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Energy Procedia 71 (2015) 352 – 359

Energy Procedia

The Fourth International Symposium on Innovative Nuclear Energy Systems, INES-4

A Study of Air-coupled Ultrasonic Flowmeter Using Beam Focusing

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Abstract

A non-contact flowrate measurement using the air-coupled ultrasound beam focusing technique is applied to the flowrate measurement in aluminum pipe. Flowrate measurement in the metal pipe by the air-coupled ultrasonic flowmeter has difficulty, because of the multipath of ultrasonic propagation. Bulk wave and guided wave are separated by experiment using metal pipes with and without an obstacle. The algorism for signal separation is built for the metal pipe measurement. Flowrate is calculated by the signal of bulk wave. Accordingly, the flowrate measurement on the aluminum pipe has been demonstrated, and the result shows the capability of measurement in metal pipes using air-coupled ultrasound.

Keywords: Ultrasonic flow meter, Air-coupled ultrasound, Time of flight, Beam focusing, Guided wave

1. Introduction

The flowrate measurement is applied in the controlling and monitoring industrial processing. In the nuclear power plants, the feed water flowrate is monitored to control the thermal output. However, the flowmeter method for feed water under high pressure and high temperature is limited. The conventional measuring equipment is orifice-type flowmeter. Orifice-type flowmeter is simple and capable of applying in high temperature condition. However, the maintenance and the recalibration are required for using the orifice-type flowmeter. For these concerns, the ultrasonic flowmeter has been used recently [1, 2]. The ultrasonic flowmeter is able to apply non-invasive measurement, and on-line maintenance is available [3, 4]. Besides, the acoustic technique development enables higher measurement accuracy [5-7]. However, the Piezo-electric element in the ultrasonic sensor has difficulty in applying the high temperature condition, particularly in the higher temperature condition than the Curie-temperature of Piezoelectric elements, the ultrasonic sensor loses the piezoelectricity and causes the desensitization. Additionally, ultrasonic technique is employed for the nondestructive testing, and air-coupled ultrasonic testing is developed and

doi:10.1016/j.egypro.2014.11.888

applied to the high temperature materials testing [8- 13]. The air-coupled ultrasound applies ultrasonic sensors in air. The sensor emits ultrasound into the air, propagates through the air, and enters test bodies. After that, ultrasound returns to the air, and finally it is received by an ultrasonic sensor in the air. The non-contact air-coupled ultrasonic flowmeter is developed, because it has the advantage for severe conditions.

In the air-coupled ultrasonic flowrate measurement, the refraction and reflection between the air and pipe cause decrease of the amplitude of detected signals [14]. To overcome the signal amplitude reduction, enlarging the cross section of the ultrasonic beam is one of the solutions. However, the conventional ultrasonic sensors have planar vibrating surface, and emitted plane wave is refracted along the curve of pipe. In order to reduce the refraction of the ultrasonic sound from the edge of the sensor, using focusing senor is one of the methods [15, 16]. The focusing sensor with the cylindrical vibrating surface transmits ultrasound then directs the ultrasound to the center of the pipe. The focusing sensor is able to transmit the ultrasound to the pipe, and prevent the refraction. Even if focusing sensors is applied, detected signal contains that of ultrasound which propagates as bulk wave and as guided wave. The bulk wave propagates in the fluid straightly from sensor to sensor, therefore, the signal has the phase shift by the flow. In addition, the guided wave propagated along the pipe, and detected signals due to the guided wave are not affected by the flow. Thus, the signal processing method for the separation of bulk wave signal is developed for air-coupled ultrasonic sensors, and flowrate measurement in the aluminum pipe is demonstrated in this study.

2. The measurement principle of air-coupled ultrasonic flowmeter

The conventional ultrasonic flowmeter, two ultrasonic sensors are contacted with the pipe (Fig. 1). And the ultrasound is transmitted from one sensor setup in the upstream to the flow and propagates in the fluid. The ultrasound is received by the downstream sensor. The time of flight (TOF) is affected by the flow. When the flowrate is increased, the TOF becomes shorter. On the other hand, the TOF is longer, when the flowrate is decreased. From the difference of TOF, the flowrate can be measured. Based on the conventional flowrate measurement method, the air-coupled ultrasonic flowmeter is developed. The air-coupled ultrasound propagates in the air and enters to the pipe. Therefore the refraction in the boundary between the air and pipe (Fig. 2) and the propagation time in air (Fig. 3) are taken into consideration.

