Analytical design of the vertical balancing device for hematocrit centrifuge machine

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Abstract Hematocrit Centrifuge Machines (HCM) apply centrifugal force to separate suspended particles from a liquid or liquids which have different densities. Centrifuges of which the forces are greater than gravity can greatly accelerate separations that occur naturally as a result of density differences HCM were intended to separate red blood cells from plasma in order to facilitate later diagnosis process Main components include a motor that supplies power to the disk to quickly attain required speed. An unbalance found on a disk which creates vibration on the structure of HCM was caused by either non-homogeneous material or manufacturing process. Therefore, to balance the disk, this paper presents the analysis and design of the Vertical Balancing Device (VBD) for HCM using inexpensive accelerometer to measure amplitude with Hall-effect sensor to estimate rotating speed and maximum phase trigger for balancing. The experimental results show that VBD can balance the disk which in turn effectively reduces vibration to the determined dynamic response criteria effectively of unbalance vibration.

1. Introduction and problem statement

The measuring hematocrit technique was discussed of the method which consists of the components of whole blood, indications for measuring hematocrit and measuring technologies [1]. Those processes require a microhematocrit centrifugation technique of the HCM that used to help diagnose blood loss. The HCM devices intended to determine the blood’s hematocrit, the ratio of red-cell volume to whole blood volume, expressed as a decimal, a fraction, or a percentage. Figure 1 (a) shows the components including a motor that supplies power to the shaft and disk, centrifuge heads that spin on the disk, and a lid latch with lid. The centrifuge head contains shields that cover the disk and turns on a spindle. A safety shield in the chamber surrounds the disk. This model is equipped with an LCD display, a keypad, a timer, a braking system, and a tachometer, enabling the user to program a specific speed up to 20,000 rpm and view timer status. Principles of operation, centrifuge heads apply centrifugal force to separate liquids of different densities in the tubes. By generating forces many times greater than gravity, centrifuges can greatly accelerate separations [2]. The HCM, a capillary tube pocket slot of a centrifuge head unit, quickly attains required speed to spin microcapillary tube samples as shown in figure 1(b). These tubes require only small blood samples taken from a puncture site or from venous blood specimen.
However, configurations of many disks are manufactured in the ways that produce dissymmetry, rough surfaces on turning or milling, shown in figure 1(c). As mentioned previously, the rotating disk at high speed is affected by the vibration. The operation of the HCM may be noisy from vibration of being dragged into the tube cracking. It will also shorten the life of the machine. It causes a problem of unbalance which is often simply defined as the unequal distribution of the weight of a disk about its rotating centerline. The International Standard ISO 10816 in the Class 1 at Zone A \[3\] is general used as conditions and procedures for the measurement. The general evaluation criteria, presented in terms of both vibration magnitude and changing vibration, are related to both operational monitoring and acceptance testing. Therefore, it is necessary to correct the rotating disk unbalance before use. Nowadays, the tools used to find the unbalance for high performance rotary disk are very expensive and unsuitable for use in small and medium-size industries with limited operating costs.

This project is a research and development study jointly with a private company in Thailand who is a manufacturer of the vertical balancing device for HCM. VBD determines an analytical design qualification for balancing HCM, balancing the disks to reduce unbalance to minimum. Select a balance tolerance within this range that is cost effective and amount of unbalance allowed in a product can easily be determined by the manufacturer.

2. HCM system and controller identification
Controller is a HCM which monitors and alters the operating conditions of a given dynamical system. The control algorithms are usually divided into two main types: open-loop for parameter identification and closed-loop for designing PID controller \[4\]. So the mathematical model of the BLDC motor is controlled by the DC link voltage \(v\). The transfer function of the BLDC motor can be described by the following equation:

\[
\frac{\omega(s)}{v(s)} = \frac{K_i}{JLs^2 + (JR + BL)s + (BR + K_aK_p)}
\]  \(1\)

where \(\omega\) is the reference speed. Specifications and system parameters used Parameter Estimation Toolbox in MATLAB for the parameters identification of the HCM system and controller identification are listed in table 1. Parameter Estimation toolbox is a Simulink-based product for estimating parameters of model from experimental data \[5\]. The investigation of the coefficients in the mathematical models equation (1) is a very simple problem because of restricted information. Input voltage and speed can be measured, where \(\dot{\omega}\) is the speed from the mathematical model and \(e\) is the error with difference between two outputs as shown in figure 2(a).

