

A sound-based measurement of sway angle for anti-sway control of overhead crane

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Abstract

For anti-swing control of overhead crane, a deflection angle must be estimated. However, it is difficult to estimate deflection angles with a contact sensor such as rotary encoder. Therefore, we show a non-contact measurement method for the deflection angles by using two microphones. This method is based on the sound source location in a human with two ears. The method employs a time delay of arrival (TDOA) of acoustic signals which are picked up by the two microphones. Also, we show an algorithm to obtain the angle from the TDOA by using the Newton's method. Finally, we show experimental results to demonstrate the effectiveness of the proposed method.

Keywords: Overhead crane, microphones, correlation function, Newton's method

1. Introduction

Overhead cranes are well-used for transportation of load in factory and dock. For safety and efficiency transportation with the overhead cranes, the anti-sway control¹⁻⁵ has been received remarkable attention.

Since the dynamics of the sway angle of the crane can be described by the state-space equations, the sway can be controlled. However, the sway angle should be obtained for anti-sway control. It is known that the measurement of the sway angle is very difficult with contact sensor due to the hardware constraint.

From the background above, we focus on the sound signal⁶ for the anti-sway control of overhead cranes. This scheme is inspired by the human hearing mechanism with

two ears. Our measurement scheme is to obtain the sway angle without attached angle sensor. Here, we assume the payload includes a sound source such as friction sound, squeak noise or active noise. With two microphones, we detect the sound (acoustic) signal generated in the payload. That is, we use the microphones for contact-less sensing of the angle. Next, we estimate the time delay of arrival (TDOA) between the acoustic signals obtained from the two microphones where the TDOA can be computed from the correlation function. Also, we transform the TDOA to the sway angle by using the Newton's method.

In the experiment, we treat the case when the payload is swaying and the position of trolley is changed. From

experimental results, we show the proposed method can follow the sway angle even when the payload is moving.

2. Anti-sway Control of Overhead Crane

In the crane, a road is moved by motor driven trolley. Table I shows the parameters of the overhead crane. Let l_w be the distance from fulcrum of the trolley to the payload (sound source). x ($0 \leq x \leq X$) is the position of the trolley where $x=0$ is the left end and $x=X$ is the right end. That is, the distance between the Microphone 1 and the trolley is x (variable). Also, θ is the angle of the line (sway angle). Assume T is kinetic energy and U is potential energy. Then, we have

$$T = \frac{1}{2} M \dot{x}^2 + \frac{1}{2} m v^2$$

$$U = mgl_w(1 - \cos \theta)$$

Also, define $L=T-U$ is the Lagrangian. Now, let the state vector be

$$x(t) = [x - x_d \quad \theta \quad \dot{x} \quad \dot{\theta}]^T,$$

where x_d is the desired position, and its time derivation be

$$\dot{x}(t) = [\dot{x} \quad \dot{\theta} \quad \ddot{x} \quad \ddot{\theta}]^T$$

Based on the Euler-Lagrange equation, the dynamics of the crane can be written in a state space from:

$$\dot{x}(t) = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{mg}{M} & 0 & 0 \\ 0 & -\frac{(M+m)g}{Ml_w} & 0 & 0 \end{bmatrix} x(t)$$

$$+ \begin{bmatrix} 0 \\ 0 \\ \frac{1}{M} \\ -\frac{1}{ml_w} \end{bmatrix} u(t)$$

$$y(t) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} x(t)$$

where $u(t)$ is an input signal, $y(t)$ is an output signal. Based on the state-space model above, x and θ can be

controlled using a state feedback. To achieve the control, the angle θ must be estimated.

Table 1. Parameters of the overhead crane

weight of trolley	M
weight of payload	m
velocity of payload	v
external force	f
acceleration of gravity	g

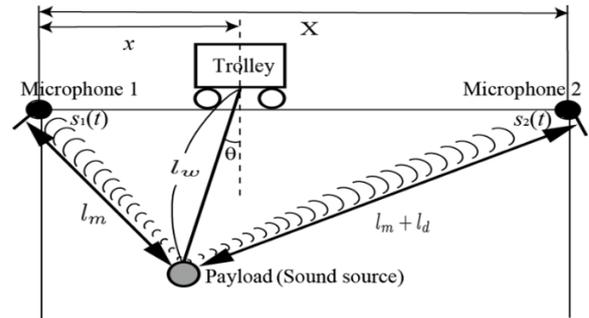


Fig. 1. Overhead crane with two microphones (Microphone 1 and Microphone 2) and sound source

