INVESTIGATION OF STRESSES IN ARM TYPE ROTATING FLYWHEEL

*S. M. Dhengle, ** Dr. D. V. Bhope, ***S. D. Khamankar

* P.G. Student, Department of Mechanical Engineering, Rajiv Gandhi College of Engineering Research and Technology, Chandrapur 442 403, Maharashtra, India.
sanjay_dhengle23@rediffmail.com
** Professor, Department of Mechanical Engineering, Rajiv Gandhi College of Engineering Research and Technology, Chandrapur 442 403, Maharashtra, India.
dvbhope@rediffmail.com
***Associate Professor, Department of Mechanical Engineering, Rajiv Gandhi College of Engineering Research and Technology, Chandrapur 442 403, Maharashtra, India.
sudhakarkhamankar@rediffmail.com

Abstract

There are many causes of flywheel failure. Among them, maximum tensile and bending stresses induced in the rim and tensile stresses induced in the arm under the action of centrifugal forces are the main causes of flywheel failure. Hence in this work evaluation of stresses in the rim and arm are studied using finite element method and results are validated by analytical calculations .The models of flywheel having four, six and eight no. arms are developed for FE analysis. The FE analysis is carried out for different cases of loading applied on the flywheel and the maximum Von mises stresses and deflection in the rim are determined. From this analysis it is found that Maximum stresses induced are in the rim and arm junction. Due to tangential forces, maximum bending stresses occurs near the hub end of the arm. It is also observed that for low angular velocity the effect gravity on stresses and deflection of rim and arm is predominant.

Keywords: Flywheel, Arm, FEM

1. Introduction

Stress analysis is the complete and comprehensive study of stress distribution in the specimen under study. To improve the quality of the product and in order to have safe and reliable design, it is necessary to investigate the stresses induced in the component during working condition. Flywheel is an inertial storage device which acts as reservoir of energy. When the flywheel rotates, centrifugal forces acts on the flywheel due to which tensile and bending stress are induced in a rim of flywheel.

This paper deals with FE analysis of flywheel having 4,6 and 8 number of arms. The stress analysis of the flywheel is carried out under different cases such as (1) Keeping constant angular velocity (2) Increasing angular velocity (3) Combined loading of angular velocity and gravity (4) Increasing angular velocity with effect of gravity (5) Applying tangential forces on rim (6) Combined loading of angular velocity, Gravity and tangential forces (7) Providing larger fillet size at the both ends of the arm. FE analysis is carried using ANSYS . The results of FE analysis are verified by analytical calculation.

2. Geometrical Dimensions of Flywheel

It is intended to use the same geometric model of flywheel under identical loading condition for FE analysis and analytical estimation of stresses. The major dimensions of flywheel considered for present analysis are as follows.

Outer Diameter of flywheel rim D_o= 1.1 m Inner Diameter of flywheel rim (Di)= 0.904m
Mean Diameter of flywheel rim(D_m)= 1 m Mean radius of flywheel rim (R)= 0.5 m
Thickness of rim (H) = 0.098m Width of rim (B)= 0.0147 m Diameter of shaft(d)=0.160 m
Diameter of hub(d_h) =0.340m Radius of hub (r) =0.0170 Hub length (L)= 0.147m
Major axis of arm at hub end (a)= 0.102m Minor axis of arm at rim end (b)= 0.051m
Major axis of arm at rim end (c) = 0.082m Minor axis of arm at rim end (d) = 0.041m

3. Material properties of Flywheel

The material properties considered for the flywheel with above geometric dimensions are given table1.

Table 1. material properties

Material	Gray cast iron
Ultimate strength	Sut = 214 Mpa Sus = 303 Mpa
Modulus of elasticity &modulus of rigidity	E = 101 Gpa G = 41 Gpa
Density	ρ =7510 Kg/m^3
Poisson's Ratio	μ = 0.23

4. Finite Element Analysis of Flywheel

For FE analysis, the FE models of 4, 6 and 8 number of arms are considered. A SOLID 72 element and tetrahedral meshing is used for FE analysis. The various cases considered for the analysis are given in forth coming sections

4.1. *Analysis by considering constant angular velocity of flywheel*

Fig.1 shows the Von mises stress contour in flywheel having 4, 6 and 8 no. of arms. Table 2 shows Von mises stresses and max.deflection in the rim of flywheel with 4,6 and 8 no. of arms at an angular velocity of 25.12 rad/sec and at an angular position of arms 45°, 30° & 22.5°. The variation of von mises stresses and deflection w.r.t. number of arms of flywheel are shown Fig. 2 and 3 respectively.

.

