A Study of the Effective Lifetime of Aluminum Buckets Used in Blood Bank Centrifuges

Mohammad Fallah Tafti
Blood Transfusion Research Center
Inst. of Research & Education in Transfusion Medicine
Tehran, Iran
m.falah@ibto.ir

Reza Golestani
Sina Ebtekar Company,
Tehran, Iran
golestani@sinaebtekar.ir

Mahmoud Salari
Dept. of Mech. Eng.
Imam Hossein University
Tehran, Iran
msalari@ihu.ac.ir

Abstract—**Rotating parts of blood bank centrifuges are under heavy mechanical cyclic stresses due to their centrifugal loading conditions. Estimating the effective lifetime for these parts is very important for their application. Providing safety requirements for these components is mandatory in blood transfusion centers (BTC). Failure occurs in the engineering parts for both loading conditions of steady and cyclic. The fatigue phenomenon is the main reason for mechanical failures at least in 90 % of fractures during operation. In this paper, the effects of fatigue caused by centrifugal loadings on aluminum buckets produced by the Iranian Sina Ebtekar Company (ISECo) are investigated experimentally. In this study, 48 aluminum buckets are chosen from a set of 500 buckets. The numbers of service of the samples are accounted for a period of 7 months. Finite element analysis, FEM, is done for an aluminum bucket and the relevant maximum stresses due to the rotating loads of centrifugation are determined. Analyzing the numerical results and using the fatigue, lifetime diagrams according to the number of operating cycles is presented for the samples. A good consistency is observed between the experimental and numerical results. Based on the results, a new correlation is presented for estimating the aluminum bucket's lifetime made by ISECO**.

Keywords-failure; FEM; fatigue; lifetime; aluminum buckets; blood bank centrifuges

I. INTRODUCTION

The application of organized knowledge and skills in the form of devices, medicine, procedures and systems development to solve a health problem and improve quality of lives is referred as "health technology" [1]. The term "healthcare technology" describes the type of device or equipment used in health facilities. The blood bank centrifuges are machines used to separate blood components like platelet, plasma and red blood cells. They rotates the blood bags placed in swing aluminum buckets with a rotational speed of 4000 to 5000 rpm [2]. The process is conducted in blood bank centers. Mechanical safety evaluation of rotating parts of the centrifuges is an important issue for designers, manufacturers of medical equipment and their operators. Aluminum buckets used as parts in centrifuges are used for keeping the liners included blood bags. It is obvious that these rotating parts are under heavy mechanical stresses during the centrifuge process [3-7].

During blood processing, buckets and other parts with rotational motion are under continuous loading, which starts from zero and reaches to a maximum stress and works for a programmed time. After the separation process, through a braking function, the amount of bucket stress decreases to zero again. As a result, the assessment of load conditions indicated the dominant failure mechanism for these buckets would be the fatigue. In [8], authors reported that such loads, that may not cause failure of a structure in a steady state, may cause fracture when they are applied repeatedly on structures. Failure may occur after a number of cycles of loading and unloading, usually a few millions of cycle, depending on the amplitude of the applied load. Therefore the fatigue phenomenon can be also a main reason for failure of these type of parts [9–13].

This study tries to finds a method to estimate the lifetime of aluminum buckets used in blood bank centrifuges and to develop instructions for their preventative maintenance. Stability and practically unlimited lifetime for engineering parts is a necessity because a sudden fracture can endanger peoples' life and cause financial damages. There are different bases to investigate the lifetime of an engineering part. All topics from fracture progress theories in dynamical loading till creep analysis in static loading are developed for the purpose of estimating the lifetime of engineering parts. For metals, theoretical basis included fatigue; fracture and etc. are developed topics. Some proposed topics in mechanical metallurgy [2] are theoretical basis of fracture, fatigue and creep. But according to the functional loading condition and environmental conditions for each engineering part the effective lifetime and exchanging time should be provided before occurring sudden fracture to avoid possible damages.

