Development of a VIV observation method of rotating drill pipe using accelerometers

Zengo Yoshida, Chang-Kyu Rheem
Institute of Industrial Science
The University of Tokyo
Tokyo, Japan
zengo@iis.u-tokyo.ac.jp

Tomoya Inoue
Center of Deep Earth Exploration
JAMSTECH
Yokohama, Japan

Abstract— **The marine drilling riser is used for various purposes today. Particularly, it is well known that Vortex Induced Vibration (VIV) occurs when a riser pipe is located under a flow. Therefore, many studies in VIV are conducted as the issue of representative fluid-structure vibration. We have also study about VIV, and investigated the behavior of a drill pipe model under various conditions in order to understand VIV properties in a drill pipe. As an observation method of this drill pipe model, we have ever obtained the displacement information of the drill pipe model with a stereo camera system. However, it takes time to obtain an analysis result in this method. Therefore it is inefficient to carry out various experiments to understand an observed phenomenon only in this analysis method. It was necessary to develop a new method that the displacement information of the drill pipe model was analyzed immediately to perform the experiment that changed various conditions (the uniform flow, the tension, rotating speed of a drill model) effectively. As that solution, we developed the analytical method using the acceleration sensor. In this paper, we discuss it about the new measurement method by the accelerometer.**

Keywords— accelerometers; FFT; VIV observation

I. INTRODUCTION

The marine drilling riser is used for the purpose of exploration of ocean floor resources and scientific drilling. Particularly, it is well known that Vortex Induced Vibration (VIV) occurs when a riser pipe is located under a flow [1]. Therefore, many studies in VIV are conducted as the issue of representative fluid-structure vibration. We have also study about VIV, and investigated the behavior of a drill pipe model under various conditions in order to understand VIV properties in a drill pipe [2,3]. A used drill pipe model has some length and moves with the whole vibrate. As an observation method of this drill pipe model, we acquired the displacement information in each part of the drill pipe model with a stereo camera system. However, it takes time to obtain an analysis result in this method. For example, it takes approximately one hour to process observation data (100FPS) of one minute by our analysis system. As described previously, it is inefficient in performing various experiments to understand an observed phenomenon by the existing system. Particularly, under the experiment using this model, the phenomenon that the whole model greatly whirl and turned around to the opposite rotate direction (counterclockwise direction) of a drill pipe model itself sometimes occurred. The occurred condition of this large whirl motion is considerably interesting in considering VIV properties. In order to prepare consideration materials, it necessary for us to change experimental conditions. If an analysis result is obtained immediately, experiment efficiency is improved, and various experiments can be carried out. We decided to develop the analytical method using the acceleration sensor.

This study is aimed for the development of the analytical method with the displacement in each part of the drill pipe model. Therefore we do not mention the cause that the drill pipe model whirl happens, but take up motion in itself as an observation object because it is interesting. Gyroscope sensors are used by the moving body observation in rotating system well, but we cannot obtain large whirl motion information of whole model with the gyroscope sensor. On the other hand, we can observe that motion with the accelerometer. However, one of the matters that require attention includes the need to process the data of the accelerometer appropriately, because accelerometer oneself turns with a pipe model. We discuss Item in conjunction with analysis and the process of these accelerometers data with section 3. In that section, at first, we built motion model of a specific pattern (whirl motion) from the displacement information that we obtained in a stereo camera system and expressed this in a numerical formula, and we compared it with the accelerometer data to inspect the introduced numerical formula. As a result, we can confirm that only accelerometer data provide a trajectory of the displacement.

II. SUMMARRY OF THE EXPERIMENT

The experiment was conducted at the Ocean Engineering Basin of the Institute of Industrial Science, the University of Tokyo whose width is 10 m, depth is 5 m, and length is 50 m. The specifications of the drill pipe model are shown in Table 1.

TABLE I. SPECIFICATIONS OF THE DRILL PIPE MODEL

Length	5.5 [m]
Outer diameter	19.0 [mm]
Inner diameter	16.0 [mm]
Material	Teflon
Specific Weight	2.17
Young modulus	0.5 [GPa]

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Figure 1 shows the configuration of the experiment. The lower end of the pipe model is fixed on the bottom of the basin with universal joint and the other end is connected to some weights to apply top tension.

