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Reprogrammable Logic-Memory Operation in a Nonlinear MEMS Resonator

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Abstract—From the viewpoint of application of nonlinear dynamics, this study focuses on a reprogrammable logic-memory operation in a single nonlinear microelectromechanical system (MEMS) resonator. The nonlinear MEMS resonator shows coexistence of multi-states and can be used as mechanical logic and memory devices. In order to realize the reprogrammable logic-memory operation in the nonlinear MEMS resonator, the nonlinear dynamics with and without control input is examined. Through numerical simulations, we achieve the reprogrammable logic gate and the memory of the single nonlinear MEMS resonator.

1. Introduction

Microelectromechanical systems or nanoelectromechanical systems (MEMS or NEMS) resonators have been used as frequency references, sensor elements, and filters due to high quality factor [1]. At large excitation force, the MEMS and NEMS resonators exhibit the nonlinear responses that have two coexisting stable states and one unstable state [1, 2]. Recently, many studies have addressed mechanical computation based on nonlinear MEMS or NEMS resonator [3]-[21]. In particular, we have demonstrated a "logic-memory operation" that offers a combination of OR gate and memory operations in a single nonlinear MEMS resonator [21]. Guerra *et al.* have reported that the nonlinear mechanical resonator can be used as a reprogrammable logic gate [7]. The next phase is to develop a "reprogrammable logic-memory device" in the single nonlinear MEMS resonator. From the viewpoint of application of nonlinear dynamics in the MEMS resonator, this paper numerically discusses the reprogrammable logic gate and the memory operations.

2. Dynamical Model and Control Method

In this section, the nonlinear dynamical model of the MEMS resonator and the control method are discussed.

2.1. Steady States

Figure 1 shows the fabricated MEMS resonator [22, 23] and the control system. The dynamical model of the MEMS resonator under control is given by the following non-dimensional equation [21]:

$$\frac{\mathrm{d}^2x}{\mathrm{d}t^2} + \frac{1}{Q}\frac{\mathrm{d}x}{\mathrm{d}t} + x + \alpha_3 x^3 = (k_{\mathrm{n}} + u_{\mathrm{n}})\sin\omega t, \qquad (1)$$

where x denotes the displacement, ω the excitation frequency, Q $(= 282)$ the quality factor, k_{n} the amplitude of excitation, u_{n} the control input, and α_3 $(= 3.23)$ the coefficient of cubic correction to the linear restoring force. The parameter settings are due to Ref. [24] because the same design of MEMS resonator is assigned.

Figure 2 shows the numerically calculated amplitude-frequency response curves of the MEMS resonator at $k_{\mathrm{n}} = 0.001$ and $u_{\mathrm{n}} = 0.0$. At nonlinear responses, amplitude-frequency response curves bend toward higher frequencies owing to a hard spring effect [13, 18, 21, 24, 25]. The red (aqua) line shows the responses at the upsweep (downsweep) of frequency. The solid (red and aqua) lines correspond to two stable solutions and the dashed (green) line shows an unstable solution. At any given frequency in the hysteretic region, the MEMS resonator has two coexisting stable states. In the following simulations, the excitation frequency ω is set at 1.02.

Figure 3 shows the hysteretic behavior as a function of the excitation amplitude k_{n} without control input by numerical simulations. The model of the MEMS resonator has the hysteretic behavior when the excitation amplitude is swept from left to right (thick red line) and right to left (thin aqua line). In the hysteretic region, the nonlinear MEMS resonator shows two coexisting stable states (solid line) and one unstable state (dashed green line) [21]. These stable states are defined as the two states of the single output of logic or memory operations in a single nonlinear MEMS resonator [21]. In this study, a displacement amplitude greater (less) than 0.100 is quantized as a logical "1" ("0") for logic and memory output.

2.2. Control System

This subsection addresses the control input as a logic operation. Fig. 1 shows the control system to perform

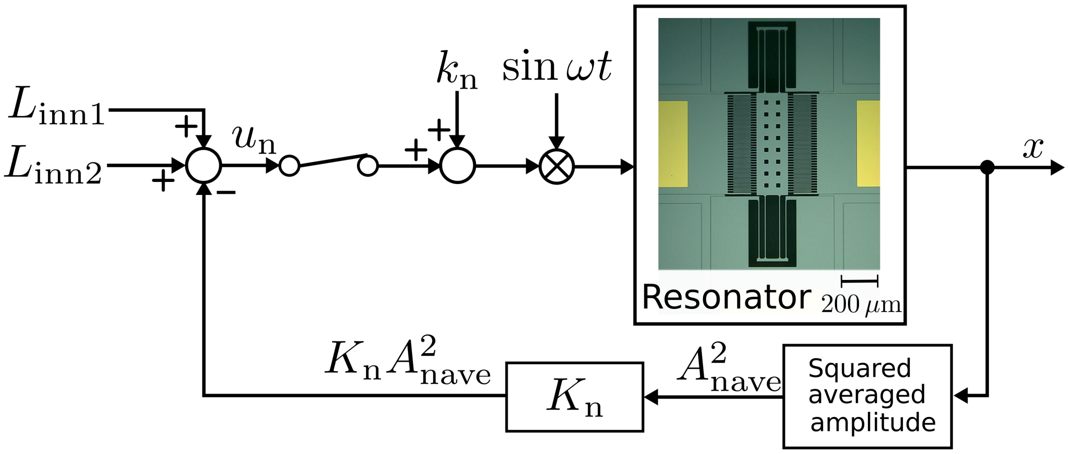


Figure 1: Schematic of MEMS resonator and control system.

