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Design and development of a modular vibration test rig for combination types of fault in rotating machinery health diagnosis

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ABSTRACT

As a basis to real application of rotating machineries operation, a test rig imitating the operation is designed for the research environment. The purpose of this study is to design a modular test rig which is able to facilitate different fault component combinations and evaluate the deformation pattern of the fabricated test rig. Rotating machineries face the probability of having simultaneous different faults and the study of this condition is limited. The designed test rig could be arranged into multiple configurations by adding or excluding desired components due to its modularity. This will be useful to study the response of each component during operation as well as the response of combinations of fault components. Included in this study is the analysis of the design where the maximum possible operating condition at 60Hz speed was considered. The final test rig design was included as well as the experimental displacement data results of the fabricated test rig showing 17.5% measurements to exceed 1mm displacement. This test rig is beneficial for understanding the vibrational behavior of components and is designed for educational environment.

Keywords: Rotating machine; vibration test rig; fault diagnosis; modular.

INTRODUCTION

All systems possess their own natural frequency in which, if fault frequency coincides with the natural frequency of the system, resonance occur [1]. This phenomenon leads to disastrous event if left unattended. Health conditions of the components specifically in rotating machines systems can be attained through condition monitoring. Periodic condition monitoring of machineries is widely used to help schedule efficient maintenance as well as early fault detection [2]. It is able to determine the reliability of machineries, prolong their life expectancy, reduce maintenance costs while assuring safe operation of critical machines [3].

The vital components of machines need to be well investigated. Rotating machine includes fundamental components such as bearings, gears, shafts, rotor, etc. All these components are prone to defect throughout their operation. Several common types of faults in rotating machineries include bearing fault, gear fault, misalignment and imbalance fault

[3, 4]. Vibration analysis becomes a common condition monitoring method of rotating machinery faults since they can be detected by studying the vibration signal collected on the machine [5].

Bediaga et al. [4] described that for a ball bearing fault, it produces significant level of vibration during operation due to the striking motion between the fault area and other surfaces which causes excitation at bearing's resonance frequency. Some different types of bearing fault include outer race crack, inner race and bearing corrosion [4].

Other than bearings, the gear component is prone to fault such as gear pitting, tooth fracture and wear [7, 8]. For a gearbox system, several conditions that affect performance are inadequate lubrication, installation error and wear [10]. Another common fault in machineries is imbalance [11]. When imbalance is present, a harmonic frequency elements of system's rotating speed is produced [12].

In a study conducted by Plante et al. [13], the usage of vibration simulator had been applied where experiments were conducted to test three different conditions of the motor system. The healthy motor condition signal was used as the reference signal. The other two conditions tested are misalignment and rotor imbalance. These faults were able to be simulated due to the capability of the simulator to accommodate different types of faults. Similarly, in another study by Li et al. [14], five health conditions were tested on a single rig which include healthy condition, imbalance and three different faults on bearing.

To be able to test for different faults simultaneously, a test rig capable to facilitate this is needed. Hence, the objective of this paper is to develop a modular test rig which can assist components fault study in addition to compare and evaluate the estimated and experimental vibration of the test rig in terms of deformation shape and measurement. The development of the test rig applied common engineering design process while using weighted rating matrix further during conceptual evaluation. The deformation shape of design was obtained through simulation in SolidWorks by frequency study. Experimentally, vibration signals were collected at nine locations on test rig with seven variation of operational speed. It was expected that the deformation data plotted based on the experiment coincides with the simulated deformation shape.

TEST RIG DESIGN AND ANALYSIS

In this section, the engineering design process for the modular vibration test rig and its evaluation method are described. Engineering design process includes the problem defining process as the initial step. This is then followed by information gathering process to obtain knowledge regarding studied matter. The conceptual design is generated along with the design evaluation before the design is fabricated and tested. These processes are summarized in Figure 1.

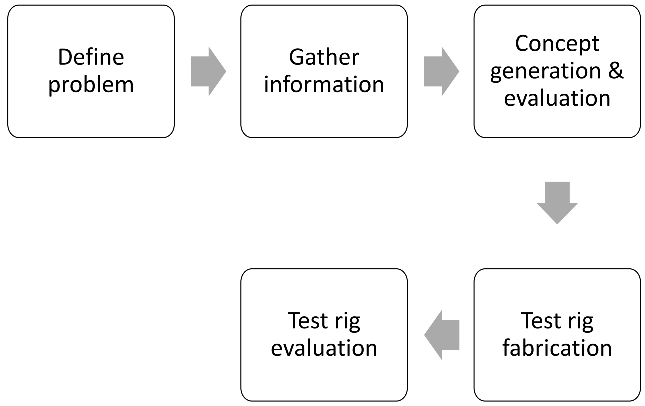


Figure 1. Flowchart of design process and test rig evaluation

Defining Problem

This project is limited to designing a rotating machine test rig to simulate bearing fault, gear fault and imbalance. The rig is driven by an electrical motor. The concept of a modular design will be applied to enhance the test rig ability. Identification of problems and related engineering characteristics are as in Table 1.