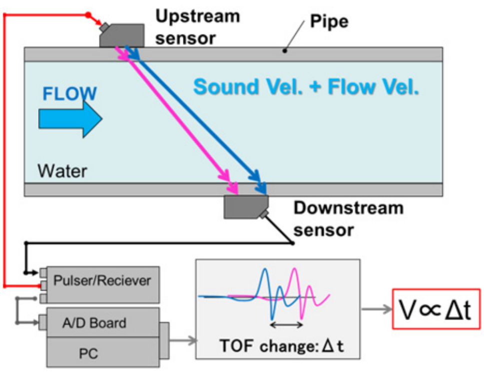


Fig. 1 Conventional ultrasonic flowmeter.

When wave propagates from the air to water, the incident angle α and the refracted angle β is related with the speed of sound in water C_w and in the air C_a as

$$\frac{\sin\alpha}{\sin\beta} = \frac{C_a}{C_w}. \tag{1}$$

The propagation time for the upstream of the flow t_{up} is calculated using the average velocity of water V, the distance between the surface of the pipe and the surface of ultrasonic sensors L_1, L_2 and the diameter of the pipe D as

$$t_{up} = \frac{L_1 + L_2}{C_a} + \frac{D}{\cos\beta\,(C_w + V\sin\beta)}. \tag{2}$$

Substituting $V = 0$ into the Eq. 2, the no flowing propagation time t_0 is obtained. And, the time difference between Δt means

$$\Delta t = t_{up} - t_0 = \frac{V\tan\beta}{C_w + V\sin\beta}. \tag{3}$$

From the Eq. 3, the average velocity of flow is expressed as

$$V = \frac{C_w\, \Delta t}{\tan\beta - \Delta t \sin\beta}\,. \tag{4}$$

Then, the flowrate Q can be calculated from the average velocity as

$$Q = \frac{\pi\, D^2}{4} V = \frac{\pi\, D^2\, C_w\, \Delta t}{4\,(\tan\beta - \Delta t \sin\beta)}\,. \tag{5}$$

To measure the average flow velocity, the speed of sound in water, that in the air, the incident angle and time difference are required in Eq. 1 and Eq. 5. And the difference from the conventional method is the effect of the refraction, and the effect of propagation time in the air is cancelled. Thus, the flowrate can be obtained by measuring the TOFs when there is no flowing.

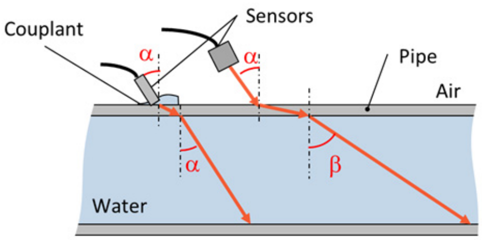


Fig. 2 The refraction on boundary between air and pipe.

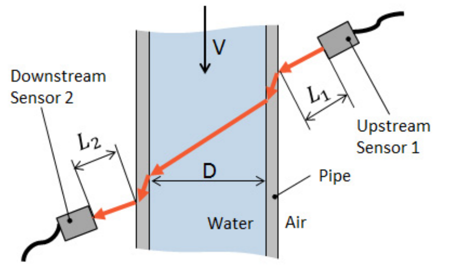


Fig. 3 The measurement principle of TOF method in the air-coupled ultrasonic flowmeter.

3. The focusing sensor

The conventional ultrasonic sensors have planar vibration surfaces, ultrasound emitted at the edge of the sensors is refracted at the curve of pipe and without reach the other sensor (Fig. 4). It causes the decrease of signal to noise ratio (SNR). Even if the cross section of the sensor is enlarged, the effect of the refraction is also increased, that is few influence on the result of SNR. In order to prevent the refraction at the curve of pipe, focusing sensors are developed. There are vibrating elements facing to the surface of pipe in focusing sensors, therefore the emitted ultrasound directs to the pipe and the effect of the refraction is decreased (Fig. 5). The focusing sensor is optimized to measure the pipe whose outer diameter is 60 mm, and the distance between the pipe and sensor is 10 mm. Therefore, the focusing sensor has radius 40 mm surface and focusing point is 40 mm from the sensor. It has 20 × 20 mm and radius 40 mm round vibrating surface shown in Fig. 6 (right). Conventional planar sensor (14 × 20 mm) is also shown in Fig. 6 (left).