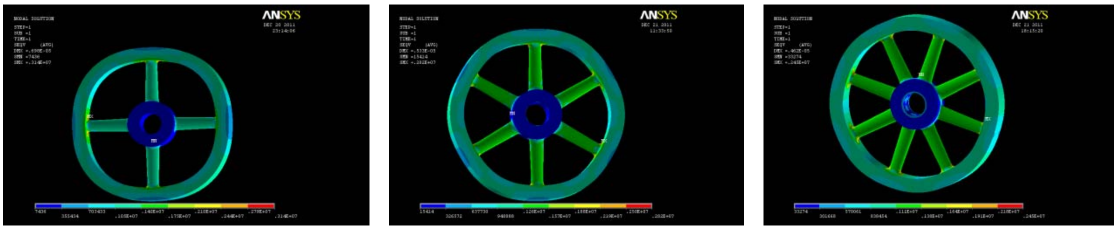


Fig. 1. Von mises stresses in 4, 6 and 8 arm flywheel

Table 2. Von mises stresses and max. deflection for constant angular velocity of flywheel

No. of Arms	Load(ω)	Von mises stresses in rim at 45°, 30° & 22.5° (N/m²)	Maximum deflection (m)
4	Omega_z 25.12 rad/sec	0.170×10^{7}	0.69×10^{-5}
6	Omega_z 25.12rad/sec	0.140×10^{7}	0.53×10^{-5}
8	Omega_z 25.12rad/sec	0.120×10^{7}	0.46×10^{-5}

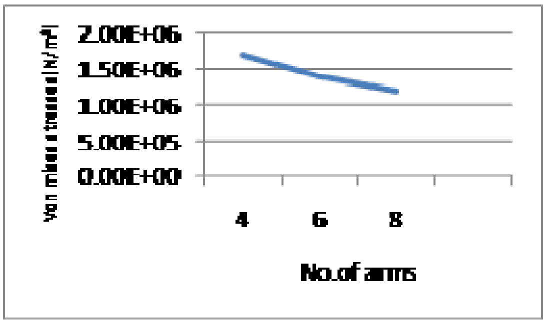


Fig. 2 Variation in Von mises stresses w.r.t. no. of arms

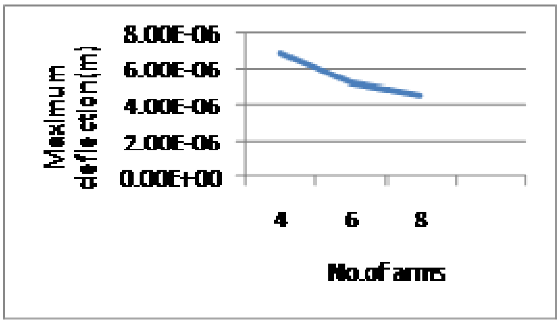


Fig. 3 Variation in maximum deflection w.r.t .no. of arms

4.2. *Analysis by increase in angular velocity of flywheel*

Table 3 shows the Von mises stresses and maximum deflection by varying angular velocity and no. of arms of flywheel. The Fig. 4 and 5 shows variation of Von mises stresses and maximum deflection w.r.t. increase in angular velocity of flywheel.

Table 3. Von mises stresses and max. deflection with increase in angular velocity

No. of arms	Load (ω)	Von mises stresses(N/m²)	Max. deflection(m)
4	Omega_z 25.12rad/sec	$0.314x10^{7}$	$0.69x10^{-5}$
	Omega_z 30 rad/sec	$0.448x10^{7}$	$0.99x10^{-5}$
	Omega_z 35 rad/sec	$0.609x10^{7}$	$0.135x10^{-4}$
	Omega_z 50 rad/sec	$0.124x10^{8}$	$0.277x10^{-4}$
6	Omega_z25.12rad/sec	$0.282x10^{7}$	$0.533x10^{-5}$
	Omega_z 30 rad/sec	$0.402x10^{7}$	$0.760x10^{-5}$
	Omega_z 35 rad/sec	$0.547x10^{7}$	$0.103x10^{-4}$
	Omega_z 50 rad/sec	$0.112x10^{8}$	$0.211x10^{-4}$
8	Omega_z25.12rad/sec	$0.245x10^{7}$	$0.46x10^{-5}$
	Omega_z 30 rad/sec	$0.349x10^{7}$	$0.65x10^{-5}$
	Omega_z 35 rad/sec	$0.475x10^{7}$	$0.89x10^{-5}$
	Omega_z 50 rad/sec	$0.970x10^{7}$	$0.183x10^{-4}$

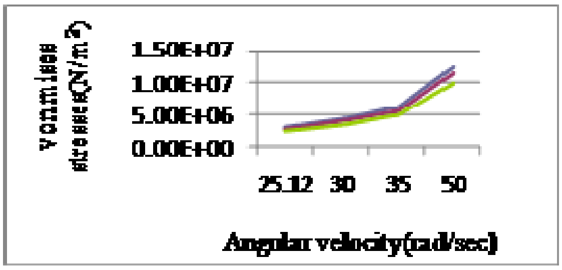


Fig.4 Variation in Von mises stresses w.r.t. angular velocity

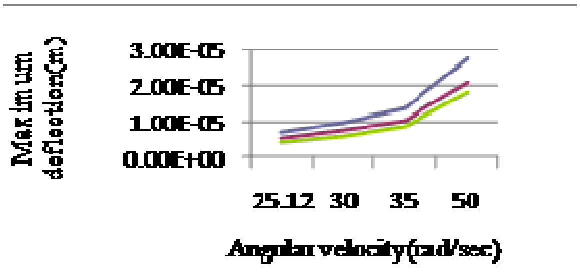


Fig. 5 Variation in maximum deflection w.r.t . angular velocity

4.3. *Analysis by considering combined loading of angular velocity and gravity of rotating flywheel*

Fig. 6 shows Von mises stress contour for 4, 6 and 8 no. of arms . Table 4 shows Von mises stresses and max.deflection in the rim of flywheel with 4, 6 and 8 no. of arms. Variation of Von mises stresses and max. deflection for 4, 6 and 8 number of arm of flywheel are shown in Fig.7 and 8.

