A REVIEW ON OPTIMIZATION OF LABORATORY CENTRIFUGE ROTOR USING SIMULATION TOOLS

Mr. Himanshu J Gajjar[1], Mr. Nikunj Modh[2], Mr. Killol Kothari[3]

[1] *M.E. (AMS), Mechanical Department, Venus International College of Technology,Gujarat, India*
[2] *Asst. Professor, Mechanical Department, Venus International College of Technology,Gujarat, India*
[3] *Asst. Professor, Mechanical Department, Venus International College of Technology,Gujarat, India*

ABSTRACT

In the present review paper an effort is made to study the previous investigations which have been made in the different structural analysis and optimization techniques of Rotor of Laboratory High Speed Micro Centrifuge. That analysis may be static or dynamic analysis. A number of analysis techniques like analytical and experimental are available for the structural analysis of High Speed Micro Centrifuge Rotor. Same as no of optimization techniques are available for optimization of it like Taguchi method.. In this scenario, a structural optimization tool like topology optimization is becoming more relevant and attractive in product design processes. Determination of the different structural or topology analysis and optimization through the various methods like FEA, in high speed laboratory centrifuge rotor has been reported in literature.

Keyword : - *Structural Optimization, Finite Element Analysis, Laboratory Centrifuge, ANSYS*

1. INTRODUCTION

A Laboratory centrifuge is a device that is used for the separation of fluids, gas or liquid, based on density. Separation is achieved by spinning a vessel (rotor) containing material at high speed; the centrifugal force pushes heavier materials to the outside of the vessel. This apparatus is found in most laboratories from academic to clinical to research and used to purify cells, subcellular organelles, viruses, proteins, and nucleic acids. There are multiple types of centrifuge, which can be classified by intended use or by rotor design. From the large floor variety to the micro-centrifuge, there are many varieties available for the researcher [16].

Centrifugation is an indispensable separation and concentration tool for many areas of research. High-speed centrifugation (approximately 15,000 to 40,000 RPMs, or 14,000 to 100,000 x g, or higher) is especially valuable in the biosciences for applications such as concentrating cells in suspension, isolating and separating cell membranes from cytosolic contents and purifying and isolating genetic material.

A laboratory centrifuge is used to spin fluid samples at high speeds. The resultant centrifugal effect causes particles suspended in the fluid to migrate to the bottom of the tube as a precipitate (the pellet). The remaining fluid is termed the supernatant. Centrifuges come in different sizes, with different maximum speed and different uses.

1.1 Theory of Centrifuge Operation

An example of a fixed angle centrifuge is the Neuation iFuge M12 device. This is illustrated in figure 1.1 which shows the device with the lid raised and twelve micro centrifuge tubes placed in the rotor.

The theory of centrifuge operation can be developed as follows. Let a centrifuge tube of length l_0 metres and cross sectional area A m^2 be filled to a height of l metres with fluid of density ρ_s. Let the fluid contains a suspension of spherical particles of radius r metres and density ρ_p kg/m^3. See figure 1.2.

The tube is inserted into the centrifuge and the device operated. In practice a centrifuge must always be loaded with an even number of tubes, diametrically opposed containing the same mass of liquid so that the rotor is balanced. Running a centrifuge with a single tube would certainly make the centrifuge vibrate and could quite easily break the device. However for the point of developing theory, only the forces acting on a single tube will be considered. As the rotor spins, an apparent centrifugal force acts on the sample of fluid and the particles inside it, pushing both radially outwards towards the side of the centrifuge tube.

Fig:1.1 High Speed Centrifuge with Fixed Angle (NTPL, Gandhinagar) [16]

The magnitude of the centrifugal force, F_C can be show to be [6] given by equation (1.1).

FC = mω2R

(1.1)

where

Symbol	Represents
FC	Magnitude of the centrifugal force (units Newton)
ω	Angular Velocity of the Centrifuge (units radian/second)
R	Radius of the circular motion of the centrifuge (unit metre)

M Mass of the particle being spun. This could be either the mass of the total solution, or the mass of a particle depending on the context of the discussion.

The linear velocity v of the tube as it moves in a circle is given by equation (1.2).