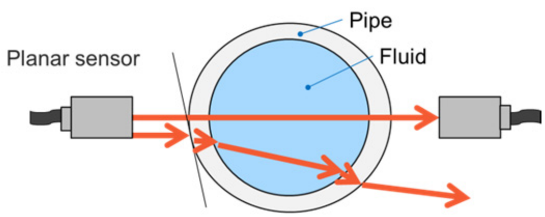


Fig. 4 The ultrasound path by using planar sensors.

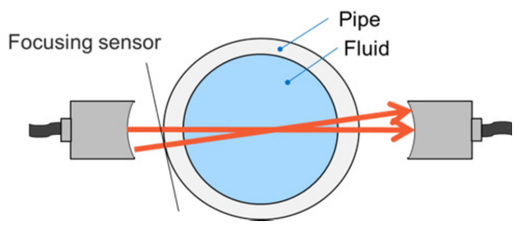


Fig. 5 The ultrasound path by using focusing sensors.

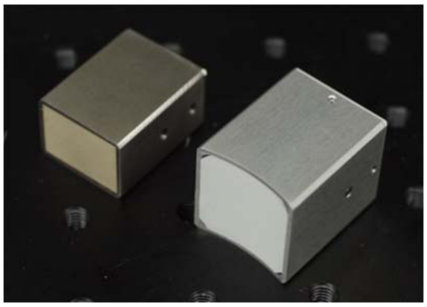


Fig. 6 The developed focusing sensor (right) and the planar sensor (left).

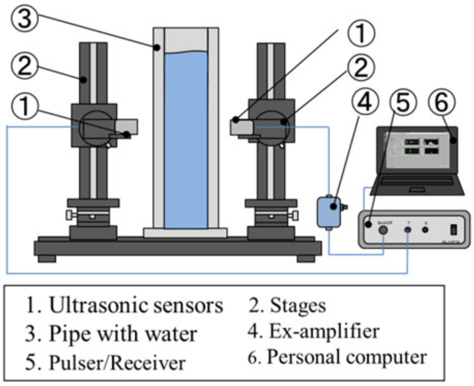


Fig. 7 The experimental apparatus.

3.1. Preliminary experiment

In the focusing sensors, ultrasonic beam spread is prevented and high amplitude and SNR signal are able to be detected. For the application to the metal pipe flow measurement, the preliminary experiment is performed. Figure 7 shows the experimental apparatus that consists of the ultrasonic sensors, three axis stage, metal pipe fulfilled with water, ex-amplifier, pulser/receiver(Japan Probe, JP-10CN), and personal computer. The pulser emits the burst signal to one of the sensor, and the electric signals are converted to ultrasound. The propagated ultrasound is detected on the other sensor, amplified 60 dB on ex-Amplifier, and transfered to the receiver. In the receiver, the signal is converted to digital data by the digitizer in the pulser/receiver, and recorded in the PC. The distance between sensors and the pipe wall is 10 mm, and testing materials of pipes are aluminum and stainless steel. The tested sensors are focusing sensors (Japan Probe Focusing 0.4K20 × 20N40R). The center frequencies of the sensors are 360 kHz. Transmitted signal is 200 V, two waves burst signal.

