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Vibration Reduction Filter Design for Balancing Control of GYROBO Using an AHRS

S. D. Lee and S. Jung, *Member, IEEE*

***Abstract*—This paper presents the application of an AHRS(attitude and heading reference sensor) manufactured for sensing the orientation to measure vibration for the better balancing control of a single-wheel mobile robot, GYROBO. GYROBO uses a gyroscopically induced force to balance. Since the high speed flywheel generates a vibration, the vibrational frequency of the flywheel is detected and a filter is designed to suppress it. The vibration is detected by AHRS. The filter is implemented into the DSP that is the main controller of the robot. Balancing control performances of GYROBO are tested and those with and without a filter are compared. Experimental studies confirm that the filter design through the detection of the flywheel's vibration helps GYROBO maintain balancing better.**

***Index Terms*—Vibration detection, notch filter, AHRS, GYROBO, balancing control**

I. Introduction

THE technique of the vibration detection and reduction has been studied for a long time in the area of motion control systems as well as machinery systems. The commercial servo control systems were already equipped with the various vibration reduction filter algorithms. In the automation area including robot systems, control system engineers can use various commercial servo control systems from the various makers.

GYROBO developed at Chungnam National University is a single-wheel mobile robot as shown in Fig. 1. A gyroscopically induced force is used to maintain balance [1,2]. The gyroscopically induced force is generated by a combination of two velocities of a high speed flywheel and a gimbal system including the flywheel as shown in Fig. 1. Since the flywheel rotates at high speed, the relevant vibration occurs. To enhance the balancing performance of GYROBO, the suppression of the vibration is required.

Detection and suppression of vibration in rotational motion systems have been a major problem to be taken into consideration for satisfying the desired specifications [3-10].

In this framework, the vibration tracking method in the servo control system area was presented [3]. PMSM(Permanent Magnet Synchronous Motor) motion control application was presented [4]. An input shaping technique was introduced to reduce the vibration effect of the system [5]. They designed a notch filter, a low pass filter, and an input shaper. The mechanical vibration occurred at the frequency about 160Hz was studied using the high speed servo control system [6]. To detect the vibration frequency, the velocity error of the servo control loop was used. The notch filter was designed to eliminate the spurious signals [7,8]. The industrial robot application using a notch filter was designed [9]. Matlab software was used to design the notch filter [10]. The adaptive notch filter design has been studied as well [11-13].

In most of research on vibration suppression, the vibrational frequencies using the velocity error term of the controller are detected and reduced by compensation of filers [14-19]. The resonant frequency of a dual inertia spring system using an FFT is measured and filtered out by filter design techniques.

Unlike the industrial applications, the low cost control systems have poor functions of the control logic and interface protocol comparing with the industrially applicable systems. And sometimes they have no possible way to interface the encoder signals. Accordingly, general methods to detect and eliminate the vibration of the systems cannot be applicable.

Therefore, in this paper, we present the vibration detection and reduction filter design methodology for the cost-effective system, GYROBO using AHRS. Although AHRS is used for sensing a heading angle, it can be also used for detecting vibration.

Vibration frequency caused by a high speed rotational flywheel is detected by the sensor and the corresponding notch filter is designed to reduce the vibration. Finally, experimental studies of the balancing control performance of GYROBO are conducted to verify the performance of the designed filter.

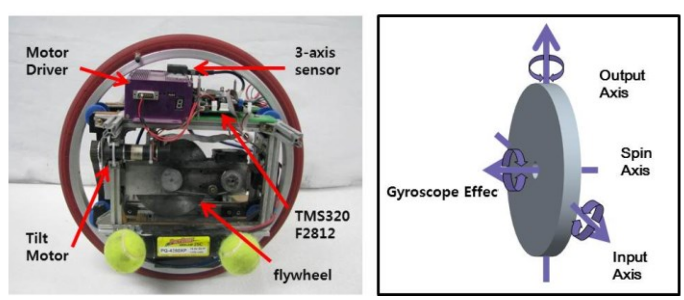

Fig. 1 GYOROBO System

S. D. Lee and S. Jung are with the Mechatronics Engineering Department, Chungnam National University, Daejeon, Korea 305-704. (e-mail : jungs@cnu.ac.kr).

