Measurement of Frequency Response of Giant Magnetostrictive Material by Use of M-transform

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Abstract: In this paper, impulse response of giant magnetostrictive material (GMM) is identified by using M-transform. First, the displacement of GMM was measured by using the dual frequency laser interferometer. The noise included in the measured signal was removed by using M-transform. The impulse response of the GMM was identified from the input current of the driving coil and the displacement.
Key Words:giant magnetostrictive material, impulse response, M-transform, signal processing

1. Introduction

Giant magnetostrictive material (GMM) is a material that causes an extremely large distortion under magnetic field. GMM has the following features compared with the piezoelectric material that is generally used as a solid-state actuator.

- The generated displacement is large.
- The generated stress is large.
- It is possible to drive by a non-contact method.

GMM are thought to have many potential applications owing to the properties mentioned above. There are a number of references that describe the dynamic behavior of GMM [1], [2]. In this paper, the authors identify the impulse response of GMM by using M-transform. The measuring method of displacement of GMM rod is described in section 2. Because a lot of impulsive noises had been included in the measured displacement, we removed the impulsive noise by the method shown in section 3. As shown in section 4, the impulse response of GMM rod was estimated by using M-transform [4]. Frequency response of the GMM rod was obtained by the Fourier transform of the estimated impulse response. The resonant frequencies calculated from the obtained frequency response agreed quite well with the theoretical ones. Finally, in section 5, we summarize the obtained results.

2. Measurement of displacement of GMM

One of authors has been researching the driving method where the micrometer displacement of the GMM is caused at the time of the microsecond order [3].

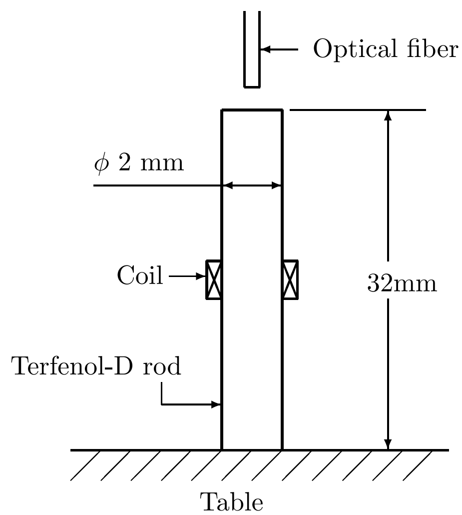

Fig. 1. Experimental set up for measurement of the displacement of GMM

Fig. 1 shows the experimental set up for the measurement of the displacement of GMM. The GMM used for the measurement is a rod made by Terfenol-D of 2mm in the diameter and 32mm in length. The GMM was driven by the coil, which is arranged at the center of the rod. The coil consists of the copper wire of 0.2mm in the diameter and the turn of the coil is 16.

The circuit, which was used to apply a current to the coil, is shown in Fig. 2. The circuit was made to store an electric charge in a capacitor and to discharge it instantaneously through the coil. When a trigger pulse was inputted to the driving circuit, a half sine wave current, the duration of which was 6μs and the

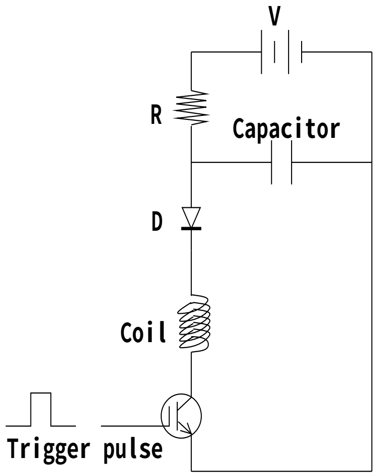

Fig. 2. Driving circuit

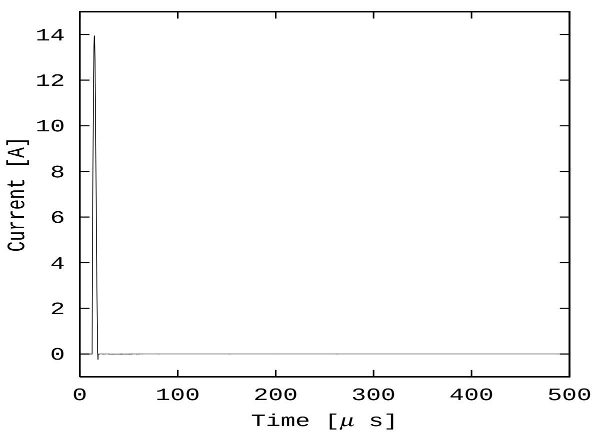

Fig. 3. Electric current applied to the driving coil

maximum value of which was 14A, was applied to the coil. The applied current $u(t)$ is shown in Fig. 3.

