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Design Analysis of Shafts using Simulation Softwares

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Abstract— a *shaft* is a mechanical component for transmitting torque and rotation, usually used to connect other components of a drive train that cannot be connected directly because of distance or the need to allow for relative movement between them. As torque carriers, shafts are subject to torsion and shear stress, they must therefore be strong enough to bear the stress, whilst avoiding too much additional weight as that would in turn increase their inertia. Now, generally the *shafts* are cylindrical in shape and have a keyway (a slot or pocket in which a key fits). A key is a machine element used to connect a rotating machine element to a shaft. A keyway or a slot is thus a point of high stress concentration and as the shafts are subjected to high torsion and shear stress, in order to have required optimal strength, additional weight has to be used, which inturn increases inertia and cost. Moreover, in long run wear & tear and the maintainance cost is also to be taken into consideration. In this research, we have analysed shafts having shapes other than circular (cylindrical shape) cross-section such as triangle, rectangle, ellipse, hexagon and pentagon. The stress has been calculated for each shape to get the shape with less stress value than the cylindrical one. This result will help us in reducing the additional weight added thereby reducing inertia and decreasing the overall material cost. The Factors such as cost and material (weight) used is important because of the application of the shafts, for example in gear boxes, ships, refineries, automobiles.

Index Terms—Pro-E, ANSYS, Shaft, Keyway.

1 Introduction

A shaft is a mechanical component for transmitting torque and rotation, usually used to connect other components of a drive train that cannot be connected directly because of distance or the need to allow for relative movement between them.

As torque carriers, shafts are subject to torsion and shear stress, equivalent to the difference between the input torque and the load. They must therefore be strong enough to bear the stress, whilst avoiding too much additional weight as that would in turn increase their inertia.

Figure 1.1: A five speed gearbox with gears connected to shafts

Now, a key is a machine element used to connect a rotating machine element to a shaft. The key prevents relative rotation between the two parts and enables torque transmission. For a key to function, the shaft and rotating machine element must have a keyway and a keyseat, which is a slot and pocket in which the key fits. The whole system is called a keyed joint. A keyed joint may allow relative axial movement between the parts depending on the applications.
Shafts are used in many industries, some important applications are in the gearbox (Figure 1.1), which inturn is used in marine applications, automobiles, power generation equipments, manufacturing industries, machines used to transmit power in various industries. Hence it can be seen that the applications are many.

As mentioned, the shaft contains a key and a keyway, which is basically a slot hence a point of high stress concentaration and as it is already pointed out that strenghh is very important factor from design point of view for the shaft to perform its function, hence additional material has to be used to compensate for the slot and achieve the required strength as needed in the application. The result is that due to this additional weight the inertia increases, cost of material and manufacturing cost (make the keyway) increases and in long run costs associated with wear and tear and maintainance increases.

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In this study we have used Pro-E, a design software, to design a shaft and ANSYS, a simulation software, to simulate the actual working conditions of a shaft and pulley attached to it at its centre. We have considered various other shapes for design apart from the cylindrical (General shape of the shaft) such as triangle, square, rectangle, rectangle with two semi circles at two opposite ends, pentagon, hexagon & ellipse. Kindly note that due to the crosssection of the shafts they do not require a keyway and a key to transmit the power. Thus, we will simulate the actual working condition on the shaft and calculate the stress at the intersection (maximum at the intersection). We will then analyse the results and come to a conclusion based on those results.

Calculations:

1. Cross section area of the shaft = 10000 mm2
2. Length of the shaft = 1000 mm
3. Material of the shaft = Mild Steel
4. Diameter of pulley = 500 mm
5. Width of the pulley = 100 mm
6. Material of the pulley = Cast Iron
7. Angular rotation of the assembly = 100 rad/s

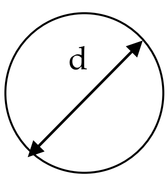
We calculate the dimensions for all the shafts with respect to 10000 mm2 cross section area.

1. Circle

Area of circle = 10000 mm^2

$$\therefore \frac{\pi}{4} \times d^2 = 10000 \text{ mm}^2$$

$$\therefore \mathbf{d = 112.8665\ mm}$$



2. Triangle

Area of triangle = 10000 mm^2

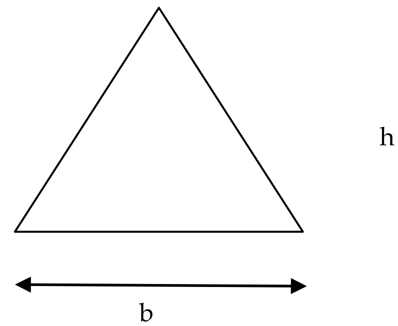
∴1/2×b ×h=10000 mm^2

For equilateral triangle: h=√ (3)/2 ×b

∴1/2 ×b ×√3/2 × b=10000 mm^2

∴b=151.9649 mm

& h=131.6094 mm

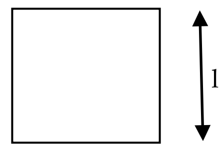


3. Square

Area of square = 10000 mm^2

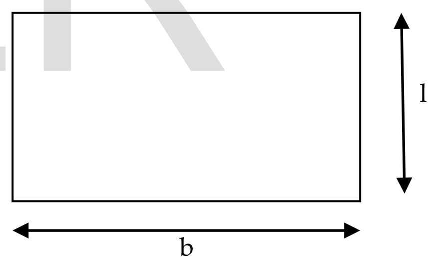
∴ l^2=10000 mm^2

∴ l =100 mm



4. Rectangle:

We take following 5 cases for the analysis of rectangular cross sectional shaft:



(I) l = 1.25 b
Area of rectangle = 10000 mm2
∴l × b=10000 mm^2
∴1.25 b × b=10000 mm^2
∴b=89.4427 mm & l =111.8034 mm

(II) l = 1.5 b
Area of rectangle = 10000 mm2
∴l × b=10000 mm^2
∴1.5 b × b=10000 mm^2
∴b=81.6496 mm & l =122.4745 mm

(III) l = 2 b

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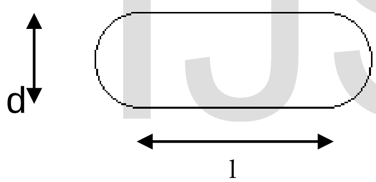
Area of rectangle = 10000 mm2
$\therefore l \times b = 10000\ mm^2$
$\therefore 2b \times b = 10000\ mm^2$
$\therefore b = 70.7107\ mm\ \&\ l = 141.4214\ mm$