υ = ωR (1.2)

The force FC acts on the particles in the fluid sample, pushing them towards the outside of the centrifuge tube and thence causing them to slide down the tube to form a pellet at the bottom. This force plays the same role as that played by gravity in the sedimentation. Again there is a force of Buoyancy FB played a role. However in this case the buoyancy force acts in the opposite direction to the centrifugal force rather than towards the fluid surface. Also there is again a drag force FD, as the solution resists the flow of particles and again this acts to oppose the motion of the particles. Equating all forces, we find that when the suspended particles attain terminal velocity, they behave as predicted by equation (1.3).

$$\frac{4}{3}\pi r^3(\rho_p - \rho_s)\omega^2 R = 6\pi r\eta\upsilon_T \quad (1.3)$$

S

The time for all particles to collect into the pellet in the centrifuge tube

T is thus given by dividing l, the depth of fluid in the centrifuge tube by υT, the terminal velocity, and see equation (1.4).

$$T = \frac{9l\eta}{2r^2(\rho_p - \rho_s)\omega^2 R} \quad (1.4)$$

where

Symbol Represents

T	Time taken to precipitate all suspended particles (unit seconds)
ω	Angular velocity of the centrifuge (units radian/second)
r	Radius of suspended particles (m)
η	Viscosity of the solution (units Pa.s)
ρp	Density of suspended particles (kg / m3)
ρs	Density of solution (kg / m3)
R	Radius of the circular motion of the centrifuge (unit metres)

1.2 Details of Centrifuge Operation

Given a centrifuge, it is interesting to see how the equations derived so far affect its use.

1.2.1 Relative Centrifugal Force (RCF)

The force exerted onto a particle in solution when centrifuged depends both on the speed of the rotation ω and on the radius of the centrifuge rotor R, see equation (1.1). Since the latter varies with different models of centrifuge, this makes it difficult to compare centrifuge times and speeds across different devices.

This issues is resolved by quoting centrifugation in terms of relative centrifugal force (RCF) rather than rotational speeds. The RCF is defined as the ratio of the force acting on a particle by centrifugation to the force acting on the particle by gravity. Thus the value of RCF says how many g forces a particle experiences when processed in a centrifuge.

The equation for the force on a particle due to gravity is

$$FG = m\ g \qquad (1.5)$$

where

Symbol	Represents
m	The mass of particle (expressed in kg)
g	The acceleration due to gravity (approximately 9.81 m/s2)

and centrifugal force is given by equation (1.1). Dividing these gives the equation for the RCF, see equation (1.5).

$$RCF = \omega 2R / g \quad (1.6)$$

However the equation (1.6) is usually rearranged to the form shown (1.7) by putting the value of $\omega = 2\pi n/60$ (where n is rotation speed RPM) and gravitation acceleration,

$$RCF = 1.118 \ R \ (RPM / 1000) \quad (1.7)$$

where

Symbol	Represents
RPM	Rotational Speed (unit revolution per minute)
R	Radius of Centrifuge Rotor (unit millimetres)

Given the M12P centrifuge has a rotor radius Rmax of 62.5 mm and a maximum rotational speed of 15000 rpm, it follows from equation (1.1) that the relative centrifugal force exerted is 15596g, which is almost 15600 times the force of gravity.

Now the M12P centrifuge holds twelve sample tube and the limit of operation is that each tube can hold 2 ml of a fluid of density 1200 kg/m3, which is 2.4 gram of sample. Since the mass of a centrifuge tube is 1.2 gram, this means the total mass of each sample can be up to 3.6 gram. The radius of the rotor is 62.5 mm. Thus from equation (1.1) it follows that the centrifugal force experience by a single tube and its contents is 555 newton, or approximately 56 kg force.

The energy E stored in a single sample of mass m spinning at top speed of in the M12P centrifuge is calculated with equation (1.8) as 17.33 Joule. Hence the energy stored in all twelve samples is 207.96 Joule. If it were possible to capture all this energy and apply it to a single 1kg mass it would be sufficient to fling it some 35 metres vertically into the air.

$$E = \tfrac{1}{2} m (R \omega) 2 \quad (1.8)$$

where

Symbol	Represents
ω	Rotational Speed of Centrifuge (unit radian/seconds)
R	Radius of Centrifuge Rotor (unit metre)
E	Kinetic Energy of Rotation (unit Joule)

1.2.2 Centrifugation of Dense Sample

A centrifuge will typically be rated with the following information

Maximum number of samples that can be held

This will be determined with the number of holes on the rotor, a typical value being 12.

Maximum allowed volume of each sample V

For the M12P centrifuge with a 12 place rotor this value is 2 ml.

