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Analysis of Tumbling Motions by Combining Telemetry Data and Radio Signal

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ABSTRACT

The pointing accuracy and stabilization property of the payload of a satellite depends on performance of attitude determination and control system (ADCS). An essential role of the ADCS is to stabilize the spacecraft in early operation stage and in the presence of anomalies. During this stage, the satellite may be subject to tumbling and a high-reliability method is deemed important to recover the satellite from this stage into its normal operation stage. In the paper, the use of magnetometer data and radio signal characteristics is investigated with the goal of determining the satellite tumbling rate confidently. The proposed method is applied to the PHOENIX CubeSat, which is a CubeSat that is developed by National Cheng Kung University, Taiwan as a part of the QB50 project, at its early orbit stage.

I. INTRODUCTION

Tumbling motions can be separate into direction of rotation and magnitude of rotation. With the certain amount of successive magnetometer data, the direction of rotation can be determined approximately, which shows PHOENIX mainly spin in Y-axis, which have the larger moment of inertia. On the other hand, magnitude of rotation can be viewed as the frequency of change of magnitude in 3-axis magnetometers.

However, if there are some issues about calibration of 3-axis magnetometers, there is still other way to obtain information about tumbling motions and verify the result from Magnetometer Rate Estimator. RF signal for instance, by receiving successive RF signal, magnitude of rotation can also be regarded as frequency of change in power of signal. With ceaselessly rotation, the envelope of power signal will be a periodic curve resulting from antenna pattern. In this paper, time-frequency analysis can tell more related messages such bandwidth of RF signal, useful to filter signal, and frequency shift during the communication, correlating with relative motions between CubeSat and ground station.

Overview of PHOENIX CubeSat

PHOENIX is a 2U CubeSat that is developed by the National Cheng Kung University as a part of the QB50 project. Fig. 1 shows PHOENIX flight model and its coordinate. The RF information of PHOENIX is shown in Table. 1. PHOENIX was deployed from ISS in May, 2017 and has been successfully communicated with ground station in Taiwan ever since. Details about the PHOENIX CubeSat can be found at [1-3]. At the early orbit phase, the tumbling rate of the PHOENIX has once been found to be very high to the extent that the rate sensor along the Y-body axis was saturated. This high-rate condition has been confirmed with received RF signal from PHOENIX and magnetometers data.

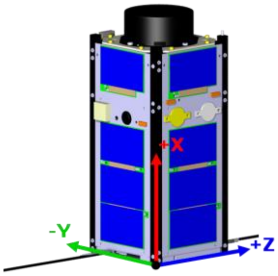


Figure 1: PHOENIX Model

Table 1: RF information of PHOENIX

Downlink Frequency	Modulation	Call Sign	Max Power
436.915MHZ	GMSK	ON01TW	1W

Ground Station Setup

As for hardware and software in the ground station, Elveti mission control system is used as the interface to downlink telemetry data and uplink commands. We use NI USRP hardware as the receiver to demodulate and collect RF signal and design the receiver interface with LabVIEW software. High Definition Software Defined Signal (HDSDR) could be also used as the receiver interface and the difference is just data format. RF signal is collected to binary file format in LabVIEW interface and waveform audio file format in HDSDR. USRP hardware is shown in Fig. 2 and the receiver interface is shown in Fig. 3.

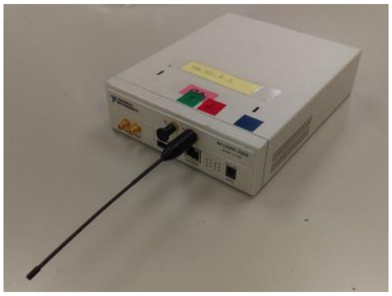
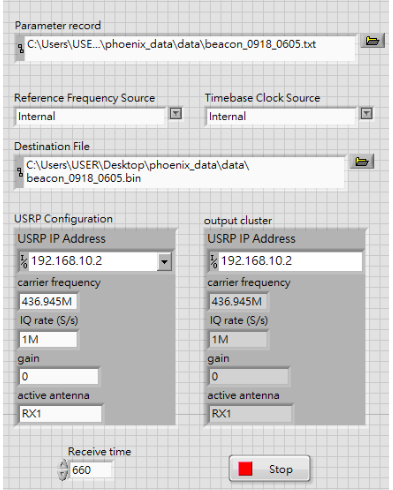