(IV) $l = 2.5\ b$
Area of rectangle = 10000 mm2
$\therefore l \times b = 10000\ mm^2$
$\therefore 2.5\ b \times b = 10000\ mm^2$
$\therefore b = 63.2456\ mm\ \&\ l = 158.1139\ mm$

(V) $l = 2.75\ b$
Area of rectangle = 10000 mm2
$\therefore l \times b = 10000\ mm^2$
$\therefore 2.75\ b \times b = 10000\ mm^2$
$\therefore b = 60.3023\ mm\ \&\ l = 165.8312\ mm$

5. Rectangle with semi-circles at two opposite ends

We take following 8 cases for the analysis of rectangular cross sectional shaft with semi-circles at two opposite ends:



(I) $l = 0.25\ d$
Area = 10000 mm2
$\therefore (l \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore (0.25\ d \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore d = 49.1473\ mm\ \&\ l = 12.2868\ mm$

(II) $l = 0.5\ d$
Area = 10000 mm2
$\therefore (l \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore (0.5\ d \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore d = 88.2162\ mm\ \&\ l = 44.1081\ mm$

(III) $l = 0.75\ d$
Area = 10000 mm2
$\therefore (l \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore (0.75\ d \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore d = 80.7134\ mm\ \&\ l = 60.5351\ mm$

(IV) $l = d$
Area = 10000 mm2
$\therefore (l \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore (d \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore d = 74.8481\ mm\ \&\ l = 74.8481\ mm$

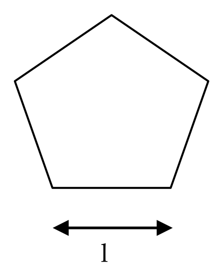
(V) $l = 1.25\ d$
Area = 10000 mm2
$\therefore (l \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore (1.25\ d \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore d = 70, 0999\ mm\ \&\ l = 87.6249\ mm$

(VI) $l = 1.5\ d$
Area = 10000 mm2
$\therefore (l \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore (1.5\ d \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore d = 66.1541\ mm\ \&\ l = 99.2312\ mm$

(VII) $l = 1.75\ d$
Area = 10000 mm2
$\therefore (l \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore (1.75\ d \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore d = 62.8074\ mm\ \&\ l = 109.9130\ mm$

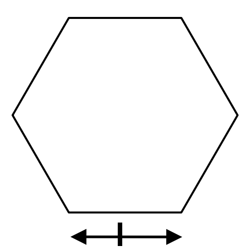
(VIII) $l = 2\ d$
Area = 10000 mm2
$\therefore (l \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore (2\ d \times d) + (\pi/4 \times d^2) = 10000\ mm^2$
$\therefore d = 59.9222\ mm\ \&\ l = 119.8443\ mm$

6. Pentagon:



Area of pentagon = 10000 mm2
$\therefore 1.7205\ l^2 = 10000\ mm^2$
$\therefore l = 76.2382\ mm$

7. Hexagon:

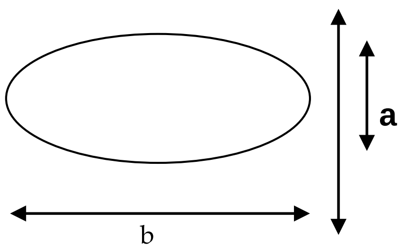


Area of hexagon = 10000 mm2

∴2.6 l^2=10000 mm^2
∴l =62.0174 mm

8. Ellipse:

We take following 4 cases for the analysis of elliptical cross sectional shaft:



(I) Area of ellipse = 10000 mm2
∴π/4 a × b= 10000 mm^2
∴π/4 a × (1.25 a) = 10000 mm^2
∴a= 100.9509 mm & b=126.1886 mm

(II) b = 1.5 a
Area of ellipse = 10000 mm2
∴π/4 a × b= 10000 mm^2
∴π/4 a × (1.5 a) = 10000 mm^2
∴a= 92.1551 mm & b=138.2327 mm

(III) b = 1.75 a
Area of ellipse = 10000 mm2
∴π/4 a × b= 10000 mm^2
∴π/4 a × (1.75 a) = 10000 mm^2
∴a= 85.3191 mm & b=149.3084 mm

(IV) b = 2 a
Area of ellipse = 10000 mm2
∴π/4 a × b= 10000 mm^2
∴π/4 a × (2 a) = 10000 mm^2
∴a= 79.8087 mm & b=159.6174 mm

Modelling and Analysis Procedure

Using Pro-E, we first make the parts (Shaft and pulley) that we are going to use for analysis and assemble the pulley with the shaft in such a way that it remains on the centre of the shaft. At both the ends of the shaft, we provide cylindrical extension of 100 mm length and diameter equal to the least distance from the centre of the cross sectional geometry of the shaft. The extension is provided considering the bearings mounted in actual working conditions. Then we browse that assembly in Ansys Workbench. In Ansys Workbench, we select 'Static Structural Analysis' as our project.

Then, we Import 'Mild steel' and 'Grey cast iron' amongst available engineering materials. In the Design modular, first of all we assign the materials to respective parts i.e. 'mild steel' to the shaft and 'grey cast iron' to the pulley. Then we set the co-ordinate system according to our requirement. Next, we apply the connection between the mating surfaces of both part as 'rigid connection, considering that in practical situation the fit (connection) would be interference fit.

For the next step, we apply the necessary boundary conditions, we apply 'cylindrical support' to the cylindrical extension of the shaft, keep the tangential component 'free' so that the shaft can rotate about its axis of rotation and apply angular rotation to the pulley of magnitude '100 rad/s'.

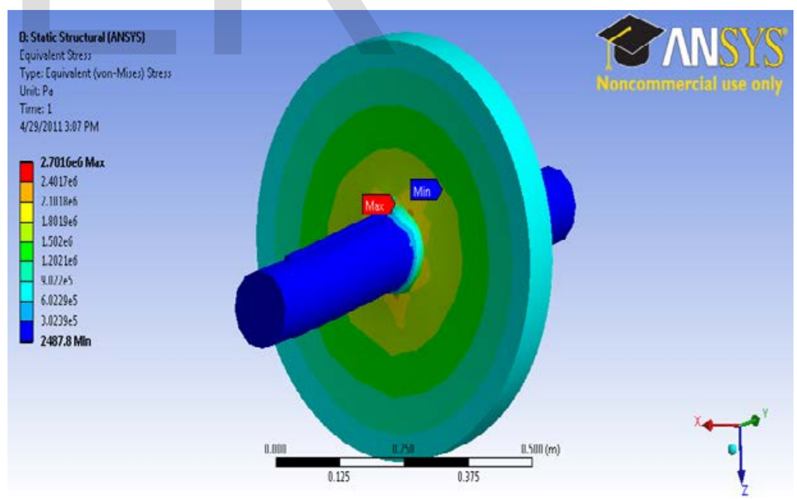
Now, to select the type of solution required from the available solutions, we select equivalent (von-Mises) stress for consideration.

