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Logical Behavior in Memory Devices of Coupled Nonlinear MEMS Resonators

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Abstract—This paper focuses on a logical behavior of coupled memory devices consisting of nonlinear micro-electro-mechanical systems (MEMS) resonators. A nonlinear MEMS resonator substantially exhibits two coexisting stable states, hysteretic characteristics, and so on. Previous studies showed that a nonlinear MEMS resonator can be applied as a mechanical 1-bit memory device and can be used as AND and OR logic gates. From the standpoint of application of logic system by using the coupled nonlinear MEMS resonators, we address the controlling nonlinear behavior by numerical simulations.

1. Introduction

Micro-electro-mechanical systems (MEMS) devices have micron-scale dimensions and contain both electrical and mechanical components. MEMS resonators, fabricated by MEMS technology, have been used as frequency references, sensor elements, and filters. At higher vibration amplitudes, a MEMS resonator exhibits interesting nonlinear responses such as softening behavior and hardening behavior [1]. In particular, such a nonlinear MEMS resonator exhibits hysteretic responses. At any given frequency in the hysteretic regime, a MEMS resonator can exist in two coexisting stable states and an unstable state [2].

Recently, mechanical information processing has been studied in micro- and nano-electro-mechanical resonators as for logic [3]∼[6] and memory [7]∼[12] devices. Having two coexisting stable states corresponding to large and small amplitude vibrations, a nonlinear MEMS resonator can function as a 1-bit mechanical memory indicating "1" and "0" at large and small vibrations [7]. Guerra *et al.* demonstrated that a nonlinear MEMS resonator can be used as AND and OR logic gates [4]. These preceding results motivated us to develop a logic device with coupled multi-resonators.

This paper addresses a 2-bit counter [13] in the logic system. The logic system is a prospective application of nonlinear dynamics and resonance in coupled MEMS resonators. The authors have already shown the experimental success of the 2-bit binary counter that consists of coupled nonlinear MEMS resonators [14]. Based on our previous study, we numerically confirm the switching control in coupled nonlinear MEMS resonators as a 2-bit binary counter.

2. MEMS resonator and its steady states

A single MEMS resonator is fabricated using silicon on insulator (SOI) technology as shown in Fig. 1 [15, 16]. When the MEMS resonator is excited, the mass vibrates in the lateral direction with weak link to the longitudinal and vertical directions. In this paper, two MEMS resonators are used. The dynamics of a MEMS resonator, which is a single element of the coupled MEMS resonators, is described by

$$\begin{cases} \dfrac{\mathrm{d}x_j}{\mathrm{d}t} = y_j, \\ \dfrac{\mathrm{d}y_j}{\mathrm{d}t} = -\dfrac{y_j}{Q_j} - x_j - \alpha_j x_j^3 + (k_j + u_j)\sin\omega_j t, \end{cases} \tag{1}$$

where $j = 1, 2$. Here x_j denotes the displacement of the j-th MEMS resonator in the coupled system, y_j the velocity of displacement, Q_j the quality factor ($Q_1 = Q_2 = 282$), α_j the coefficient of cubic correction to linear restoring force ($\alpha_1 = \alpha_2 = 3.23$), k_j the amplitude of the excitation force, u_j the control input, and ω_j the excitation frequency ($\omega_1 = \omega_2$). The parameter settings, owing to [17], are used because the same device is assigned to the coupled system. In Sec. 2, the dynamics of a single MEMS resonator is considered without control input u_j.

Figure 2 shows the amplitude-frequency response curve of the resonator by a numerical simulation at $k_j = 0.001$. The red and aqua lines correspond to two stable states and an unstable state, respectively. The

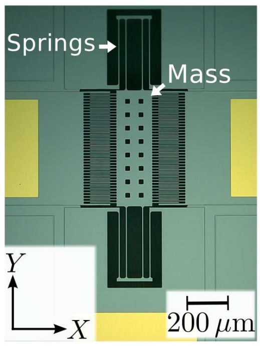


Figure 1: Schematic diagram of a single resonator.

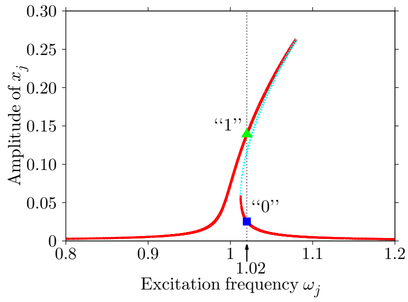


Figure 2: Amplitude-frequency response curve at $k_j = 0.001$. Red lines show two stable solutions and the aqua line an unstable solution.