The fatigue phenomenon is the main factor of fracture creation and destruction and thus the major factor that determines the bucket's lifetime. Because of the creep, the aluminum material in a temperature lower than 100 ºC doesn't have sensitivity and the creep process is not observed [14-17]. Although stress release doesn't occur suddenly but over time, it still may cause sudden and friable fractures in the part [18–21].

Other factors, usually considered are the effect of environmental corrosion, the effect of structure defects and the effect of structure tolerances. With regards to high rotational speed and weight of components during rotation in these devices, predicting the useful effective lifetime and estimating time to exchange buckets during operation is necessary, keeping in mind that fracture of buckets in these rotational speeds will cause irreparable damages [22–25].

II. ANALYSIS METHOD

The present study focused on investigating the lifetime of 48 buckets in 3 blood bank centers in Mashhad. It includes surveys undertaken in 7 months. It aims to determine the factors that adversely affect the operation, maintenance and disposal of the device. For analytical study of the lifetime of buckets, a chain of engineering steps were followed: a) determine loading conditions, b) model the system in a CAD software, c) analyze stress in an FEM software, d) extract lifetime results fatigue standard data based on maximum stress and finally e) use an innovative formula to construct some sample instructions for predicting the lifetime of buckets in a blood bank center and determine replacement time.

To estimate the lifetimes of buckets, designed and manufactured by Sina Ebtekar Company, one blood bank centrifuge from one of the six blood bank centers of IBTO in Mashhad was considered. The main reason for this selection was that the base of maintenance supplied unit of Sina Ebtekar Company is in Mashhad and the recording experimental results are a time consuming work and need the cooperation of these units. For this study, 48 Aluminum buckets of the Sina Ebtekar Plus brand were randomly selected from 500 buckets and the lifetimes of these buckets were studied for 7 months (from February 5 to August 21, 2014). Normally the amount of load mass for each bucket during a cycle was about 2500 gr and the RCF was between 4500 and 5000 rpm. At the same time, with the gathering of the statistics of the 48 buckets, the lifetime of buckets was estimated. In this method by reviewing the loading conditions, determining the initial and boundary conditions and material characteristics of buckets and using the Finite Element Method (FEM) analyses, the maximum stress related to cyclic loads (repeated loading and unloading of accelerating and braking) was extracted (Figure 1) and by mapping the maximum stress of buckets from FEM analysis onto (S-N) Fatigue Life Curve of the aluminum of bucket (Figure 2) the safe zone for blood bank centrifuge's bucket, was extracted and shown in Figure 3 and the buckets lifetime was estimated (in cycles).

A 3D modeling of the bucket was done using Solid works modeling software and to obtain the maximum stress during cyclic loading, the finite element analysis was used. For this method, the COSMOS software has been used. By simulating the operating conditions, the stresses on the body of bucket have been calculated. Figure 4 shows the 3D model. In order to decrease the amount of unnecessary calculations, the 3D model was simplified in the region far from the stress concentration points. Figure 1 shows the results of the finite elements analysis.

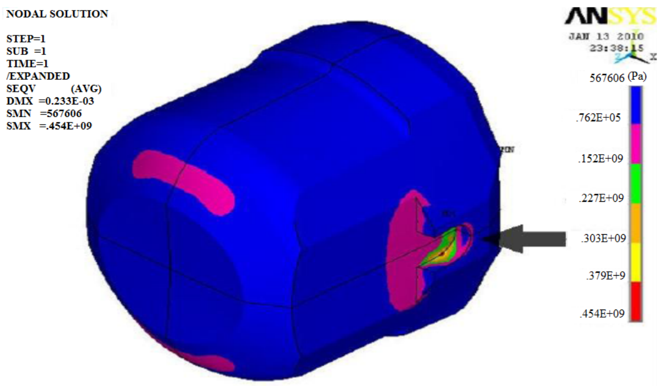

Fig. 1. The FEM results of the stress contours occurred in a bucket during centrifuge process.