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II. GYROBO SYSTEM

GYROBO shown in Fig. 1 has one digital signal processor, a velocity controller which is a black box, and an AHRS sensor. The DSP sends commands to the velocity controller without any feedback of the current, the velocity, and the position. And this black box-type velocity controller works without information about the detectable vibration signals. There are no encoders, resolvers, and counters to detect the motion states in this velocity controller.

GYROBO has the flywheel which rotates at very high speed to control the balance of the system. This rotating part makes an unwanted vibration although the mechanical isolation is used during the mechanical drawing step.

The control signals to calculate control command from AHRS undergoes the influence of the vibration from the flywheel as shown in Fig. 2. In controlling the robot, we use the rate of roll and yaw from AHRS. This signal is contaminated by the flywheel's vibration. This influence of the noise affects the balancing control performance.

Therefore, the method to detect the flywheel's vibration without added vibration detectable sensors is presented. This method does not require the velocity error information from the velocity controller. And the notch filter is designed to remove the vibrational frequency.

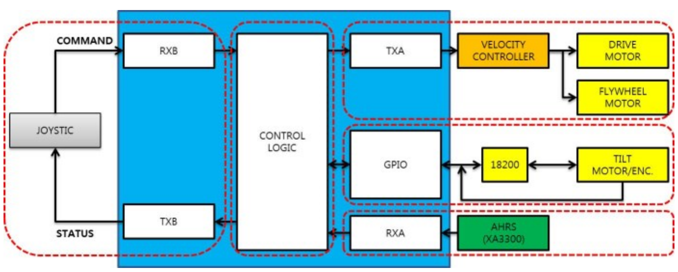


Fig. 2 GYOROBO System structure

III. SYSTEM ANALYSIS

A. AHRS System

AHRS is the attitude and heading reference sensor that contains 3 gyros, 3 accelerometers, and 3 magnetic compasses. They have their own sensor characteristics such as low bandwidth, group delay, a drift phenomenon, and electromagnetic compliance. A lot of works have been conducted to compensate for their own weakness using the fusion technique.

From the coordination systems to represent the orientation without gimbal lock to the estimation technique to reduce the sensing errors using the well-known Kalman filtering technique, AHRS is continuously developed to enhance its performance.

AHRS can be used for the vibration detection as well as its own roles. AHRS sensor guarantees the maximum error under 2 degrees with the resolution of 0.01 degrees. So, its sensing ability is sufficient to control GYROBO. The sampling rate of the sensor is 100 Hz so that we can get 100 data during a second.

GYROBO designed for balancing laterally using the gyroscopic effect induced by flywheel's rotation at a rate of 5,700 rpm. The vibration frequency can be easily estimated about 50 Hz using this sensor according to the Nyquist sampling theorem. This means that our AHRS cannot detect the GYROBO's vibrational frequency directly. But, this is possible using indirect experiment.

B. Vibration Detection

The experimental setup is shown in Fig 3 to detect the GYROBO's vibrational frequency. GYROBO is hanging to detect its own motion. We use the wire to hold the robot and the rolling direction's movement is not free. It is sufficient to get the results from the yaw directional component of vibrations.

The flywheel driving motor has 12,000rpm rate velocity without load, and the rate voltage of it is +18V. For GYROBO to balance, the rate speed of 5,700rpm is used.

The voltage range is divided into 16 levels which correspond to 16 steps of PWM signal values. Total sixteen steps of PWMs(Pulse Width Modulations) are applied to the driving motor. The maximum voltage of the flywheel driving motor is the 16 step PWM. At the maximum 16 step of PWM, we get the motor driven voltage about +4.5V in this battery situation.

From this experiment, we estimate the relationship between the motor voltage and the motor speed as listed in Table 1.