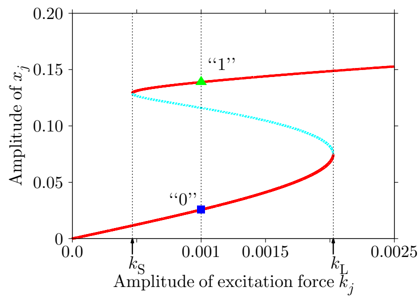


Figure 3: Hysteretic characteristics with respect to the excitation amplitude k_j at $\omega_j = 1.02$. Red lines show the stable states and aqua line the unstable state.

hysteresis region exists at $1.011 < \omega < 1.080$ in Fig. 2. In the hysteresis region, two coexisting stable states strongly depend on the sweep direction. In the following calculations, the excitation frequency ω_j is set at 1.02 as shown in Fig. 2. The green point is regarded as the "1" state and the blue point as the "0" state.

Figure 3 shows a simulated response as a function of the amplitude of the excitation force at $\omega_j = 1.02$. This simulated curve shows the hysteric behavior when the amplitude of excitation is swept from left to right (increase) and right to left (decrease). When the excitation force is increased (decreased), the state is switched to the large (small) amplitude vibration at k_{L} (k_{S}) as shown in Fig. 3. Hereafter, in the steady states, the amplitude of the excitation force k_j is set at 0.001. In Fig. 3, the blue and the green points correspond to the points in Fig. 2.

In order to realize a 2-bit binary counter in two coupled MEMS resonators, we need to control desired switching behaviors between four coexisting stable states at a fixed excitation frequency ($\omega_1 = \omega_2 = 1.02$). The first (second) MEMS resonator is called Res. 1 (Res. 2) that holds the first (second) bit.

3. Switching control method

Based on our experimental set up [14], we construct a switching control system in a 2-bit binary counter as shown in Fig. 4. In the 2-bit binary counter, the output transition of one MEMS resonator triggers the switching control of the other MEMS resonator. Thus, the 2-bit binary counter consists of a series connection of two MEMS resonators. The excitation force of Res. 2 is given as the input depending on the output of Res. 1.

According to [11, 14, 18], the control input u_1 of Res. 1, the control input u_2 of Res. 2, and the excitation force k_2 of Res. 2 are described by

$$u_1 = A_{\mathrm{ref}}^2 - K_1 A_{\mathrm{ave1}}^2, \quad (2)$$

$$u_2 = K_{\mathrm{con2}} A_{\mathrm{ave2}}^2, \quad (3)$$

$$k_2 = K_2 A_{\mathrm{ave1}}^2, \quad (4)$$

$$A_{\mathrm{ave}j}^2 = \frac{A_{j1}^2 + A_{j2}^2 + \cdots + A_{jm}^2 + \cdots + A_{jM}^2}{M}, \quad (5)$$

where $j = 1, 2$. K_1 denotes the feedback gain of Res. 1, K_{con2} the control gain of Res. 2, K_2 the gain of Res. 2, A_{ref}^2 the external reference signal, m natural number, A_{jm} the displacement amplitude of the j-th MEMS resonator at the preceding m period within $1 \le m \le M$, and M the number of terms. Then, A_{avej}^2 is the average of A_{jm}^2 of the j-th MEMS resonator. We set M at 100 for each resonator.

When the state of Res. 1 is switched to the large (small) amplitude vibration, the external reference signal A_{ref}^2 is set at $K_1 A_{\mathrm{ave1}}^{\mathrm{L2}}$ ($K_1 A_{\mathrm{ave1}}^{\mathrm{S2}}$) and the gain K_2 of the excitation force is set at K_2^{L} (K_2^{S}). Here $A_{\mathrm{ave1}}^{\mathrm{L2}}$ ($A_{\mathrm{ave1}}^{\mathrm{S2}}$) corresponds to the target of squared averaged amplitude to the large (small) vibration. In addition, $K_2^{\mathrm{L}} A_{\mathrm{ave2}}^{\mathrm{L2}}$ and $K_2^{\mathrm{S}} A_{\mathrm{ave2}}^{\mathrm{S2}}$ are adjusted at 0.001.