Maximum allowed density of the fluid sample, $\rho 0$

For the M12P this is 1200 kg/m3.

Maximum angular velocity that the centrifuge can operate, $\omega 0$

For the M12P this is 15000 rpm or 500 π radian/seconds.

The question arises, if there is a need to centrifuge a liquid with density ρl such that $\rho l > \rho 0$, what is the maximum speed ωl that the centrifuge can safely operate. This is given by calculating the centrifugal force exerted by the higher density fluid and ensuring this does not exceed the safe working limit of the device, that is

$$\rho 0\ V\ \omega 02\ R = \rho l\ V\ \omega l2\ R \quad (1.9)$$

which on rearranging gives equation (1.10)

$$\omega l = (\ \rho 0 / \rho l\ )\omega 0 \quad (1.10)$$

where

Symbol	Represents
ωl	Maximum Rotational Speed of Rotor with high density fluid
$\omega 0$	Maximum Rotational Speed of unrestricted centrifuge use
$\rho 0$	Maximum density of sample for unrestricted centrifuge use
ρl	Density of sample where $\rho l > \rho 0$

Thus if there were a need to centrifuge a sample of liquid with a density of 1600 kg/m3, the maximum safe speed for operation ωl would be given by

$\omega l = (\ 1200 / 1600\ )\ 15000 = 12990$ rpm.

1.3 Types of Rotors

There are two fundamental types of rotors:

- **Fixed Angle Rotor:**

These hold the tubes in the centrifuge at a fixed inclination (typically about 35 degrees) to the vertical. The most common devices hold eight tubes and they have the advantage of not having moving parts on the rotor. This arrangement means that the solute is forced against the side of the tube. This leads to a faster separation of the solute from fluid, but risks abrasion of the particles as they are forced down the wall of the centrifuge tube. Also the end result is a smear along the side of the tube rather than the precipitate forming a neat pellet.

Advantage:

Sedimenting particles have only short distance to travel before pelleting.
Shorter run time
This is the most widely used rotor type.

- **Swinging Bucket Rotor:**

This form of rotor allows the centrifuge tubes to freely swing out towards the horizontal as the device operates. This gives the longest path of particle movement as the centrifugation proceeds and has the advantage that the solid forms in a clear pellet at the bottom of the centrifuge tube.

Advantage:

Longer distance of travel may allow better separation eg. Density gradient centrifugation.
Easier to withdraw supernatant without disturbing pellet.

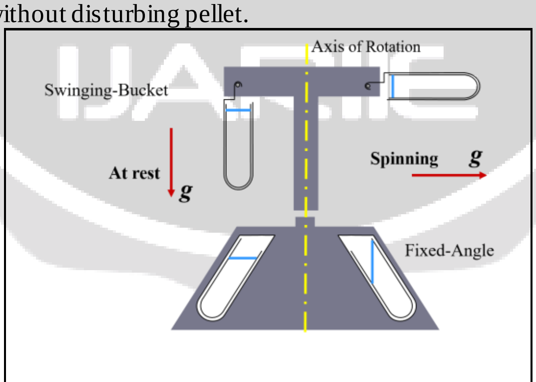

Fig:1.2 Types of Rotors

1.4 Application of Centrifuges

Production of bulk drugs:

In the bulk drug industry, whenever a crystalline material is to be separated from a suspension, e.g., aspirin is separated from its mother liquor by centrifugation.

Production of biological products:

a. Separation of blood cells.

b. Purification of insulin by selectively precipitating other fraction of proteins.

c. Separation of most of the proteinaceous drugs and macromolecules.

Biopharmaceutical analysis of drugs:

Drugs present in the blood, tissue fluids and urine are normally present in the form of colloidal dispersion. Centrifugation is used for separating the drugs which is essential for the evaluation of pharmacokinetic parameters and bioequivalence studies.

Evaluation of suspension and emulsion:

Centrifugation method is used as a rapid empirical test parameter for the evaluation of suspension and emulsion.

e.g., A stable emulsion should not show any signs of separation even after centrifuging at 2000-3000 rpm at room temperature.

Ultracentrifugation are used for determination of molecular weight of serum albumin, insulin etc.

Isolation of bacterial cells, fungal and actinomycete mycelium and spores from liquid growth and fermentation media is facilitated by laboratory centrifuge.

Removal of finely suspended solid matter (clarification) from aqueous or oily materials can be carried out by centrifuging at high speeds without the necessity of a filter.