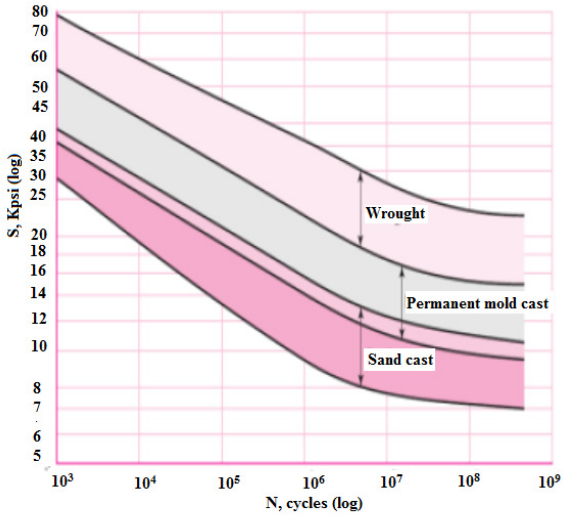

Fig. 2. S-N diagram for aluminum alloys

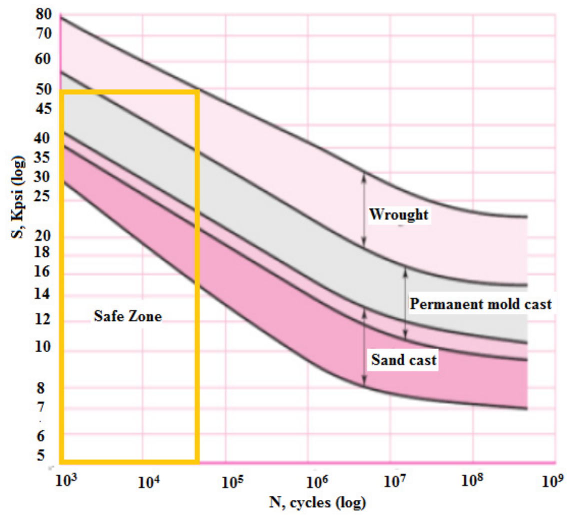

Fig. 3. The safe zone for blood bank centrifuge's bucket.

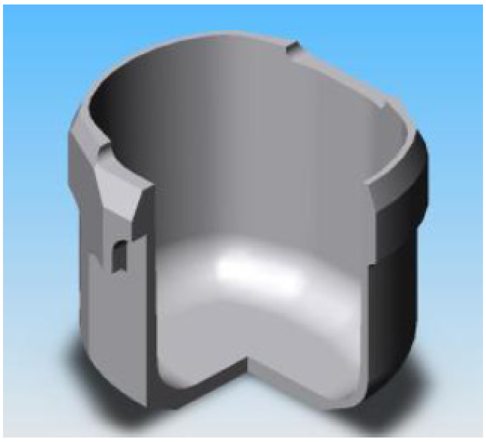

Fig. 4. Three diensional model of the aluminum bucket

For modeling blood bags in the liner, by considering weight and volume of bags, the irregular geometric square was used. According to material characteristics of liners, the Mechanical property of liners for "Static Structural Characteristics" has been considered as "Linear Elastic-Isotropic" with elasticity modulus of 1.2GPa and Poisson's ratio of 0.41. Loading has done as a Centrifuge Rotation with a rotational speed of 4000 RPM and the radius of the rotor has been considered 280 mm. These conditions caused 5000 units for RCF. It has been observed that maximum stress σ is approximately 18 to 20 MPa.

Briefly, for the lifetime assessment analytically based on fatigue, following phases were done step by step:

- The loading conditions were assessed. During this step the boundary conditions and initial conditions were defined.
- CAD Model of the system was built in SOLIDWORKS software and exported in standard CAD Format for Finite Element analysis.
- The Finite Element Model of the system was built in COSMOS software. Pyramid elements with four nodes and linear shape function were used.
- Material Characteristics, boundary conditions and initial conditions were imposed to the Finite Element model and the problem was solved by using default setting. The most important result of the FEM was the maximum stress in liner part during centrifugation operation.