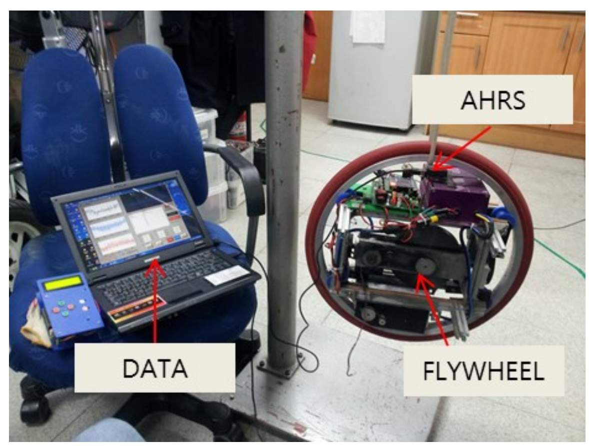


Fig. 3 Vibration Detection Experimental setup

Table 1. Estimated Voltage-speed Relationship

Motor Voltage(V)	Motor Speed(RPM)
0	0
2.25	1,425
4.5	2,850
9	5,700

The frequency of vibration is calculated as 23.75 Hz at 1,425 rpm. This estimation plays an important role during the detection procedure of the vibrational frequency because the possibility of vibrational frequency exists nearby here.

Fig. 4 and 5 show the comparison between the zero velocity and the maximum velocity of the flywheel. Fig. 4 shows that the sensor's error specification about the static condition meets well in the experiment. Fig. 5 shows that there are some additional frequencies of signals because the sensor's error specification was under the value of 2 degrees and the measured amplitude of the signals is over it. This difference comes from the vibrational effect. The values over the sensor's dynamic error limitation are induced by the mechanical vibration. This comes from the imbalance of the system structure or the nutation. The differentiation of them is not considered in this paper.

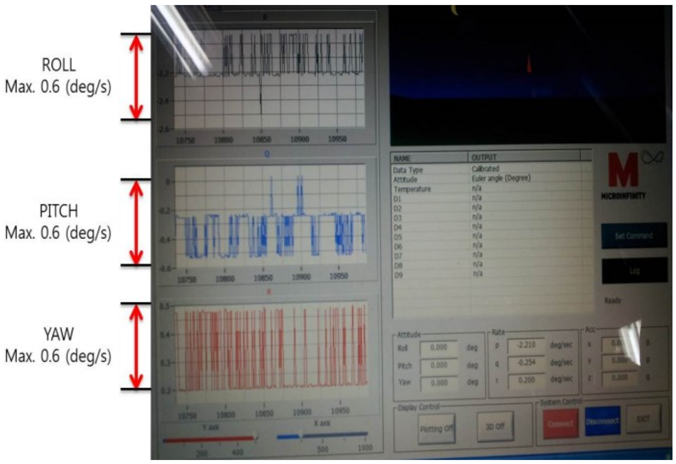


Fig. 4 AHRS Response in Static Condition

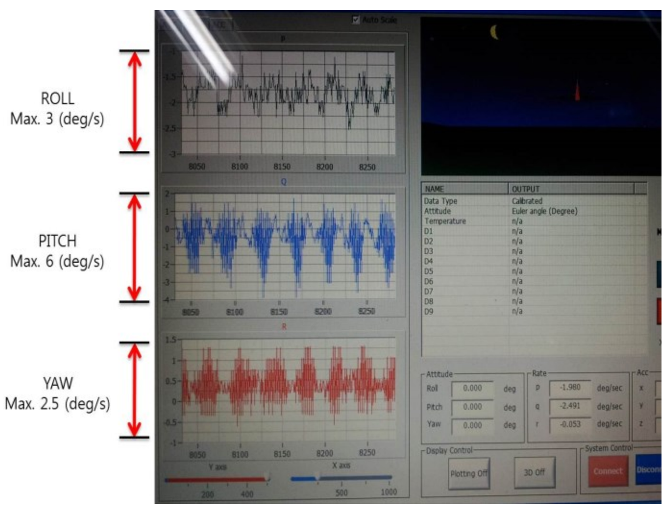
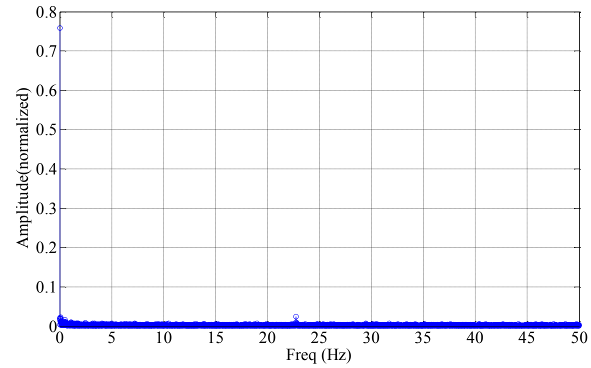


