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Systematic Proportional Method for Improving the Measurement Accuracy of Passive Sensor Measurement System

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ABSTRACT The accuracy and stability of excitation source determine the measurement accuracy of passive sensor measurement system, but the implementation of high-precision excitation source (especially AC excitation source) is difficult or costly in design and process. For this purpose, this paper proposes a systematic proportional method. In this method, the DC voltage converted by the excitation signal is taken as the reference voltage of the ADC used in this system. And then the ratio of the measured signal to the excitation signal is obtained by using the transmission characteristics of the ADC, therefore the amplitude fluctuation of the excitation signal is compensated. The method can greatly suppress the measurement error caused by the amplitude fluctuation of the excitation signal and the fluctuation of the ADC reference voltage, and effectively improve the measurement accuracy of the measurement system. To verify the effectiveness of the proposed method, the Wheatstone bridge measurement circuit is designed. The experimental results show that when the amplitude of the excitation signal changes 50%, the measurement result of the measurement system using non-proportional method changes about 50%, while that of the measurement system using proportional method only changes about 1%. To further improve the measurement accuracy, the DC bias voltage compensation circuit is added, and the maximum variation error of the measurement result after compensation is only 0.3%. More importantly, the method can also be extended to other linear measurement systems with excitation source in principle, which has greater application value.

INDEX TERMS Systematic proportional method, measurement accuracy, passive sensor, excitation source, reference voltage, DC bias compensation.

I. INTRODUCTION

The accurate detection of sensor signal is the basis for the effective operation of modern measurement and control system [1]. With the advancement of modern science and technology and the development of electronic information technology, more and more sensors are applied to industrial manufacturing [2], safety control [3], medical instrument [4], environmental detection [5], aerospace [6] and other fields. According to the need of external energy in the detection process, the sensor can be divided into active sensor and passive sensor. The sensitive component of passive sensor itself has no energy conversion capability, so an external excitation source is needed in use [7].

For the measurement system containing excitation source, one of the main factors affecting the measurement accuracy of the system is the amplitude fluctuation of the excitation signal. The accuracy and stability of the excitation source determine the measurement accuracy of the system to a certain extent [8]. However, the improvement of the amplitude accuracy and stability of the excitation source (especially the AC excitation source) is quite difficult or costly in design and process, which becomes a bottleneck for improving the measurement accuracy of passive sensor measurement system [9]. Taking the displacement measurement system based on Hall sensor as an example, to improve the anti-interference

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and stability of the Hall sensor, the excitation signal usually adopts AC excitation signal. To ensure the measurement accuracy of the system, a high-precision AC excitation source is required [10].

In order to solve the system error caused by the instability of the excitation source in the existing measurement system, many scholars have conducted related research. A main method is to develop high-precision excitation source by using modern electronic technology. It mainly includes the following several kinds: the excitation source composed of PLD, programmable clock chip and high-speed DAC [11], the excitation source realized by programmable signal generator MAX038, the excitation source based on direct digital synthesis (DDS) principle realized by FPGA [12], and the excitation source realized by the existing specialized DDS integrated chip. Among them, the use of FPGA or DDS integrated chip to generate a certain precision excitation signal is widely used. It is not difficult to see that this method can only improve the frequency accuracy of the excitation signal, but not improve its amplitude accuracy and stability, because its amplitude accuracy mainly depends on the accuracy of the integrated DAC, and this method greatly increases the system cost [13]. Another method is to compensate the measurement error caused by the amplitude fluctuation of the excitation signal [14]. A traditional compensation method is to separately collect the measured signal and the excitation signal by using two ADCs, and finally perform digital signal division operation of the two conversion results. However, this method has some limitations. For example, the sampling time and channel conversion time of the ADC should meet the requirement, the ADC itself should achieve relatively high conversion accuracy, the ADC reference voltage should achieve relatively high precision, and the microprocessor used in the system should have sufficiently high operation speed.

In order to effectively improve the measurement accuracy of passive sensor measurement system without increasing the system cost, a systematic proportional method is proposed in this paper. Specifically, the excitation signal is converted to a DC voltage as the reference voltage of the ADC. And then the proportional relationship between the measured signal and the excitation signal is established by using the transmission characteristics of the ADC, therefore the amplitude fluctuation of the excitation signal is compensated in a proportional manner. Compared with the compensation method by using two ADCs as described above, the systematic proportional method saves a high-precision reference source, and also reduces the performance requirement of the ADC, as well as the accuracy and stability requirement of its reference voltage. This method can significantly reduce the measurement error caused by the amplitude fluctuation of the excitation signal and the fluctuation of the ADC reference voltage. In particular, for the sensor measurement system with AC excitation [15], this method is expected to show unique advantages in improving detection accuracy.