When the pulse current passed through the coil, a local deformation was produced in the GMM rod. Then, the local deformation was transmitted through the GMM rod as an elastic wave, and the displacement appeared at the end surface of the rod. The displacement of the GMM was measured by using the dual frequency laser interferometer, the beat frequency of which is 640MHz, and the displacement can be measured by the accuracy of 5nm. The measured displacement is shown in Fig. 4. From this figure, it is clear that there are a lot of impulsive noises in the data of the measured displacement. Then, we tried to remove the impulsive noise by the method of using M-transform[4].

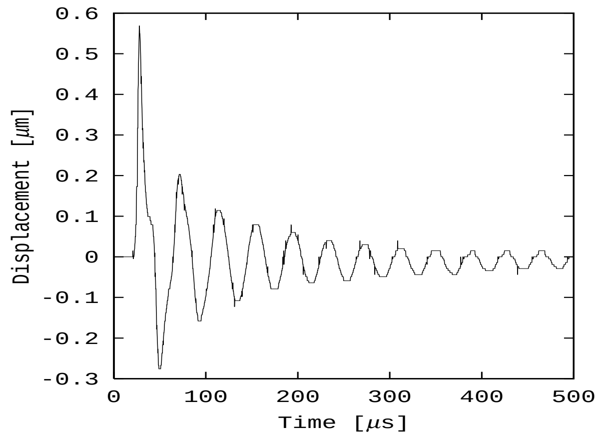

Fig. 4. Measured displacement of GMM

3. Impulsive noise reduction by use of M-transform

M-transform is a new signal processing technique proposed by the authors. This transform is based on the pseudo-orthogonal property of a pseudo-random M-sequence. Just like in case of Fourier transform where any time signal can be expressed as a sum of sinusoidal signals by use of Fourier transform, any periodic time function can be considered to be a weighed sum of M-sequences.

Let $\{a_i\}$ ($a_i = 1$ or 0) be an $n-$th order M-sequence. Then, another binary sequence $\{m_i\}$ is defined as

$$m_i = 1 - 2a_i \quad (0 \le i \le N-1) \tag{1}$$

Here, $N = 2^n - 1$ is a period of the M-sequence. A matrix $\boldsymbol{M}_i$ of $N \times N$ degree is defined by

$$\boldsymbol{M}_i = \begin{bmatrix} m_i & m_{i-1} & \dots & m_{i-N+1} \\ m_{i+1} & m_i & \dots & m_{i-N+2} \\ \vdots & \vdots & \ddots & \vdots \\ m_{i+N-1} & m_{i+N-2} & \dots & m_i \end{bmatrix} \tag{2}$$

Let $\boldsymbol{X}_i$ be an arbitrary periodic discrete time signal represented as

$$\begin{aligned} \boldsymbol{X}_i &= (x(i), x(i+1), \dots, x(i+N-1))^T \\ x(i) &= x(i\Delta t) \end{aligned} \tag{3}$$

where Δt is a sampling period. Then, M-transform $\boldsymbol{A}$ of the signal $\boldsymbol{X}_i$ is uniquely determined as

$$\boldsymbol{X}_i = \boldsymbol{M}_i \boldsymbol{A} \tag{4}$$

$$\boldsymbol{A} = \boldsymbol{M}_i^{-1} \boldsymbol{X}_i \tag{5}$$

The difinition of M-transform is shown in Fig. 5. Any periodic time signal $\boldsymbol{X}_i$ can be considered as the output of a filter whose input is an M-sequence. The cross-correlation function $\phi_{xm}(k)$ between a signal $x(i)$ and

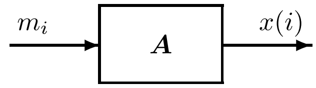

Fig. 5. Definition of M-transform

M-sequence m_i can be represented by M-transform $\boldsymbol{A}$ as follows.

$$\phi_{mx}(k) = \frac{N+1}{N}\alpha_k - \frac{1}{N}\sum_{l=0}^{N-1}\alpha_l \quad (6)$$