4. Switching control results and discussions

4.1. Gain dependence

Here we investigate the gain dependence of the switching control. It has already been explained that a stable state disappears through the saddle-node bifurcation, denoted by k_{S} and k_{L}, in the quasi-static change as shown in Fig. 3. This subsection focuses on the capable of the switching control between two stable

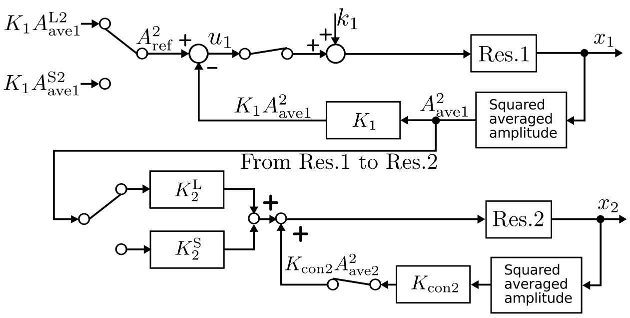
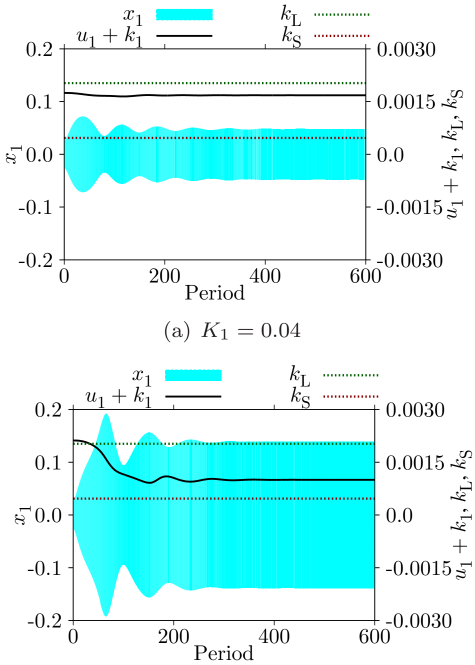


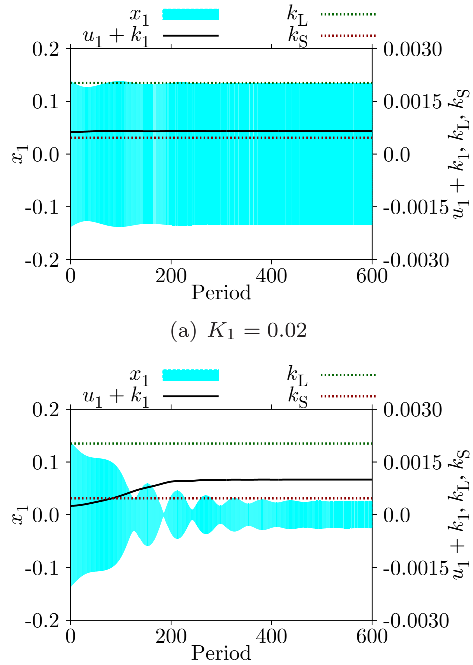
Figure 4: Switching control system in coupled MEMS resonators.



(a) $K_1 = 0.04$

(b) $K_1 = 0.06$

Figure 5: Switching control from small to large amplitude vibrations.



(a) $K_1 = 0.02$

(b) $K_1 = 0.04$

Figure 6: Switching control from large to small amplitude vibrations.

periodic vibrations when the control input is applied to Res. 1.

Figures 5(a) and (b) are obtained at the switching from small amplitude solution at $K_1 = 0.04$ and at $K_1 = 0.06$, respectively. The switching control does not work at $K_1 = 0.04$ as shown in Fig. 5(a). At $K_1 = 0.04$, there still remains the control input when the vibration converges to the steady state. On the other hand, the switching control is achieved at $K_1 = 0.06$ as shown in Fig. 5(b). At $K_1 = 0.06$, the control input disappears after disappearance of transients. Note that the sum of the excitation force and the control input $u_1 + k_1$ is less (more) than k_{L} at $K_1 = 0.04$ ($K_1 = 0.06$). It is concluded that we can achieve the switching control from small to large amplitude states when $u_1 + k_1$ exceeds the value around k_{L}, defined by $k_{\mathrm{L}}^{'}$, at the beginning of the control.

Figures 6(a) and (b) are also obtained at the switching from large amplitude solution at $K_1 = 0.02$ and at $K_1 = 0.04$, respectively. At $K_1 = 0.02$, there exists the steady state near the initial state as shown in Fig. 6(a). Fig. 6(b) shows that the states change from large to small amplitude solutions. These results suggest that the switching control from large to small amplitude states can be realized when $u_1 + k_1$ becomes less than the value around k_{S}, defined by $k_{\mathrm{S}}^{'}$, at the onset of the control.