Fig. 5 AHRS Response in Dynamic Condition

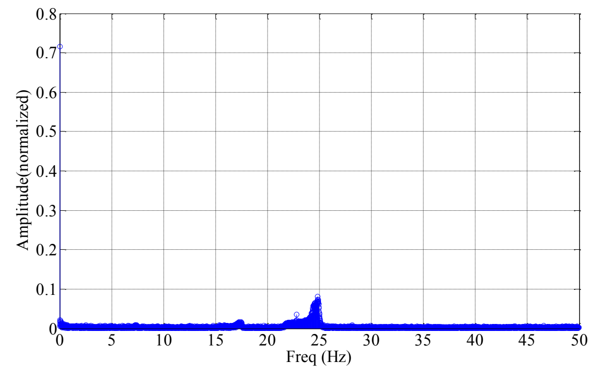
C. FFT Analysis

Next, we analyze the data using FFT(Fast Fourier Transform). In Fig. 6, during the variance of the flywheel's speed, the unwanted frequency components are shown.

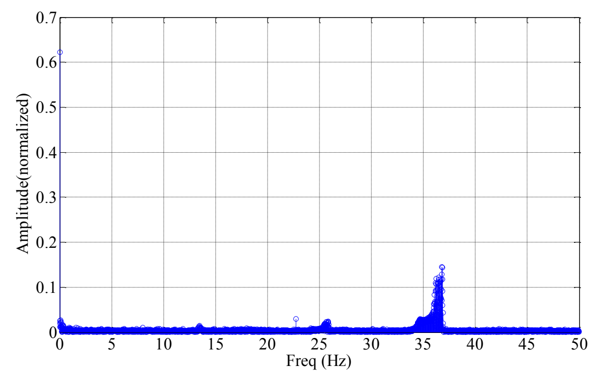
In step 0, two components of the frequency are shown in Fig. 6 (a). One is the dc component and the other is an unknown frequency between 20 Hz and 25 Hz. In step 8, Fig. 6 (b) shows that the unwanted signals are in the nearby of 25 Hz also having the step zero's signals. For the step 10, the frequency moves to the 35 Hz as shown in Fig. 6 (c). In step 16, the signal moves to the right direction of the frequency axis. The signals are shown between 40 Hz and 45 Hz as shown in Fig. 6 (d).



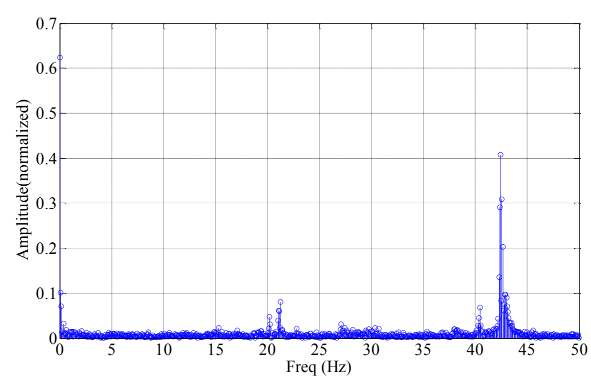
(a) STEP 0



(b) STEP 8



(c) STEP 10



(d) STEP 16

Fig. 6 FFT Results of different steps of velocities

We found that the unwanted frequency of step 16 is about the double frequency of step 8.

