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Vibration-sensing-actuation device for pipe diagnosis using in-plane bending vibration mode

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Abstract. Infrastructure built in the 1950s has deteriorated beyond its service life. However, replacing all infrastructure is difficult and involves huge replacement costs. The optimization of maintenance and participation of various maintenance stakeholders is required. In this paper, we propose a prototype to improve maintenance technology and social cognition. However, technological issues exist, such as a lack of high-reliability diagnoses, optimized maintenance scheduling, and repair methods. In particular, high-reliability diagnosis is focused on herein. Communication of information between stakeholders and infrastructure is essential to improve social cognition in terms of infrastructure deterioration. In this paper, a communication function between the residents and infrastructure is referred to as “future intelligent infrastructure.” We demonstrate a vibration-sensing-actuation device for the future intelligent infrastructure. In particular, we focus on the vibration-sensing-actuation device for pipe diagnosis using an in-plane bending vibration mode. First, a prototype of the vibration-sensing-actuation device is developed. The device is constructed from an IoT sensor module, an electrical relay circuit, a white noise generator, a pipe, and an electrodynamic exciter and a fundamental operation test is performed. As a result, ring vibrations and the fluctuation of the sampling period is observed. Moreover, the theoretical analysis based on the continuum and random vibration theories is conducted. As a result, the fitting model of the acceleration distribution was obtained. Finally, a diagnosis simulation is conducted using the fitting model of the acceleration distribution and the diagnosis algorithm is proposed based on the recursive root mean square value.

1. Introduction

Infrastructure built in the 1950s in Japan has deteriorated beyond its service life. There are problems in many fields such as highway bridges, road surfaces, water supply facilities, power transmission facilities, and power plants. However, replacing all infrastructure is very difficult and involves huge replacement costs. To address this problem, the optimization of maintenance operations and participation of various stakeholders (for example public institutions, private enterprises, local residents) are required; however, maintenance technology and social cognition in terms of infrastructure deterioration are insufficient. In this study, we conducted research and development simultaneously to address the two problems of improvement in maintenance technology and social cognition.

First, there are technological issues such as high-reliability diagnosis, optimized scheduling, and optimized repair methods for the improvement of maintenance technology. In particular, this research is primarily focused on high-reliability diagnosis because diagnosis technology is the starting point of maintenance operations. Second, communication of information between stakeholders and infrastructure is required to improve social cognition in terms of deterioration. Various systems for maintenance are planned but not implemented because of a lack of communication. Communication between people and infrastructure is expected to be realized through a two-way interaction interface device. Particularly, incorporation of a communication function between people and infrastructure can be referred to as "future intelligent infrastructure." In this study, we conducted research and development on a two-way interaction interface device for future intelligent infrastructure.

The two-way interaction interface device requires the following: a high-reliability sensing function, an intelligence function which involves the simplified discrimination of deterioration, and an interaction function between the infrastructure and residents. High-reliability sensing functions are well developed in many fields [1, 2, 3, 4, 5]. The measurement is based on physical intensive properties; however, existing measurement devices mainly use a passive sensing method. Active sensing methods mainly use scientific measurement specifications, and structural monitoring using these methods is limited. In this study, the vibration-sensing-actuation method was considered for high-reliability diagnosis. The diagnosis reliability is expected to improve because of the use of the deterministic input signal in forced vibration. In particular, the vibration response indicates changes in mechanical properties (for example stiffness decrease, lack of mass, change of damping), and a detailed understanding of the infrastructure. Intelligence of a simplified discrimination of deterioration has been well developed in many applications. Well-known technologies include linear/quadratic discrimination [6], decision trees [7], support vector machines [8] and neural networks [9]. In this study, we considered the most simplified threshold method based on the knowledge of the physical forced vibration response and wired and wireless communication methods already exist. The communication method should agree with the constraint condition of the actual application.

In our previous study, a prototype for the vibration-sensing-actuation device for several infra-sensing applications were developed [10, 11]. Particularly, the applications of the water main diagnosis [10] and landslide disaster detection [11] were considered. However, the previous diagnosis algorithm was based on threshold values using the empirical knowledge in terms of response amplitude, therefore the theoretical and systematical discrimination could not be realized. Moreover, the vibration exciter was controlled using the function generator, and the simplified control circuit using the IoT sensor module could not be developed.

In this paper, we present the development of the simplified control circuit of a vibration exciter using the IoT sensor module which confirms the fundamental operation. Furthermore, the diagnosis algorithm is improved based on the random vibration theory using the acceleration distribution.