Table 1. Summary of problems and engineering characteristics of desired test rig

Problems	Required Function	Engineering Characteristics	Limitations
Varying testing speed	To control speed	Speed	< 3600 RPM (revolution per minute) (60Hz)
Easy assembly and disassembly	To connect	Modularity	Robust, rotating machine
Different component testing	To conduct different tests	Flexibility	Bearing, imbalance and gear fault
Bearing fault testing	To introduce fault	Vibration	Single bearing fault type (inner bearing race crack)
Imbalance fault testing	To introduce fault	Vibration	Single rotor disk
Gear fault testing	To introduce fault	Vibration	Spur gear system, single fault

Gather Information

It is crucial to obtain enough knowledge to relate and solve the problems listed. With the intent of designing a modular test rig, literatures are obtained from proceedings, journals and companies' catalogues. The advantages and ability of modular design are reviewed. Table 2 shows a summary of the ability of modular design system.

Table 2. Summary of the ability of modular design system

Application of Modular Design of a System	
Scalability	Grow and shrink in size [15].
Functionability	Combine more than one function [16].
Remanufacturing	Dissemble and reuse of module [15].

Concept Generation

Modular design is a concept which is currently applied in machine design due to various advantages. Applying modular design in a system contributes to the ability of producing various possible construction of a system and the flexibility in operation of the system, depending on the level of assembly on which a certain module of the system is able to connect to [15, 16]. The test rig in this study is designed to incorporate this concept to fulfill the freedom of building desired components in a single kit. Components are classified into specific modules and a single main bed is included as the base of the rig building.

During the development of design, the functional decomposition of components is listed as reference on the fundamental and desired components of rotating machine. The functional decomposition of the test rig breaks down each device to its required input, function and output. This process provides a clearer idea to assure the function and requirements are fulfilled in the design. Table 3 shows the functional decomposition of a standard rotating machine system.

Table 3. Functional decomposition of test rig (Source: [18])

Device	**Function**	**Device**	**Function**
Motor	Convert electrical energy to rotating mechanical energy	Shaft	Transmit rotating mechanical energy
Coupling	Transmit power to shaft	Bearing	Support rotating assemblies
Base	Hold subassemblies and rig components	Housing	Locate and hold bearing
Gear	Transmit torsional moments	Balance disc	Balance the rotating assembly

Concept Evaluation

Selection of concept is conducted through critical evaluation by applying weighted rating method. Each criterion is scored by their importance towards the design ranging from 1 to 5, where 5 being the highly important criterion, and each concept is then scored depending on the best suited method between 1 to 10. The score of each concept is multiplied by the weightage of criterion and the highest score is chosen as the best method. Table 4 shows the rating matrix in which the option with the highest score for each criterion is chosen.

Table 5 summarizes the available concepts for each criterion in this study.

Table 4. Weighted rating method matrix

	Concept	Option 1	Option 2
Engineering Characteristics	Score	6	8
Criteria 1	4	24	32
Criteria 2	3	18	24

Table 5. Available concept for each criterion

Needed functions	Engineering Characteristics	Option 1	Option 2	Option 3
To control speed	Speed	Motor speed controller	-	-
To connect	Modularity	Magnet	Coupling	Fix end key and keyway
To conduct different tests	Flexibility	Various fixed configuration	Different module	-
To introduce fault	Vibration	Induce during fabrication	Run component until fail	-

Product Architecture and Design Analysis

Bearing fault is introduced into the system by including a problematic bearing module together in the system. Imbalance is introduced in the rig by adding weights to a rotor disk. The disk is designed to enable the addition and attachment of bolts as weights around its face. Gear fault comes into the system by inserting a simple spur gear box with double gear transmission system inclusive of two different sized spur gears. The design reference of spur gear box is obtained from an online open source for Computer Aided Design (CAD), GrabCAD. Each of the components stated which are used to introduce fault into the system are being designed as single module in which are fixed on their respective shafts. To obtain normal operating signal of rig, the fault component modules are excluded during testing.