Based on the results of FEM and using fatigue data for the material of liner (co-polymer polypropylene) the lifetime of liners was estimated in cycles (the number of repeated loading and unloading that liner can bear to show the first sign of fracture). This result is adequate for any designer. But in order to prevent unwanted failure and loss of life, every technician of preventative maintenance system or technical staff of blood bank centers needs to know how many days the liners must be used and according to their own daily schedule when liners need to be replaced with new ones. Finally, according to the plan for daily blood bags that are processed in each center, a simple but applicable formula was developed. It is useful for each machine, because some centers have more than one machine for blood processing. So it's possible to know how many days a liner could be used.

III. Results and Discussion

Experimental and analytical results show that the prediction success rate reached 97%. About 3% of the buckets have a lifetime more or less than the predicted amount and 75% of the buckets have an effective lifetime between the lower and upper bound (13000 to 18000 cycles). About 22% of buckets have a lifetime larger than the predicted one. This is shown clearly in Figure 1. As shown, if the lower bound is considered a success rate of 97% is achieved. If the upper bound is considered the success rate falls to 78%. Here we presented a Hypothetical formula which could be used to estimate the possible working time of copolymer buckets in the centrifuges of any blood bank with the same circumstance.

The formula to calculate the number of operating days of buckets can be calculated as:

$$\text{Number of operating days} = \frac{12x_5x_3}{x_1x_2}$$

Where:

x_1: the number of centrifuging of each blood bag according to the statistic and existent reports

x_2: the number of blood bags in blood transfusion center bag according to the statistic and existent reports. The capacity of each centrifuge is 12 blood bags.

x_3: the number of centrifuge systems in blood transfusion center.

x_5: the useful lifetime of bucket by the number of operation according to bucket' volume.

This functions is hyperbolic (Figure 5). Comparing between the experimental and analytical lifetimes shows reasonably compatibility. The useful lifetime of buckets according to the fatigue analysis is between 13000 and 18000. According to the existent statistic, each blood bag centrifuges on average 2 times.

Table I shows the lower bound lifetime (13000 cycles) results for the "Sina Ebtekar Plus" buckets. It's advised that these amounts are considered as the ultimate lifetime of buckets. By this assumption you can prevent 97% of unwanted failure. In Figure 5, the curves of "upper and lower fatigue life of liners" in days upon "the numbers of blood bags plus liners that processed daily in a blood bank center" are shown. The analytical results show that the lifetime should be between 13000 Cycles (Lower Predicted Bound) and 18000 Cycles (Upper Predicted Bound). Curves are formed by output of the innovative formula with locating appropriate amount for variables.

TABLE I. THE MAIN INSTRUCTION FOR REPLACEMENT THE BUCKETS OF SINA EBTEKAR COMPANY IN A PREVENTATIVE MAINTENANCE SYSTEM.

Number of blood bags per day	50	60	80	100
Lifetime (days)	192	160	120	96

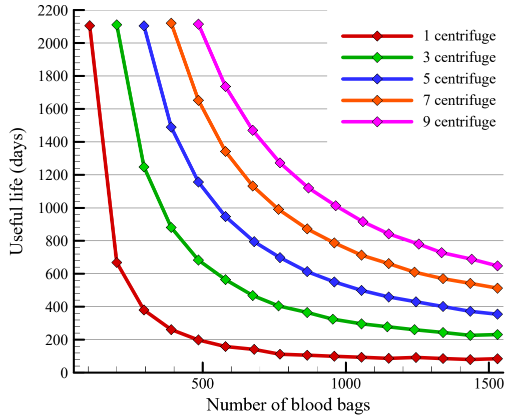

Fig. 5. Buckets lifetime (day) according to the number of blood bags and devices.