2. Vibration-sensing-actuation device

A concept sketch of a future intelligent infrastructure is shown in Fig. 1. Future intelligent infrastructure is mainly composed of sensing-actuation devices, terminal devices and other relational communication interfaces.

When residents operate the terminal device, the operation command is sent to the sensing-actuation device. Consequently, the infrastructure is stimulated by the sensing-actuation device with an electrodynamic actuator. The forced response reflects mechanical properties, such as the angular eigen-frequency, damping ratio, and eigen-mode vector. In particular, the diagnoses of the specific structural element and boundary condition are realized using the driving mode, which is stimulated at the resonance frequency. The forced responses are measured by a sensing-actuation device; typically, the device uses an IoT sensor. Diagnosis discrimination is conducted using a sensing-actuation device. The diagnosis results are sent to the residents through the terminal device.

These functions produce communication between residents and the infrastructure, resulting in residential awareness about the infrastructure health condition. Consequently, residents are expected to participate routine maintenance operations, which is the main concept of the future intelligent infrastructure.

In this study, we focused on the development of excitation, measurement, and discrimination functions. In particular, the excitation is composed of white noise excitation to realize the diagnosis function of the specific structure element. An implementation example for the deterioration detection of pipe is presented in the following section.

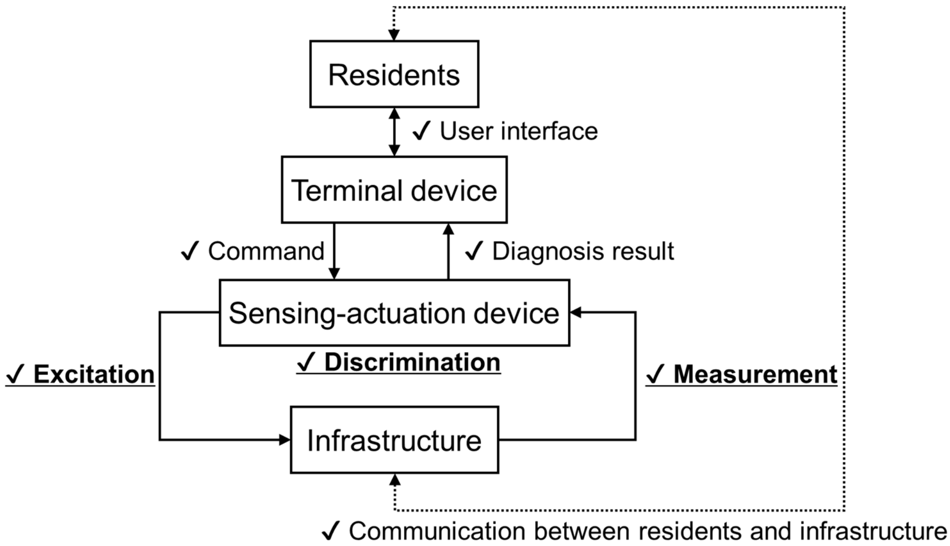


Fig. 1. Concept sketch of future intelligent infrastructure.

3. Implementation and fundamental operation

The system block of the vibration-sensing-actuation device and experimental implementation overviews are shown in Fig. 2 and Fig. 3. The implemented system is composed of an IoT sensor module (M5StickC; SWITCH SCIENCE), electrical relay circuit (KKHMF), a white noise generator (EQKIT), pipe and an electrodynamic exciter (Oasis Electric).