3. Sound-based Measurement of the Sway Angle

3.1. Estimate of the TDOA

Fig. 1 shows the overhead crane system with two microphones (Microphone 1 and Microphone 2). With two microphones, we observe the sound signal originated from the sound source in the payload. Since the microphones have a directivity, the sensitivity of microphone is very low to the sound signal which is coming behind the microphones. Now, let $s_1(t)$ and $s_2(t)$ be the sound signal observed in the Microphone 1 and the Microphone 2, respectively. The distance between the two microphones is X since the microphone is located on the end of trolley rail. Further, let the distance between the Microphone 1 and the sound source be $l_m + l_d$ and the distance between the Microphone 2 and the sound source be l_m . Thus, l_d is the difference of the distances. Assume that x, X, l_w , are known. Now, the purpose is to estimate l_d based on the TDOA.

Using the two acoustic signals, we compute a correlation coefficients of $s_1(t + \tau)s_2(t)$ as follows.

$$\Phi(\tau) = \sum_{t=0}^{T_0} s_1(t + \tau) \cdot s_2(t) \quad (1)$$

where T_0 the number of sampled point.

Let τ' be the sampled point which maximizes (1). Now, the TDOA between the Microphone 1 and the Microphone 2 is $\tau' T_s$ where T_s is the sampling period. It follows that

$$l_d = \tau' T_s v_a \quad (2)$$

where v_a is the velocity of sound.

3.2. Conversion to angle θ

We introduce how to obtain θ with l_d . Using the law of cosines in Fig. 1, we have simultaneous equations as:

$$l_m = \sqrt{x^2 + l_w^2 - 2xl_w \cos\left(\frac{\pi}{2} - \theta\right)} \quad (3)$$

$$l_m + l_d = \sqrt{(X - x)^2 + l_w^2 - 2(X - x)l_w \cos\left(\frac{\pi}{2} + \theta\right)} \quad (4)$$

Now, eliminating l_m in (3) and (4), we have a function below.

$$f(\theta, l_d) = \left\{ x^2 + l_w^2 - 2xl_w \cos\left(\frac{\pi}{2} - \theta\right) \right\}^{\frac{1}{2}} + l_d - \left\{ (X - x)^2 + l_w^2 - 2(X - x)l_w \cos\left(\frac{\pi}{2} + \theta\right) \right\}^{\frac{1}{2}} \quad (5)$$

Hence, we can obtain θ corresponds l_d by computing the solution which satisfies

$$f(\theta, l_d) = 0, \theta \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right). \quad (6)$$

It should be noted that since l_m can also be obtained from (3) or (4), sensor delay can also be estimated by the velocity of sound v_a .

Here, let us show how to compute the solution of (6). Now, we employ the Newton's method to solve the solution of (6). The Newton's method uses the iterative equation as

$$\theta_{n+1} = \theta_n - \frac{f(\theta_n, l_d)}{\left\{ \frac{\partial f(\theta_n, l_d)}{\partial \theta} \right\}} \quad (7)$$

where θ_n is the angle at n -th iteration.

4. Experiment

Fig. 2 shows the experimental equipment. We use a Gaussian random signal with 0~1000 [Hz] as the sound source. The signal is generated by an electronic device. The sampling frequency is 14700 [Hz]. The correlation is calculated with data of samples corresponding to the position x . We consider the case when the payload is swaying (i.e. the sway angle is moving). Fig. 3 shows the result with $x=20$ where the vertical axis is the sway angle [deg.]. From Fig. 3, we can see that the payload is swaying around 0 [deg.]. In the same way, we show the results the position x is changed as $x=30$, $x=40$, and $x=50$. Similarly, Figs. 4-6 show the result with $x=30$, $x=40$, and $x=50$, respectively.