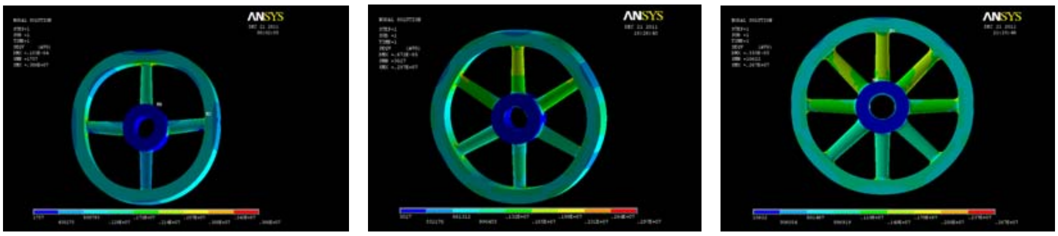


Fig. 6 Von mises stress contour for 4, 6 and 8 arm fly wheel considering gravity effect

Table 4. Von mises stresses and Max. deflection with combined loading of angular velocity and gravity

No. of arms	Loads(ω,g)	Von mises stresses(N/m²)	Maximum deflection(m)
4	Omega_z 25.12rad/sec Gravity_y -9.81m/s²	$0.386x10^{7}$	$0.103x10^{-4}$
6	Omega_z 25.12rad/sec Gravity_y -9.81m/s²	$0.297x10^{7}$	$0.672x10^{-5}$
8	Omega_z 25.12rad/sec Gravity_y-9.81m/s²	$0.267x10^{7}$	$0.55x10^{-5}$

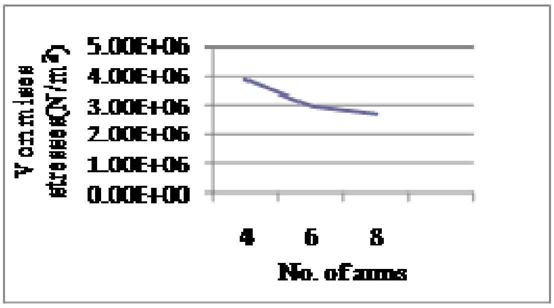


Fig .7 Variation in Von mises stresses w.r.t. number of arms

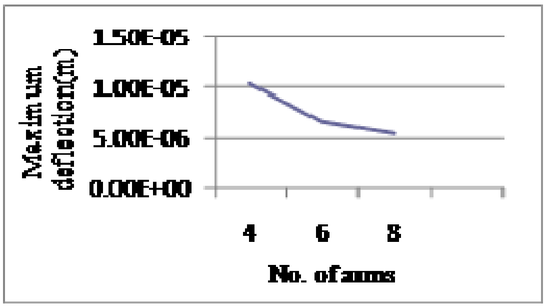


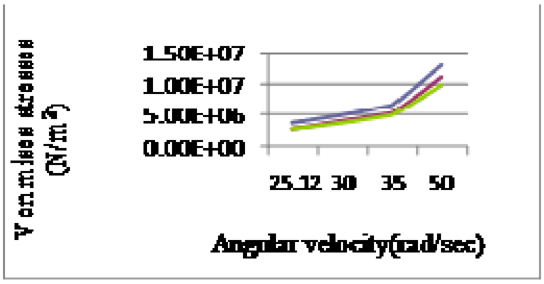
Fig .8 Variation in maximum deflection w.r.t. number of arms

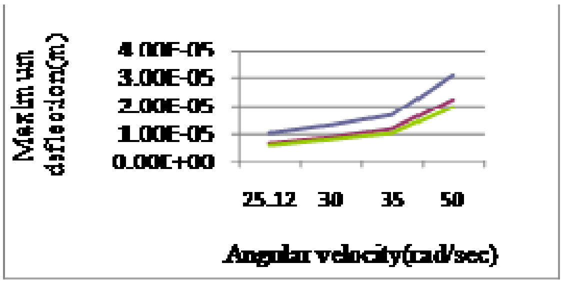
4. 4. *Analysis by increasing angular velocity and considering effect of gravity*

Table 5 shows the effect the Von misses stresses and maximum deflection by increasing angular velocity with effect of gravity for varying number of arms. Fig. 9 and 10 shows variation in Von mises stresses and maximum deflection w.r.t. angular velocity with effect of gravity respectively.