From Fig. 6, we know that the flywheel's speed has an effect on the vibrational frequency as expected. The vibrational frequency moves to the high frequency with increasing of the rotating speed of the flywheel. In this manner, we can analyze the relationship between the flywheel speed and the vibration. Here, the target vibration frequency of our system is found to be about 42.5 Hz. Next is to design a filter to minimize the signal at 42.5 Hz.

D. Filter Enhancement Design

The enhanced notch filter is designed to optimize the performance of it. The new filter coefficients are found as in (1) from the filter design specifications.

- Sampling rate = 100 Hz
- Sampling time interval = 0.01 sec
- Number of samples = 100;
- Notch frequency = 42.5 Hz
- Notch bandwidth = 1.5 Hz

$$G_e(z)\,|_{3dBspec.} = \frac{1.0000 + 1.7820\,z^{-1} + 1.0000\,z^{-2}}{1 - 0.8910\,z^{-1} + 0.2500\,z^{-2}} \quad (1)$$

FFT after using the enhanced filter characteristics is shown in Fig. 7. We clearly see that vibrational components at a typical frequency at 42.5 Hz are almost eliminated.

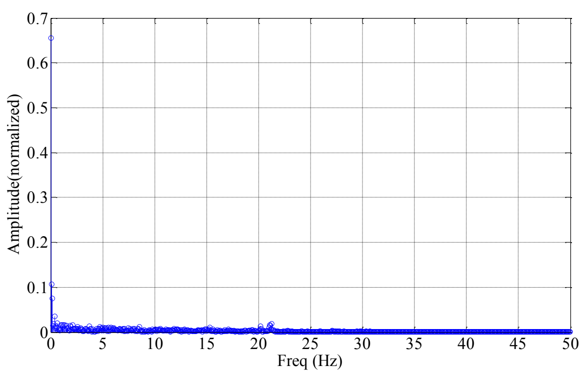


Fig. 7 FFT result using an enhanced filter

As shown in Fig. 7, the enhanced filter eliminates the vibrational frequency almost completely. Comparing with Fig. 6, we realize the performance of the enhanced filter. The enhanced filter is implemented on the DSP in the next section.

IV. Experimental verification

So far the vibrational frequency of GYROBO using AHRS is detected and the collected data are analyzed from the static experiment. The relationship between the flywheel's speed and the vibrational frequency is investigated using the FFT analysis. The notch filter is designed to eliminate the data set at the unwanted frequency.

The implementation of the filter in the real system and the verification from the experiment during the control states are accomplished.

The control algorithm shown in Fig. 8 is implemented on a DSP. PD control is used here. From the experiment, the vibration has an effect on the rate signal, that is to say, the vibrational frequencies are just shown in the rate of the AHRS. From this, the notch filters for the rate of alpha, $\dot{\alpha}$ and the rate of beta, $\dot{\beta}$ are implemented.

After designing notch filters to suppress vibration, the actual experimentation of balancing GYROBO is conducted. In the real implementation, the notch filter is located in the front of the controller gains as shown in Fig. 8.

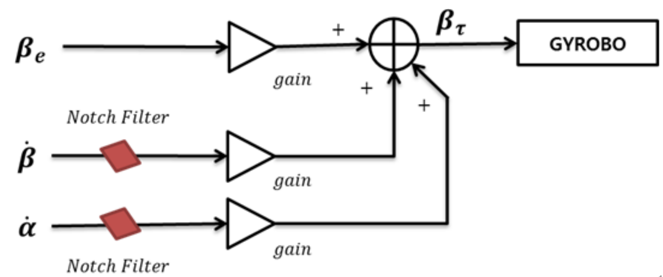


Fig. 8 Control Algorithm

An additional sensor is used to check the lateral angle deviation of the robot during the balance control. This test shows that the balance performance is well maintained.