In order to achieve the optimum size of shaft design, the range of operating speed is determined to be below 3600 RPM which is equivalent to 60 Hz. The desired motor power is 1 HP. Using these values, the minimum design shaft diameter is calculated for main transmitting shaft size formula [20]. Based on Equation (1), the minimum diameter of shaft is 7.175 mm.

$$D = \sqrt[3]{\frac{1.33 \times 10^6 \times P}{N}} \tag{1}$$

Where,
D is Diameter in mm,
P is Power in HP,
N is Speed in RPM.

A frequency study analysis was conducted for the final design to estimate the natural frequencies of the overall system. The results will also determine the running speed variables for the validation experiment to avoid resonance.

Test Rig Evaluation

The fabricated test rig was tested to collect normal condition vibration data. The data were collected using different motor speed settings at 10, 15, 20, 25, 30, 35 and 40 Hz. These speeds were set at the motor speed controller supplied together with the motor. A program was build using LabVIEW software to assist in data acquisition and further analyze the data. Acquired data was filtered using Butterworth filter to remove signal background noise. The acceleration waveform obtained was double integrated and the overall displacement was obtained using root mean square operation. Overall displacement was obtained to compare the deformation of the fabricated test rig with the evaluation obtained in the finite element analysis simulation.

The experiment was carried out on the fabricated test rig. Complete configuration of test rig was used where all components were connected. The vibration signal was collected using PCB triaxial accelerometer located at nine different locations on the test rig. Figure 2 shows the experimental setup. The accelerometer was connected to USB 4431 National Instrument's data acquisition module and the module was connected to computer loaded with data acquisition and analysis program.

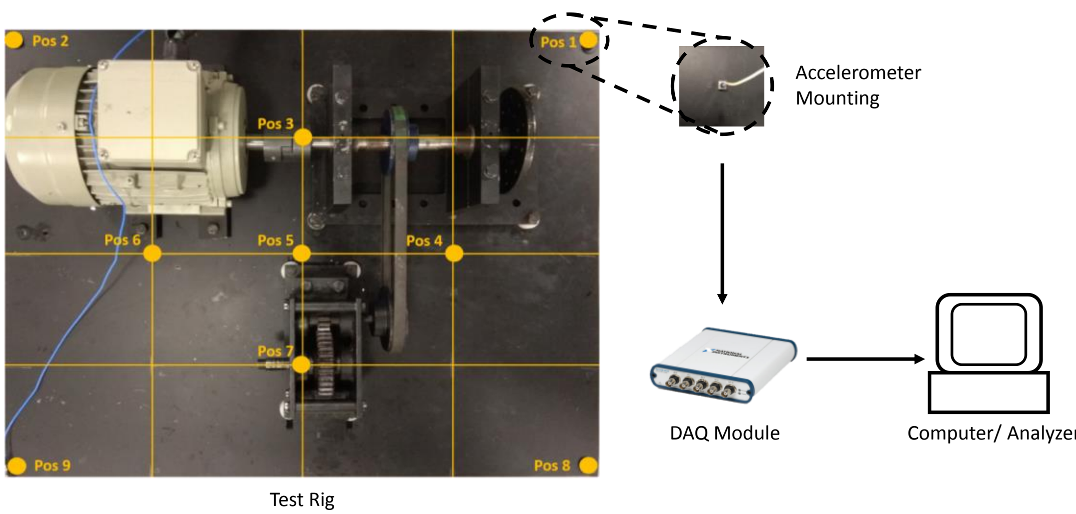


Figure 2. Experimental setup with nine different marked position on test rig

RESULTS AND DISCUSSION

Test Rig Analysis and Evaluation

Based on the engineering design process, the concept for each engineering criterion was finalised. These concepts scored the highest according to weighted rating matrix. The functions desired for the test rig was fulfilled according to the selected concept. Motor speed controller was included in the test rig to allow speed manipulation. The end of each shaft was fabricated with keyways and each shaft posed as a single module. The fault to be tested using this test rig was able to be introduced deliberately when needed. Table 6 summarizes the selected concept.