Table 5. Von mises stresses and Max. deflection with increase in angular velocity with effect of gravity

No. of arms	Loads(ω,g)	Von mises stresses(N/m²)	Max. deflection(m)
4	Omega_z 25.12rad/sec Gravity _y-9.81m/s²	0.386×10^{7}	0.103×10^{-4}
	Omega _z 30 rad/sec Gravity_y-9.81m/s²	0.515×10^{7}	0.132×10^{-4}
	Omega_z 35 rad/sec Gravity_- 9.81m/s²	0.671×10^{7}	0.168×10^{-4}
	Omega 50 rad/sec Gravity_y -9.81m/s²	0.129×10^{8}	0.308×10^{-4}
6	Omega_z 25.12rad/sec Gravity_y -9.81m/s²	0.297×10^{7}	0.671×10^{-5}
	Omega_z 30 rad/sec Gravity _-9.81m/s²	0.407×10^{7}	0.89×10^{-5}
	Omega_z 35 rad/sec Gravity_y -9.81m/s²	0.544x107	0.117×10^{-4}
	Omega_z 50 rad/sec Gravity_y -9.81m/s²	0.111×10^{8}	0.22×10^{-4}
8	Omega_z25.12rad/sec Gravity_y-9.81m/s²	0.267×10^{7}	0.55×10^{-5}
	Omega_z 30 rad/sec Gravity_y -9.81m/s²	0.365×10^{7}	0.752×10^{-5}
	Omega_z 35 rad/sec Gravity_y-9.81m/s²	0.491×10^{7}	0.99×10^{-5}
	Omega_z 50 rad/sec Gravity_y -9.81m/s²	0.986×10^{7}	0.192×10^{-4}





For 4 arms For 6 arms For 8 arms

Fig. 9 Variation in Von mises stresses w.r.t. angular velocity with gravity

Fig.10 Variation in maximum deflection w.r.t. angular velocity with gravity

4. 5. *Analysis by applying tangential forces on rim of flywheel*

Fig. 11 shows Von mises stress contours of 4, 6 and 8 arm flywheel. Table 6 shows the Von mises stresses and maximum deflection under tangential forces for 4, 6 and 8 arm of flywheel. The Fig. 12 and 13 shows the variation in Von mises stresses and maximum deflections w.r.t. number of arms of flywheel. In the rotating flywheel tangential forces are acting on the mean diameter of flywheel and it causes bending stress which developed near the hub end of the arm. This approach is based on cantilever beam theory.

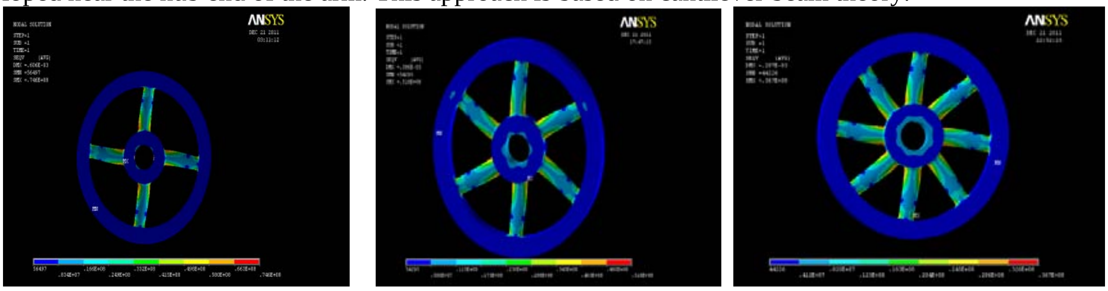


Fig. 11. Von mises stresse contour for 4,6 and 8 arm flywheel

Table 6. Von mises stresses and max. deflection in arm due to tangential forces

No of arms	Loads F (N)	Von mises stress (N/m²)	Deflection (m)
4	13375.8	$0.746x10^{8}$	$0.579x10^{-3}$
6	8917.2	$0.518x10^{8}$	$0.384x10^{-3}$
8	6687.9	$0.367x10^{8}$	$0.287x10^{-3}$

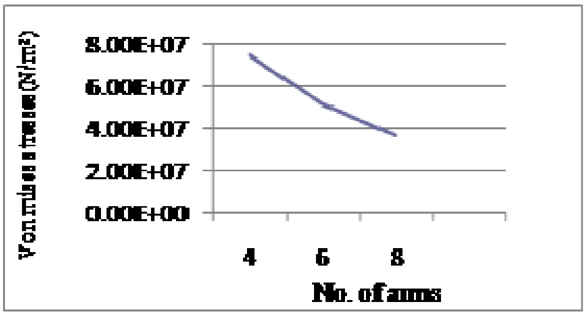


Fig.12 Variation in Von mises stresses w.r.t. no. of arms

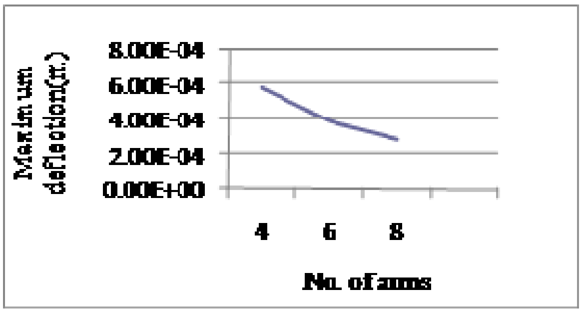


Fig. 13 Variation in maximum deflections w.r.t. no. of arms

4. 6 *Analysis by Considering combined loading of angular velocity (ω), gravity (g) & tangential force (F)*

Fig .14 shows von mises stress counters for4, 6 and 8 of arms flywheel. Table 7 shows the Von misses stresses and max deflection by applying combined loading of angular velocity, gravity and tangential forces at mean diameter of flywheel. Fig. 15 and 16 shows variation in Von mises stresses and maximum deflection w.r.t. number of arms.