In practice, the PID controller has been widely used in industrial applications owing to its simplicity, robustness, reliability and easy tuning parameters. PID commonly interpreted as
proportional, integral and derivative controller possesses the step response conditions following at operating speed 2,000 rpm: the steady state error is less than 0.5%, maximum overshoot is 5% and settling time at 1.0% error is less than 15 sec. As a result, PID Tuner provides a fast and widely applicable single-loop PID tuning method for the Simulink® PID Controller blocks [6], as listed in table 1. This method, PID controller parameters can be tuned to achieve a robust design with the desired response time as shown in figure 2(b).

![Diagram](image)

**Figure 2.** (a) Parameter estimation diagram (b) Response of PID controller at operating speed.

**Table 1.** Parameter of the HCM system and controller identification.

| Description            | Parameters | Value  | Unit       |
|------------------------|------------|--------|------------|
| BLDC motor             |            |        |            |
| Moment of Inertia      | $J$        | 4.37   | Kg.m$^2$   |
| Friction Coefficient   | $B$        | 4.88   | Nm.s.rad   |
| Resistance             | $R$        | 28.94  | $\Omega$.phase |
| Inductance             | $L$        | 27.17  | H.phase    |
| Back-EMF               | $K_b$      | 0.1x10$^3$ | V/1000 rpm |
| Torque Constant        | $K_t$      | 0.912  | kNm/A      |
| PID Controller         |            |        |            |
| Proportional Gain      | $K_p$      | 0.0100 | -          |
| Integral Gain          | $K_i$      | 0.0045 | sec$^{-1}$ |
| Derivative Gain        | $K_d$      | 0.0010 | sec        |

3. **Magnitude and phase processing**

A vibration is the movement of a physical quantity in relation to a reference location in a cyclically increasing and decreasing manner as a function of time. The most important features of machine vibration change according to equation (2).

$$x(t) = A\sin(\omega t + \phi)$$  \hspace{1cm} (2)

where $A$ is amplitude of vibration. In this paper Arduino UNO, which is a microcontroller with 3-axis accelerometer (ADXL-335) was measured signal voltage output from magnitude of vibration transmission. It is suitable because of the VBD speed operated under our condition. Hall-effect sensor was applied for referenced signal between speed signal of motor and acceleration signal to find phase angle that can bring about balancing HCM disk. The response to compare signal between accelerometer and Hall-effect for finding the phase of maximum vibration by

$$\phi = \frac{(T_m - T_w) \times 360}{T_w}$$  \hspace{1cm} (3)
where $\phi$ is the phase angle of maximum vibration, $T_m$ is the maximum vibration period in each cycle, $T_0$ is starting time, $T_1$ is ending time and $T_w = T_1 - T_0$ is period time between $T_0$ and $T_1$.

Signal data of the vibration and speed rotor from the accelerometer and Hall-effect sensor are acquired for signal processing. Vibration due to the unbalance is seen as a maximum peak-amplitude in the harmonic at the vibration frequency. The vibration level and the phase of the rotational frequency of the rotor signal could be read directly from the display. Figure 3 shows the proposed methodology, which combines the amplitude of vibration and the trigger pulse reference signals from rotor analyses to precisely determine the motor condition according to the following procedure:

1. Holding vibration and rotational frequency signals during BLDC motor operation;
2. Processing vibration and rotation frequency signals in the time domain to determine the phase angle between the signals from (2) and (3);
3. Accepting whether the disk is balanced or unbalanced from the results of the above analyses;
4. Predetermining the trial mass and its position for correcting unbalance if any.