We have kept the parameters such as material of shaft, material of pulley, cross section area of shaft, length of the shaft, dimensions of pulley, angular rotation, etc constant for all the analysis.

We now solve the model and get the result. As noted earlier that the stress will be considered at the intersection of the shaft and the pulley.

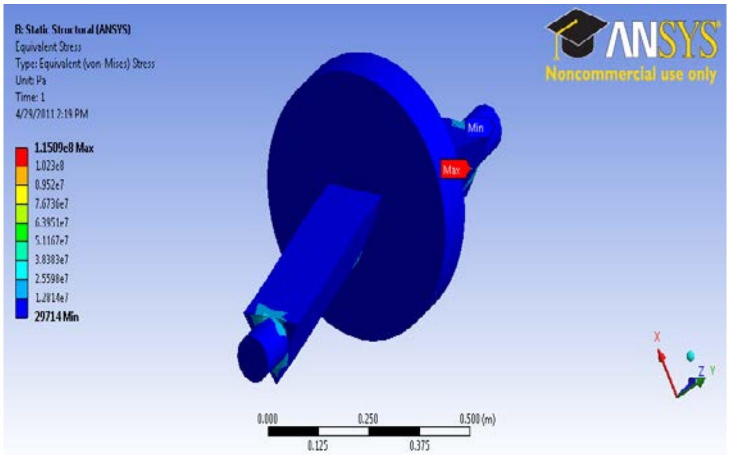
Analysis of the Result

1. Circular (cylindrical) cross-section:



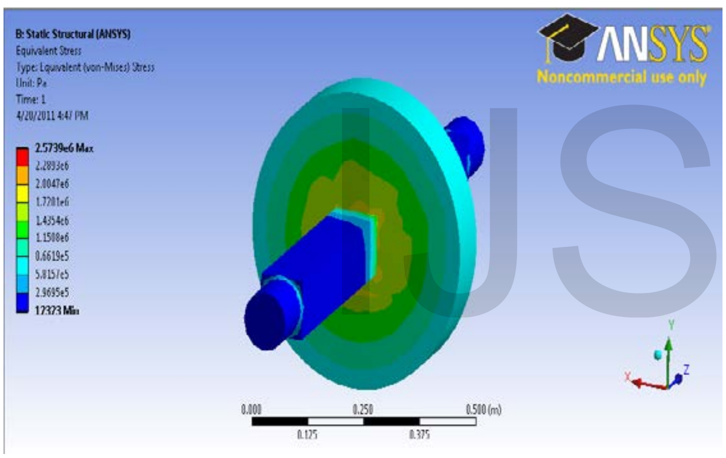
Comment: Stress generated in the shaft near pulley is 1.2021x10^6 Pa.

2. Triangular Cross-section:



Comment: Stress generated in the shaft near pulley is 2.5598x10^6 Pa. The shaft gets bend.

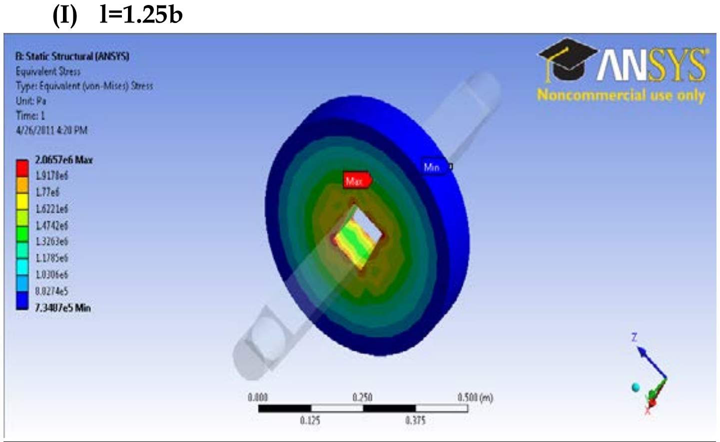
3. Square Cross-section:



Comment: Stress generated in the shaft near pulley is 1.720x10^6 Pa.

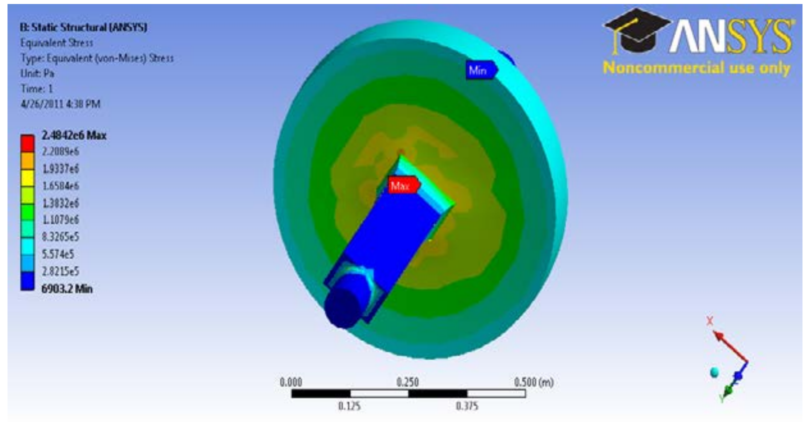
4. Rectangular Cross-section:

(I) l=1.25b



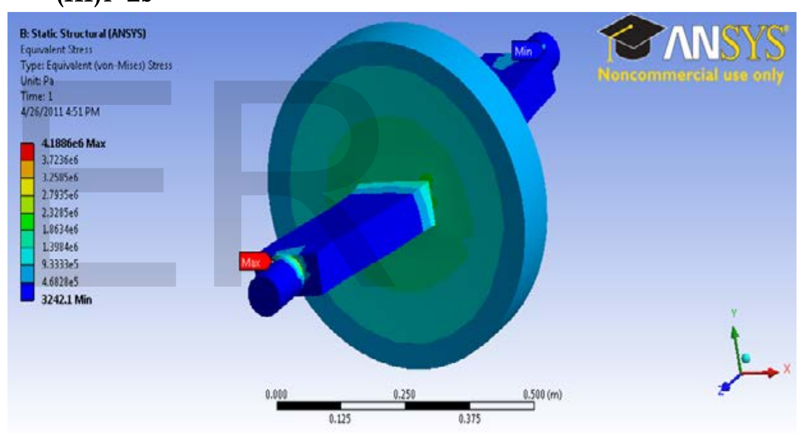
Comment: Stress generated in the shaft near pulley is 1.4742x10^6 Pa.

