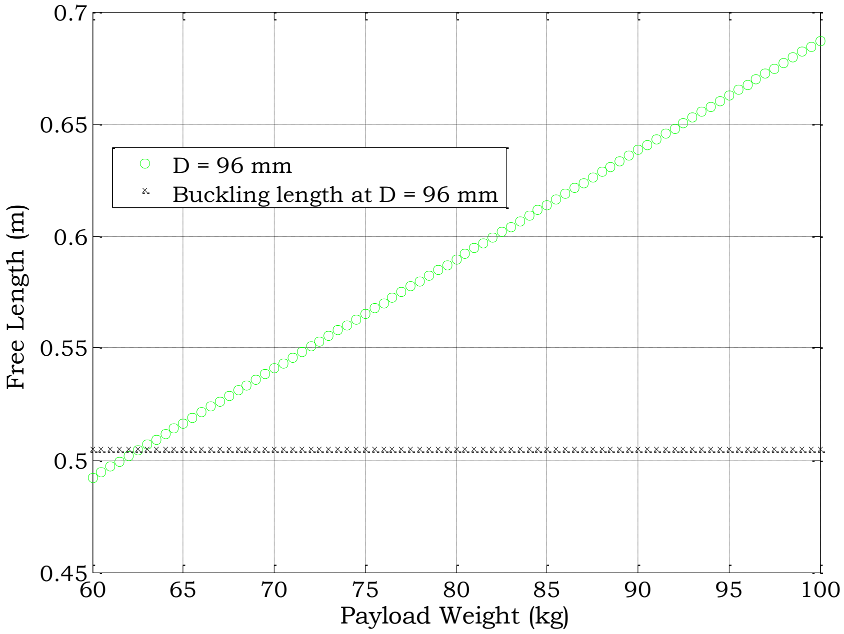

Figure 3-6: Payload Weight Vs Free Length with D = 96 mm.

Figure 3-7 shows the relationship between mean coil diameter and energy storing at the certain payload weight. As shown in the figure, energy storing increased with increasing mean coil diameter. The energy storing of 51.3 N.m was obtained with the payload weight of 61 kg and mean coil diameter of 80 mm. Meanwhile, the combination between the payload weight of 69 and 77 kg with mean coil diameter of 80 mm resulted in energy storing of 65.7 N.m and 81.8 N.m, respectively. In addition, energy storing of 68.4 N.m was obtained by using the payload weight of 61 kg and mean coil diameter of 88 mm. Meanwhile, the combination between the payload weight of 77 kg with mean coil diameter of 88 mm resulted in energy storing of 87.5 N.m.

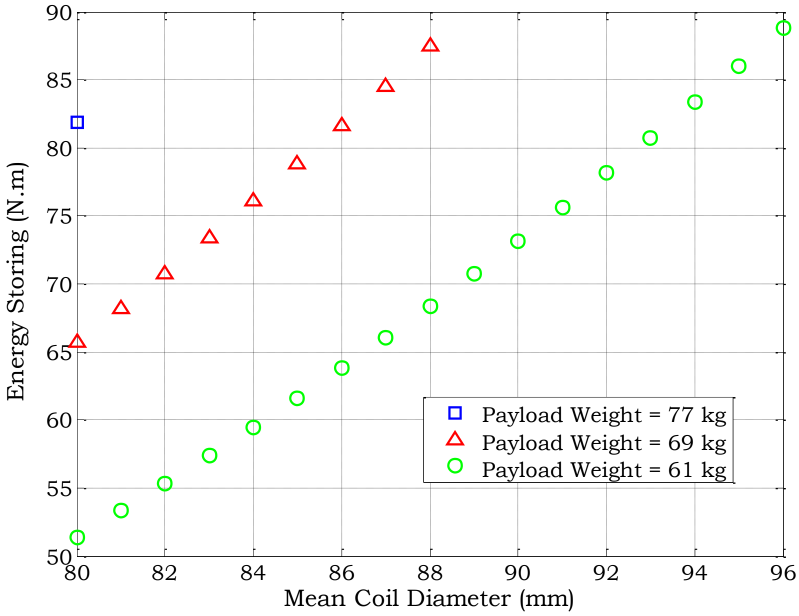

Figure 3-7 : Mean Coil Diameter vs Energy Storing.

4. Conclusions

Study the effect of payload weight to mean coil diameter of helical compression spring for payload separation system has been performed. The results showed that maximum shear stress increased with increasing payload weight and mean coil diameter. In order to increase the payload weight, the mean coil diameter must be decreased. The obtained result show that the payload weight of 77 kg was the maximum weight that the spring can overcome without mechanical failure. This condition was achieved by the maximum mean coil diameter of 80 mm and free length of 0.417 m. In addition, a safety factor of 1.65 and energy storing of 81.8 N.m was obtained.

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