Ultracentrifuge can be used for separation of virus particles which has potential industrial applications.

1.5 Types of Centrifuges

Centrifuges can be classified on the basis of speed, temperature.

SPEED

The "speed" of a centrifuge is measured in revolutions per minute, or rpm. Centrifuges are generally divided into 3 categories based on their maximum attainable speed:

"Low-speed": to maximum of ~ 5 x 103 rpm.

"High-speed": to maximum of ~2 x 104 rpm.

"Ultracentrifuges": to maximum of ~105 rpm.

TEMPERATURE

Centrifuges are either refrigerated or not refrigerated.

Refrigerated centrifuges have a built-in refrigeration unit surrounding the rotor, with a temperature sensor and thermostat permitting selection of a particular temperature or a permissible temperature range that is maintained during centrifugation. Many biological samples are temperature sensitive, and centrifugation in the cold (say, 1-4oC) is frequently required.

Centrifuges that are not refrigerated are normally used at whatever temperature the room they are in happens to be. This is typically described in research reports as "room temperature" or "ambient temperature”.

2. LITERATURE REVIEW WORK CARRIED OUT

2.1 Literature Survey

In this Literature Survey, an overview of important of laboratory centrifuge rotor design and other parameter selection is presented. It is mainly focused on studying the different parameters of laboratory centrifuge rotor to improve the strength of the rotor and safety of the product.

Paper-1: ***Xuan Hai-jun, Song Jian, “Failure analysis and optimization design of a centrifuge rotor”, Science Direct, Engineering Failure Analysis Vol. 14 (2007) Pages: 101–109***

In this Research Paper, Chemical analysis and microstructure observation were used for material inspection. It was identified that the material of the rotor was as per specified grade of high strength aluminum alloy and there was no material degradation. Therefore, mechanical stress analysis using finite element method was carried out for failure analysis after the metallurgical examination. It was found that the rupture was due to insufficient integrated strength of the rotor as maximum centrifugal stress exceeds the ultimate strength of the material. Further works were done for the structure optimization of the rotor standing centrifugal loading at 2 times the maximum operation speed. The rotor dimensions have been changed at two regions and the maximum centrifugal stress was reduced to a relative low level with an improved safety performance. The structure optimized centrifuge rotor was machined by the manufacturer and stood 2 times the maximum operation speed of 46,600 rpm with 5 min in the later over-speed spin testing. It can be concluded that 3-dimensions stress analysis and structure optimization based on finite element method are essential for the safety performance improvement of centrifuge rotors [12].

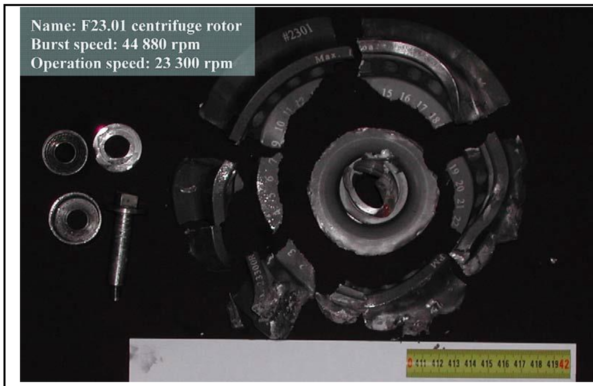

Fig. 2.1 Post-test reassembled rotor fragments.

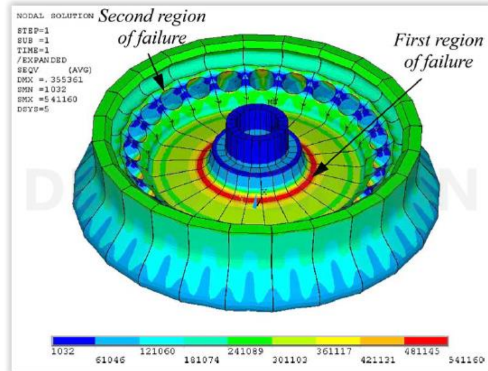

Fig. 2.2 Von Mises stress contour at speed 44,880 rpm (10^{-3} MPa).

