저주파운동해석을 위한 MEMS 가속도계를 이용한 변위 추정

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Displacement Estimation using MEMS Accelerometer for Low Frequency Motion

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요 약

MEMS 가속도계는 운동측정을 위하여 가속도신호를 해석하는 저비용의 방안이다. 이론적으로 변위는 가속도신호를 두 번 적분함으로써 계산될 수 있으나 실제로는 실제 존재하는 여러 가지 원인에 의해서 이 방법으로는 계산 될 수가 없다. 본 실험은 실제적인 가속도신호를 획득하여 저주파 운동해석을 위하여 처리하는 과정에 대하여 보여준다.

ABSTRACT

MEMS accelerometer provides a low cost alternative in retrieving the acceleration signal for motion sensing. Theoretically, displacement can be calculated by double integrate the acceleration signal. However, in practical, it could not be done in straight forward manner due to several factors that exist in the real world. This experiment focuses on the processes from practical accelerometer signal acquisition till the result of double integration for low frequency vertical motion

키워드

Double Integration, Acceleration, Displacement, Accelerometer
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1. INTRODUCTION

Usage of accelerometer is getting wider nowadays and tons of researches are focusing on this important sensing device for more scientific breakthroughs. Accelerometer able to measure the acceleration of an object by attaches itself on it. For a moving object, people are interested to know

about its acceleration and some other parameters such as velocity and displacement. With current technology such as Global Positioning System, displacement or distance travelled by a moving object can be tracked very easily in fairly good accuracy. Nevertheless, the vertical displacement for an object is relatively difficult to be measured. A good example of vertical displacement is the heave

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motion of a floating vessel. Heave motion is an important parameter to describe vessel's motion. It is greatly related to the safety aspect especially for helicopter, crane and emergency operations. [1]

Acceleration, velocity and displacement are interrelated with respect to time. From acceleration signal, displacement can be calculated by integrate the signal twice. However, for the acceleration signal that practically obtained from an accelerometer, direct integration for two times will not produce a reasonable result due to unknown initial condition and sensor errors such as bias drift and noises [5,6,7,8]

In this paper, digital integration in frequency domain is applied together with Kalman filter and High-pass filter to retrieve the displacement output for low frequency motion. The accuracy and errors are also being discussed. [9,10,11,12]

II. SIGNAL ACQUISITION

A 6-DOF IMU is attached on the manipulator of the Fanuc R-2000iB articulated industrial robot. As the experiment objective is to retrieve heave amplitude from acceleration, the setup is done by setting the robot end effector with vertically 100 cm apart between top and bottom position. Figure 1 shows the illustration of the articulated robot and the motion of the attached IMU for acceleration signal acquisition. In the experiment, robot speed is set to 1000 mm/s and Acceleration override is set to the maximum value ($ACC = 100$). Acceleration override is a parameter to determine how fast the machine accelerates to meet the programmed speed. Acceleration override is set to maximum because acceleration is the source signal, if the robot accelerates slowly and the displacement is only 100 cm, the Signal-to-noise ratio (SNR) will be too low and giving negative effect to the result. The robot started to move the IMU vertically and Data

logging step is then carried out to obtain compensated Z-Axis acceleration raw signal from the IMU. Sampling frequency for the experiment is 125 Hz.

Fig. 1 Robot and IMU motion

III. DOUBLE INTEGRATION PROCESS

Double integration process can be described by the block diagram shown in Figure 2. Whole process is done in MATLAB from raw signal filtering, 3 stages of High-Pass filter and 2 stages of discrete integration. All the sub-processes will be discussed in the following sections.

Fig. 2 Double integration process

A. Raw Signal Filtering

Raw signal filtering is the first stage of the whole double integration process. It takes in the raw IMU acceleration signal and output a filtered, less noisy, smoother signal for further use. As this is the first stage of the process, everything must be taken care property because a small error might cause a snowball effect till the final result. In the experiment, Kalman filter is used together with a moving average filter to achieve this critical noise reduction task. Figure 3, shows the effect of raw signal filtering using Kalman filter and moving

average filter.