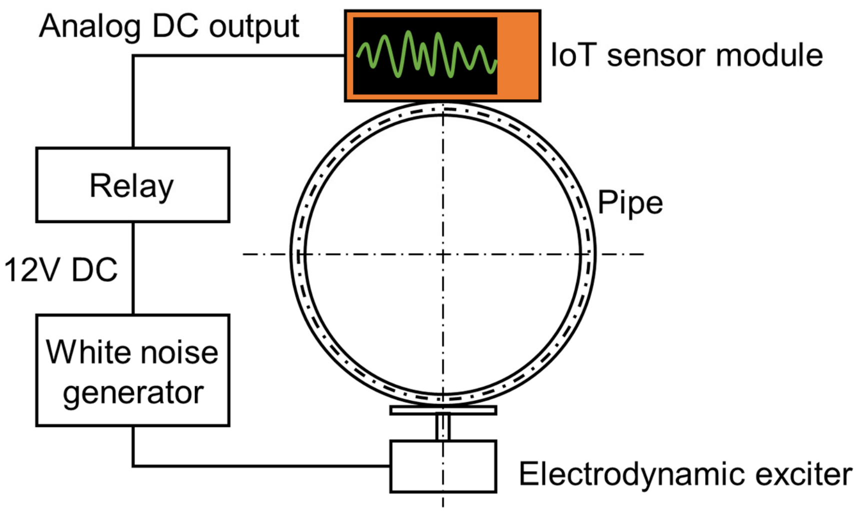
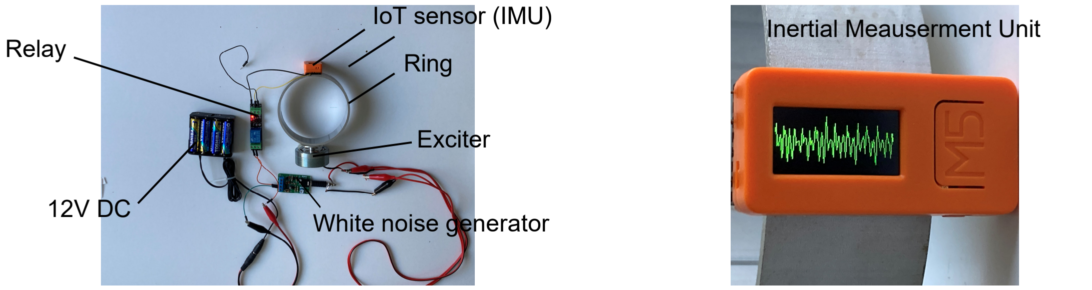


Fig. 2. System block of vibration-sensing-actuation device for pipe diagnosis.

Analog DC voltage is outputted from the IoT sensor module, 12V DC is supplied to the white noise generator which is associated with the electrical relay. The white noise voltage is supplied to the electrodynamic exciter, the pipe is subjected to the random displacement excitation in the vertical direction. Consequently, the in-plane bending vibration in the pipe is induced by the random displacement excitation and the response acceleration of the radial direction is measured by the IoT sensor module. The response acceleration is displayed as a solid green line in the monitor of the IoT sensor module The operation result is shown in Fig. 3 (b). The diagnosis result which is disseminated in the CPU of the IoT sensor module can be displayed on the monitor.



(a) Overview of proposed device. The device is attached to circular ring.

(b) Display of the vibration response. The signal is measured by IMU.

Fig. 3. Experimental implementation of vibration-sensing-actuation device.

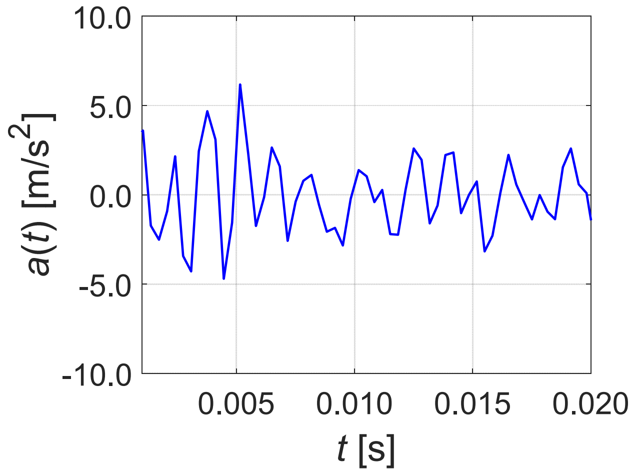


Fig. 4. Timeseries of acceleration response.

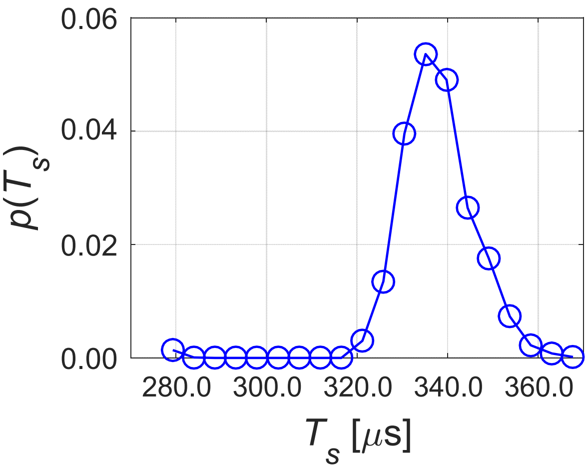


Fig. 5. The probability density function of sampling period by IoT sensor module measurement.