A. Mechanical properties of aluminum

Low special weight, low molting point, proper resistance to corrosion, good thermal and electrical conduction, being nonmagnetic and nontoxic, formability, high capacity of casting, proper stability, good appearance and color and proper cover ability make this metal to have a lot of application in automotive Industry, building, maritime industry, petrochemical, food industry, electrical and electronics, military industry, aerospace, computer and etc. aluminum allays divided into two groups of casting alloys and wrought alloys. Most of these consumable alloys are wrought which according to the aluminum association it divided into eight groups of 1xxx to 8xxx [27-28]. Buckets in blood bank centrifuges because of their operating condition mostly are built by alloys of groups 2xxx and 7xxx which are respectively Al-Cu-Mn and Al-Zn-Mg alloys [27-28]. The mechanical properties of 2xxx and 7xxx alloys are shown in Table II.

TABLE II. ELASTIC PROPERTIES OF USEFUL SAMPLES OF ALLOYS OF GROUPS 2000 AND 7000[27].

Material	Yield stress	Ultimate stress	Young's modulus	Shear modulus	Poisson's ratio
2014-T6	386.1	448.2	72	28	0.33
2014-T4	393	475.7	72	28	0.33
7075-T6	441.2	517.1	72	27	0.33

For engineering parts, two types of friable and soft fracture are possible. Classification is conducted according to plastic transformation. Soft materials typically have significant plastic transformation before fracture and also the energy absorption is high, but friable material usually have a little plastic transformation or don't have any at all and absorb little energy before fracture. Factors that cause friable fracture include temperature reduction, increasing strain rate, presence of sharp groove or grown crack and increasing sample thickness. Fatigue is a kind of friable fracture that occurs in structures which are under dynamical or switching stresses like bridges, plane and rotational parts. Under these conditions in stresses which are much lower than tensile or yield strength for static loading, friable stresses occur.

The fatigue term is used because this type of fracture usually occurs after periodic numbers of stress-strain cycle. Fatigue is important because it is one of the main reasons of metal's fracture. About 90% of metals, ceramics and polymers are disposed to this type of fracture. Furthermore such a fracture is sudden and unexpected and occurs without any pervious knowledge. Even for a soft material in friable fracture process, a little plastic transformation occurs and the process stared by germination and crack growth and fracture surface is perpendicular to applied strain. There are three methods to determine the resistance to fatigue that the most important of them are stress-life method. In this method the fatigue information of metals is plotted in S-N diagram which is fracture stress versus stress period cycles [28]. Surface under curve is the safe region from the perspective of design. For wrought alloys of aluminum S-N diagram is shown in Figure 2.

B. Fatigue Study

In this paper, fatigue effects of centrifugal stresses on aluminum buckets of blood bank centrifuges was considered for determining the effective lifetime. By considering the number of permissible cycles until fatigue fracture of the bucket's material, the number of the operating days of buckets determined by using the maximum stress cycles which calculated from finite element static analysis.

C. 3D modeling of bucket and finite elements analysis

3D modeling of bucket was performed by Solid works modeling software and ANSYS software was been used for finite element analysis. One of the important issues in bucket modeling is modeling connection of bucket to the rotor. For modeling this using joint is the easiest method and using the element contact is the most complete method to solve that. Also there are different ways for modeling the mass because of blood bags, liners and balance weights but using additional mass because of simplicity is the most appropriate way and also its doesn't have a noticeable difference in results in comparison with other methods.

D. Calculating the effective lifetime of blood bank centrifuge's bucket

It is mentioned that buckets with rotational equipment of blood bank centrifuge in each usage, are under continuous loading which starts from zero and reaches to a maximum stress and stays in that stress limitation for a specific time. And then by start braking, the stress decrease until reaches to the zero again. So applied stresses to the buckets can be divided into two groups:

- Stresses of staring and braking transient steps of device which addition of them in each operating cycle can be assumes as a one periodic cycle in constant direction. Since it's needed to have the amount of maximum cycle stresses for fatigue analysis, using the static analysis which is the determiner of maximum applied stress, is considered more valid.
- Loading can be assumed completely static as the operating temperature is under 22 ^{o}C and for this alloy, the minimum

temperature for creep is near 100 °C. So creep effects are not considered.