Fig. 3 Effect of raw acceleration signal filtering

Fig. 4 Experiment with articulated robot

B. High-Pass Filtering

High-pass filtering is very important in the double integration process. High-Pass filter is applied before and after the integration for different

reasons. A practical acceleration signal from the accelerometer should consist of DC bias which cause the signal after integration to be unbounded over time. A high-pass filter before the integration process helps to solve this issue.

However, there is another problem for integrating an acceleration signal, the initial condition. Lack of initial condition is a common problems for integrating a continuous signal. Therefore, by implementing high-pass filter right after the integration process to remove the DC component in the signal, the issue of integration errors due to the lack of initial condition can be solved.

Drawback of the high-pass filtering is the transient effect in the result signal. There are several types of high-pass filters available such as Finite Impulse Response (FIR) filter, Infinite Impulse Response (IIR) filter and Fast Fourier Transform (FFT) filter. Among the selection of filters, their advantages and disadvantages are being summarized in the table shown below.

Table 1. Comparison between high-pass filters

Type	FIR	IIR	FFT
Advantages	<ul style="list-style-type: none"> • Support Real-Time • Linear phase 	<ul style="list-style-type: none"> • Lower order • Faster • Short delay 	<ul style="list-style-type: none"> • Minimize starting transient effect • Fast computation
Drawbacks	<ul style="list-style-type: none"> • High order • Long delay time 	<ul style="list-style-type: none"> • Not support Real-Time 	<ul style="list-style-type: none"> • Not support Real-Time

In the experiment, a modified Fast Fourier Transform filter - FFT-DDI method introduced by Ribeiro in 2001 is used as High-pass filter to perform the operations stated above. This method is proven to be good for integrate low frequency accelerometer signal for the displacement measurements in huge structures [2].

C. Digital Integration

There are two solutions to perform signal integration from acceleration to velocity and displacement. The direct method is performing direct integration on continuous acceleration signal in time-domain by using RC Op-Amp circuit. Another method is the digital integration which is implemented in this experiment. One of the digital integration method is done by dividing Fourier transformed of acceleration signal by a scale factor $-\omega^2$ and then inverse transform the result [3].

This method also known as frequency domain method. There are other simpler ways to perform digital integration in time-domain which includes Rectangular integration, Trapezoidal integration and also Simpson's rule.

Integration in frequency domain, the Fourier Transform method is chosen for this project. Equation shown below is the discrete Fourier transform of an acceleration signal.

$$A_k = \frac{1}{N} \sum_{n=0}^{N-1} a_r e^{-\frac{j2\pi kn}{N}} \quad k = 0, 1, 2, \dots, N-1 \quad (1)$$

a_r is a series of digitized acceleration signal.

ω_n is given as

$$\omega_n = e^{-\frac{j2\pi}{N}} \quad (2)$$

Reconstruct equation (1) with (2), the new equation in terms of ω_n will be the following.

$$A_k = \frac{1}{N} \sum_{n=0}^{N-1} a_r \omega_n^{kn} \quad k = 0, 1, 2, \dots, N-1 \quad (3)$$

By importing the Fourier transform of the integrals, discrete Fourier transform of the velocity and the displacement are given as

$$V_k = \frac{1}{j2\pi k} A_k \quad k = 0, 1, 2, \dots, N-1 \quad (4)$$

$$D_k = -\frac{1}{(2\pi k)^2} A_k \quad k = 0, 1, 2, \dots, N-1 \quad (5)$$

Inverse Fourier Transform is given by

$$a_r = \frac{1}{N} \sum_{k=0}^{N-1} A_k e^{\frac{j2\pi kr}{N}} \quad r = 0, 1, 2, \dots, N-1 \quad (6)$$

By taking inverse Fourier transform of, V_k, D_k in (4) and (5). The Time histories of the velocity and displacement can be obtained as the equations below.

$$v_r = \frac{1}{N} \sum_{k=0}^{N-1} V_k e^{\frac{j2\pi kr}{N}} \quad r = 0, 1, 2, \dots, N-1 \quad (7)$$

$$d_r = \frac{1}{N} \sum_{k=0}^{N-1} D_k e^{\frac{j2\pi kr}{N}} \quad r = 0, 1, 2, \dots, N-1 \quad (8)$$

However, due to the scale factor of $\frac{1}{j2\pi k}$ and, $-\frac{1}{(2\pi k)^2}$ a small amount of sensor drift and noise can introduce significant displacement errors [2]. For the implementation of Fourier transform equations shown in MATLAB, both Fourier transform and its inverse can be done by using the preloaded function *fft* and *ifft* in MATLAB.