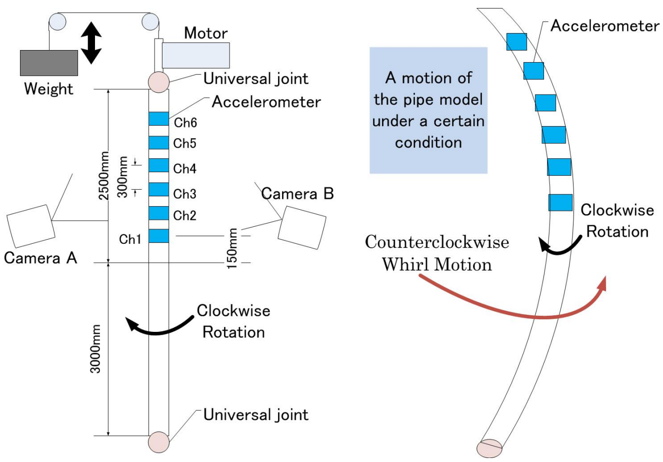


Figure 1. Experimental Configuration.

At the time of the experiment, drill pipe model is turned in the clock direction by a motor installed in the upper part. Six accelerometers installed in the pipe center in a drill pipe model in total are set up every 300mm (Ch1-Ch6). An accelerometer is two dimensions one of semiconductor type, and the measurement capacity is + 6G from - 6G. A reflector was attached to the each part of the drill pipe which an accelerometer was installed in, and the displacement of this part was measured by a stereo camera system. The stereo camera system was comprised of two underwater high speed cameras, and video data of 50 or 100 fps were recorded by these cameras in order to track the motion of dill pipe model. when cameras were placed in order to track the part with the accelerometer, the distance between each camera was approximately 3.7m, and the distance between a drill pipe model and each camera was approximately 3m.. Motion tracking analysis was performed using a video tracker motion measurement system (Dipp Motion Pro, DITECT).

III. EXPERIMENTAL RESULTS AND DISCUSSION

Only the case when the drill pipe model whirl was observed is considered as follow.

Figure 2 shows that the trajectory and FFT processing result of the horizontal motion (X-Z plane) of the target “Ch2” by a stereo camera system.

Figure 3 shows that accelerometer data and the FFT processing result measured under a condition same as figure 2.

From figure 2, it is understood that the drill pipe model whirl was comprised of two circular motion. On the other hand, by the accelerometer data, the peak of the spectrum is seen in a specific frequency component different from drill rotary frequency and the integral multiple frequency component. The difference in FFT processing result must be explained in order to measure the displacement by the accelerometer. Therefore, the next procedure will be necessary

At first a motion model is built by the displacement information obtained from the stereo camera system, and it is necessary for the consideration about acceleration data to be carried out. Then, it is necessary to express the motion model that we suggested in a numerical formula. Several sets of validity in a numerical formula must be inspected.