II. SYSTEMATIC PROPORTIONAL METHOD

A. GENERAL PASSIVE SENSOR MEASUREMENT SYSTEM

The block diagram of general passive sensor measurement system is shown in Fig.1. The sensor responds to the measured parameter X under the action of the voltage (current) excitation signal S_i provided by the excitation source, and outputs the signal V_1, which is ideally proportional to S_i. After the sensor output signal is linearly processed by the signal processing circuit, such as filtering, amplification, etc., the output signal is V_2. The output signal of the signal processing circuit is sampled and quantized by the ADC into the digital output D.

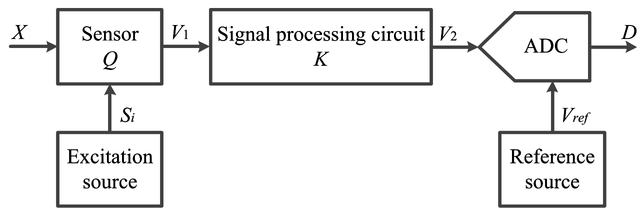

FIGURE 1. **Block diagram of general passive sensor measurement system.**

The following relationship can be drawn from the block diagram shown in Fig.1:

$$V_1 = X \cdot Q \cdot S_i \tag{1}$$

where X is the strength of the measured parameter, Q is the sensitivity coefficient of the sensor, and S_i is the amplitude of the excitation signal.

$$V_2 = K \cdot V_1 = K \cdot X \cdot Q \cdot S_i \tag{2}$$

where K is the gain of the signal processing circuit, and when the circuit structure is fixed, K is a constant.

$$D = \frac{V_2}{V_{ref}} \cdot F_s = K \cdot X \cdot Q \cdot F_s \cdot \frac{S_i}{V_{ref}} \tag{3}$$

where F_s is the full scale of the ADC, and V_{ref} is the reference voltage of the ADC.

Therefore, in the measurement process, when the circuit structure and the device are fixed, Q, K and F_s can be regarded as constants without considering the influence of temperature. At this time, the measurement accuracy of the measured parameter X mainly depends on the accuracy and stability of the excitation source output S_i and the ADC reference voltage V_{ref}.

B. PASSIVE SENSOR MEASUREMENT SYSTEM BASED ON SYSTEMATIC PROPORTIONAL METHOD

In order to reduce the measurement error caused by the fluctuation of the excitation source and the reference voltage, a systematic proportional method is proposed in this paper. Specifically, the excitation signal S_i is used to provide the reference voltage V_{ref} of the ADC after passing through a certain conversion circuit. If the excitation signal S_i is a current excitation signal, it needs to be converted into a voltage signal by the current/voltage conversion circuit. The system block diagram is shown in Fig.2.

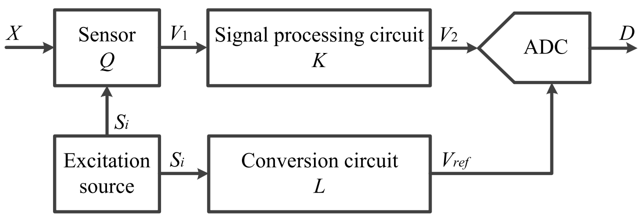

FIGURE 2. Block diagram of proportional measurement system.

When the excitation signal S_i is DC, the conversion circuit is usually a voltage-dividing circuit or a linear amplification circuit; when the excitation signal S_i is AC, the conversion circuit is usually a precision rectifier circuit and a filter circuit or an RMS-DC circuit. L is the conversion coefficient of the conversion circuit, and L can be regarded as a constant when the structure of the conversion circuit is fixed. Then at this time:

$$V_{ref} = L \cdot S_i \tag{4}$$

Substituting (4) into (3) can be obtained:

$$D = \frac{V_2}{V_{ref}} \cdot F_s = K \cdot X \cdot Q \cdot F_s \cdot \frac{1}{L} \tag{5}$$

It can be seen that when the circuit structure and the device are fixed, the digital output of the system is only related to the strength of the measured parameter, and is unrelated to the absolute value of the excitation signal and the reference voltage, thereby avoiding the problem that the amplitude fluctuation of the excitation signal and the fluctuation of the ADC reference voltage affect the measurement accuracy of the system. According to (5), the ratio of the measured signal to the excitation signal is obtained by using the transmission characteristics of the ADC, and then the amplitude fluctuation of the excitation signal is compensated in a proportional manner, which effectively improves the measurement accuracy.