The time series of the acceleration response is shown in Fig. 4. The time series was measured by inertial measurement unit (MPU6886) in the IoT sensor module and the raw data was outputted using the serial communication. Periodical vibration around 720 Hz was observed and the frequency is roughly in agreement with the ring frequency of the pipe (the pipe material is aluminum, the radius is 50 mm, the thickness is 3 mm, and the width is 30 mm). In contract, the sampling period fluctuated because of the IoT sensor module measurement.

The measurement result of the sampling period is shown in Fig. 5. The uni-modal distribution is observed, the average value of the sampling period is 337.5 μs and the variance is 79.1 $(\mu s)^2$. Because of the fluctuation is small, we used the average value of the sampling period (i.e., T_s = 337.5 μs).

4. Consideration of acceleration response based on random vibration theory

A cylindrical ring model is shown in Fig. 6. The coordinate axes are as follows: the axial coordinate is x, the polar coordinate is y, and the radial coordinate is z. The pipe width is b, the pipe radius is R, and the pipe thickness is h. In addition, the displacement of each coordinate are as follows: the deflection in the radial direction is w, and the displacement in the circumferential direction is v.

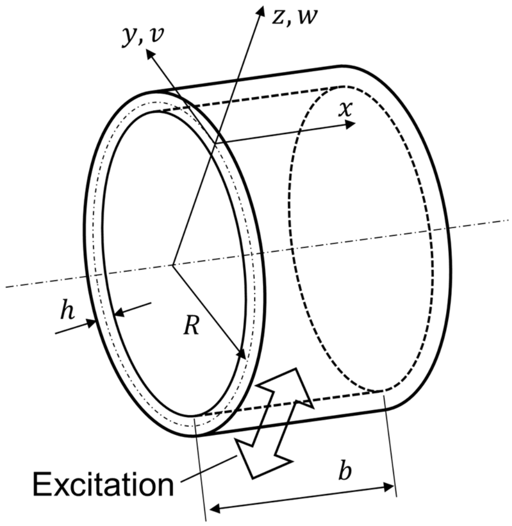


Fig. 6. Model of circular a cylindrical ring.

The Lagrangian for the case of the in-extensional vibration (no stretching of the middle surface of the shell) is given by Eq. (1).

$$L = \int_0^{2\pi} \frac{1}{2}\rho A\left\{\left(\frac{\partial w}{\partial t}\right)^2 + \left(\frac{\partial v}{\partial t}\right)^2\right\} Rd\theta - \int_0^{2\pi} \frac{EI}{2R^4}\left(\frac{\partial^2 w}{\partial \theta^2} + w\right)^2 Rd\theta - \int_0^{2\pi} \rho a A(w\cos\theta + v\sin\theta)\delta(\theta - \pi)Rd\theta. \quad (1)$$

Here, excitation acceleration is a, Young's modulus is E, pipe density is ρ, sectional area is A, and moment of inertia is I. In addition, we assume the following deflection function:

$$w = a_2 \cos 2\theta + b_2 \sin 2\theta. \quad (2)$$

Here, a_2, b_2 represent the modal coordinate of the second wave number. The non-dimensional equation of motion is obtained as follows by using the damping term:

$$\ddot{a}_2 + c'\dot{a}_2 + k'a_2 = -\frac{4}{5\pi}\alpha. \tag{3}$$

Here, the radius displacement is obtained by the relationship of $w = a_2$ because the measurement position is $\theta = 0$. Furthermore, the white noise excitation of acceleration α is considered. The Fokker–Planck equation for unit mass in a 1-DoF system subjected to a white noise excitation force is as follows [12]:

$$\frac{\partial f(a_2, \dot{a}_2, t)}{\partial t} = -\dot{a}_2 \frac{\partial f(a_2, \dot{a}_2, t)}{\partial a_2} + (k'a_2 + c'\dot{a}_2)\frac{\partial f(a_2, \dot{a}_2, t)}{\partial \dot{a}_2} + c' f(a_2, \dot{a}_2, t) + D' \frac{\partial^2 f(a_2, \dot{a}_2, t)}{\partial \dot{a}_2^2}, \tag{4}$$

where $f(a_2, \dot{a}_2, t)$ and D' represent the probability density function of the stochastic response and the diffusion coefficient, respectively, and k' and c' represent the spring constant and damping coefficient, respectively. The analytical solution for the stationary Fokker–Planck equation is as follows:

$$f_s(a_2, \dot{a}_2) = \frac{c'\sqrt{k'}}{2\pi D'} \exp\left[-\frac{c'}{2D'}(k'a_2^2 + \dot{a}_2^2)\right]. \tag{5}$$