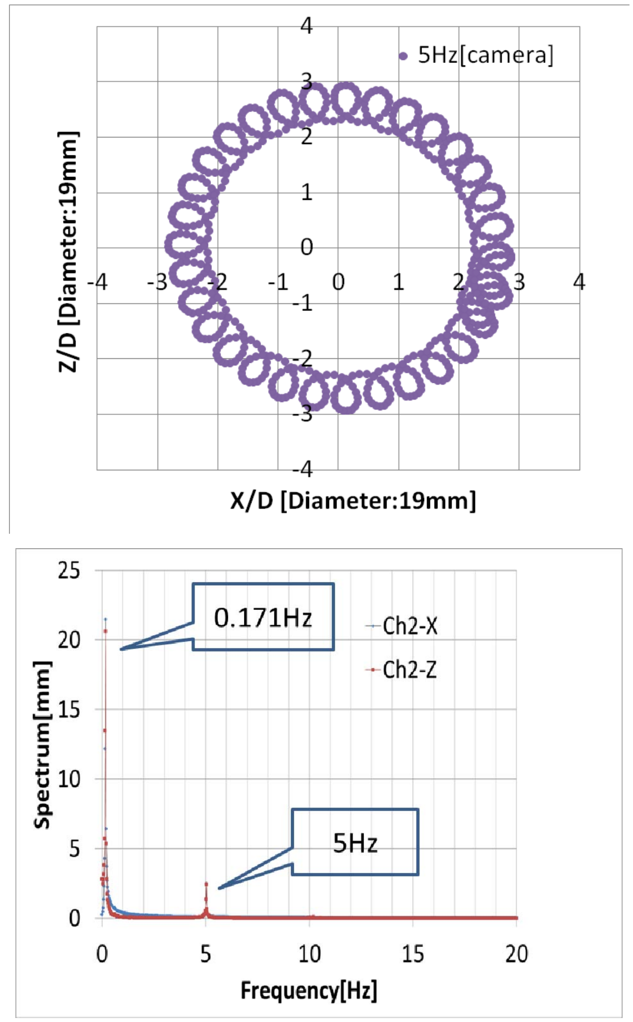
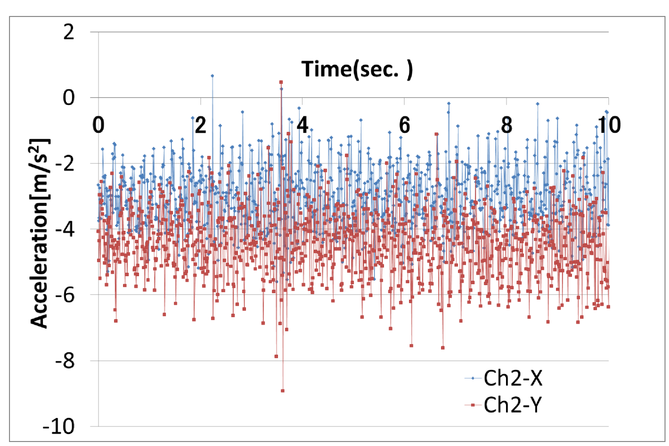


Figure 2. Trajectory (top) and FFT processing result (bottom) of the horizontal motion of the target “Ch2” by a stereo camera system.



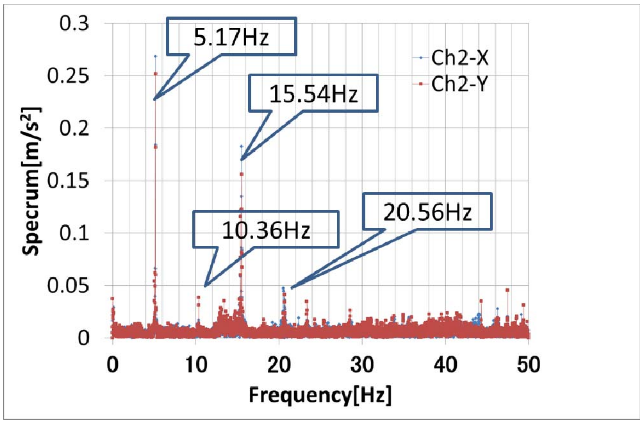


Figure 3. accelerometer data (previous page) and the FFT processing result (this page) measured under a condition same as figure 2.

A. Motion model of drill Pipe Whirl

From figure 2, it is understood that the drill pipe model whirl was comprised of two circular motion. As illustrated in Figure 4, a center (x, y) of acceleration sensor (accelerometer) is defined.

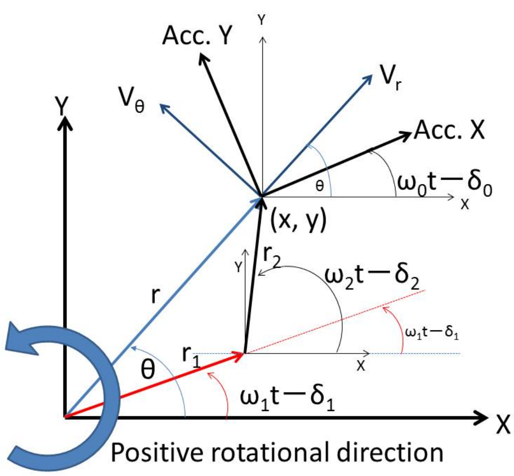


Figure 4. Definition of the motion model and the coordinate system.