(II) l=1.5b



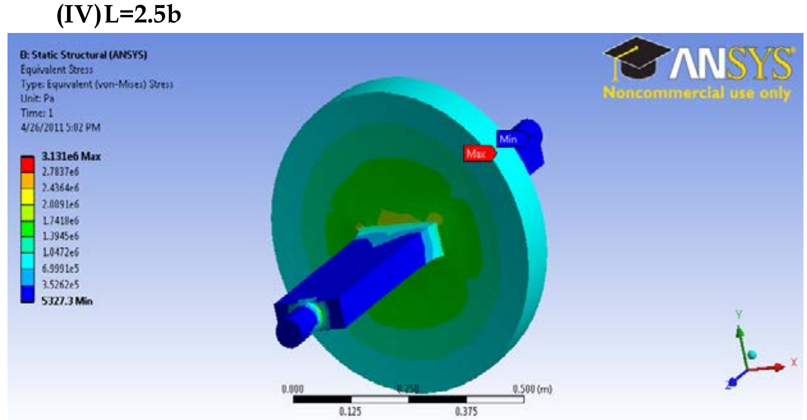
Comment: Stress generated in the shaft near pulley is 1.658x10^6 Pa.

(III)l=2b



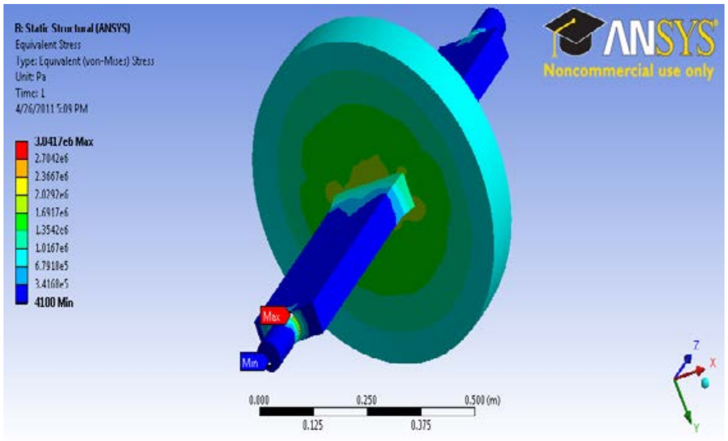
Comment: Stress generated in the shaft near pulley is 1.863x10^6 Pa. Vibration of the amplitude 1.8123x10^-6 m starts.

(IV)L=2.5b



Comment: Stress generated in the shaft near pulley is 2.089x10^6 Pa. Vibration of the amplitude 1.8817x10^-6 m starts.

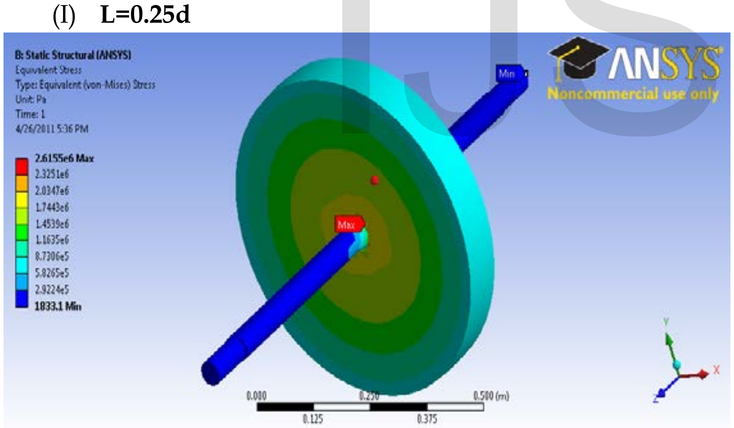
(V) L=2.75b



Comment: Stress generated in the shaft near pulley is 2.3667x10^6 Pa. Vibration of the amplitude 1.8467x10^-6 m starts.

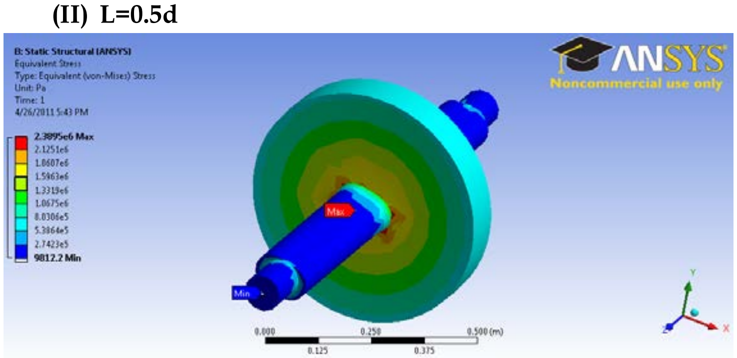
5. Rectangular cross-section with semi circles at two opposite ends:

(I) **L=0.25d**



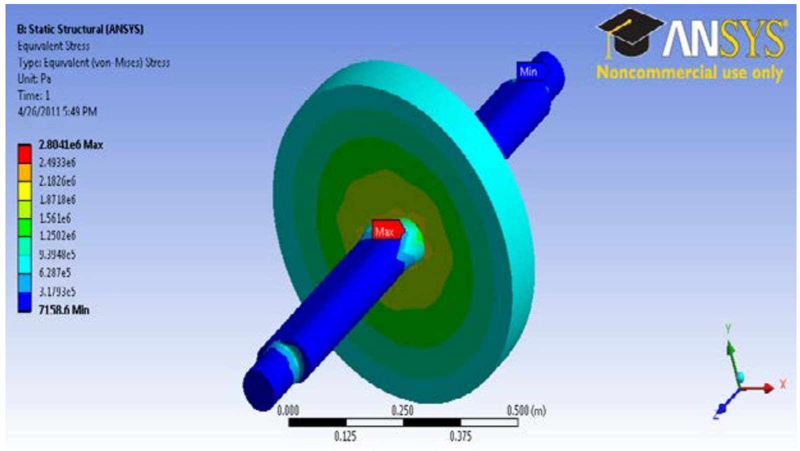
Comment: Stress generated in the shaft near pulley is 1.7443x10^6 Pa.