C. ERROR ANALYSIS OF PROPORTIONAL MEASUREMENT SYSTEM

In theory, the systematic proportional method is introduced into general passive sensor measurement system, which can completely suppress the influence of the amplitude fluctuation of the excitation signal on the measurement accuracy. But in practice, there are certain errors in the circuit devices used in the system. Suppose that the signal output errors caused by the device errors of the sensor, the signal processing circuit and the conversion circuit are δ_Q, δ_K and δ_L, respectively. Then, according to the system block diagram shown in Fig.2, the relationship derivation that is more in line with the actual situation is as follows:

The output signal V_1 of the sensor is:

$$V_1 = X \cdot Q \cdot S_i + \delta_Q \tag{6}$$

Then, the output signal V_2 of the signal processing circuit is:

$$V_2 = K \cdot V_1 + \delta_K = K \cdot (X \cdot Q \cdot S_i + \delta_Q) + \delta_K \tag{7}$$

In addition, the output signal V_{ref} of the conversion circuit is:

$$V_{ref} = L \cdot S_i + \delta_L \tag{8}$$

At this time, the digital output D of the system is:

$$D = \frac{V_2}{V_{ref}} \cdot F_s = \frac{K \cdot X \cdot Q \cdot S_i + K \cdot \delta_Q + \delta_K}{L \cdot S_i + \delta_L} \cdot F_s \tag{9}$$

It can be seen from (9) that due to the device errors in the system, the output DC bias voltages of the signal processing circuit and the conversion circuit are $K \cdot \delta_Q + \delta_K$ and δ_L, respectively. Although the DC bias is relatively small in general, it will still affect the full play of the systematic proportional method. Therefore, when using the systematic proportional method, in order to further improve the measurement accuracy of the system, a DC bias voltage compensation circuit is usually introduced to compensate for the DC bias.

III. EXPERIMENTS AND RESULTS

A. EXPERIMENTAL SCHEME

In order to verify the conclusion that introducing the systematic proportional method into general passive sensor measurement system can improve the measurement accuracy and reduce the performance requirement on the excitation source, a Wheatstone bridge measurement circuit is designed [16], which can be regarded as the simplified model of the pressure sensor [17]. In this experiment, the AC voltage is used as the excitation signal. Compared with the system shown in Fig.2, the signal processing circuit and the conversion circuit are both realized by the precision rectifier circuit and the filter circuit. The block diagram of the experiment is shown in Fig.3.

The Wheatstone bridge consists of two 10kΩ and two 20kΩ metal film resistors. It is excited by the sinusoidal voltage with a frequency of 1kHz using an ATF20B type function generator. The voltage excitation signal V_i is converted into the DC voltage through the voltage follower, the precision rectifier circuit I and the filter circuit I, and it is taken as the reference voltage of the ADC. The voltage output signal V_o is converted into the DC voltage through the differential amplifier, the precision rectifier circuit II and the filter circuit II, and it is taken as the input of the ADC. And then the digital quantity converted by A/D is taken as the output of the system. The ADC is a 12-bit ADC provided by the microprocessor STM32F103VET6. The microprocessor communicates with the host computer through the serial port. It uploads the digital result of the ADC conversion to the host computer, and then converts the obtained hexadecimal number into the decimal number in the host computer. The decimal number is divided by the full scale 2^{12} of the ADC to obtain the final measurement result. In theory, the result will

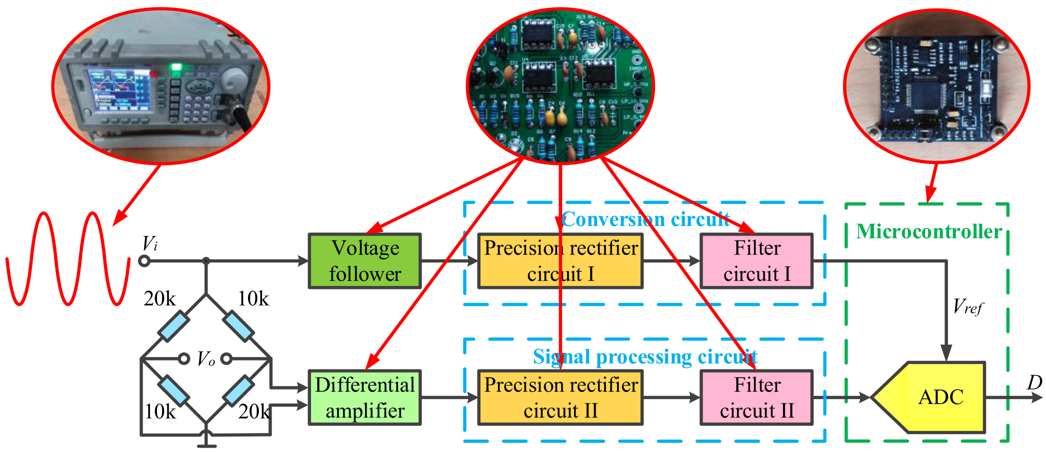

FIGURE 3. Structure block diagram of Wheatstone bridge measurement circuit.