The authors also proposed a new method for impulsive noise reduction by use of M-transform [5]. First, it is shown that both impulsive noise and white noise are converted into small-amplitude random signals through the M-transform. Let $\boldsymbol{P}_j$ be a periodic time signal, in which a single impulse is included, represented as

$$\boldsymbol{P}_j = (0, 0, \ldots, p_j, 0 \ldots, 0)^T \quad (7)$$

Here, j means a position of the impulse and p_j is the amplitude of the impulse. Substituting eqn. (7) into eqn. (5), the M-transform $\boldsymbol{A}_p$ of the signal $\boldsymbol{X}_p$ is given as

$$\boldsymbol{A}_p = (\alpha_{p,0}, \alpha_{p,1}, \ldots, \alpha_{p,N-1})^T \quad (8)$$

$$\alpha_{p,i} = \frac{1}{N+1}(m_{i+j} - 1)p_j \quad (9)$$

Since the amplitude p_j is a constant, it is clear that the impulsive noise is converted into a small amplitude M-sequence. Let $\boldsymbol{W}$ be a white noise which has a small amplitude and $\boldsymbol{A}_w$ be the M-transform of $\boldsymbol{W}$.

$$\boldsymbol{W} = (w_0, w_1, \ldots, w_{N-1})^T \quad (10)$$

$$\boldsymbol{A}_w = (\alpha_{w,0}, \alpha_{w,1}, \ldots, \alpha_{w,N-1})^T \quad (11)$$

Substituting eqn. (11) into eqn. (6), the i-th element $\alpha_{w,i}$ of the M-transform of the white noise is given as

$$\alpha_{w,i} = \frac{N}{N+1}\phi_{mw}(i) + \frac{1}{N}\sum_{l=0}^{N-1}\alpha_{w,l} \quad (12)$$

Because the white noise does not correlate with an M-sequence, the M-transform of the white signal also becomes a random signal that has small amplitude. Thus, these two different kinds of noise become the small-amplitude random signal through the M-transform.

The noise reduction method is as follows. Let $\boldsymbol{X}_n$ be a time signal which includes impulsive noise and white noise and and $\boldsymbol{A}$ be the M-transform of $\boldsymbol{X}_n$.

$$\boldsymbol{X}_n = (x_{n,0}, x_{n,1}, \ldots, x_{n,N-1})^T \quad (13)$$

$$\boldsymbol{A} = (\alpha_0, \alpha_1, \ldots, \alpha_{N-1})^T \quad (14)$$

As mentioned above, both impulsive noise and white noise are converted into small-amplitude random signals through the M-transform. These small-amplitude

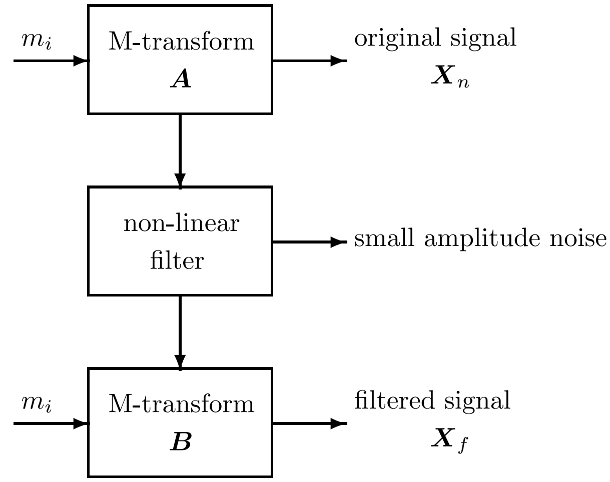

Fig. 6. Procedure of the proposed noise reduction method

random signals which are included in the M-transform $\boldsymbol{A}$ can be removed by using some non-linear filter. Let $\boldsymbol{B}$ be the filtered M-transform. Then, the i -th element of the filtered M-transfor can be represented by the next equation.

$$\boldsymbol{B} = (\beta_0, \beta_1, \ldots, \beta_{N-1})^T \quad (15)$$

$$\beta_j = F(\alpha_{i-L}, \alpha_{i-L+1}, \ldots, \alpha_i)^T \quad (16)$$

Here, F is an non-linear function and L is a filter length. By using eqn. (17), the filtered signal $\boldsymbol{B}$ is transformed into time domain through the inverse M-transform and the obtained signal $\boldsymbol{X}_f$ does not contain both impulsive noise and white noise.

$$\boldsymbol{X}_f = \boldsymbol{M}_i\boldsymbol{B} \quad (17)$$

Thus the noise reduction procedure is completed. Fig. 6 shows the procedure of the proposed noise reduction method.

The authors applied this noise reduction method to the displacement signal shown in Fig. 4. In this case, the length N of the displacement signal is equal to 2047, then we use the 11-th order M-sequence the characteristic polynomial of which is given as

$$f(x) = x^{11} + x^2 + 1 \quad (18)$$

In Fig. 7, the solid line is the M-transform $\boldsymbol{A}$ of the measured displacement and the dotted line is the filtered M-transform $\boldsymbol{B}$.