(II) L=0.5d



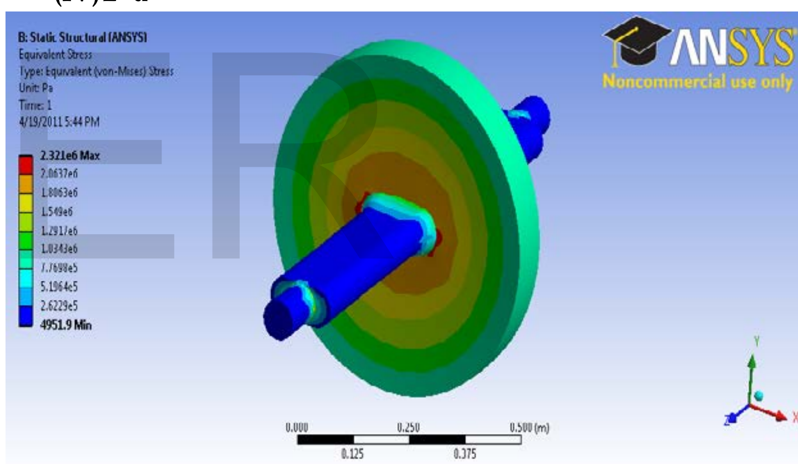
Comment: Stress generated in the shaft near pulley is 1.8607x10^6 Pa.

(III) L=0.75d



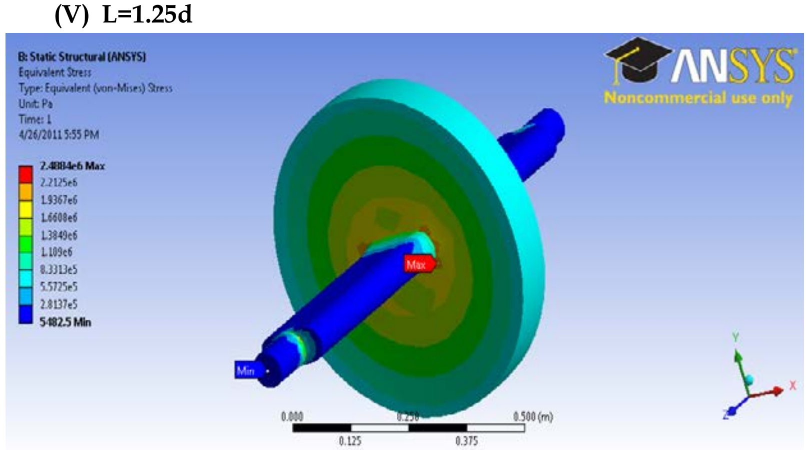
Comment: Stress generated in the shaft near pulley is 1.8718x10^6 Pa.

(IV) L=d



Comment: Stress generated in the shaft near pulley is 1.549x10^6 Pa.

(V) L=1.25d



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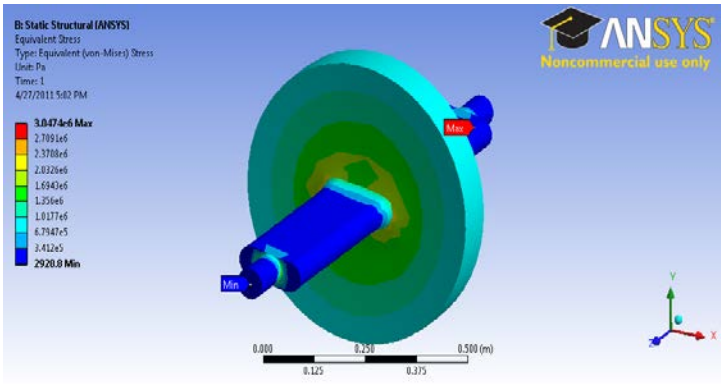
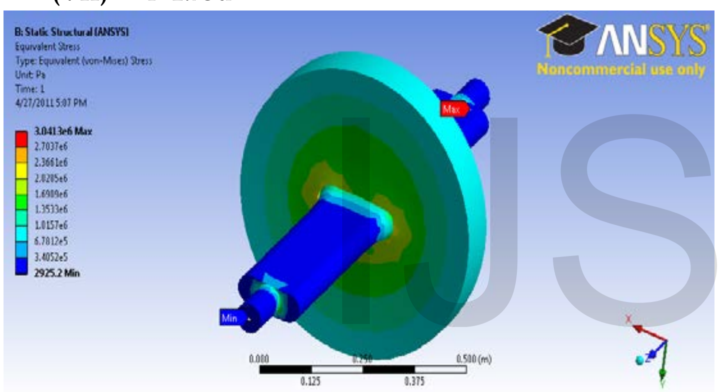
Comment: Stress generated in the shaft near pulley is 1.6608x10^6 Pa.

(VI) L=1.5d



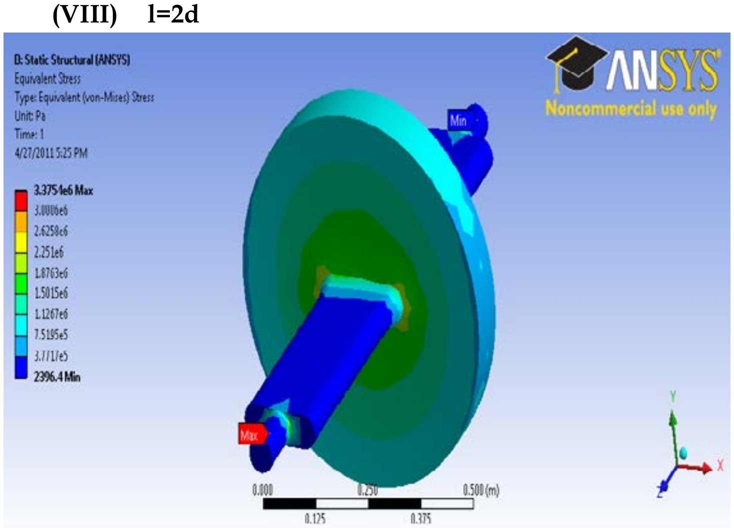
Comment: Stress generated in the shaft near pulley is 1.52515x10^6 Pa.