Table 6. Summarizes the selected concept for each criterion

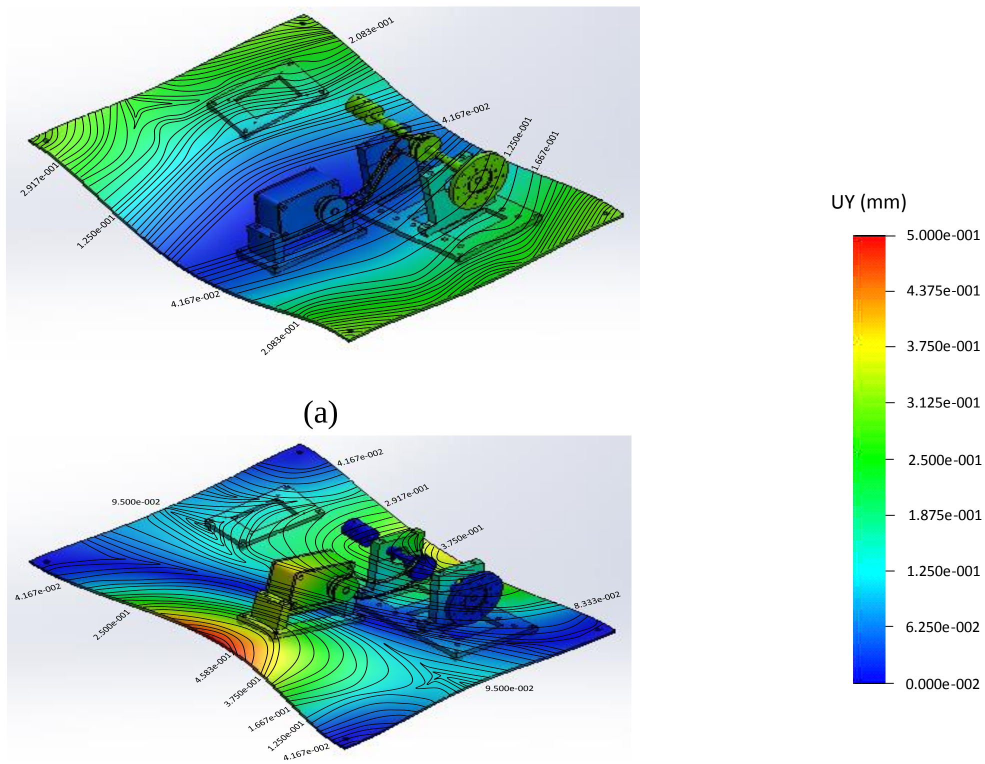
Needed functions	Engineering Characteristics	Selected Concept
To control speed	Speed	Motor speed controller
To connect	Modularity	Fix end key and keyway
To conduct different tests	Flexibility	Different module
To introduce fault	Vibration	Induce during fabrication

Several natural frequency values are listed in Table 7, those of which are lower than designed motor speed at 60 Hz. The natural frequency above this value is irrelevant in speed setting determination due to stated design factor.

Table 7. List of natural frequency of test rig below 60 Hz using SolidWorks

Mode number	Frequency (Hz)	Mode number	Frequency (Hz)
1	10.14	4	32.21
2	18.57	5	51.30
3	23.81	6	54.30

The y- axis (vertical) deformation of third and fourth mode shapes of test rig as estimated using frequency study in SolidWorks are included in Figure 3. The mode shapes are seen to be most significantly agreeing to collected response of test rig in evaluation test. Other mode shapes obtained through the simulation did not indicate any deflection on the base plate. This was observed due to the concern that the vibration on tested components originated from the base plate movement. Thus, only the third and fourth mode shapes were used for deflection comparison with nearest operating speed to the simulated modal frequency. The mode shapes direction of deformation shown are in the y-axis since the collection of response in evaluation test are also in y-axis.



(a)

(b)

Figure 3. (a) Third mode shape at 23.81 Hz, (b) Fourth mode shape at 51.30 Hz

The overall displacement at nine different positions collected are plotted in displacement vs position graph as in

Figure 4. Especially for 20 Hz of running motor speed, the overall displacement shows a significant amplitude at position 2 and 8. At 25 Hz motor speed, significant peak can be seen at position 2 and 5. These peaks are seen to be partially agreeable with the mode shape in Figure 3(a). However, for 40 Hz motor speed, peaks at position 2 and 8 are significant in the graph. These peaks are not expected and are unable to be compared to any simulated mode shapes obtained. Somehow, these scenarios occurring in fabricated test rig is a representation of real performance of the rig which deviates from estimation due to limitation and alteration during fabrication. During fabrication, fabricator might find some parts impossible to be exactly made due to the limitation of machine availability and sorts. Some alterations from the original design might occurred where some areas and parts were slightly uneven because of unintended working and precision factors [20].