It is necessary for acceleration to be considered in each of the X - Y coordinate system at rest, V_r - V_θ noninertial coordinate system in the synthetic circular motion, and Acc. X - Acc. Y noninertial coordinate system in the accelerometer measurement. If acceleration in each system is calculated and finally all acceleration are integrated with the coordinate system of the accelerometer measurement, acceleration measured in an accelerometer is calculated. In this motion model, a rotational direction in radius r_1 is positive, but a rotational direction in rotation of drill pipe model oneself and circular motion of radius r_2 are negative.

Figure 3 shows that there is a direct current component though an accelerometer turns. It is suggested that a rotary frequency of circular motion of radius r_2 and a rotary frequency of rotation of accelerometer oneself synchronize (Figure 5).

As illustrated in Figure 5, when a rotary period accords, directions of the X, Y axis of the accelerometers always turn to the same direction for a center of circle motion.

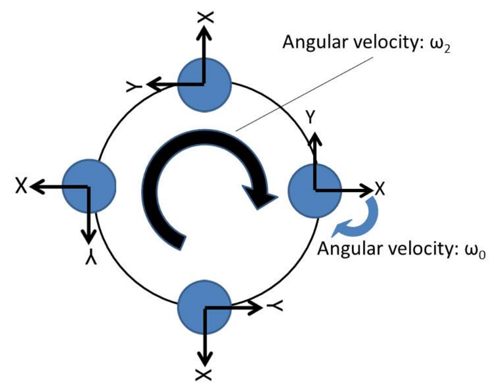


Figure 5. Structure of DC component in acceleration data.

As a result, accelerometers will always detect centrifugal force by the rotary motion of radius r_2. In this way, the meaning included in acceleration data becomes clear by defining the motion model.

B. Mathematization of the motion model

A center position (x, y) of accelerometer is expressed as a function of the time to be shown by Figure 4. In the X - Y coordinate system at rest, (1) – (6) are derived.

$$x = r_1 \cos(\omega_1 t - \delta_1) + r_2 \cos(\omega_2 t - \delta_2) \tag{1}$$

$$y = r_1 \sin(\omega_1 t - \delta_1) + r_2 \sin(\omega_2 t - \delta_2) \tag{2}$$

$$V_x = -r_1 \omega_1 \sin(\omega_1 t - \delta_1) - r_2 \omega_2 \sin(\omega_2 t - \delta_2) \tag{3}$$

$$V_y = r_1 \omega_1 \cos(\omega_1 t - \delta_1) + r_2 \omega_2 \cos(\omega_2 t - \delta_2) \tag{4}$$

$$A_x = -r_1 \omega_1^2 \cos(\omega_1 t - \delta_1) - r_2 \omega_2^2 \cos(\omega_2 t - \delta_2) \tag{5}$$

$$A_y = -r_1 \omega_1^2 \sin(\omega_1 t - \delta_1) - r_2 \omega_2^2 \sin(\omega_2 t - \delta_2) \tag{6}$$

ω_1 is angular velocity of large circle trajectory, ω_2 is angular velocity of small circle trajectory in Figure 2, and ω_0 is angular velocity of rotation of drill pipe model oneself. V_x and V_y are velocity. A_x and A_y are acceleration.