not change with the change of the amplitude of the excitation signal.

The two precision rectifier circuits and filter circuits in this experiment adopt the same circuit structure and device parameter. The design of these two circuits is the key to this experiment, which is related to whether the output of the ADC can keep a good proportional relationship with the measured quantity.

The precision rectifier circuit adopts low-noise, high-speed operational amplifier AD8022 to realize the precision full-wave rectifier circuit, and ensures its good rectifier performance by strict resistance matching [18]. The filter circuit adopts low-noise, low bias current precise operational amplifier AD8622 to realize the second-order low-pass filter circuit of voltage-controlled voltage source, so that the pulsating DC after rectification can be transformed into a stable DC.

The precision full-wave rectifier circuit is shown in Fig.4. This circuit can eliminate the effects of the nonlinearity and the dead zone existing in ordinary diode, primarily because the diodes are in the closed loop of the operational amplifier and the amplifier has a high open-loop gain. The second-order low-pass filter circuit of voltage-controlled voltage source is shown in Fig.5. The filter circuit not only acts as a filter, but also acts as a driver for the ADC. It is implemented with the

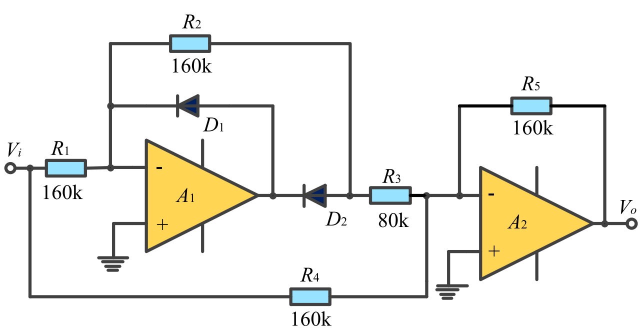

FIGURE 4. Precision full-wave rectifier circuit.

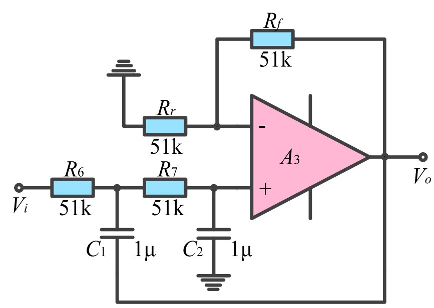

FIGURE 5. Second-order low-pass filter circuit of voltage-controlled voltage source.

precise operational amplifier AD8622. The amplifier has a low DC bias current, so that it only shows a small output DC bias in the case of high input impedance.

B. RESULTS AND ANALYSIS

Based on the circuit structure shown in Fig.3, the output of the conversion circuit is used as the reference voltage of the ADC, and the output of the Wheatstone bridge is measured to observe the influence of the amplitude change of the excitation signal on the measurement result. As the experimental control group, the reference source ADR4533 is used to output 3.3V reference voltage, which is used as the reference voltage of the ADC. The similar measurement process is performed to obtain the control data. The measurement result that the conversion circuit provides the ADC with the reference voltage (proportional method) and the measurement result that the reference source provides the ADC with the reference voltage (non-proportional method) are as shown in Fig.6.

As can be seen from Fig.6, when the excitation voltage changes, the measurement result of the measurement system using proportional method changes extremely slightly. When the amplitude of the excitation signal changes 50%, the measurement result of the measurement system using

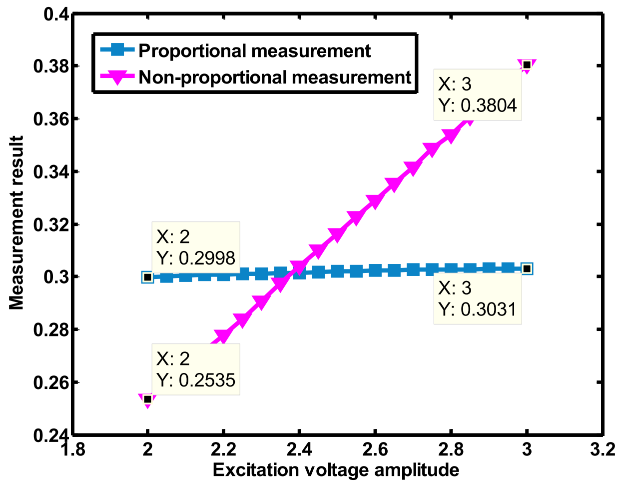

FIGURE 6. Measurement result when the amplitude of the excitation signal changes.