(VII) l=1.75d



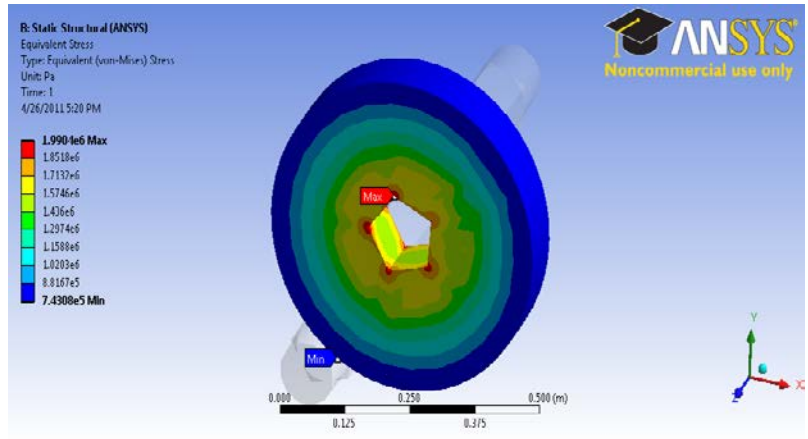
Comment: Stress generated in the shaft near pulley is 1.3533x10^6 Pa. Vibration of the amplitude 1.842x10^-6 m starts.

(VIII) l=2d



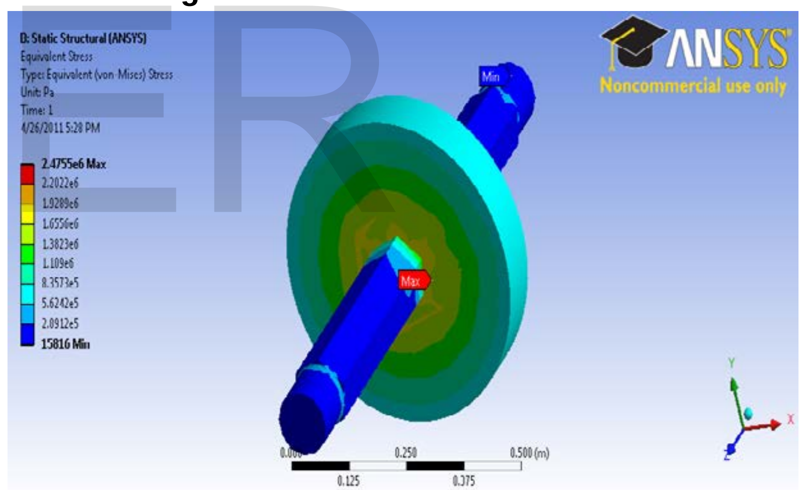
Comment: Stress generated in the shaft near pulley is 1.1267x10^6 Pa. Vibration of the amplitude 1.8654x10^-6 m starts.

6. Pentagon Cross-section:



Comment: Stress generated in the shaft near pulley is 1.5746x10^6 Pa.

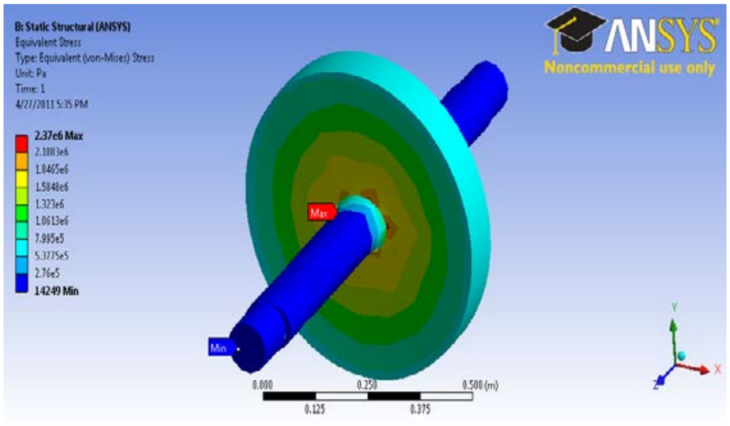
7. Hexagonal Cross-section:



Comment: Stress generated in the shaft near pulley is 1.3823x10^6 Pa.

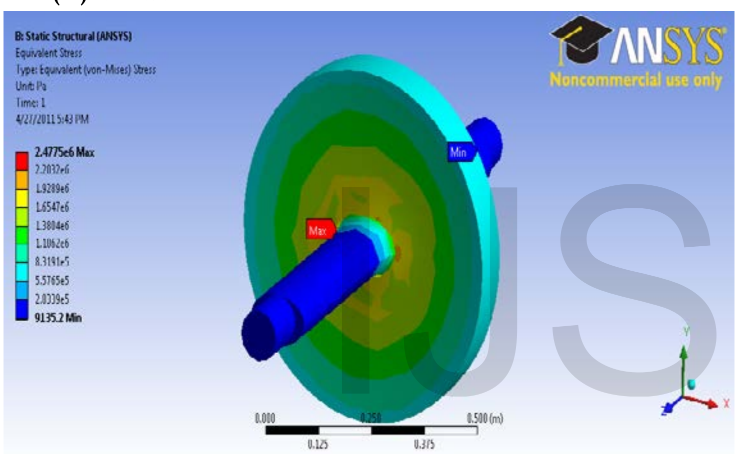
8. Elliptical Cross-section:

(I) b=1.25a



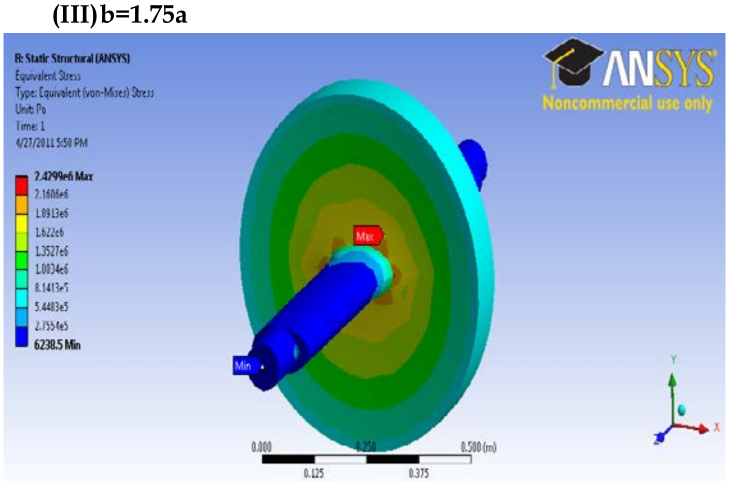
Comment: Stress generated in the shaft near pulley is 1.0613x10^6 Pa.