Paper-2: ***Hak Gu Lee, Jisang Park, Ji Hoon Kim, "Design theory and optimization method of a hybrid composite rotor for an ultracentrifuge", Science Direct, Mechanism and Machine Theory, Volume 59 (2013), Pages: 78-95***

In this study, the optimization method of a hybrid composite disc that can be applied to the preliminary design of centrifuge rotors was developed based on the analytical solutions of a rotating orthotropic disc loaded by centrifugal body force under the plane stress condition. Since the results of the optimized disc give higher stress values than that of the 3-D rotor structure does, they can predict the performance of a designed hybrid composite rotor conservatively. If PEI, AS4/3501-6, and Kevlar/epoxy are used for the core, the composite outer layer, and the composite insert with the thickness of 2 mm, respectively, the optimized dimensions of a hybrid composite disc having 12 tube holes with the hole radius of 5 mm are the inner radius of 25.8 mm, the boundary radius of 43.0 mm, and the outer radius of 55.1 mm. The hybrid composite rotor having the above dimensions at its maximum radius can operate at 94 H.G. Lee et al. / Mechanism and Machine Theory 59 (2013) 78–95 99,000 rpm with a safety factor higher than 1.50 and at 116,000 rpm with a safety factor higher than 1.09. From the results, it can be found that the ultimate condition of the designed hybrid composite rotor reaches an ultracentrifuge region (≥600,000×g) [13].

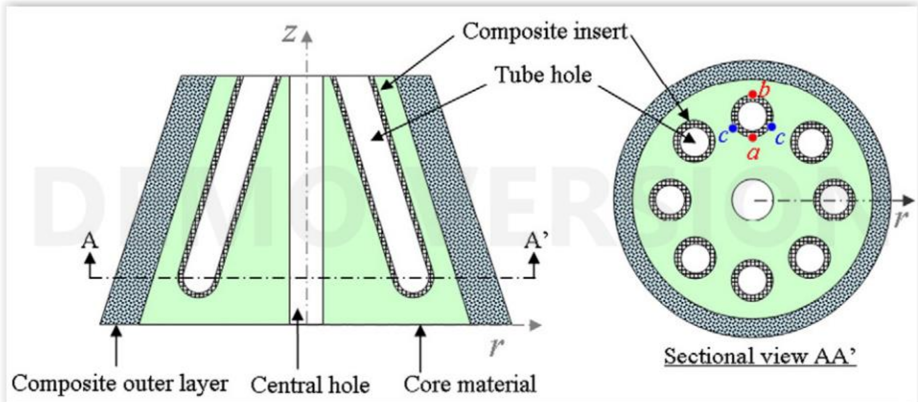

Fig. 2.3 Cross-section view of a hybrid composite rotor for an ultracentrifuge

Paper-3: ***M. Bayat , B.B. Sahari , M. Saleem, Aidy Ali, S.V. Wong, "Bending analysis of a functionally graded rotating disk based on the first order shear deformation theory", Science Direct, Applied Mathematical Modelling Vol. 33 (2009), Pages: 4215–4230***

The theoretical formulation for bending analysis of functionally graded (FG) rotating disks based on first order shear deformation theory (FSDT) is presented. The material properties of the disk are assumed to be graded in the radial direction by a power law distribution of volume fractions of the constituents. New set of equilibrium equations with small deflections are developed. A semi-analytical solution for displacement field is given under three types of boundary conditions applied for solid and annular disks. Results are verified with known results reported in the literature. Also, mechanical responses are compared between homogeneous and FG disks. It is found that the stress couple resultants in a FG solid disk are less than the stress resultants in full-ceramic and full-metal disk. It is observed that the vertical displacements for FG mounted disk with free condition at the outer surface do not occur between the vertical displacements of the full-metal and fullceramic disk. More specifically, the vertical displacement in a FG mounted disk with free condition at the outer surface can even be greater than vertical displacement in a full-metal disk. It can be concluded from this work that the gradation of the constitutive components is a significant parameter that can influence the mechanical responses of FG disks [14].

Paper-5: ***Naik Shashank Giridhar, Sneh Hetawal, Baskar P.; "Finite Element Analysis of Universal Joint and Propeller Shaft Assembly", International Journal of Engineering Trends and Technology (IJETT) – Volume 5 Number 5 - Nov 2013, Pages: 226-229*** [16]

In this Paper, Analysis of the Yoke clearly shows that by a small modification in the existing design the strength of the part can be increased significantly. Also with the same changes they obtain a small amount of weight reduction in the design. The maximum stress values generated are significantly reduced and the stress is evenly distributed over the entire part. Propeller shaft can be made either from steel or from the aluminium. The stress generated are approximately the same but the deformation in aluminium shafts is higher than that of the steel shaft. FEA has been carried out with ANSYS Workbench Software.