The signal detection for aluminum pipe and stainless steel pipe by focusing sensors are performed (Fig. 8, 9). Detected signal contains the signal of ultrasound propagated as bulk wave and guided wave. The bulk wave propagates straightly from sensor to sensor, therefore, the signal has the phase shift by the flow. The guided wave propagated along the pipe and does not have the phase shift by the flow. For the measurement of the flowrate, guided wave signal is noise and signal separation is required. To verify the signal by bulk wave and that by guided wave, the obstacle that is 3 mm thickness stainless steel plate is inserted in the center of pipe. In this case, the bulk wave is reflected on the obstacles and is not detected. Therefore, the disappeared ultrasound signal difference means the bulk signal. The peak around 95 μs is detected in the both conditions. On the other hand, the signals around 105 μs is detected without the obstacle, however the signal is not detected with the obstacle. Thus, the peak around 95 μs is concluded as the guided wave signal, and the peak around 105 μs as the bulk wave signal. To verify the bulk wave signal clearly, the detected signal differences between that with and without the obstacle by envelop detection of Hirbert transform are shown in Fig. 10 and 11. And, peaks around 105 μs are verified as signals of the bulk wave. From the speed of sound, the signal propagation time can be estimated. The bulk wave propagates 10 mm air zone, 3 mm pipe material zone, 56 mm water area zone, 2 mm pipe material zone, and 10 mm air zone, then detected. Thus, propagation time is estimated approximately as 100 μs by the speed of sound, 330 m/s in the air, 6000 m/s in the stainless steel and 1500 m/s in the water. On the other hand, the guided wave propagation time also can be estimated. The sear wave speed in the stainless steel is 3000 m/s, and ultrasound propagates half circuit along the pipe, and the propagation time is estimated as 90 μs approximately. Therefore, in the theory, the guided wave reaches 10 μs earlier than the bulk wave. In the experiment, the guided wave reaches the sensor earlier than the bulk wave, and the guided wave is detected 10 μs earlier than the bulk wave. Thus, the signal verification is appropriate.

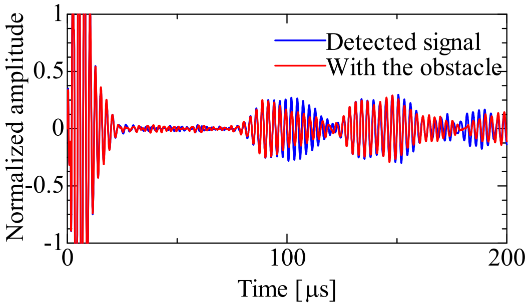


Fig. 8 The detected signal in the aluminum pipe by focusing sensors with and without the obstacle.

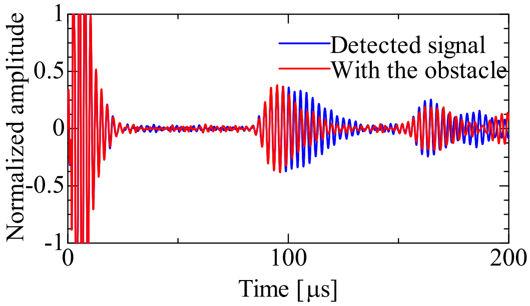


Fig. 9 The detected signal in the stainless steel pipe by focusing sensors with and without the obstacle.

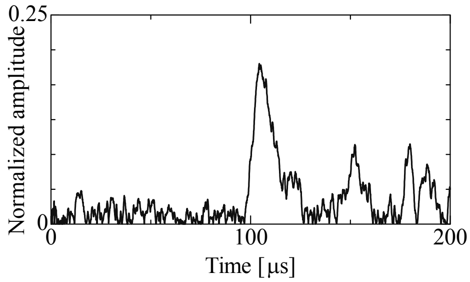


Fig. 10 The signal difference between that with and wihout the obstacle by envelop detection in the aluminum pipe.

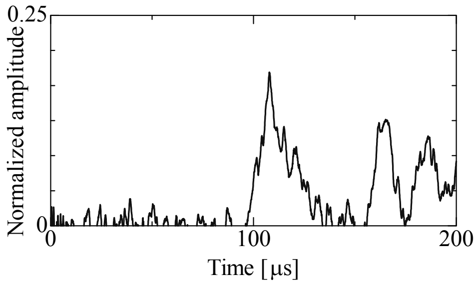


Fig. 11 The signal difference between that with and wihout the obstacle by envelop detection in the stainless steel pipe.