Eq. (5) contains the parameters k', D' and c' and the stationary distribution is represented by $f_s(a_2, \dot{a}_2)$. In actual measurement by the IoT module, only the acceleration response is obtained. Hence, the response distribution should be rewritten to the acceleration form. Now, we consider the equation of motion in Eq. (3), which represents the linear relationship between the acceleration and displacement, velocity. The sum of the Gaussian variable is also the Gaussian variable. Consequently, the acceleration distribution is as follows:

$$p(\ddot{a}_2 | 0, \sigma_{\ddot{a}_2}^2) = \frac{1}{\sqrt{2\pi}\sigma_{\ddot{a}_2}} \exp\left[-\frac{\ddot{a}_2^2}{2\sigma_{\ddot{a}_2}^2}\right], \qquad \sigma_{\ddot{a}_2}^2 / D' = \frac{k'}{c'} + c' + \frac{2}{T_s}. \tag{6}$$

Parameter fitting is required in order to consider the diagnosis method. The shape of the ratio between the acceleration variance and the diffusion coefficient with respect to the damping constant is shown in Fig. 7. The existence of a minimum value of the ratio is observed in Fig. 7. The theoretical value is obtained as $c' = \sqrt{k'}$ from the simple optimization respect to c' using Eq. (6). As a result, the only free parameter is the diffusion coefficient D'. Therefore, the diffusion coefficient is obtained from Eq. (7).

$$D' = \frac{\mathrm{E}[\ddot{a}_2^2]}{2\left(\sqrt{k'} + 1/T_s\right)} \tag{7}$$

The fitting results of the acceleration distribution is shown in Fig. 8. Here, the experimental values are the blue circles and the estimation values are the black solid line. The calculation conditions are as follows: the sampling frequency is 3300 Hz, Young's modulus is 68 GPa, density is 2700 kg/m^3, radius is 50 mm, thickness is 3 mm and width is 30 mm. The estimation values in good agreement with the experimental values. In the next chapter the consideration of diagnosis method will be conducted using the above acceleration distribution model.

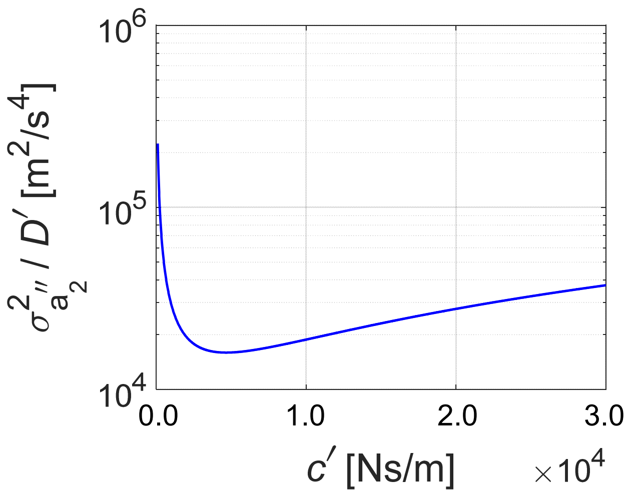


Fig. 7. Damping coefficient dependency of acceleration response variance in the case of unit diffusion coefficient.

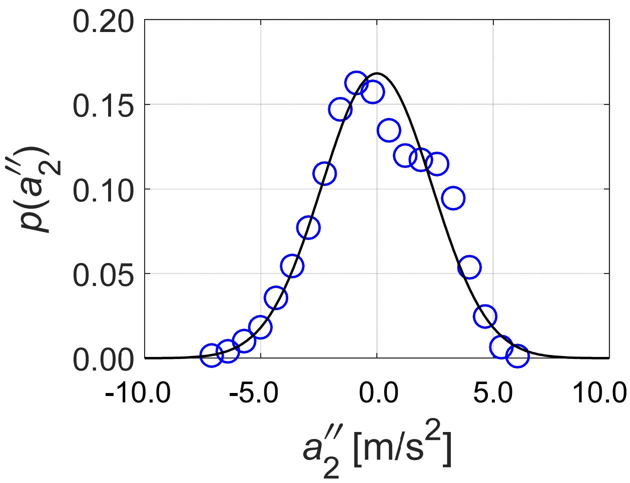


Fig. 8. Fitting result of acceleration response distribution.