Figure 2: NI USRP 2920



Parameter record
C:\Users\USE...\phoenix_data\data\beacon_0918_0605.txt

Reference Frequency Source
Internal

Timebase Clock Source
Internal

Destination File
C:\Users\USER\Desktop\phoenix_data\data\beacon_0918_0605.bin

USRP Configuration
USRP IP Address
192.168.10.2
carrier frequency
436.945M
IQ rate (S/s)
1M
gain
0
active antenna
RX1

output cluster
USRP IP Address
192.168.10.2
carrier frequency
436.945M
IQ rate (S/s)
1M
gain
0
active antenna
RX1

Receive time
660

Figure 3: Receiver Interface

On the other hand, USRP would create a peak signal in its carrier frequency. in order not to mix satellite signal, we set carrier frequency of USRP with a shift, instead of center frequency of the satellite.

The rest of this paper is organized as follows: Tumbling motion analysis is given in Section II and Section III, for two proposed analysis methods: magnetometer data analysis and RF signal analysis respectively. In flight verification result for two analysis methods is presented in Section IV. Finally, Section V concludes this paper

II. MAGNETOMETERS DATA ANALYSIS

To analyze tumbling motions, first, we have to estimate the rotation axis $\vec{\omega}$.

Magnetometer data contains 3-axis magnetic field for B_x, B_y, B_z, and $\boldsymbol{B}_i = [B_{ix}, B_{iy}, B_{iz}]$, $i = 0,\ldots,\infty$. $\boldsymbol{B}_i$ can be thought as points in 3d space. First, we define dot difference:

$$\dot{\vec{b}}_0 = B_{i+1} - B_i$$

$$\dot{\vec{b}}_1 = B_{i+2} - B_{i+1} \tag{1}$$

Besides, the rotation axis can be determined simply:

$$\vec{\omega} = \dot{\vec{b}}_1 \times \dot{\vec{b}}_0 \tag{2}$$

Where $\vec{\omega} = [\vec{\omega}_x, \vec{\omega}_y, \vec{\omega}_z]$. The concept of formula (2) is shown in Fig. 4. $\dot{\vec{b}}_0$ and $\dot{\vec{b}}_1$ are approximate tangent vectors of the rotation plane. With cross product of these two tangent vectors, we can find rotation axis.

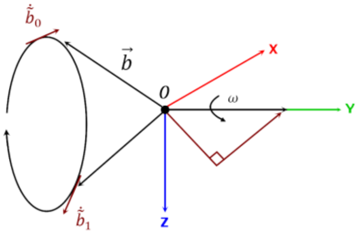


Figure 4: Rotation Axis Determination

Second, we define a plane $\boldsymbol{P}$ which has normal vector $\vec{\omega}$ and passes the origin $\boldsymbol{O}$. After projecting $\boldsymbol{B}_i$ to $\boldsymbol{P}$, we can get projection points $\boldsymbol{B}_{Pi}$. Moreover, we find that plane $\boldsymbol{P}$ is approximate a circle whose center is $\boldsymbol{O}$. Now we have determined rotation axis. The estimated angle θ_{est} of each pair of projection points is

$$\theta_{est} = \cos^{-1}\left(\frac{\boldsymbol{B}_{Pi} \bullet \boldsymbol{B}_{Pi+1}}{\left\|\boldsymbol{B}_{Pi}\right\| \left\|\boldsymbol{B}_{Pi+1}\right\|}\right) \tag{3}$$

Fig. 5 shows θ_{est} on projection plane $\boldsymbol{P}$ and true angle θ_{true} is given in formula (4).