3.2. Flow measurement method for metal pipes

The detected signal includes both effects of guided wave and bulk wave. The guided wave propagated along the pipe and does not have the effect of flow. It is necessary to separate these two signals, and signal processing for air-coupled ultrasonic flowmeter is developed. There is a phase shift on the bulk wave signal, by contrast no phase shift on the guide wave signal. The detected signal on the upstream is calculated by using the phase shift θ, the angular frequency ω, (constant A, B), as

$$f_{u,} = A\cos\omega t + B\cos(\omega t - \theta)\,. \tag{6}$$

And the signal on the downstream is calculated as

$$f_d = A\cos\omega t + B\cos(\omega t + \theta)\,. \tag{7}$$

Here, A is the amplitude of the guided wave signal, and B is the amplitude of bulk wave signal. From the detected signal, the phase shift θ is calculated to measure the flowrate. When there is no flow, substituting $\theta = 0$, detected signal is expressed as the following equation.

$$f_0 = (A+B)\cos\omega t\ \ . \tag{8}$$

The signal difference between Eq. 6 and Eq. 8, and that between Eq. 7 and Eq. 8 are expressed as

$$f_{u,d} - f_0 = B\cos\omega t + B\cos(\omega t \mp \theta) = B\cos\frac{\theta}{2}\cos(\omega t \mp \frac{\theta}{2})\,. \tag{9}$$

The phase of Eq. 9 is detected as $\theta/2$ by the FFT (Fast Fourier Transform). However, the detected signal is clipped and calculated phases contain the initial phase: θ_0 that is caused by the clipping. Therefore the detected phase ϕ is

$$\phi_{u,d} = \theta_0 \mp \frac{\theta}{2} . \tag{10}$$

And the difference between ϕ_u and ϕ_d is θ, thus, the time difference is expressed as

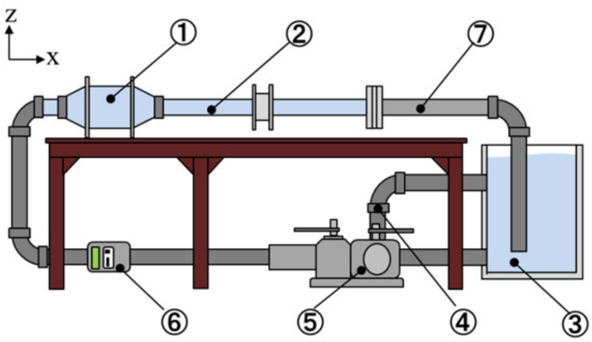
$$\Delta t = \frac{\theta}{\omega} = \frac{\phi_d - \phi_u}{\omega} . \tag{11}$$

The phase change of detected signal is $\theta/2$, thus the real phase shift is two times of detected signal phase. The signal separation is performed by comparing the waveform in measurement with that in the case of no flow. The phase shift is available to be measured by the difference between the phase shift detected on upstream and downstream. Based on this method, the flowrate measurement program for the metal pipe measurement is built.

4. Experiment

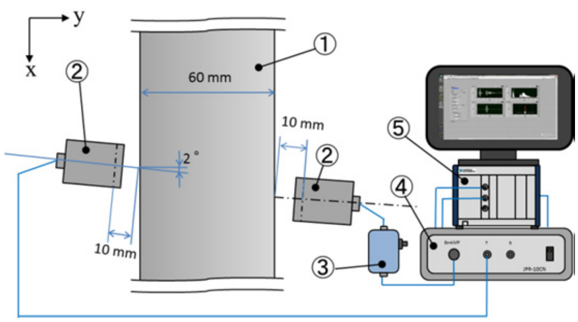
4.1. Experimental setup

The flowrate measurement in the aluminum pipe is conducted, under the applying focusing sensor and the built measurement program. The experimental setup is shown in Fig. 12. This apparatus consists of an electromagnetic flowmeter, a test section, and an air coupled ultrasonic flowmeter. Working fluid is tap water, which is stored in the reserve tank and pump to the straightener through the electromagnetic flowmeter. It flows through the test section and, goes back to the reserve tank. The test section is composed of an aluminum pipe. The outer diameter of the aluminum pipe is 60 mm, and the internal diameter is 56 mm, and the length of the test section is 1000 mm. The air-coupled ultrasonic flowmeter is set up at 2500 mm from the outlet of the straightener. The incident angle of air-coupled ultrasonic transducers (Japan Probe, Focusing 0.4K20 × 20N40R) is 2 degree (Fig. 13), and the distance between the surface of the transducer and the surface of the aluminum pipe is 10 mm. The center frequency of the ultrasonic transducers is 360 kHz, and the transducers have 20 × 20 mm vibration surfaces. The air-couple ultrasonic flowmeter system consists of a Pulser/Receiver (Japan Probe, JPR-10CN), an 8-bit Digitizer (National Instruments, PXI-5114) which the sampling speed is 250 MS/s, a PXI-Express Chassis (National Instruments, PXIe-1062Q) that contains a personal computer, an Ext-Amplifier and developed air-coupled ultrasonic sensors. The electromagnetic flowmeter is set up at the inlet of the straightener because it has no interfere with the ultrasonic flowmeter. The electromagnetic flowmeter has full-scale 3% error with the calibration.