V_r and V_θ are able to be described using a rotary matrix, because it is understood that V_r - V_θ coordinate system in the synthetic circular motion is the coordinate system that turned for X - Y coordinate system at only θ. Then velocity in V_r - V_θ coordinate system in the synthetic circular motion are as following.

$$V_r = V_x \cos(\theta) + V_y \sin(\theta) \tag{7}$$

$$V_\theta = -V_x \sin(\theta) + V_y \cos(\theta) \tag{8}$$

$$\theta = \tan^{-1}(y/x) \tag{9}$$

$$r = x^2 + y^2 \tag{10}$$

θ is angle between X - Y coordinate system and V_r - V_θ coordinate system in the synthetic circular motion, and r is radius of the synthetic circular motion. Because centrifugal force V_θ^2/r adds to the acceleration of the V_r - V_θ coordinate system in the synthetic circular motion, a centrifugal force component must be added to an Ar component which is acceleration of the V_r - V_θ coordinate system in the synthetic circular motion.

$$A_r = A_x \cos(\theta) + A_y \sin(\theta) + V_\theta{}^2/r \tag{11}$$

$$A_\theta = -A_x \sin(\theta) + A_y \cos(\theta) \tag{12}$$

The acceleration (Acc. X, Acc. Y) in the coordinate system of the accelerometer is expressed as follows when (1) - (12) are arranged, because the coordinate system of the accelerometer is the coordinate system that turned for X - Y coordinate system at only (ω_0t-θ-δ_0).

$$\begin{aligned} Acc.X = &-r_1\omega_1{}^2\cos(\omega_1 t - \delta_1 - \omega_0 t + \delta_0) - r_2\omega_2{}^2\cos(\omega_2 t - \delta_2 - \omega_0 t + \delta_0) \\ &+ \frac{V_\theta{}^2}{r}\cos(\omega_0 t - \delta_0 - \theta) \end{aligned} \tag{13}$$

$$\begin{aligned} Acc.Y = &-r_1\omega_1{}^2\sin(\omega_1 t - \delta_1 - \omega_0 t + \delta_0) - r_2\omega_2{}^2\sin(\omega_2 t - \delta_2 - \omega_0 t + \delta_0) \\ &+ \frac{V_\theta{}^2}{r}\sin(\omega_0 t - \delta_0 - \theta) \end{aligned} \tag{14}$$

θ and V_θ^2/r should be arranged to express (13) and (14) only in r_1, r_2, ω_0, ω_1, and ω_2. At first, θ should be arranged.

$$r = x^2 + y^2 = \sqrt{r_1{}^2 + r_2{}^2 + 2r_1r_2\cos(\omega_1 t - \delta_1 - \omega_2 t + \delta_2)} \tag{15}$$

$$\cos(\alpha(t)) = \frac{(r_1 + r_2\cos(\omega_1 t - \delta_1 - \omega_2 t + \delta_2))}{\sqrt{r_1{}^2 + r_2{}^2 + 2r_1r_2\cos(\omega_1 t - \delta_1 - \omega_2 t + \delta_2)}} \tag{16}$$

$$\sin(\alpha(t)) = \frac{r_2\sin(\omega_1 t - \delta_1 - \omega_2 t + \delta_2)}{\sqrt{r_1{}^2 + r_2{}^2 + 2r_1r_2\cos(\omega_1 t - \delta_1 - \omega_2 t + \delta_2)}} \tag{17}$$

Angle α(t) is defined to satisfy (16), (17) by (15).

$$\frac{y}{x} = \frac{\sin(\omega_1 t - \delta_1 - \alpha(t))}{\cos(\omega_1 t - \delta_1 - \alpha(t))} \tag{18}$$

Using (18) and (9), (19) is provided.

$$\theta = \omega_1 t - \delta_1 - \alpha(t) \tag{19}$$

The following relations can be found in (16) and (17).

$$\frac{d}{dt}\cos(\alpha(t)) = \frac{d}{dt}\alpha(t)(-\sin(\alpha(t))) \tag{20}$$

$$\frac{d}{dt}\alpha(t) = \frac{(r_2{}^2 + r_1r_2\cos(\omega_1 t - \delta_1 - \omega_2 t + \delta_2))(\omega_1 - \omega_2)}{r_1{}^2 + r_2{}^2 + 2r_1r_2\cos(\omega_1 t - \delta_1 - \omega_2 t + \delta_2)} \tag{21}$$

When (21) is integrated in time and approximate calculation is performed, it is shown that α(t) is the constant number not to depend on the time. r_2 is smaller than r_1, and α(t) can be considered to be the constant number. Therefore, α(t) can be treated as zero. As a result, (19) can be considered as (22).

$$\theta \cong \omega_1 t - \delta_1 \tag{22}$$

Next, V_θ^2/r should be arranged. At first β is defined as follows.

$$\beta = (\omega_1 - \omega_2)t - \delta_1 + \delta_2 \tag{23}$$

It is found that β correspond to a specific frequency component different from drill rotary frequency in Figure 3.