Substituting the filtered M-transform $\boldsymbol{B}$ into eqn. (17), the filtered signal $\boldsymbol{X}_f$ is obtained. The obtained signal is shown in Fig. 8. In this case, the degree n of the M-sequence is equal to 12, and the $\varepsilon-$ separating filter [6] was used as a low-pass filter. Comparing

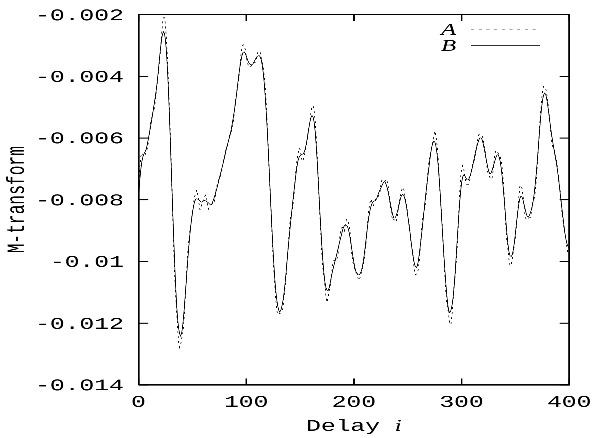

Fig. 7. M-transform of the displacement

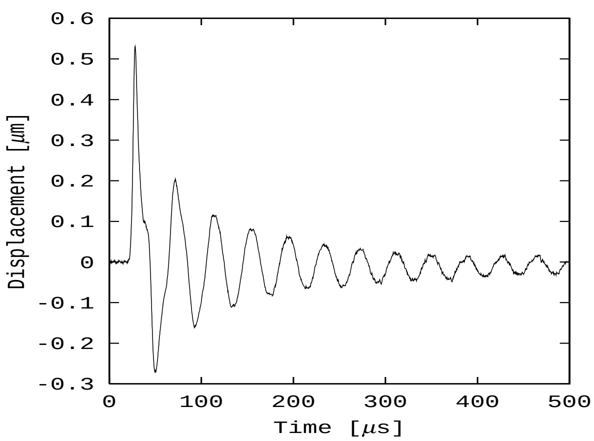

Fig. 8. Displacement of GMM after noise reduction

Fig. 4 and Fig. 8, it is clear that the impulsive noise is removed from the original signal.

4. Calculation of impulse response by use of M-transform

The impulse response of the GMM rod can be calculated by using M-transform. The method is as follows. Let m_i be the $n-$th order M-sequence and $u(i)$ be the input current of the coil, respectively. As shown in Fig. 9, the input current $u(i)$ can be considered to be the output of a filter whose input is an $n-$th order M-sequence $\{m_i\}$[4] . Here, $\boldsymbol{A}_u$ is the M-transform of $u(i)$.

$$\boldsymbol{A}_u = (\alpha_{u,0}, \alpha_{u,1}, \ldots, \alpha_{u,N-1})^T \tag{19}$$

Let $g(i)$ be the impulse response of GMM rod. Then, the displacement $x(i)$ of the GMM can be represented

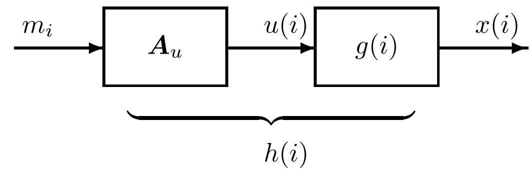

Fig. 9. Linear system identification

as

$$x(i) = \sum_{j=0}^{N-1} h(j) \cdot m_{i-j} \tag{20}$$

$$\boldsymbol{X} = \boldsymbol{M}_i \boldsymbol{H} \tag{21}$$

Here, $h(i)$ is the impulse response of the linear system, which is a cascaded system of $\boldsymbol{A}_u$ and $g(i)$. So, by use of M-sequence correlation method, $h(i)$ is given as

$$\boldsymbol{H} = \boldsymbol{M}_i^{-1} \boldsymbol{X} \tag{22}$$

Since $h(i)$ is the impulse response of the cascaded system of $\boldsymbol{A}_u$ and $g(i)$, $h(i)$ can be expressed as

$$h(i) = \sum_{j=0}^{N-1} \alpha_{u,i-j} \cdot g(j) \tag{23}$$

By using eqns. (21), (22), the impulse response $\boldsymbol{g}$ of the GMM rod is obtained by solving the next equation.

$$\boldsymbol{g} = \boldsymbol{\alpha}^{-1} \boldsymbol{H} \tag{24}$$

Here, $\boldsymbol{\alpha}$ is a matrix defined as

$$\boldsymbol{\alpha} = \begin{bmatrix} \alpha_{u,0} & \alpha_{u,-1} & \cdots & \alpha_{u,-N+1} \\ \alpha_{u,1} & \alpha_{u,0} & \cdots & \alpha_{u,-N+2} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{u,N-1} & \alpha_{u,N-2} & \cdots & \alpha_{u,0} \end{bmatrix} \tag{25}$$

The impulse response of the GMM rod was identified by using the method mentioned above. In this case, the input of the GMM is the input current of the coil shown in Fig. 3 , and the output is the displacement of the GMM shown in Fig. 8. Fig. 10 is the obtained impulse response $g(i)$.