5. Numerical simulation of diagnosis method

The acceleration distributions are shown in Fig. 9 for several pipe thickness. The distribution of the narrow broadening observed is associated with pipe thinning. Therefore, for a diagnosis, the root mean square value is available. Here, we consider the diagnosis algorithm which is focused on the broadening distribution. The root mean square value can be calculated recursively. The recursive algorithm is as follows:

$$\mathrm{E}[\ddot{a}_2(k)^2] = \frac{1}{k}\{(k-1)\mathrm{E}[\ddot{a}_2(k-1)^2] + \ddot{a}_2(k)^2\}. \tag{8}$$

Here, the index k represents the discrete time. The algorithm does not require an equidistant sampling period because the root mean square value is based on the statistics of samples. Therefore, it is available from the fluctuating sampling measurement data.

The results of the fundamental operation simulations of the proposed algorithm are shown in Fig. 10. The test samples were generated by the fourth order Runge-Kutta method for several pipe thicknesses. Here, all parameters except for the pipe thicknesses were maintained at the above fitted parameters. The converged estimation values of the root mean square value systematically changed with respect to pipe thickness changes. Therefore, the realization of the pipe thinning diagnosis was implied using the random acceleration response. Confirmation of the experiment will be performed in the future work.

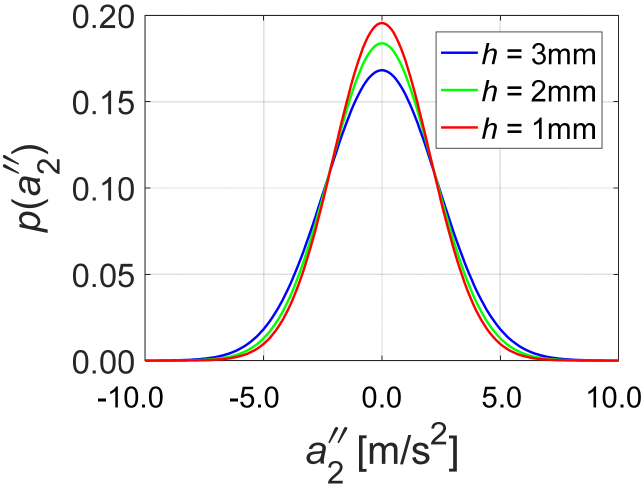


Fig. 9. Acceleration distribution respect to thickness change.

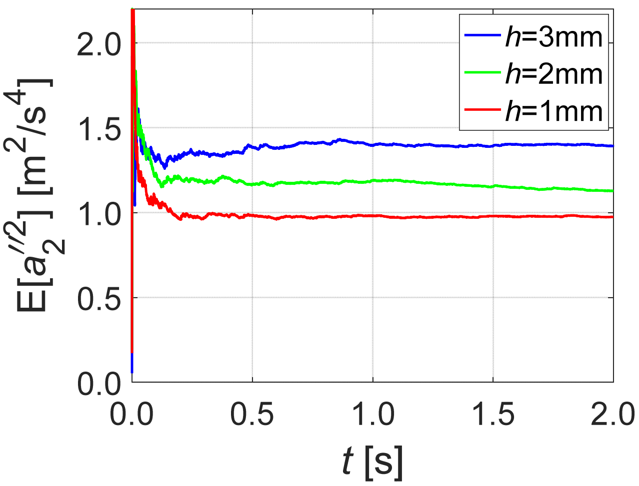


Fig. 10. Recursive estimation result of root mean square value.

6. Conclusions

In this study, we have presented a vibration-sensing-actuation device for pipe diagnosis using an in-plane bending vibration mode. The following results were obtained.

(1) The prototype of the vibration-sensing-actuation device was developed. The device was constructed from an IoT sensor module, an electrical relay circuit, a white noise generator, a pipe, and an electrodynamic exciter.
(2) A fundamental operational test of the vibration-sensing-actuation device was performed. As a result, ring resonance vibrations were observed. Moreover, the fluctuation of the sampling period was observed.
(3) The theoretical analysis based on the continuum and random vibration theories was conducted. As a result, the fitting model of the acceleration distribution was obtained.
(4) The diagnosis simulation was conducted using the fitting model of the acceleration distribution. The diagnosis algorithm is proposed based on the recursive root mean square value.

Acknowledgments

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