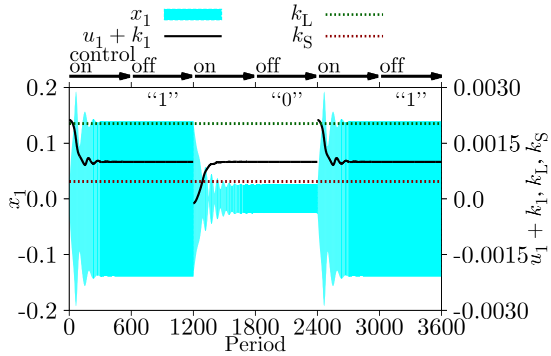
The switching control results in the state were obtained by using $k_{\mathrm{L}}^{'}$ and $k_{\mathrm{S}}^{'}$. In order to realize the 2-bit binary counter, we need to satisfy requirements as shown in Tab. 1. There possibly happens a fault of the switching control when the state of the resonator is perturbed by noises at the onset of the control. In the following simulations, K_1 and K_{con2} are fixed at 0.06 and at 0.03.

4.2. Counter operation

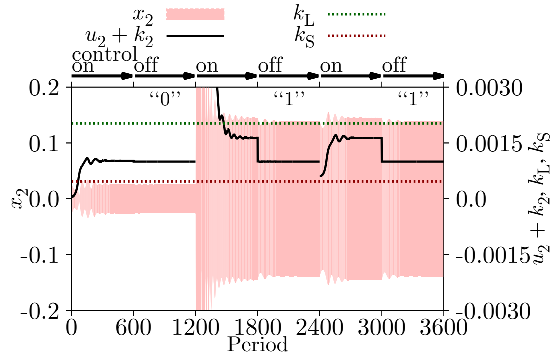
Figures 7(a) and (b) show the switching control sequence ("00" → "01" → "10" → "11") in two coupled MEMS resonators. In these figures, the control input is switched at intervals of 600 periods. Fig. 7(c) gives a partially magnified view of Fig. 7(b) and shows the switching control from "0" to "1" in Res. 2. The states in two resonators must repeat the binary count sequence with a return to "00". However, the switching control from "11" to "00" is not realized in the proposed switching system. For the switching control from "11" to "00", the operation of the coupled MEMS

Table 1: Requirements for 2-bit binary counter.

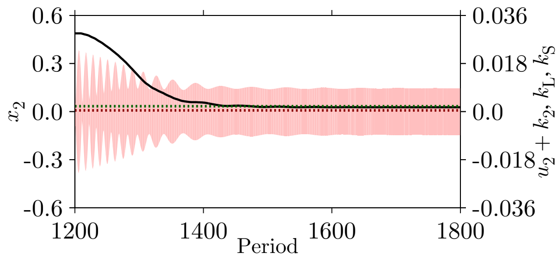
Count	Switching results	Res. 1 $u_1 + k_1$	Res. 2 $u_2 + k_2$
1	"00" → "01"	$u_1 + k_1 > k_{\mathrm{L}}^{'}$	$u_2 + k_2 < k_{\mathrm{L}}^{'}$
2	"01" → "10"	$u_1 + k_1 < k_{\mathrm{S}}^{'}$	$u_2 + k_2 > k_{\mathrm{L}}^{'}$
3	"10" → "11"	$u_1 + k_1 > k_{\mathrm{L}}^{'}$	$u_2 + k_2 > k_{\mathrm{S}}^{'}$
0	"11" → "00"	$u_1 + k_1 < k_{\mathrm{S}}^{'}$	$u_2 + k_2 < k_{\mathrm{S}}^{'}$



(a) Result of switching control in Res. 1.



(b) Result of switching control in Res. 2.



(c) Magnified view of Fig. 7(b)

Figure 7: Switching control from "00" to "11".

resonators is reset. As a result, the operation of the 2-bit binary counter can be achieved. The switching from large to small (small to large) amplitude vibrations was completed after around 300 periods (350 periods) in Res. 1. In Res. 2, the duration of the transient state was around 800 periods (700 periods) when the state stayed at the large (small) amplitude vibrations. It was found that the transition is slow from small to large amplitude vibrations in Res. 2. It took around 900 periods until the conversion.

5. Summary

This paper focuses on a 2-bit binary counter in two coupled MEMS resonators by numerical simulations. We cleared the requirements of the gain and realized the switching control sequence ("00" → "01" → "10" → "11") by using the proposed switching control method. There still remained the reset operation for the complete operation. Nevertheless, we numerically showed the implementation of a novel logic system that consists of electrically coupled nonlinear MEMS resonators.

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