From (3), (4), (8), (15), (22) and (23),

$$\frac{V_\theta{}^2}{r} = \frac{\frac{1}{2}(r_2\omega_2)^2\cos(2\beta) + 2r_1r_2\omega_1\omega_2\cos(\beta) + \frac{1}{2}\{2(r_1\omega_1)^2 + (r_2\omega_2)^2\}}{r} \tag{24}$$

$$\begin{aligned} \frac{1}{r} &= \frac{1}{r_1 + r_2}\left\{1 + \frac{2r_1r_2}{(r_1+r_2)^2}(\cos(\beta) - 1)\right\}^{-1/2} \\ &\cong \frac{(r_1+r_2)^2 + r_1r_2}{(r_1+r_2)^3} - \frac{r_1r_2}{(r_1+r_2)^3}\cos(\beta) \end{aligned} \tag{25}$$

(24) and (25) are obtained. (25) is replaced with (26).

$$\frac{1}{r} = A - B\cos(\beta) \tag{26}$$

The following equations are provided from (24) and (26).

$$\begin{aligned} &\frac{V_\theta{}^2}{r} \\ &= \left[\frac{A}{2}\{2(r_1\omega_1)^2 + (r_2\omega_2)^2\} - r_1r_2\omega_1\omega_2 B\right] \\ &+ \left[2Ar_1r_2\omega_1\omega_2 - \frac{B}{4}\{4(r_1\omega_1)^2 + 3(r_2\omega_2)^2\}\right]\cos(\beta) \\ &+ \left\{\frac{A}{2}(r_2\omega_2)^2 - r_1r_2\omega_1\omega_2 B\right\}\cos(2\beta) - \frac{B}{4}(r_2\omega_2)^2\cos(3\beta) \end{aligned} \tag{27}$$

$$\frac{V_\theta{}^2}{r} = X_1 + X_2\cos(\beta) + X_3\cos(2\beta) + X_4\cos(3\beta) \tag{28}$$

Because a rotary frequency of circular motion of radius r_2 and a rotary frequency of rotation of accelerometer oneself synchronize,

$$\omega_0 = \omega_2 \tag{29}$$

$$\omega_0 t - \delta_0 - \theta = -\beta + \delta_2 - \delta_0 \tag{30}$$

(29) and (30) are shown. By arranging (28), (29) and (30), and processing of approximate calculation, (31), (32) are obtained.

$$\begin{aligned} Acc.X \cong &\left(\frac{X_2}{2} - r_2\omega_2{}^2\right)\cos(\delta_0 - \delta_2) \\ &+ \left\{X_1\cos(\beta - \delta_2 + \delta_0) + \frac{X_3}{2}\cos(\beta + \delta_2 - \delta_0)\right\} \\ &- r_1\omega_1{}^2\cos(\beta - \delta_2 + \delta_0) \\ &+ \left\{\frac{X_2}{2}\cos(2\beta - \delta_2 + \delta_0) + \frac{X_4}{2}\cos(2\beta + \delta_2 - \delta_0)\right\} \\ &+ \frac{X_3}{2}\cos(3\beta - \delta_2 + \delta_0) + \frac{X_4}{2}\cos(4\beta - \delta_2 + \delta_0) \end{aligned} \tag{31}$$

