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Logic-memory device of a mechanical resonator
Atsushi Yao and Takashi Hikihara

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Mechanical mixing in nonlinear nanomechanical resonators
Logic-memory device of a mechanical resonator

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We report multifunctional operation based on the nonlinear dynamics in a single microelectromechanical system (MEMS) resonator. This letter focuses on a logic-memory device that uses a closed loop control and a nonlinear MEMS resonator in which multiple states coexist. To obtain both logic and memory operations in a MEMS resonator, we examine the nonlinear dynamics with and without control input. Based on both experiments and numerical simulations, we develop a device that combines an OR gate and memory functions in a single MEMS resonator.

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Microelectromechanical systems or nanoelectromechanical systems (MEMS or NEMS) resonators have been developed for use as filters, frequency references, and sensor elements.\textsuperscript{1} Recently, significant research has focused on mechanical computation based on MEMS or NEMS resonators.\textsuperscript{2–17} Some studies have shown that a single mechanical resonator can be used as a mechanical 1-bit memory\textsuperscript{3,5,7,8,11–15,15} or as mechanical logic gates.\textsuperscript{6,9,10}

Recently, multifunctional operation has been demonstrated in the form of a shift-register and a controlled NOT gate made from a single mechanical resonator.\textsuperscript{17} The next phase is to use a closed loop control to generate multifunction devices, which consist of memory and multiple-input gates, in a single device. The closed loop allows output and excitation signals to be fixed at a single frequency. The goal of the work presented in this letter is to develop multifunction operation from a nonlinear MEMS resonator in which multiple states coexist with closed loop control.

Nonlinear dynamical responses are commonly observed in a microelectromechanical or nanoelectromechanical resonator. The nonlinear dynamics of the resonator is well known to be described by the Duffing equation.\textsuperscript{2,8,12,18–20} Such a resonator is equipped with a comb drive that normally serves as a displacement sensor.\textsuperscript{11,16} When the comb-drive resonator is electrically excited, the mass vibrates in the lateral direction. The vibration displacement is measured without additional sensors; therefore, the MEMS resonator is equipped with a comb drive that normally serves as a forcing actuator, but which simultaneously serves as a displacement sensor.\textsuperscript{11,16}

Figure 2(a) shows the amplitude frequency response (without control input \(u_c\)). The MEMS resonator produces a hysteric response: the curves differ for increasing and decreasing frequency sweeps. The nonlinear dynamics of the MEMS resonator is qualitatively modeled as follows:

\[
d^2x/dt^2 + 2\pi f_0 dx/Q dr^2 + (2\pi f_0)^2 x + 2\pi^2 x^3
= 4.0 m(V_s^2)^{-1} \times (V_{dcn} + u_c)\sin 2\pi f_0 t,
\]

FIG. 1. Schematic of MEMS resonator, measurement system, and control system that relates to logic inputs. The nonlinear MEMS resonator, fabricated using silicon-on-insulator technology, is actuated by an ac excitation voltage \(V_{ac}\) with a dc bias voltage \(V_{dc}\). When the MEMS resonator is excited, the mass vibrates in the X-direction. In the measurement system, the output voltage \(V_{out}\) depends on the amplitude and phase of the displacement in the nonlinear MEMS resonator. The control system is implemented with a feedback input and logic inputs. The feedback input is given as the slowly changing dc voltage \(V_{dcn}\), to which the output voltage \(V_{out}\) is converted by an analog multiplier and a low-pass filter (see Ref. 11 for more details). The time constant of the low-pass filter is set to about 0.47 s. The logic inputs, represented by two dc voltages (\(L_{in1}\) and \(L_{in2}\)), are added to the dc bias voltage \(V_{dc}\). As a result, the excitation force under control becomes proportional to \(V_{dc} + u_c = V_{dc} + L_{in1} + L_{in2} - K_r V_{out}\). Here \(L_{in1}\) and \(L_{in2}\) denote the input signals, which serve as the logic inputs, \(u_c\) is the control input, and \(K_r\) (= 11 V\(^{-1}\)) is the feedback gain in the experiments.

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where $x$ denotes the displacement, $f_n$ is the excitation frequency, $f_0 (= 8.6644$ kHz) is the resonance frequency, $Q (= 25 \times 10^3)$ is the quality factor, $\alpha_3 (= 7.06 \times 10^{16}$ (sm)$^{-2}$) is the nonlinear mechanical spring constant, $V_{dcn}$ is the dc bias voltage, and $u_n$ is the control input. The parameters are obtained based on our reported parameter estimation method.25 Fig. 2(b) shows the amplitude as a function of excitation frequency for the resonator as determined by numerical simulations at $V_{dcn} = 150$ mV and $u_e = 0$ mV. At any given frequency in the hysteretic region, the MEMS resonator exhibits two coexisting stable states. In the following experiments and simulations, the excitation frequency is fixed at 8.6654 kHz.