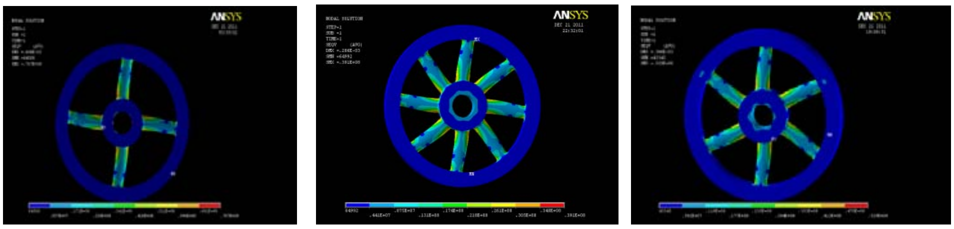


Fig. 14 Von mises stresss contour of 4, 6 and 8 arm flywheel

Table 7. Von mises stresses and maximum deflection with combined loading of angular velocity, gravity, and tangential force

No. of arm	Load(ω,g,F)	Von mises stresses(N/m²)	Max. deflection(m)
4	Omega_z 25.12 rad/sec Gravity_y -9.81 m/s² Force 13375.8 N	0.767×10^{8}	0.581×10^{-3}
6	Omega_z 25.12 rad/sec Gravity_y 9.81 m/s² Force 8917.20 N	0.529×10^{8}	0.386×10^{-3}
8	Omega_z 25.12 rad/s Gravity_y9.81 m/s Force 6687.9 N	0.391×10^{8}	0.286×10^{-3}

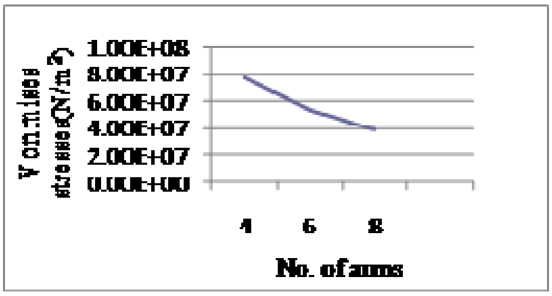


Fig. 15 Variation in Von mises stresses w.r.t. no. of arms

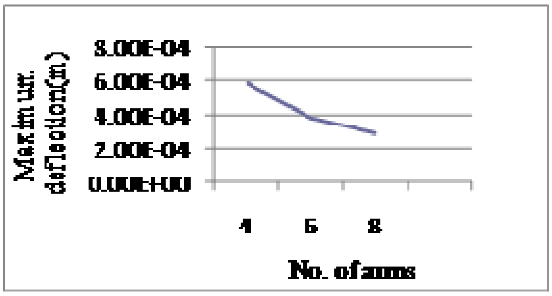
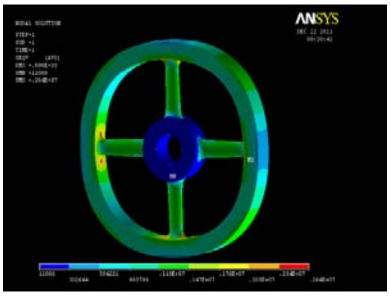
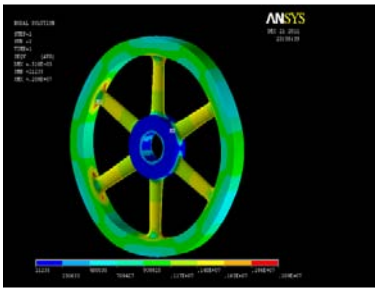


Fig.16 Variation in maximum deflection w.r.t. no. of arms

4.7 *Analysis by providing larger fillet size at both ends of arm*

Fig. 17 shows the stress contour of Von mises stresses in 4,6, and 8 arm of flywheel .Table 8 shows Von misses stresses and maximum deflection by providing larger fillet size for 4,6 and 8 number of arms at constant angular velocity. Variation in Von mises stresses and maximum deflection w.r.t. no. of arms are shown in Fig. 18 and 19.