Figure 3. Signal of accelerometer and Hall-effect sensor, left (Simulation) and right (Experimental).

4. Unbalance correction algorithm

The unbalance correction algorithm used herein is based on vector diagram calculations for single-plane balancing [7]. The magnitude and angular position of the correction mass can be determined by representing in figure 4 as follows:

i. Measuring; $A_0$ is the initial amplitude, $\phi_0$ is initial phase of vibration, and its direction is given in polar coordinate.

ii. Installing trial the given mass, $M_T$ is known as trial mass and $\theta_T$ is trial phase to install on disk. After that, executing and measuring amplitude and phase again in terms $A_1$ and $\phi_1$ respectively.

iii. Transforming amplitudes and phases in (i) and (ii) into rectangular coordinate, calculating the net amplitude, $A_T$ between $A_0$ and $A_1$ given by

$$A_T = \sqrt{(A_x)^2 + (A_y)^2}$$

(4)

where $A_x = A_1 \cos \phi_1 - A_0 \cos \phi_0$ and $A_y = A_1 \sin \phi_1 - A_0 \sin \phi_0$.

iv. Calculating the net phase $\phi_T$ from quadrant condition and $A^T = A_y / A_x$ is defined according to the following procedure in table 2.

v. After that, calculating the vibration amplitude that is proportional to the unbalanced mass $M_B$ which obtains the relationship

$$M_B = \frac{A_0}{A_T} M_T$$

(5)
vi. Determining the position of the mass relative to the position of the trial mass as,

\[ \theta_b = \theta_f + \phi_f - \phi_b \left\{ \begin{array}{ll} \phi_b = \phi_0 + 180^\circ & ; \quad 0^\circ \leq \phi_0 < 179^\circ \\ \phi_b = \phi_0 - 180^\circ & ; \quad 180^\circ \leq \phi_0 < 359^\circ \end{array} \right. \] (6)

\[ \begin{array}{cccc} \text{Running motor and} & \text{Installing: Trial mass} \\
\text{Measuring initial} & \text{Removing: Trail mass} \\
\text{amplitude & phase (i)} & \end{array} \]

\[ \begin{array}{cccc} \text{Calculating the balancing} & \text{Vibration reduces} \\
\text{mass and phase to install (iii) -} & \text{less than 80%} \\
\text{(vi)} & \end{array} \]

\[ \begin{array}{cccc} \text{Measuring amplitude &} & \text{STOP} \\
\text{phase after balancing} & \text{No} \\
\end{array} \]

**Figure 4.** Block diagram of algorithm for automatic unbalance detection and correction.

The calculated angle is measured from the position marked on the rotor indicating the point where the trial mass was mounted. If it is a positive angle, it is measured in the direction of rotation. A negative angle is measured in the opposite sense from condition equation (6).

**Table 2.** Phase quadrant condition.

| Condition | Phase formulas |
|-----------|----------------|
| \( A_y \geq 0 \) and \( A_x > 0 \) | \( \phi_f - \tan^{-1}(A') \) |
| \( A_y > 0 \) and \( A_x < 0 \) | \( \phi_f - 180^\circ - \tan^{-1}(A') \) |
| \( A_y < 0 \) and \( A_x < 0 \) | \( \phi_f - 180^\circ + \tan^{-1}(A') \) |
| \( A_y < 0 \) and \( A_x > 0 \) | \( \phi_f - 360^\circ - \tan^{-1}(A') \) |

5. Experimental results and analysis

Experiments were also carried out to verify the correction algorithm. The balance correction algorithms were developed under the Arduino UNO-R3. A widely used open-source microcontroller board base on the Arduino software in Windows makes it easy to write a code and upload it to the board. The board was equipped with sets of digital and analog input/output (I/O) pins that were interfaced to various expansion boards or other circuits and experimental setup in figure 5. They were
composed of (a) Arduino UNO-R3 microcontroller board; (b) a brushless DC motor (300 Watt, 220-240 VDC with drive board); (c) 3-axis accelerometer to measure acceleration with a minimum full-scale range of 3± g (Arduino-ADXL335); (d) Hematocrit Centrifuge disk setup on head of motor (diameter 175 mm., weight 420 g., material made of Aluminum 6063); (e) laptops running the application software in Arduino IDE. The BLDC motor was operated at a constant speed of 33.33 Hz (2,000 rpm).