(II) b=1.5a



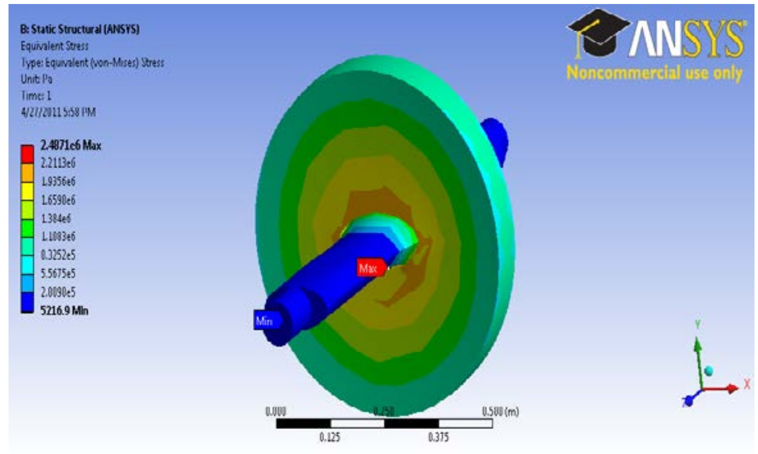
Comment: Stress generated in the shaft near pulley is 1.3804x10^6 Pa.

(III) b=1.75a



Comment: Stress generated in the shaft near pulley is 2.089x10^6 Pa.

(IV) b=2a

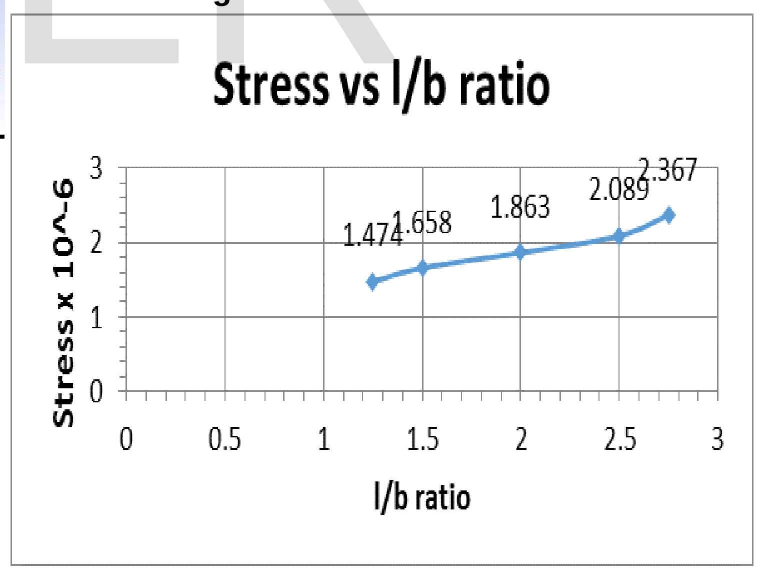


Comment: Stress generated in the shaft near pulley is 1.6598dx106 Pa. Vibration of the amplitude 1.2009x10^-6 m starts.

Interpretation of result:

We have carried out various analyses for the same geometry but different dimensional proportion so as to establish the characteristic of dimensional proportion with the stress generated or a user can find out, from the stress value, the suitable dimensional proportion.
Such characteristics are shown below:

1. Rectangular Cross-section:



Comment: From the above characteristic of rectangular cross section, the value of stress can be estimated according to l/b dimensional ratio. It is observed that beyond l/b = 2, the vibration of the range of 10-6 m starts.

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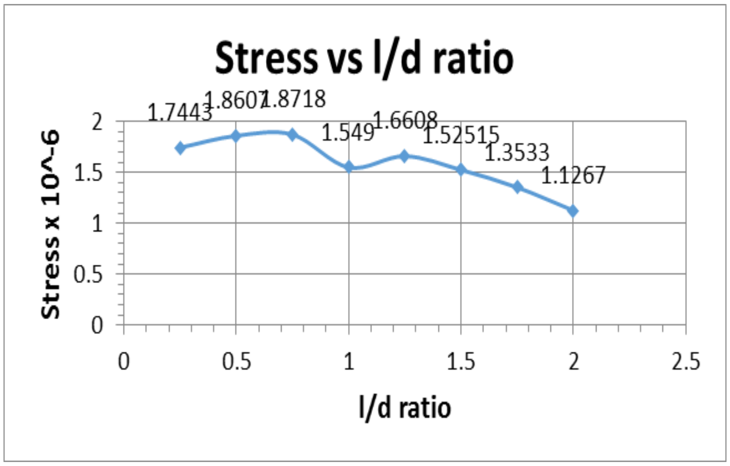
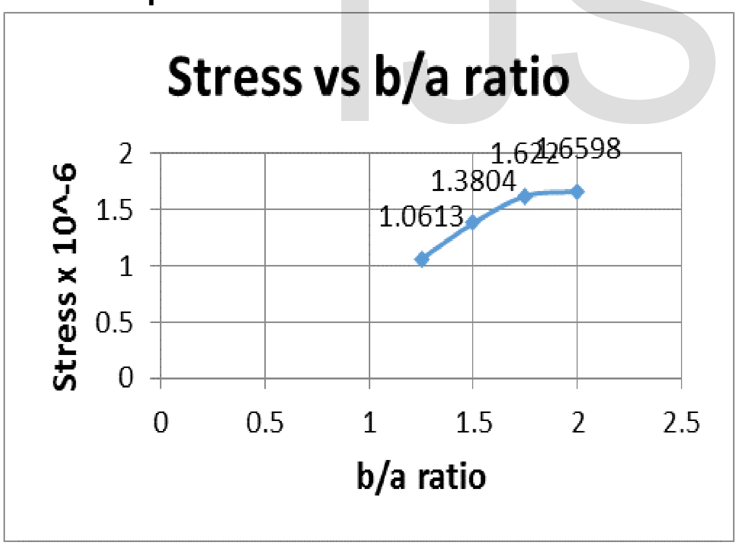
2. Rectangular cross section with semi-circles at two opposite ends:



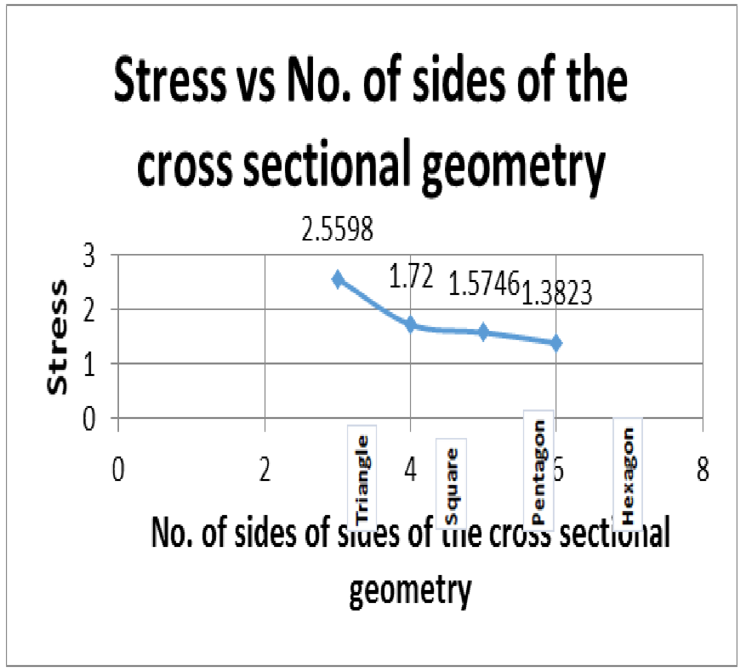
Comment: From the above characteristic of rectangular cross section with semicircles at two opposite ends, the value of stress can be estimated according to l/d dimensional ratio. It is observed that beyond l/d = 1.75, the vibration of the range of 10-6 m starts. The stress value drastically decreases at l/d = 1.