The frequency response $G(j\omega)$ of the GMM was also obtained from the Fourier transform of the impulse response $g(i)$. The obtained frequency response $|G(j\omega)|$ is shown in Fig. 11. From this figure, it is shown that there are two resonant modes in the frequency response.

The theoretical frequency f_n of the resonant mode can be calculated as follows. Let ξ be the distance from the bottom of the GMM rod. Then, the displacement $x(\xi, t)$ of the GMM rod satisfies the next partial differential equation.

$$\rho \frac{\partial^2 x(\xi, t)}{\partial t^2} = E \frac{\partial^2 x(\xi, t)}{\partial \xi^2} \tag{26}$$

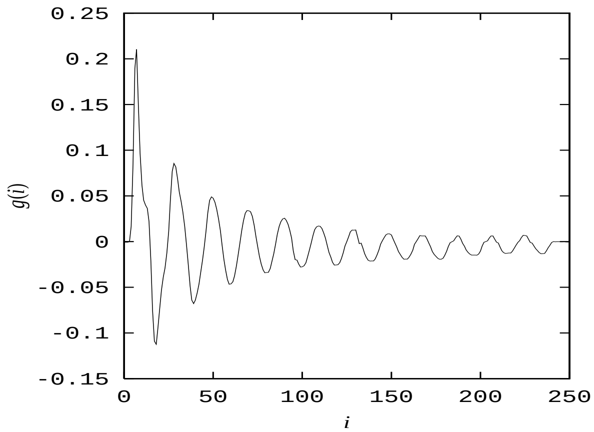

Fig. 10. Impulse response of GMM

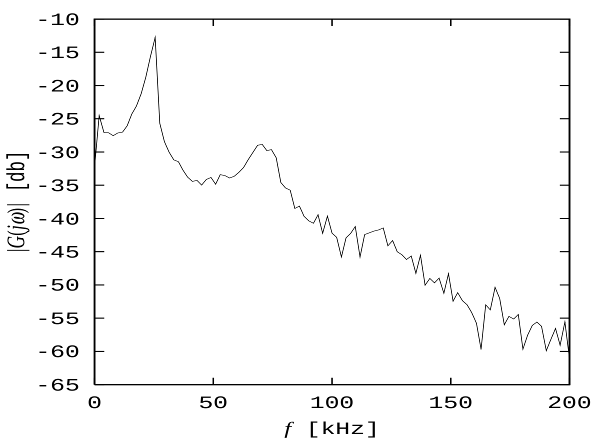

Fig. 11. Frequency response of GMM

Here, ρ is the density of the GMM, E is the Young's module. In this case, the bottom of the GMM rod is fixed on the table and the another end of the rod is a free surface, then the boundary conditions are given by the next equation.

$$x(0,t) = 0 \quad (27)$$

$$\frac{\partial x(l,t)}{\partial \xi} = 0 \quad (28)$$

Here, l is the length of the GMM rod. By solving the eqn. (26), the $n-$th mode resonant frequency f_n of the GMM rod is given by

$$f_n = \frac{(2n-1)}{2l}\sqrt{\frac{E}{\rho}} \quad (29)$$

$$\rho = 9.25 \times 10^3 \text{kg/m}^3 \quad (30)$$

$$E = 2.55 \times 10^{13} \text{Pa} \quad (31)$$

The theoretical resonant frequencies calculated from eqn. (29) and measured resonant frequencies are shown in Table 1. From the results shown in Table 1 , the measured frequencies agree quite well with the theoretical ones.

Table 1 Resonant Frequency

mode n	theoretical [kHz]	measured [kHz]
f_1	25.94	23.59
f_2	77.81	74.51

5. Conclusion

In this paper, frequency response of giant magnetostrictive material is identified. The displacement of the GMM was measured by using the dual frequency laser interferometer. Impulsive noise included in the measured displacement was removed by use of M-transform. The impulse response of the GMM rod was also calculated by using M-transform.

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