1. Straightener	2. Acrylic pipe
3. Reserve tank	4. Bypath
5. Water pump	6. Electromagnetic flowmeter
7. Test section	

Fig. 12 Experimental apparatus of the vertical pipe flow rate measurement.



1. Aluminum pipe (50A)	2. Focusing sensors
3. Ex-amplifier	4. Pulse/Receiver
5. Personal computer with A/D board	

Fig. 13 The flow measurement system setup.

4.2. Result and discussion

The measured average flow rates by the air-coupled ultrasonic flowmeter compared with the measured average flowrate by the electromagnetic flowmeter are shown in Fig. 14. The vertical axis means the flow rates measured by the air-coupled ultrasonic flowmeter, and the horizontal axis means the flow rates measured by the electromagnetic flowmeter. The measurement by the air-coupled ultrasonic flowmeter is repeated 200 times. The plots of Fig. 14 show the average of measured flowrates. Error bar shows the standard deviations of measured flow rates. The solid line is drawn by the least-squares method, and the zero point is fixed because of the measurement principle. The slope of the line is 1.03 and the fitting value of R2 is 0.959. It shows linearity and the capability to measure the flowrate by the focusing sensor. Standard deviations are larger on the lower flowrate, it caused by the signal processing. Because in the signal processing, detected phase shift is half of the real shift, and there is limitation of phase resolution due to the sampling speed. And the results of flowmeter have larger error over the 250 L/min, because the pressure inside the pipe is getting larger and the speed of the guided wave is also changed. The speed of guided wave is affected by the boundary condition between pipe and fluid [17, 18]. Thus, the guided wave signal is not the same with the reference signal, and it causes error. Thus, the result shows capability of air-coupled ultrasonic flowmeter for the metal pipe application, however, the improvement of the accuracy is required by the development of the signal processing.

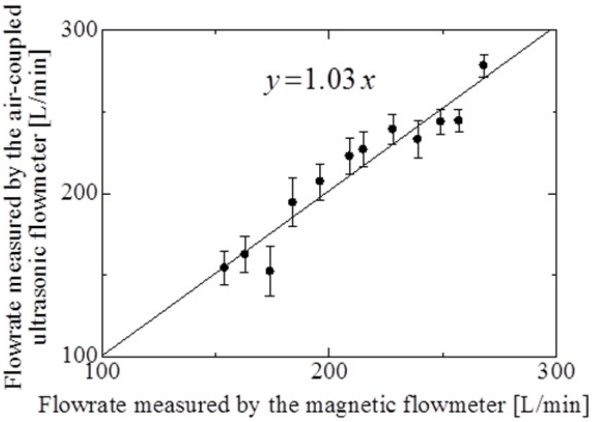


Fig. 14 The result of flow rate measurements by the developed focusing sensors and the electromagnetic flowmeter.

5. Conclusion

The focusing ultrasonic sensors were applied to the air-coupled ultrasonic flowmeter to increase amplitude of detected signal. However, there are two ultrasonic paths in the aluminum and stainless steel pipe, bulk wave and guided wave. The guided wave is not affected by the flow. Accordingly, separating two signals by the experiment, the flowrate measurement algorism including the signal separation is built for the metal pipe application. For the demonstration of the developed measurement algorism, the aluminum pipe flowrate is measured by the focusing ultrasonic flowmeter and electromagnetic flowmeter. And the result of the measurement is evaluated, and it has linearity to the measurements of the electromagnetic flowmeter. Thus, the pipe flow measurement by the air-coupled ultrasound is demonstrated, and it shows the air-coupled ultrasound has the measurement capability for the metal pipe application. However, the error of the flowmeter is larger than conventional flowmeter through this study, the improvement of the accuracy of measurement is required. In particular, it is considered that the improvement of the signal separation method is necessary, and this will contribute to the accuracy by using air-coupled ultrasonic flowmeter in future work.

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