There is also *fftshift* function to shift the zero amplitude frequency in the frequency domain.

IV. RESULT and DISCUSSION

The process is not done in real-time but post-processing of time history data logged from the IMU output. Result is manually tuned at the high-pass filter to get rid of low frequency noises and DC bias of the input signal. The result below shows the result for 100 cm vertical swing with frequency at 0.3 Hz.

Fig. 5 Time series acceleration, velocity and displacement signal

With a fairly good result at frequency of 0.3 Hz at programmed speed 1000 mm/s. The robot programmed speed is then reduced by 200 mm/s and observe the output until the programmed speed reaches 400 mm/s.

Time-series plots in Fig 7, 8, 9. below show the results of the whole process from 800mm/s to 400mm/s and relationship between speed or frequency and the accuracy of the final displacement result is observed. In every experiment with different speed or frequency, a tuning of the high-pass filter configuration must be done for each high-pass filter to optimize the result. The parameter has the direct relationship with the cut-off frequency of the filter. During the experiment, the parameter was tuned to get the best result output for each filter. In other word, 3 parameters need to be tuned for each experiment.

Fig 7, 8, 9. shows the acquisition points for the filtered acceleration signal, velocity and also the final displacement signal. All the signal waveforms are plotted after the high-pass filter of each stage.

Fig. 6 Signal acquisition points

Fig. 7 Result : time series acceleration, velocity and displacement signal (800mm/s)

Fig. 8 Result : time series acceleration, velocity and displacement signal (600mm/s)

Fig. 9 Result : time series acceleration, velocity and displacement signal (400mm/s)

Table 2 shows the result of the experiment without considering the first peak/trough and last peak/trough. With the reference displacement of 100cm, the averaged values of all peak and trough are computed and the average displacement between the peak and trough is calculated and recorded in the table. Error of the result with respect to the reference displacement is also recorded for analysis.

Table 2. Result of displacement with speed variation

programmed speed (mm/s)	Average Peak (cm)	Average Trough (cm)	Reference Displacement (cm)	Computed Average Displacement (cm)	Error (%)
1000	51.417	-50.53	100	101	1.9
800	67.447	-60.07	100	133	25.1
600	99.455	-100.7	100	200	50.0
400	177.10	-818.6	100	361	72.3

Results in lower programmed speed or lower frequency show the significant increment of errors. This could be caused by insignificant acceleration

in the low speed movement which is quite low in magnitude and insignificant in the noisy accelerometer output signal. Besides, the low frequency noise component and actual frequency component lie in almost same bandwidth is also an obvious factor of the result. Moreover, low cost MEMS accelerator tends to have random bias drift error in the output signal. This problem is hard to solve unless the system is well modeled and perform a fine tuning on the resultant signal. G. Pang and H. Liu stated 2 mg of bias error could cause 35.32 meter of distance error in 1 minute. [4][5]

There are also other factors such as robot not moving in a pure vertical line and the sensor was not oriented properly with horizon.

V. CONCLUSION

With the experiment result in this paper, vertical displacement of the motion with frequency larger than 0.3 Hz could be estimated properly by the described method. For the frequency lower than 0.3 Hz, the accuracy getting worse and the result become unrealistic. However, with a navigation grade IMU with better specification, the result for displacement estimation could be improved significantly. Aside from hardware issue, analysis of the performance on different signal filtering method and type digital integration for low frequency motion can provide a better conclusion for low frequency displacement estimation.

For application use, the method must be equipped with better hardware support such as stabilizer or gimbal for better vertical displacement measurement. Calibration on the dynamic surface is also another big challenge in the practical use.

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