In this study, an active speed control system is not available which is a drawback due to the inability to determine and monitor the operational motor speed during experiment. Speed setting was done manually each time the system was set up for experiment.

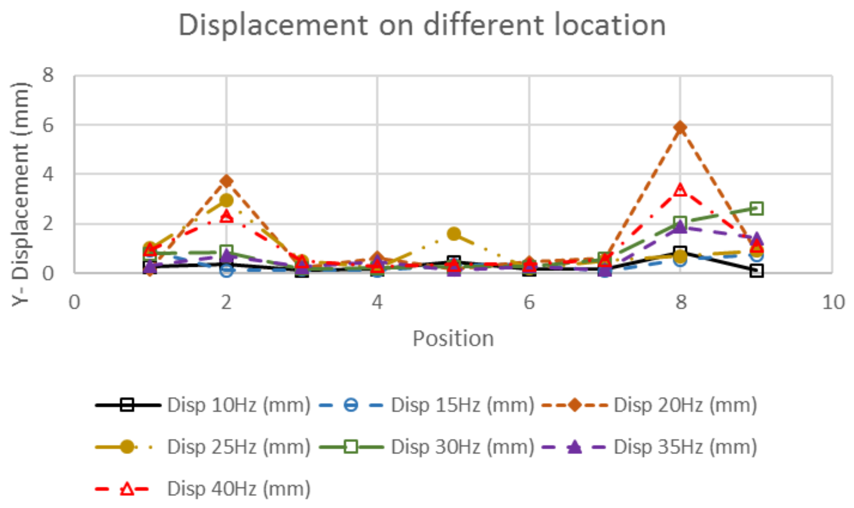


Figure 4. Displacement measured at different locations on test rig

As the collected data were compared to vibration standard using RMS overall velocity value in

Figure 5, it is found that for running speeds more than 25 Hz, the vibration of each point surpasses the acceptable limit according to ISO 2372 for class I rotating machinery. Even at 10 Hz, the vibration at position 8 is unacceptable. For positions 3, 4, 6 and 7 which are near to the actual motor and gearbox components (motor and gearbox vibration), the results show acceptable range of vibration which is less than 7.1 mm/s. Positions 1, 2, 8 and 9 refers to the positions at the corners of the base plate (base plate vibration). This can be a criterion to look at when conducting experiment using the test rig. The test rig might be going through resonance and at certain position where data is acquired, vibration level can be higher than expected.

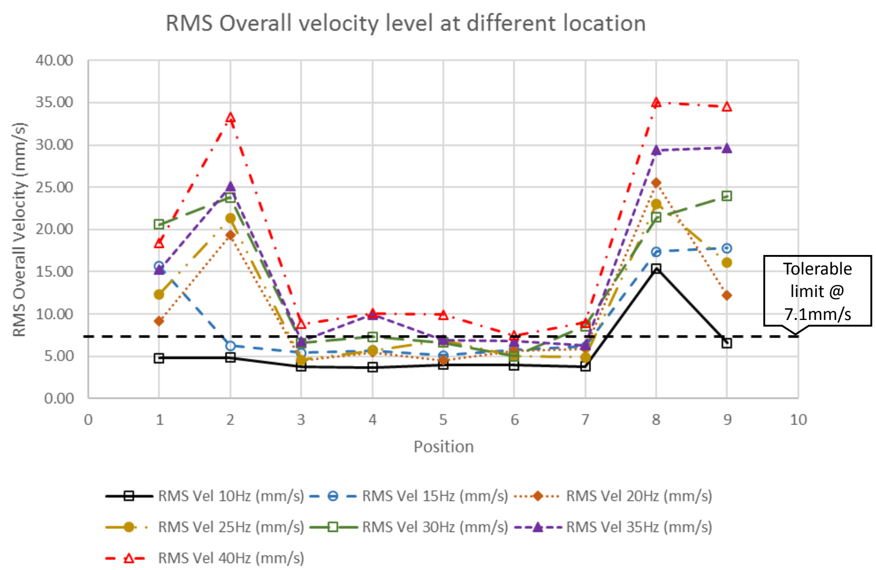


Figure 5. RMS overall velocity for each position

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REFERENCES

[1] Nikhil T, Chandrahas T, Chaitanya C, Sagar I, Sabareesh, GR. Design and Development of a Test-Rig for Determining Vibration Characteristics of a Beam, Procedia Engineering. 2016;144:312–320.