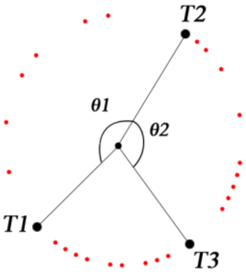


Figure 5: Estimated Angle for $\mathbf{B}_{Pi}$ on Plane P

$$\theta_{true} = \theta_{est} + N \times 360^{\circ},\ N = 0,\ldots,\infty \tag{4}$$

Rotation magnitude can be viewed as the rate of θ_{true}, so 3-axis angular velocity $\omega = [\omega_x, \omega_y, \omega_z]$ is

$$\omega = \frac{\theta_{true}}{\Delta t}\frac{\vec{\omega}}{\|\vec{\omega}\|} \tag{5}$$

In formula (4), N means the number of rotation cycles. when the satellite is in high tumbling rate situation or time difference Δt is too large, which means magnetometer data isn't successive enough, we might have to solve N. In this case, we can use RF signal analysis to measure this parameter.

In magnetometer analysis, we can calculate 3-axis angular velocity and rotation axis, which help us to judge the performance and feasibility of control laws.

III. RF SIGNAL ANALYSIS

In RF signal analysis, magnitude of rotation can also be regarded as angular frequency of power signal. In this section, we will also discuss frequency shift of satellite, which is mainly resulting from Doppler shift.

RF signal $x(t)$ contains certain amount IQ data, where expression of $x(t)$ is

$$x(t) = I(t) + jQ(t) \tag{6}$$

Furthermore, the power signal of $x(t)$ is

$$p(t) = x^2(t) \tag{7}$$

To find the angular velocity ω, first, we do time-frequency analysis to RF signal. We use Fast Fourier transform (FFT) to sample points from power signal and calculate its spectrum. However, there is an inverse proportion relationship between time resolution and frequency resolution when doing FFT. In this paper, we attach much more importance to time resolution, for the purpose of observing magnitude change of power signal in each rotation cycle of the satellite. Second, we extract maximum magnitude in frequency domain from each group of sample points. To view it easily, we fit an envelope and find that it is a periodic signal. At last, the approximate angular velocity ω is angular frequency of the envelope.

In addition to angular velocity, with power spectrum, we can also find waterfall signal of the satellite, which can help us to observe frequency shift as the satellite rotates in the orbit. Moreover, to verify RF signal whether belongs to our satellite or not. We can use some tools to do simulation and calculate data about relative information between satellite and ground station, such as elevation angle θ_E and relative velocity Δv. Based on these data and carrier frequency of the satellite f_c, the expression of Doppler shift f_D is

$$f_D = \frac{\|\Delta v\|}{c} f_c \cos(\theta_E) \tag{8}$$

In RF signal analysis, we can only determine rotation magnitude, not including rotation axis, but we can use time-frequency analysis to know more messages, like waterfall signal and frequency shift, which can help us to verify condition of the satellite.

IV. IN FLIGHT VERIFICATION RESULT

In this section, we will show verification result of PHOENIX Cubesat tumbling analysis including using magnetometer data and RF signal and compare result with angular velocity from Y-MEMS sensor which will saturate when estimated value is larger than 85 deg/sec. There are three scenarios for verification. First and second scenarios are analyzed with magnetometer data and RF signal respectively and angular velocity in both scenarios is approximate 25 deg/sec. The third scenario compares for above two methods. In this case, angular velocity is about 80 deg/sec, which can prove that these two analysis methods also work in high tumbling rate situation.

I. Magnetometer Data Verification

3-axis magnetic points $\boldsymbol{B}_i$ and projection points $\boldsymbol{B}_{Pi}$ are shown in Figure. 6. We can see rotation axis is mainly in Y axis, which have bigger moment inertia. We only use first three magnetic field point to calculate $\dot{\vec{b}}_0$, $\dot{\vec{b}}_1$ and $\vec{\omega}$. By comparing $\vec{\omega}$ calculated from different $\boldsymbol{B}_i$, we figure out that the rotation axis changes as the satellite rotates, but it has little impact on tumbling analysis.