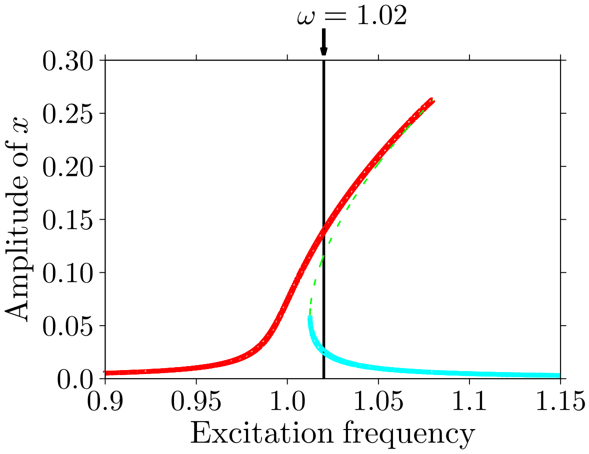


Figure 2: Numerical amplitude frequency response curves at $k_{\mathrm{n}} = 0.0001$.

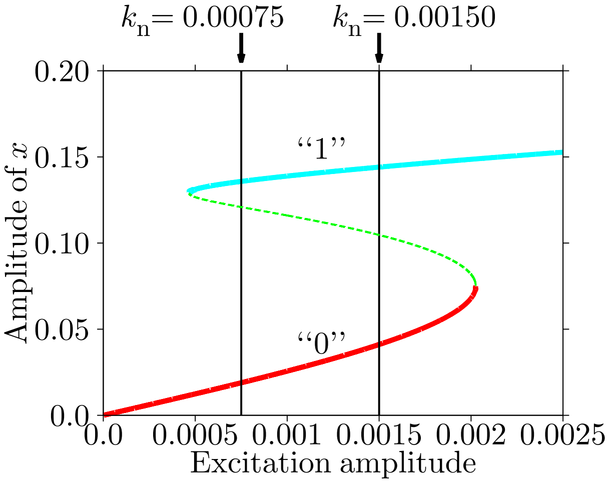


Figure 3: Hysteretic characteristics as a function of excitation force at $\omega = 1.02$.

the logic operation. Recently, we experimentally and numerically demonstrated a logic-memory operation that uses a closed loop control and a nonlinear MEMS resonator in which multiple states coexist [13]. Based on the previous study, the feedback control is performed and the logic inputs are applied to the MEMS resonator as two inputs (L_{inn1} and L_{inn2}). The control input u_{n} is described by the following equations [21]:

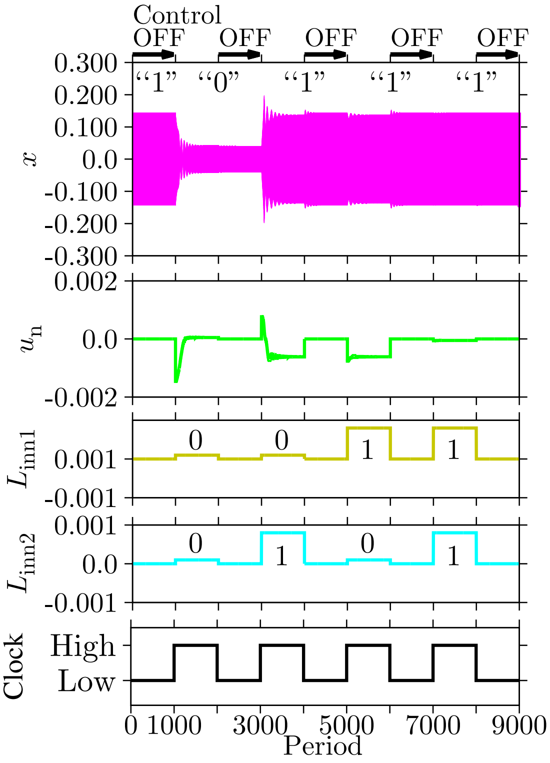
$$u_{\mathrm{n}} = L_{\mathrm{inn1}} + L_{\mathrm{inn2}} - K_{\mathrm{n}} A^2_{\mathrm{nave}}, \qquad (2)$$

$$A^2_{\mathrm{nave}} = \frac{A^2_{\mathrm{n1}} + A^2_{\mathrm{n2}} + \cdots + A^2_{\mathrm{n}m} + \cdots + A^2_{\mathrm{n}M}}{M}, \qquad (3)$$