[2] Róbert H, Pavelka P, Lengvarsky P. Vibration and modal analysis of a rotating disc using high-speed 3D digital image correlation. Mechanical Systems and Signal Processing. 2019;121:201–214.

[3] Prieto MD, Cirrincione G, Espinosa AG, Ortega JA, Henao H. Bearing fault detection by a novel condition-monitoring scheme based on statistical-time features and neural networks. Institute of Electrical and Electronic Engineers Transactions on Industrial Electronics. 2013;60(8):3398–3407.

[4] Bediaga I, Mendizabal X, Arnaiz A, Munoa J. Ball bearing damage detection using traditional signal processing algorithms. Institute of Electrical and Electronic Engineers (IEEE) Instrumentation & Measurement Magazine. 2013;16(2):20–25.

[5] Sharma S, Abed W, Sutton R, Subudhi B. Corrosion Fault Diagnosis of Rolling Element Bearing under Constant and Variable Load and Speed Conditions. International Federation of Automation Control-PapersOnLine, 2015;48(30):49–54.

[6] Henriquez P, Alonso JB, Ferrer MA, Travieso CM. Review of automatic fault diagnosis systems using audio and vibration signals. Institute of Electrical and Electronic Engineers (IEEE) Transactions on Systems, Man, and Cybernetics: Systems. 2014;44(5):642–652.

[7] Zhang Q, Zhao G, Shu L, Qin A, Zhang Y. Research of Dimensionless Index for Fault Diagnosis Positioning based on EMD. Journal of Computers, 2015;1(27):62–73.

[8] Dhamande LS, Chaudhari MB. Detection of Combined Gear-Bearing Fault in Single Stage Spur Gear Box Using Artificial Neural Network. Procedia Engineering. 2016;144:759–766.

[9] Lijesh KP. Design and Development of Test Rig to Estimate Performance of Spur Gears. International Journal of Advance Industrial Engineering. 2015;3(1):20–23.

[10] Alkhadafe H, Al-Habaibeh A, Lotfi A. Condition monitoring of helical gears using automated selection of features and sensors. Measurement. 2016;93:164–177.

[11] Yamamoto GK, Da Costa C, Da Silva Sousa JS. A smart experimental setup for vibration measurement and imbalance fault detection in rotating machinery. Case Studies in Mechanical Systems and Signal Processing. 2016;4:8–18.

[12] Lee J, Wu F, Zhao W, Ghaffari M, Liao L, Siegel D. Prognostics and health management design for rotary machinery systems—Reviews, methodology and applications. Mechanical Systems and Signal Processing. 2014;42(1–2):314–334.

[13] Plante T, Stanley L, Nejadpak A, Yang CX. Rotating machine fault detection using principal component analysis of vibration signal. In: 2016 Institute of Electrical and Electronic Engineers (IEEE) AUTOTESTCON, Anaheim, California, USA, pp. 1-7; 2016.

[14] Li W, Zhu Z, Jiang F, Zhou G, Chen G. Fault diagnosis of rotating machinery with a novel statistical feature extraction and evaluation method. Mechanical Systems and Signal Processing. 2015;50–51:414–426.

[15] Wang P, Liu Y, Ong SK, Nee AYC. Modular design of machine tools to facilitate design for disassembly and remanufacturing. Procedia College International pour la Recherche en Productique (CIRP). 2014;15:443–448.

[16] Peukert B, Saoji M, Uhlmann E. An evaluation of building sets designed for modular machine tool structures to support sustainable manufacturing. Procedia College International pour la Recherche en Productique (CIRP). 2015;26:612–617.

[17] Ito Y. Applicability of 'Platform Concept' to machining function-integrated machine tools - A new 'Raison d'être' for modular design'. Mechanical Engineering Reviews. 2015;2(1):14-00320.

[18] Dieter GE, Schmidt LC. Engineering design. vol. 3. McGraw-Hill New York, 2013.

[19] Chuck Y. Relationship of torque and shaft size | Plant Engineering. Retrieved from http://www.plantengineering.com/single-article/relationship-of-torque-and-shaft-size/97eb6b3f6b32adcdd181341ebbdc3224.html; 11 June, 2017.

[20] Lei G, Wang T, Zhu J, Guo Y, Wang S. System-Level Design Optimization Method for Electrical Drive Systems - Robust Approach. Institute of Electrical and Electronic Engineers (IEEE) Transactions on Industrial Electronics. 2015;62(8):4702–4713.