3. Elliptical Cross-section:



Comment: From the above characteristic of elliptical cross section, the value of stress can be estimated according to b/a dimensional ratio. It is observed that beyond b/a = 2, the vibration of the range of 10-6 m starts.

Variation of stress with increase in the no. of sides of the cross sectional geometry



Comment: It is observed from the above characteristics that as the no. of side of cross sectional geometry of the shaft increases (i.e. from triangle to hexagon), the stress value decreases. If we go from triangle to square geometry, the stress value decreases rapidly but then after the stress variations are moderated.

Conclusion:

From the above analysis and interpretation we conclude that:

1. Among all above cross-sections that was considered in the analysis, including circular cross-section shaft, the least stress is generated in elliptical cross-section shaft. Hence for the elliptical cross-section of the shaft, the additional weight that was required for the compensation of the stress concentration due to keyway, would be greatly reduced to become negligible theoretically. Thus there will be cost saving with respect to cost of material, manufacturing cost (Piercing a keyway), less wear and tear (as no key and keyway assembly thus mounting and disassembling becomes less cumbersome) and maintainanace costs.
2. Thus, proper shape of the shaft cross-section can be optimized according to the feasibility of manufacturing, shape of the input material for manufacturing, row material availability and requirement.
3. Apart from the elliptical cross-section, there are other shapes that have less stress as compared to circular cross-section. Thus as per the customer requirement of strength to weight ratio and criticality of application, optimal shape can be used. And with the state of manufacturing at present the shafts can be manufactured with the help of latest CNC machines in batch quantities or depending on the customer base, a system for the manufacture can be designed for mass production.

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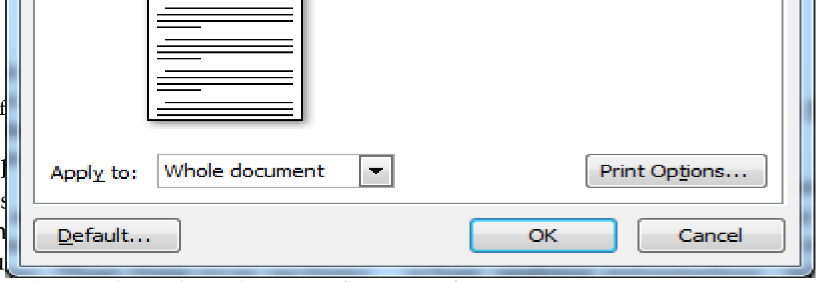

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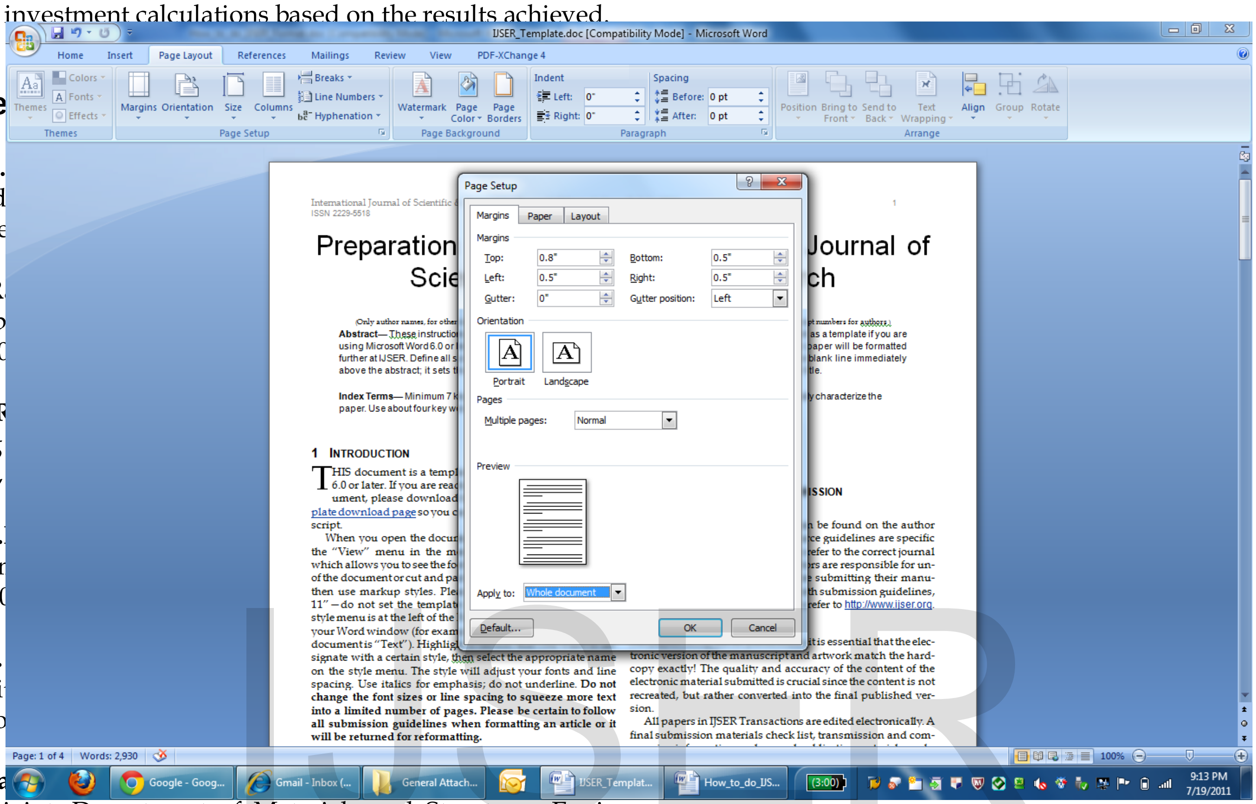

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