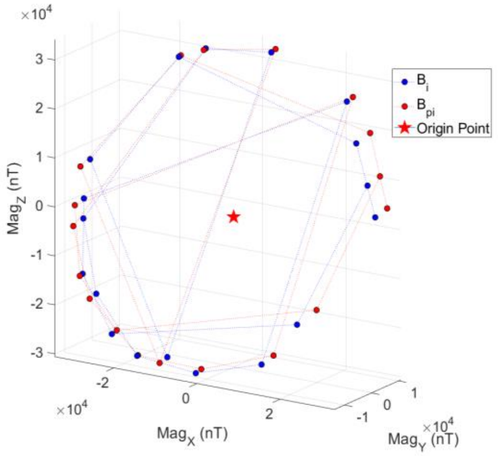


Figure 6: $\boldsymbol{B}_i$ and $\boldsymbol{B}_{Pi}$ in 3d Space

Fig. 7 shows estimated 3-axis angular velocity. We can find that PHOENIX is in a predominant Y-spin mode, which means Y body axis have the bigger moment of inertia.

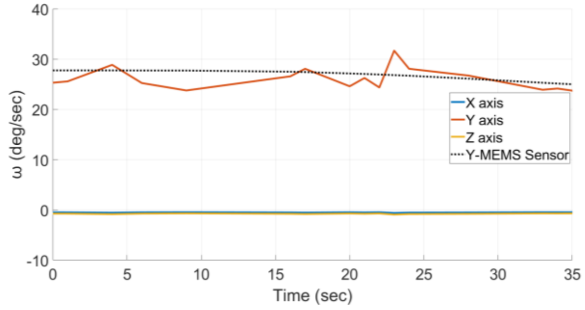


Figure 7: Estimated ω in Magnetometer Analysis

II. RF Signal Verification

Setting of RF signal analysis is given in Table. 2. From Table. 1, there is a shift with 0.03MHz between PHOENIX signal and USRP carrier frequency. We simulate with System Tool Kit (STK) to find θ_E and calculate Δv. Power spectrum of received signal is shown in Fig. 8. The center in frequency domain means 436.945MHz originally. We can find that USRP creates a peak in center frequency and there is some other signal that was received. Fig. 9 shows power spectrum of PHOENIX signal and we can find bandwidth is about 10kHz. Waterfall of PHOENIX signal and estimated Doppler shift is shown in Fig. 10. We can find that Estimated Doppler shift fits the frequency shift of PHOENIX approximately.

Table 2: RF Analysis Setting

Carrier Frequency	Sampling Rate	Sample Points	Time
436.945MHZ	1MHz	10000 points	120 sec