Figure 5. Vertical Balancing Device (VBD) experimental.

In the first trial, the HCM was operated without adding any mass to the disk and was therefore considered balanced. Figure 6 shows the signal acquired (red line) by the accelerometer, which was used to determine both the amplitudes and phases of the vibration signal before unbalancing. The signal’s peak amplitude was approximately 6.40 mm/sec. for disk I and 7.60 mm/sec. for disk II respectively. The experimentation installed, a trial mass of pre-determined weight was introduced for testing 3 cases of the trial mass and phase which was the functional validation of VBD and tests precision of correction algorithm, shown in table 3. The unbalance thus created to produce a mechanical vibration in the HCM’s structure. Vibration signal of the faulty unbalanced machine; the peak amplitude and phase signal increased, shown in table 4. This unbalance produced an increase in the HCM’s vibration level. In this unbalanced condition, the phase between the signals of the Hall-effect sensor and the accelerometer was calculated to be approximately from equation (3).

| Table 3. Testing condition of trial. |
|-------------------------------------|
|                                    | Disk I | Disk II | Disk I | Disk II |
|-------------------------------------|--------|---------|--------|---------|
|                                    | $M_T$ (grams) | $\theta_T$ (degree) | $M_T$ (grams) | $\theta_T$ (degree) |
| Case I                             | 0.53   | 0       | 0.53   | 0       |
| Case II                            | 0.79   | 0       | 0.71   | 170     |
| Case III                           | 0.21   | 120     | 0.35   | 300     |

The proposed unbalance correction algorithm was implemented after identifying the correlation between unbalance and increase in the vibration amplitude. In addition, additional experiments were conducted for validating the proposed procedure by proving its effectiveness in balancing the system. Table 4 shows six experiments in which different disks were used as unbalance masses and trial masses.

The correction process included inserting a 0.42 g correction mass at $77^\circ$ (as calculated by the system) for disk I and 0.48 g correction mass at $87^\circ$ for disk II, respectively. The results of this are shown in figure 6 (blue line) which the $A_B$ magnitude after balancing is reduced more than 80% both two disks.
Table 4. Experimentally obtained correction balance data.

| Disk | $A_0$ (mm/sec) | $\phi_0$ (%) | Trial in Case | Balancing Parameters | Results |
|------|----------------|---------------|---------------|----------------------|---------|
|      |                |               | $A_1$ (mm/sec) | $\phi_1$ (%) | $M_B$ (g) | $\theta_B$ (%) | $A_B$ (mm/sec) | % Reduce |
| Disk I | 6.40 | 255 | 9.10 | 14.70 | 4.80 | 315 | 334 | 186 | 0.42 | 77 | 0.70 | 89.06 |
| Disk II | 7.60 | 261 | 11.01 | 14.20 | 12.56 | 311 | 200 | 272 | 0.48 | 87 | 0.65 | 91.45 |

Figure 6. Behaviours of amplitude balancing, left (Disk I) and right (Disk II).

6. Conclusions
The implementation of an experimental setup with signal processor management that combines accelerometer vibration and Hall-effect sensor analyses yielded satisfactory results when detecting unbalance and manufacturing fault identification in disk of HCM. Practical experiments using the VBD showed that can effectively balance the disk. The effectiveness for reducing vibration caused by unbalance is shown through the levels similar to those of the corresponding balanced rotating machine. That was successfully tested and ready for quality control application in manufacturing process.

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