In order to determine the number of operating cycle of bucket, according to the results of the numerical finite element analysis, maximum stress would be about 303Mpa. Considering a safety factor of 1.4, the stress in the maximum value it reaches 363 Mpa which is equivalent of 52.6 ksi. In Figure 3, the safe zone for designing of centrifuge bucket and the predicted lifetime has shown. It determines that the effective lifetime of buckets is between 13000 and 18000 stress cycles. According to the effective lifetime curves, obtained in this study, the exchanging timetable for ISEC's buckets of blood bank centrifuges in each blood transfusion center was presented. For example, the maximum effective lifetime of a bucket, which used in a blood bank center with a capacity of centrifuge rate of 200 blood bags per a day, is 1400 working days or 46 months and if that mentioned centrifuge centrifuges maximum of 100 blood bags per a day, the lifetime of its buckets will be 2100 working days.

IV. CONCLUSION

In summary, our hypothetically presented formula is working when buckets made by "Sina Ebtekar Plus" are taken under centrifugal force with an RCF between 4500 and 5000 and temperature between 2 and 20 °C. Other destructive factors like solvents and humidity were not considered in this investigation. Fatigue effects of centrifugal stresses on polymer liners of blood bank centrifuges were considered for determining their effective lifetime. Experimental tests were done to validate the analytical results. The results of this study can be useful for both the centrifuges designers and the blood banks maintenance staff.

ACKNOWLEDGEMENT

The authors thank the Sina Ebtekar Company and the Iranian Blood Transfusion Organization for their support of this research.

REFERENCES

[1] A. P. Parker, "Stress intensity factors, crack profiles, and fatigue crack growth rates in residual stress fields" in Residual Stress Effects in Fatigue, ASTM International, 1982

[2] G. E. Dieter, D. J. Bacon, Mechanical metallurgy, Vol. 3, McGraw-Hill New York, 1986

[3] H. Pfister, K. H. Braun, "Induction of correct centrifugal force in a rotating mass shell", Class. Quantum Gravity, Vol. 2, No. 6, p. 909, 1985

[4] F. J. Casson, A. G. Peeters, C. Angioni, Y. Camenen, W. A. Hornsby, A. P. Snodin, G. Szepesi, "Gyrokinetic simulations including the centrifugal force in a rotating tokamak plasma", Phys. Plasmas, Vol. 17, No. 10, p. 102305, 2010

[5] B. Vonnegut, "Rotating bubble method for the determination of surface and interfacial tensions," Rev. Sci. Instrum., Vol. 13, No. 1, pp. 6–9, 1942

[6] H. R. Vosoughifar, M. A. Naderi, "Numerical Analysis of the Base-Isolated Rectangular Storage Tanks under Bi-directional Seismic Excitation", British Journal of Mathematics & Computer Science, Vol. 4, No. 21, pp. 3054–3067, 2014

[7] B. Ikhajiagbe, G. O. Anoliefo, E. O. Oshomoh, U. A. Ogedegbe, N. Airhienbuwa, "Changes in Polyaromatic Hydrocarbon Content of a Waste Engine Oil Polluted Soil Exposed to pH Adjustments", Annu. Rev. Res. Biol., Vol. 2, No. 3, pp. 66–82, 2012

[8] N. Özkaya, M. Nordin, D. Goldsheyder, D. Leger, Fundamentals of biomechanics: equilibrium, motion, and deformation. Springer Science & Business Media, 2012

[9] U. Beck, G. Reiners, D. Lerche, U. Rietz, H. Niederwald, "Quantitative adhesion testing of optical coatings by means of centrifuge technology", Surf. Coatings Technol., Vol. 205, pp. S182–S186, 2011

[10] J. C. Q. Amado, "Manufacture and testing of lightweight tubes for rocketry and centrifuges", Light. Compos. Struct. Transp. Des. Manuf. Anal. Perform., p. 421, 2016