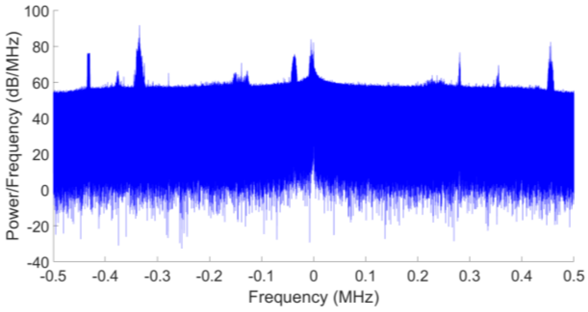


Figure 8: Power Spectrum of Received Signal

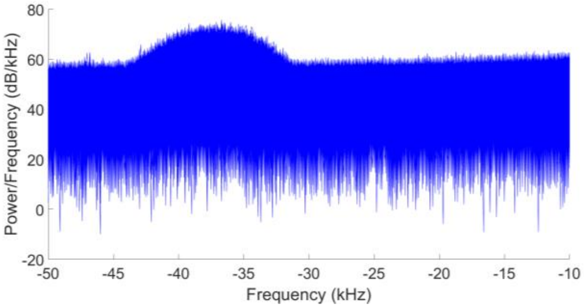


Figure 9: Power Spectrum of PHOENIX Signal

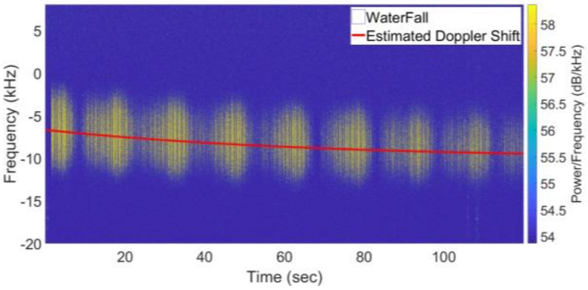


Figure 10: Waterfall of PHOENIX Signal

Maximum magnitude of power signal and its envelope is shown in Fig. 11. With antenna pattern from [6], we can know that if PHOENIX is mainly in Y spin mode, there will be at least two peak magnitudes per rotation cycle. Estimated angular velocity is shown in Figure 12.

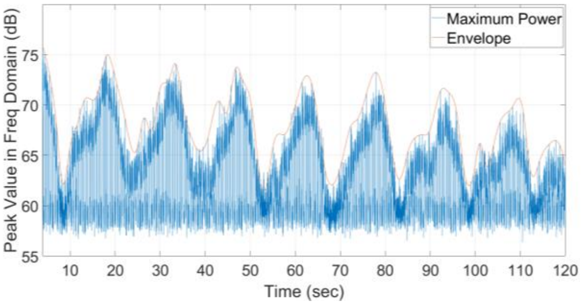


Figure 11: Maximum Power and Envelope

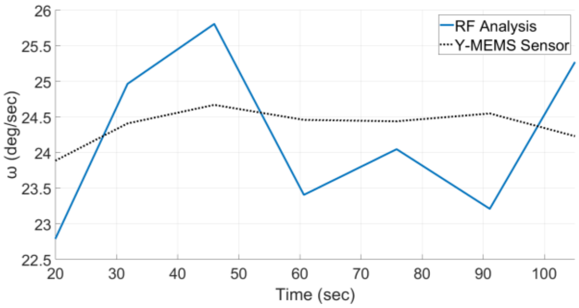


Figure 12: Estimated ω in RF Analysis

III. Magnetometer Data and RF Signal Verification

Fig.13 shows estimated angular velocity from above two analysis methods and Y-MEMS gyroscope. In this high tumbling rate situation, we use magnetometer data to calculate 3-axis angular velocity with support from RF signal.

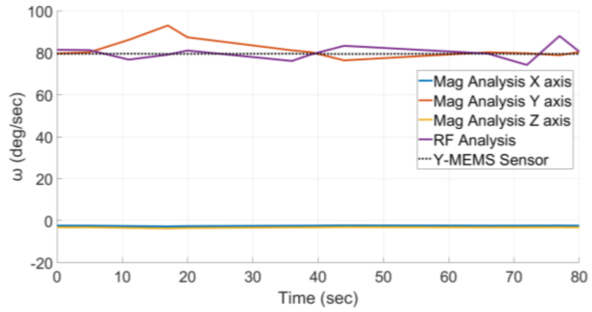


Figure 13: Estimated ω with Two Analysis

V. CONCLUSION

This paper applies two methods to analyze tumbling motions. In magnetometer data analysis, we estimate rotation axis with magnetic field measurements. Next, project magnetic field point to the rotation plane. At last, calculate the angular velocity based on the angle between each pair of magnetic field points. In the RF signal analysis, we conduct time frequency analysis of the received signal samples. Next, we extract maximum power in frequency domain. At last, the rate is estimated based on the angular frequency of power signal. In addition, we can use waterfall signal and estimated Doppler shift to verify the status. The proposed methods are shown to be applicable to analyze the tumbling behavior based on the verification of the PHOENIX in-orbit flight data.

Acknowledgement

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