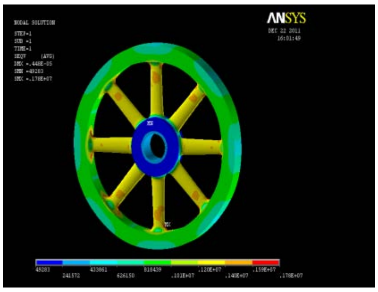


Fig. 17 Von mises stress contour of 4, 6, and 8 arm flywheel

Table 8. Providing larger fillet size

No. of arms	Load(ω)	Von mises stresses(N/m²)	Max. deflection(m)
4	Omega_z 25.12rad/sec	0.264×10^{7}	0.686×10^{-5}
6	Omega_z 25.12rad/sec	0.209×10^{7}	0.518×10^{-5}
8	Omega_z 25.12 rad/sec	0.178×10^{7}	0.44×10^{-5}

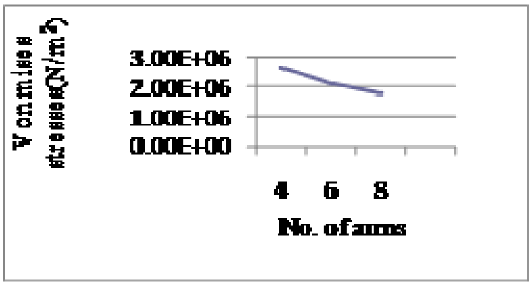


Fig. 18 Variation in von mises stresses w.r.t. no. of arms.

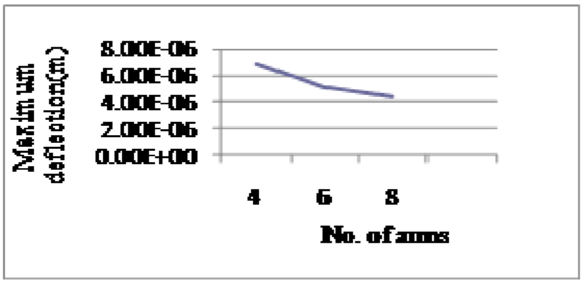


Fig. 19 Variation in maximum deflection w.r.t. no. of arm

5. Analytical estimation of stresses in arm type flywheel

An effort is made to estimate the stresses in the rim and arm of Flywheel using analytical approach described as follows

A = Area of Rim = 0.0144 m²

A1 = Area of arm = 0.00408 m²

Omega ω = 25.12 rad/sec

Velocity V=12.56m/s

Mass of rim M = 0.108 Kg /mm

Tangential force for 4 arm F = 13375.8 N

Tangential force for 6 arm F = 8917.19 N

Tangential force for arm F = 6687.89N

Angle between two arm for 4 arm flywheel 2 = 90° Ø = 45°

Angle between two arm for 6 arm flywheel 2 = 60° Ø=30°

Angle between two arm for 8 arm flywheel 2 = 45° Ø =22.5°

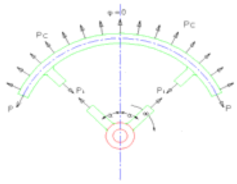


Fig. 20 Forces & moment of arm type flywheel

Stresses in Rim for 4 arm flywheel

t =1000 x M x V² /B x H [1 - cosØ /3 x C x sin + 2 x 1000 x R/ C x H (1 / - cosØ /sin)]

C= 72960 x R²/ H² + 0.643 + A / A1 Constant C=6.07

Stresses in Rim for 6 arm flywheel

t =1000 x M x V² /B x H [1 - cosØ /3 x C x sin + 2 x 1000 x R/ C x H (1 / - cosØ /sin)]

C =20280 x R² / H² + 0.957 + A /A1 Constant C= 5.01

Stresses in Rim for 8 arm flywheel

t =1000 x M x V² /B x H [1 - cosØ /3 x C x sin + 2 x 1000 x R/ C x H (1 / - cosØ /sin)]

Constant C=5.01

Bending stresses in Arm for 4, 6 and 8 arm flywheel

b = M / Z

b = F(R-r) / ∏ a^3 / 64 F = tangential force

Torque = F x R x n R = mean radius

26751592 = F x 500 x 4 n = no. of arms

F = 13375.8 N

Table 9 Analytical stresses on rim at 45^0, 30^0, 22.5^0

No. of arms	Analytical stresses on rim at 45°, 30° & 22.5° (N/m²)
4	$0.166x10^7$
6	$0.147x10^7$
8	$0.131x10^7$

Table 10 Tangential Forces for 4, 6 and 8 arms

No. of arms	Tangential Force (N)
4	13375.8
6	8917.2
8	6687.90

Table 11 Analytical bending stresses in arm of flywheel

No. of arms	Analytical bending stresses on arm(N/m²) (σ b)
4	0.856 x10^{8}
6	0.565 x10^{8}
8	0.423 x10^{8}

6. Discussion & Conclusion

6.1 *Comparison of FE stresses and Analytical stresses on Rim at 45°, 30°&22.5°*

Table 12 shows the comparison between analytical stresses and FE stresses in Rim by varying no. of arms. Fig. 21 shows the variation in stresses on rim at 45°,30°& 22.5°.