The data rate of the sensor is 100 Hz. But, in this experiment, the condition of the robot must be considered. For example, there are the tire's air condition, the battery condition, and the flywheel's condition, the control gain, the initial condition, and so forth. This means that control becomes difficult due to the dynamically varied situations.

The lateral motion of GYROBO is tested as shown in Fig. 9. Two cases, one with filter and another without a filter are tested. Balancing performances are given in Fig. 10. Although both cases are successfully maintaining balance, Fig. 10 (a) without the filter shows more oscillation in the balancing angle than that of Fig 10 (b). We clearly see the better performance by the filter design.

From this test, this filter is feasible to play a good role in the condition of vibrational circumstance and the rapidly varying velocity of the robot's heading to maintain its lateral posture.

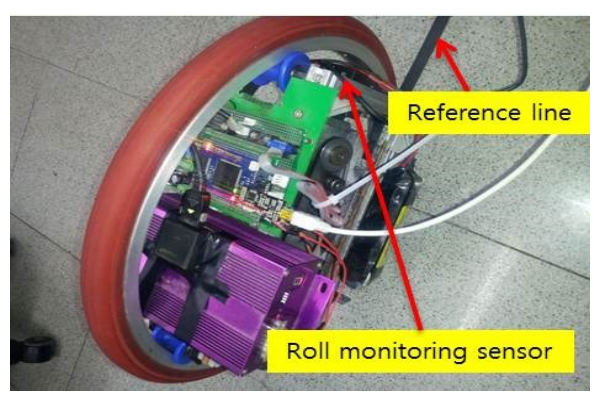
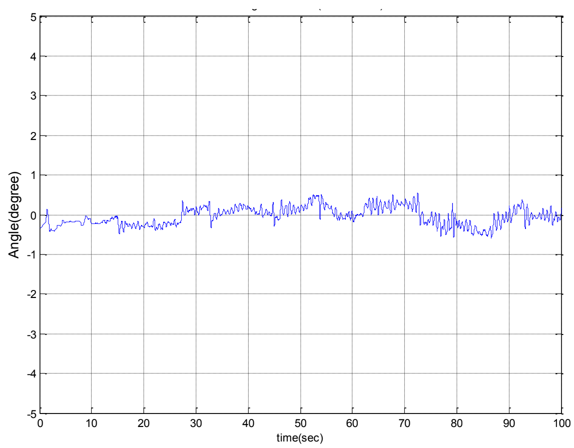
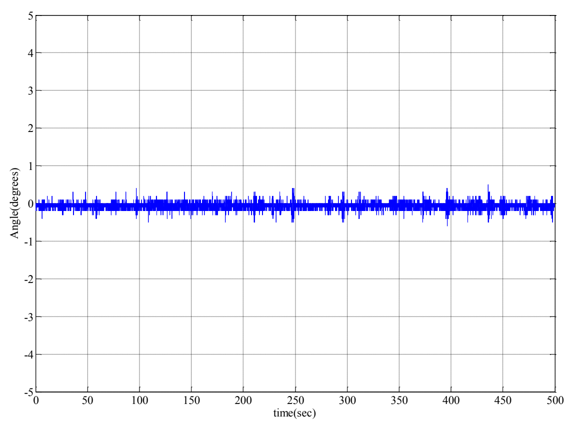


Fig. 9 Lateral Motion Test



(a) Without the filter



(b) With the filter

Fig. 10 Lateral Motion Performance

V. Conclusion

In this paper, the vibration caused by a flywheel of a single-wheel mobile robot has been investigated. Vibration frequencies are detected by using AHRS and the relevant notch filter was designed to suppress the vibration through the data analysis obtained from empirical studies. Balancing control demonstration of GYROBO has confirmed that the ultimate goal of improving the balancing control performance was satisfied by the filter design. Our proposal that AHRS can be used to detect vibration where sensors are not available has been confirmed.

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