Figure 3(a) shows the experimentally determined hysteretic behavior as a function of dc bias voltage $V_{dc}$ at $u_e = 0$ mV. The corresponding numerical results are shown in Fig. 3(b) with respect to numerical dc bias voltage $V_{dcn}$. The hysteresis region exists at 95 mV $< V_{dc} < 275$ mV in Fig. 3(a) and 105 mV $< V_{dcn} < 245$ mV in Fig. 3(b). The difference of hysteresis regions is caused by noise in Fig. 2(a). The nonlinear MEMS resonator has stable regions (solid line) that are completely separated by an unstable region (dashed line). These stable regions, which correspond to large and small amplitude vibrations, define the two states of the single-output logic or memory device in a single MEMS resonator. In the numerical simulations and experiments, a displacement amplitude greater than 3.0 $\mu$m is regarded as a logical “1”; a value less than 3.0 $\mu$m is regarded as a logical “0” for logic and memory output. Hereinafter, the numerical and experimental dc bias voltages ($V_{dcn}$ and $V_{dc}$) are fixed at 150 mV.

We now discuss the nonlinear dynamics with control input as a logic operation. Fig. 1 shows the control system to perform the logic operation. The switching between two coexisting stable states was done by a displacement feedback control in the nonlinear MEMS resonator.11 Based on the results, the feedback control is performed. The logic inputs are applied to the MEMS resonator in the form of two dc voltages ($L_{in1}$ and $L_{in2}$). In the experiments, the control input $u_e$ is described as follows:

$$u_e = L_{in1} + L_{in2} - K_e V_{ave}^2,$$

where $K_e$ denotes the feedback gain and $V_{ave}^2$ is a slowly changing dc voltage that depends on the displacement.11

The corresponding numerical control input $u_n$ is described as follows:12

$$u_n = L_{inn1} + L_{inn2} - K_n A_{ave}^2,$$

$$A_{ave}^2 = \frac{A_{n1}^2 + A_{n2}^2 + \cdots + A_{nm}^2}{M},$$

where $L_{inn1}$ and $L_{inn2}$ denote the input signals that are the logic inputs, $K_n$ is the feedback gain, $m$ is a natural number,
FIG. 4. Amplitude modulation systematically varied in input signals $L_{\text{inn1}}$ and $L_{\text{inn2}}$ at $f_0 = 8.6654$ kHz and $V_{\text{dec}} = 150$ mV (numerical results). The light (dark) region corresponds to more than (less than) 3.0 $\mu$m in displacement amplitude, corresponding to a logical “1” (logical “0”) output. For an OR gate, input signals are set to 150.0 mV and 37.5 mV, as shown by the four circles with light (aqua) color: (a) Initial state is set to the large amplitude solution (logical “1” for memory output) (b) Initial state is the small amplitude solution (logical “0” for memory output).

$M$ is the average number, and $A_{\text{amp}}$ is the displacement amplitude of the previous $m$ period within $1 \leq m \leq M$ for the numerical simulations. In this case, $A_{\text{ave}}^2$ is the average of $A_{\text{inn}}^2$. $K_a$ is set to $1.42 \times 10^{10}$ Vm$^{-2}$ and $M$ is set to 22 000.

Figure 4 shows the numerically obtained steady states when the control input is applied to the MEMS resonator. The control input can induce a modulation of the resonator’s amplitude and thus change the logical value of the output. In Fig. 4(a) (Fig. 4(b)), the initial state of memory output is a logical “1” (logical “0”). In Figs. 4(a) and 4(b), there exist regions in which the displacement amplitude is the same because the control system depends on the feedback input. Assume that the control system receives just the input signals $L_{\text{inn1}}$ and $L_{\text{inn2}}$. When the input signals $L_{\text{inn1}} = L_{\text{inn2}} = 0.0$ mV are sent to the MEMS resonator, the large stable state cannot switch to the small state. Therefore, a single MEMS resonator can be used as a logic gate because of the adjustment of the logic inputs and the feedback input.

To execute a memory operation in a MEMS resonator, we must consider the nonlinear dynamics without the control input. When the control input is not applied, every initial state corresponds to the convergence to either the small amplitude (black) or large amplitude (white) solutions, as shown in Fig. 5. In the nonlinear MEMS resonator, the small and large amplitude solutions have each basin of attraction.

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combination of an OR gate and a memory device in a single MEMS resonator. Mahboob et al. have developed a device that combines a controlled NOT gate and memory functions in a single resonator at 2 K. In this letter, we realize a logic-memory device of high reliability operating at room temperature with the logic inputs given as two dc voltages that do not depend on the phase. By considering the closed loop and bias inputs, these results open the way to further research in high and multi functionality in single and coupled resonators, which may take the form of multiple-input gates such as three- or four-input logic gates and memory.

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