Paper-6: ***F. N. Werfel, U. Flogel-Delor, R Rothfeld, D. Wippich, T Ridel, "Centrifuge advances using HTS magnetic bearings" Physica C 354 (2001), Pages: 13-17.***

A prototype centrifuge with a HTS double bearing design and an integrated 15W cryo-cooler was assembled in vertical geometry. Toward this application of SMB the rotor dynamics studied by stability measurements with and without unbalanced masses. In the resonance case extreme eccentricity values of up 2mm are safely passed due to the high damping efficiency of the SMB modules. The prototype could serve as the basis for a first advanced centrifuge type equipped with HTS bearings [11].

3. CONCLUSION

From the above literature review, it is noted that the rupture of rotor was due to insufficient integrated strength of the rotor as maximum centrifugal stress exceeds the ultimate strength of the material. Material of the rotor was as per specified grade high strength aluminium alloy and there was no degradation of material.

Ultra-centrifuge that runs the rotor more than 50000 rpm has complete vacuum in the chamber to minimize or eliminate the effect of air resistance and use composite material to reduce the weight of the rotor. That will affect the final price of the rotor.

Therefore, mechanical stress analysis using finite element method to be carried out for failure analysis by applying centrifugal force of the two times of the maximum operating speed and structural optimization to improve the performance.

4. REFERENCES

[1]. S. Rao, Engineering Optimization – Theory and Practice. NY: John Wiley & Sons, Inc., 1996.

[2]. Robert D. Cook, Finite Element Modeling For Stress Analysis NY: John Wiley & Sons, Inc., 1995.

[3]. R. J. Yang, S. Kodialam, L. Gu and C.-H. Tho, "Multidisciplinary Design Optimization in a Scalable, High Performance Computing Environment," Structural and Multidisciplinary Optimization, vol. 26, pp. 256-263, Feb. 2004.

[4]. T. W. Simpson, A. J. Booker, D. Ghosh, A. A. Giunta, P. N. Koch and R.-J. Yang, "Approximation Methods in Multidisciplinary Analysis and Optimization-A Panel Discussion," Structural and Multidisciplinary Optimization, vol. 27, pp. 302-313, July. 2004.

[5]. Ashok D Belligundu and Tirupathi R. Chandrupatla, Optimization Concepts and Application in Engineering. Prentice Hall India

[6]. Schittkowski, K., "On the convergence of a Sequential Quadratic Programming Method with an Augmented Lagrangian Line Search function," Optimization, Mathematische operationsforschung and Statistik, vol. 14, 197-216, 1983.

[7]. Pshenichny, B. N. and Danilin, Y.M., Numerical Methods in External Problems, Mir Publishers, Moscow, second printing 1982.

[8]. Holland J.H., Adaptation in natural and artificial system, Ann Arbor, The University of Michigan Press, 1975.

[9]. ANSYS V 16.0 Documentation Manual, Advanced Analysis Techniques Guide Design Optimization - Optimization Techniques

[10]. Schmit L. A., "Structural design by systematic synthesis", Proceedings, 2nd conference on electronic computation, ACSE, New York, pp. 105-122, 1960.

[11]. S-Y. Chen, "Integrating ANSYS with Modern Numerical Optimization Technologies", ANSYS Solutions Magazine, Published in Winter Issue 2001.

[12] Xuan Hai-jun, Song Jian, "Failure analysis and optimization design of a centrifuge rotor", Science Direct, Engineering Failure Analysis Vol. 14 (2007) Pages: 101–109

[13] Hak Gu Lee, Jisang Park, Ji Hoon Kim, "Design theory and optimization method of a hybrid composite rotor for an ultracentrifuge", Science Direct, Mechanism and Machine Theory, Volume 59 (2013), Pages: 78-95

[14] M. Bayat , B.B. Sahari , M. Saleem, Aidy Ali, S.V. Wong, "Bending analysis of a functionally graded rotating disk based on the first order shear deformation theory", Science Direct, Applied Mathematical Modelling Vol. 33 (2009), Pages: 4215–4230

[15] Naik Shashank Giridhar, Sneh Hetawal, Baskar P.; "Finite Element Analysis of Universal Joint and Propeller Shaft Assembly", International Journal of Engineering Trends and Technology (IJETT) – Volume 5 Number 5 - Nov 2013, Pages: 226-229

[16] Available at: <http://www.neuation.com/ifuge_m12p.html>