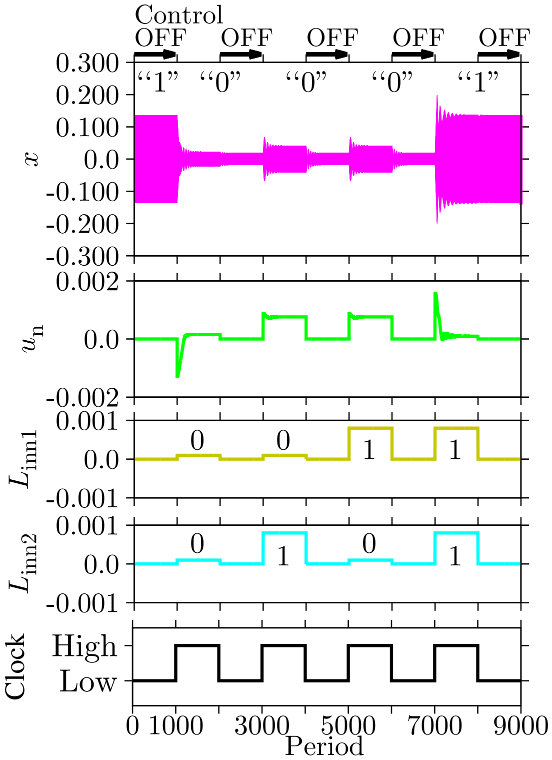
where K_{n} ($= 0.08$) denotes the feedback gain, m a natural number, M ($= 150$) the average number, and $A_{\mathrm{n}m}$ the displacement amplitude of the previous m period within $1 \leq m \leq M$. In addition, L_{inn1} (L_{inn2}) shows the input signal that corresponds to the first (second) logic input. In this study, the logic input is quantized as logical 1 (logical 0), when the input signal (L_{inn1} or L_{inn2}) is set at 0.0008 (0.0001).

3. Reprogrammable Logic-Memory Operation

This section focuses on a reprogrammable logic-memory operation in a nonlinear MEMS resonator with multiple states by numerical simulations. Both logic and memory operations can be obtained in the single MEMS resonator. These operations are confirmed for the behavior of device at clock evolution. Here, the excitation force k_{n} is set at either 0.00075 or 0.00150. Fig. 4(a) (4(b)) shows the calculated time evolutions of the device at $k_{\mathrm{n}} = 0.00150$ ($k_{\mathrm{n}} = 0.00075$). In these figures, the purple, green, yellow, aqua and black lines show the displacement x as the output of the device, control input u_{n}, the first logic input L_{inn1}, the second logic input L_{inn2}, and clock signal, respectively. When the clock signal is high (low), the control input is (is not) applied to the MEMS resonator. Note that the nonlinear MEMS



(a) OR gate and memory operations at $k_n = 0.00150$



(b) AND gate and memory operations at $k_n = 0.00075$

Figure 4: Time evolution of reprogrammable logic-memory operation.

Table 1: Truth table of OR gate.

Input		Output (Displacement)
L_{inn1}	L_{inn2}	x
0	0	"0"
0	1	"1"
1	0	"1"
1	1	"1"

Table 2: Truth table of AND gate.

Input		Output (Displacement)
L_{inn1}	L_{inn2}	x
0	0	"0"
0	1	"0"
1	0	"0"
1	1	"1"

resonator works as a logic (memory) device at high (low) clock signal.

The logic inputs of input signals (L_{inn1}, L_{inn2}) start from (0, 0) and continue to (0, 1), (1, 0), and (1, 1). As shown in Fig. 4(a), when the logic inputs are (0, 0), the output of the device becomes a logical "0" at $k_n = 0.00150$. When the logic inputs are set at (0, 1), (1, 0), or (1, 1), the output is a logical "1" at $k_n = 0.00150$. On the other hands, at $k_n = 0.00075$, when the logic inputs are set at (0, 1) or (1, 0), the output is a logical "0". Therefore, the nonlinear MEMS resonator works as an OR (AND) gate at $k_n = 0.00150$ ($k_n = 0.00075$) as shown in Tab. 1 (Tab. 2).

As shown in Fig. 4(a) (4(b)), when the control input is off at low clock signal, the nonlinear MEMS resonator can be used as the memory device by storing the output of OR (AND) gate. The single MEMS resonator combines the function of OR (AND) gate and memory at $k_n = 0.00150$ ($k_n = 0.00075$). As a result, we numerically demonstrate the reprogrammable logic function that consists of OR/AND gate and the memory function in the single nonlinear MEMS resonator due to the adjustment of the excitation amplitude.

4. Summary

In numerical simulations, the reprogrammable logic gate and memory operations were demonstrated in a single MEMS resonator. It was numerically shown that when the excitation amplitude is adjusted, the logic function as either AND or OR gates can be programmed. As a result, we numerically confirmed the realization of the reprogrammable logic-memory operation in the single nonlinear MEMS resonator. The demonstration of this reprogrammable logic-memory device affords a path to the realization of an on-demand device [26] with multi-functions based on the nonlinear MEMS resonator.

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