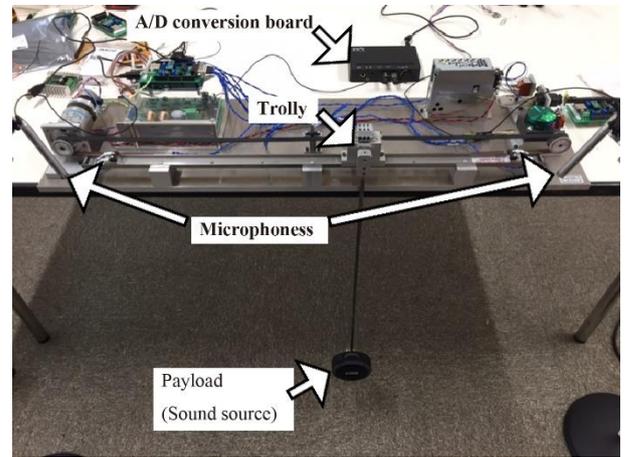


Fig. 2. Experimental equipment

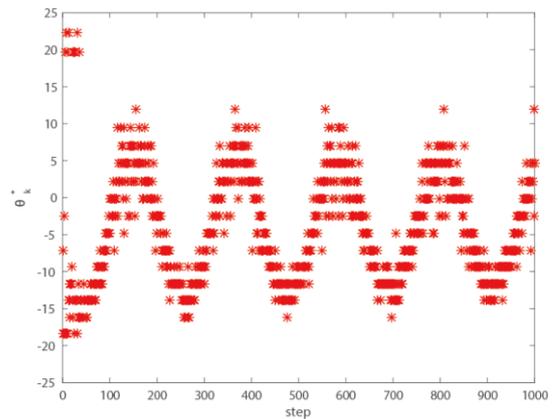


Fig. 3. Experimental result with $x = 20$

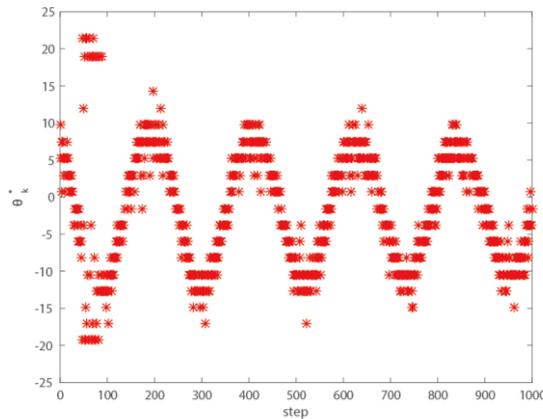


Fig. 4. Experimental result with $x = 30$

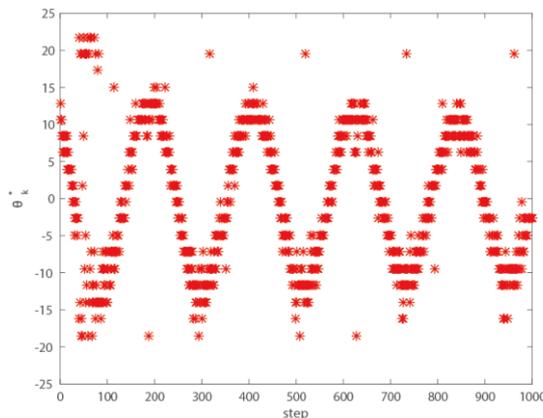


Fig. 5. Experimental result with $x = 40$

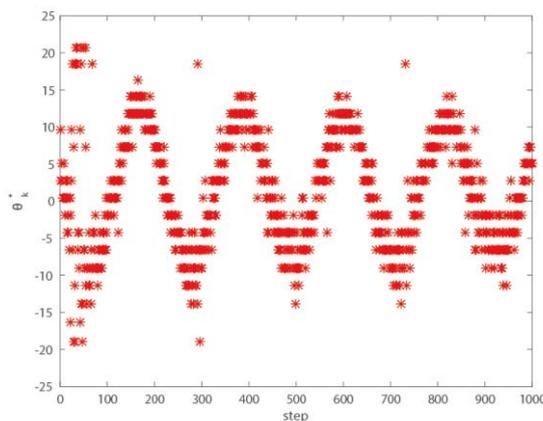


Fig. 6. Experimental result with $x = 50$

5. Conclusion

We have proposed the measurement method of sway angle for anti-sway control of overhead crane with two microphones. The method uses a time delay of arrival (TDOA) of acoustic signals measured from the microphones. Also, we have presented the algorithm to obtain the sway angle from the TDOA with the Newton's method. In experimental results, we demonstrate that our sound-based measurement method can follow the sway angle when the payload is moving.

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