[11] S. Kamandulis, T. Venckunas, A. Snieckus, E. Nickus, J. Stanislovaitiene, A. Skurvydas, "Changes of vertical jump height in response to acute and repetitive fatiguing conditions," Science & Sports, Vol. 31, No. 6, pp. e163-e171, 2016

[12] M. Tunali, H. Özdemir, Z. Küçükodaci, S. Akman, E. Öncü, M. Aydınbelge, M. Akman, E. Firatli, "A New Centrifugation Method for the Improvement of Platelet-rich Fibrin Products: A Preliminary Study", Br. J. Med. Med. Res., Vol. 13, No. 6, pp. 1–10, 2016

[13] S. Kabir, T. I. Yeo, "Characterization of Low-cycle Fatigue Parameters", Br. J. Appl. Sci. Technol., Vol. 12, No. 3, pp. 1–15, 2016

[14] M. R. Mitchell, R. W. Landgraf (eds), Advances in Fatigue Lifetime Predictive Techniques, American Society for Testing and Materials, 1993

[15] X. Hai-jun, S. Jian, "Failure analysis and optimization design of a centrifuge rotor", Eng. Fail. Anal., Vol. 14, No. 1, pp. 101–109, 2007

[16] H. Kamata, H. Mashimo, "Centrifuge model test of tunnel face reinforcement by bolting", Tunn. Undergr. Sp. Technol., Vol. 18, No. 2, pp. 205–212, 2003

[17] W. A. Take, M. D. Bolton, "The use of centrifuge modelling to investigate progressive failure of overconsolidated clay embankments", in Constitutive and Centrifuge Modelling: Two Extremes, Taylor & Francis, 2002

[18] A. Grm, M. Batista, "On the coupling of analytical and FEM solution in stress analysis around the polygonal hole shape in a finite two-dimensional domain", Int. J. Mech. Sci., Vol. 118, pp. 254–267, 2016

[19] S. M. Jang, H. W. Cho, S. K. Choi, "Design and analysis of a high-speed brushless DC motor for centrifugal compressor", IEEE Trans. Magn., Vol. 43, No. 6, pp. 2573–2575, 2007.

[20] P. Jeanjean, "Re-assessment of py curves for soft clays from centrifuge testing and finite element modeling", Offshore Technology Conference, 2009

[21] F. McKenna, M. H. Scott, G. L. Fenves, "Nonlinear finite-element analysis software architecture using object composition", J. Comput. Civ. Eng., Vol. 24, No. 1, pp. 95–107, 2009

[22] D. Wang, D. J. White, M. F. Randolph, "Large-deformation finite element analysis of pipe penetration and large-amplitude lateral displacement", Can. Geotech. J., Vol. 47, No. 8, pp. 842–856, 2010

[23] I. Anastasopoulos, G. Gazetas, M. F. Bransby, M. C. R. Davies, A. El Nahas, "Fault rupture propagation through sand: finite-element analysis and validation through centrifuge experiments", J. Geotech. Geoenvironmental Eng., Vol. 133, No. 8, pp. 943–958, 2007

[24] D. Forsström, P. Jonsén, "Calibration and validation of a large scale abrasive wear model by coupling DEM-FEM: Local failure prediction from abrasive wear of tipper bodies during unloading of granular material", Eng. Fail. Anal., Vol. 66, pp. 274–283, 2016

[25] S. Asiri, "Modal and Vibration Analysis of Functionally Graded Dental Implant", Br. J. Med. Med. Res., Vol. 12, No. 7, pp. 1–14, 2016

[26] D. G. Ullman, The mechanical design process, Vol. 2. McGraw-Hill New York, 1992.

[27] D. S. MacKenzie, G. E. Totten, Analytical characterization of aluminum, steel, and superalloys. CRC press, 2005

[28] J. E. Shigley, Shigley's mechanical engineering design. Tata McGraw-Hill Education, 2011