$$
\begin{aligned}
Acc.Y \cong & \left(\frac{X_2}{2} - r_2\omega_2{}^2\right) sin(\delta_0 - \delta_2) \\
& - \left\{X_1 \sin(\beta - \delta_2 + \delta_0) + \frac{X_3}{2}\sin(\beta + \delta_2 - \delta_0)\right\} \\
& - r_1\omega_1{}^2 \sin(\omega_1 t - \delta_1 - \omega_0 t + \delta_0) \\
& - \left\{\frac{X_2}{2}\sin(2\beta - \delta_2 + \delta_0) + \frac{X_4}{2}\sin(2\beta + \delta_2 - \delta_0)\right\} \\
& - \frac{X_3}{2}\sin(3\beta - \delta_2 + \delta_0) - \frac{X_4}{2}\sin(4\beta - \delta_2 + \delta_0)
\end{aligned} \tag{32}
$$

(31) and (32) become the final expression. A direct current component, an integral multiple component of the specific frequency are included in these equations.

C. Establishment of the measurement method by the accelerometer

It is necessary to go through the following procedure to get a trajectory of the drill pipe model from acceleration data from the foregoing analysis and consideration.

- From an FFT processing of acceleration data, a frequency component related to pipe model motion is identified.

A high-frequency component and a low frequency ingredient of the synthetic circular motion become clear from relations of (23) and (29).

- The radius r_2 of a high rotational frequency is calculated from a direct current component.

(33), (34) and (35) are calculated when Approximate calculation in the term of the direct current of (31) and (32) is performed.

$$X_{DC} \cong -r_2\omega_2{}^2 \cos(-\delta_2 + \delta_0) \tag{33}$$

$$Y_{DC} \cong -r_2\omega_2{}^2 \sin(-\delta_2 + \delta_0) \tag{34}$$

$$\frac{Y_{DC}}{X_{DC}} = \tan(-\delta_2 + \delta_0) \tag{35}$$

The radius r_2 becomes clear from (33), (34) and (35).

- The radius r_1 corresponding to the low frequency component of the synthetic circular motion is calculated from spectrum data of the acceleration and (31) and (32).

Because r_2, ω_0, ω_1, ω_2 has already become clear, r_1 is solved by technique (the Newton methods) of the numerical analysis.

For example, in the case of Figure 3, r_1, r_2, ω_0, ω_1, ω_2 are calculated as following (Table 2).

TABLE II. Various parameters of the synthetic circular motion

r_1[m]	0.0326
r_2[m]	0.00519
ω_1 [rad/sec]	2* π *(0.17)
ω_2, ω_0 [rad/sec]	2* π *(-5)

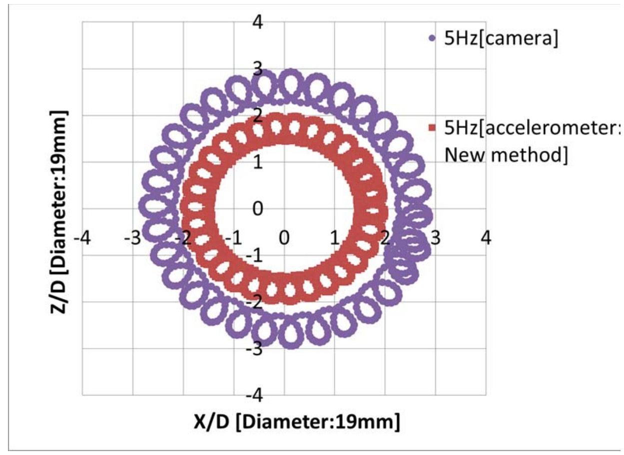


Figure 6. Comparison between stereo camera system and new method (purple: trajectory of stereo camera system, red: trajectory of new method).

Figure 6 shows that comparison between stereo camera system and new method. The new analysis result derived from the acceleration sensor data is less displacement than the analysis result by the stereo camera system, but it shows that the characteristic of the displacement is the same. As a result, we obtain a new analysis method, and can observe drill pipe model motion more easily.

IV. CONCLUSION

At first, we built motion model of a specific pattern (whirl motion) from the displacement information that we obtained in a stereo camera system and expressed this in a numerical formula, and we compared it with the accelerometer data to inspect the introduced numerical formula. As a result, we can confirm that only accelerometer data provide a trajectory of the displacement..

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