Table 12. Comparison of FE stresses and analytical stresses on Rim of flywheel

No. of arm	**Load(ω) (rad/sec)**	**Von mises stresses on rim at 45°, 30° and 22.5° (N/m²)**	**Analytical stresses on rim at 45°, 30° & 22.5° (N/m²)**
4	Omega_ 25.12	0.170x10^{7}	0.166x10^{7}
6	Omega _25.12	0.140x10^{7}	0.147x10^{7}
8	Omega _ 25.12	0.120x10^{7}	0.131x10^{7}

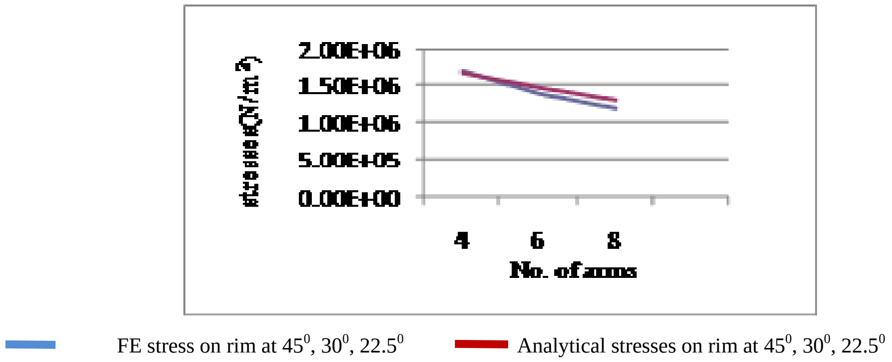


Fig. 21. Variation in stresses on rim w.r.t. no. of arms of flywheel

6.2 *Comparison of FE stresses and Analytical bending stresses in Arms*

Table 13 shows comparison between FE stresses on arm and analytical calculated bending stresses in arms. The variation of FE stresses and bending stresses on arm is shown in Fig. 22.

Table 13. Comparison of stresses in arm for 4, 6 and 8 arm flywheel

No. of arm	**Load F (N)**	**Von mises stresses on arm (N/m²)**	**Analytical bending stresses on arm (N/m²)**
4	13375.8	0.746x10^{8}	0.856x10^{8}
6	8917.19	0.518x10^{8}	0.565x10^{8}
8	6687.89	0.367x10^{8}	0.423x10^{8}

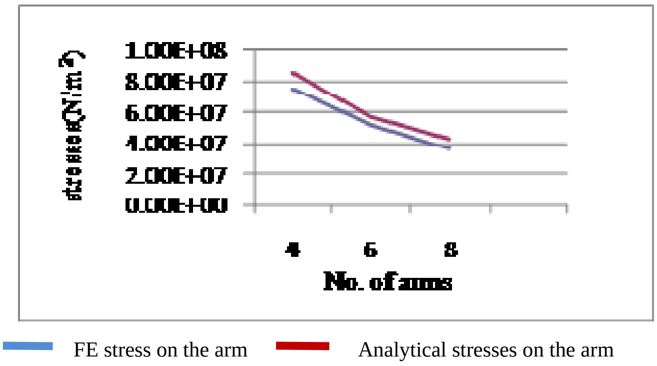


Fig. 22. Variation in stresses in arms w.r.t. no. of arm of flywheel

6.3 *Comparison of stresses by varying fillet size for 4, 6 & 8 arm Flywheel*

Table 14 and 15 shows the effect of fillet size on 4, 6 and 8 arm flywheel on stresses at arm and rim junction. The variation of FE stresses w.r.t. no. of arms is shows in Fig. 23.

Table 14. FE stresses at rim & arm junction with fillet size 0.015 m

No. of arm	Load (ω) rad/sec	Fillet on arm (m)	Von mises stresses(N/m²)
4	Omega_z 25 rad/sec	0.015	0.314×10^7
6	Omega_z 25 rad/sec	0.015	0.282×10^7
8	Omega_z 25 rad/sec	0.015	0.245×10^7

Table 15. FE stresses at rim & arm junction with fillet size 0.03 m

No. of arm	Load(ω) rad/sec	Fillet on arm(m)	Von mises stresses(N/m²)
4	Omega_z 25 rad/sec	0.030	0.264×10^7
6	Omega_z 25 rad/sec	0.030	0.209×10^7
8	Omega_z 25 rad/sec	0.030	0.178×10^7

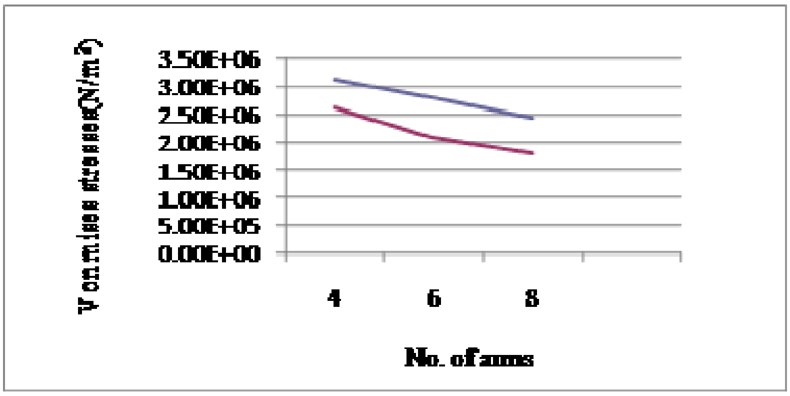
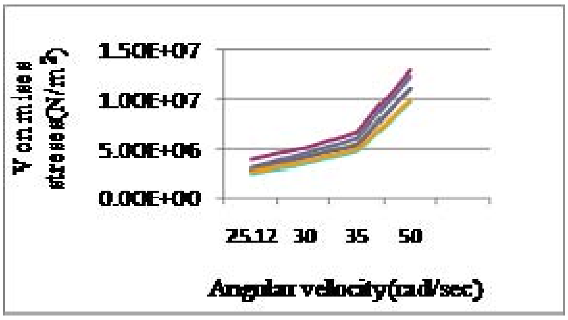


Fig. 23. Variation in von mises stresses at rim and arm junction w.r.t. no. of arms of flywheel

6.4. *Comparison of stresses with and without effect of gravity by increasing angular velocity*

The Fig. 24 shows the variation in Von mises stresses and max. deflection in flywheel rim with and without effect of gravity with increase in angular velocity .



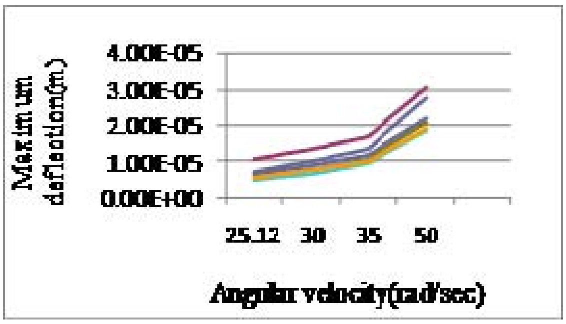


Fig. 24. Variation in Vonmises stresses and max. deflection with and without effect of gravity by increasing angular velocity

It is observed from table 12 that stresses in rim at 45^0,30^0, 22.5^0 for FE analysis and with analytical calculations closely matches for 4, 6 & 8 number of flywheel arms. It is also seen that as a number of arms increases from 4 to 8, the stresses in the arms goes on reducing. This may be due to sharing of load by larger no. of arms.

Table 3 it is seen that, with increase in angular velocity the stresses are increasing. This is due to larger centrifugal forces acting on the flywheel rim. When the gravity effect along with angular velocity are considered, it is observed from table 4 that the stresses at the junction of rim and arms are more than that of neglecting gravity effect. Thus the gravity effect contributes to rise in the stresses in flywheel rim. Table 3 & 5 shows the stresses in the flywheel rim and arm junction with increase in angular velocity without effect of gravity and with effect of gravity respectively. It is observed from the table that for low angular velocity the effect of gravity on stresses and deflection on rim is predominant but as angular velocity goes on increasing its effect on stresses and deflection of rim is negligible. Hence it can be concluded that the gravity effect is predominant for low speed and negligible for high speed flywheel are shown in Fig. 24.

Table 13 shows the comparison of FE stresses and analytical bending stresses near the hub end of arm for 4, 6 and 8 arms flywheel under the influence of tangential forces on rim. From this table it is seen that a good agreement is obtained between FE stresses and analytically calculated stresses.

Table 14 and 15 shows the stresses evaluated by varying the fillet size at arm and rim junction. It revealed that as fillet size goes on increasing the stresses are reducing considerably. Thus the suitable fillet size is recommended for lower stress values.

From this work it is seen that analytical equations available for determination of stresses in flywheel rim and arms can estimate the induced stresses accurately, though these equations are developed on the basis of certain assumptions.

REFERENCES

[1] Dilip.; P.N., Kamal, R. (2010) " An evolutionary approach for the shape optimization of flywheel" I.E. (I) Journal – MC, Vol.90, pp 8 - 12.

[2] Aziz A. A. (2001) "Structural analysis of composite flywheel an integrated NDE and FEM approach.", NASA/TM 2001-210461 pp 1 – 17

[3] Xu X., Yu Z. (2005) " Failure analysis of diesel engine flywheel.", Science direct_ engineering failure analysis Vo.12, Issue 1, pp 25 – 34.

[4] Yilmaz D., (2009) " Finite element analysis of failure in rear mounted mower pulley", Journal of food Agriculture and Environment, Vol. 7 (3 & 4) pp 856 – 868

[5] Hawkins L. (2002) "Shock vibration testing of an amb supported energy storage flywheel", 8th International Symposium on Magnetic Bearing, Aug, 26 – 28, Mito, Japan, pp 581 – 586

[6] Addas J.S. (2005) "Design of flywheel with a moving hole", American Journals of applied science 2 (1), pp 436 – 439.

[7] Colozza A. J. (2000) "High energy flywheel contentment evaluation", NASA/CR, 2000-210508, pp. 1 – 12

[8] Alex F. A., (2003) "Control of flywheel assisted drive line with continuously variable transmission", Journal of dynamic system measurement and control, Vol-125, pp 455-461.

[9] Wan J. (1996) "Optimization design and analysis of a flywheel.", A Project for MIE 605, pp. 1 – 31.

[10] Bhope D.V. (1992) "Investigation of stress pattern in arms of the pulley", UG Project, RCERT, Chandrapur.

[11] Bhandari V.B. (2001), "Design of machine element", 3rd Edition, McGraw Hill Education, India Pvt. Ltd.