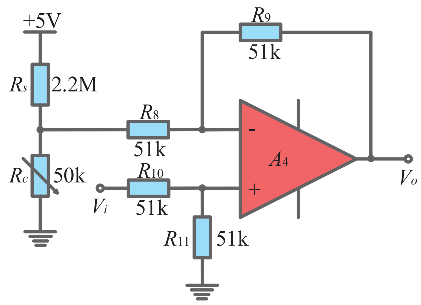

FIGURE 7. DC bias voltage compensation circuit.

non- proportional method changes about 50%, while that of the measurement system using proportional method only changes about 1%. It can be seen that the application of the systematic proportional method can significantly reduce the system error caused by the amplitude fluctuation of the excitation signal.

From the data of Fig.6, it is not difficult to find that although the measurement result using the systematic proportional method change extremely slightly, it still shows a tendency to increase as the excitation voltage increases. Through theoretical analysis and experimental verification, the main factor causing this change is the DC bias voltage in the output of the conversion circuit and the signal processing circuit. The relative magnitude of the DC bias voltage of the two circuits and the gain of the two circuits determine the change polarity and the change rate of the measurement result of the systematic proportional method. By measuring the zero-input response of the system with a six and a half digital multimeter, it is found that the output DC bias voltage of the conversion circuit and the signal processing circuit are 21.6 mV and 16.3 mV, respectively. Therefore, when designing the precision rectifier circuit and the filter circuit, the precise operational amplifier with low input offset voltage should be selected as far as possible.

C. CORRECTION EXPERIMENT

Due to the existence of the DC bias voltage in the output of the conversion circuit and the signal processing circuit, the system measurement result still has 1% error. Therefore, the DC bias voltage compensation circuit is simultaneously added at the back end of the two circuits to further improve the measurement accuracy of the systematic proportional method. The compensation circuit is shown in Fig.7, which is actually a subtraction operation circuit. The experiment adopts the same precise operational amplifier AD8622 as the filter circuit. In the zero-input state, the output DC bias voltage of the conversion circuit and the signal processing circuit is set to 0 by adjusting the potentiometer R_c. Then, the measurement is performed again according to the original input conditions, and the measurement result is shown in Fig.8.

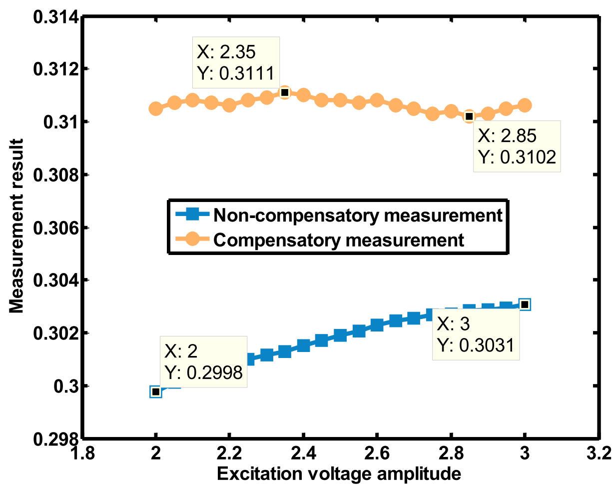

FIGURE 8. Comparison of measurement result before and after DC bias compensation.

It can be seen from Fig.8 that the measurement result after DC bias compensation remains almost unchanged. In the process of the amplitude change of the excitation signal, the maximum variation error of the measurement result is only 0.3% compared with 1% before compensation. The measurement error at this time is mainly caused by the random fluctuation of the circuit noise. Through the introduction of the DC bias voltage compensation circuit, the measurement accuracy of the systematic proportional method is further improved.

IV. DISCUSSION

The Wheatstone bridge measurement circuit is used as the experimental circuit in this paper, only to prove the effectiveness and universality of the systematic proportional method. The application significance of this method is not limited to this. It can not only be applied to the measurement system of resistance sensor [19], but also be extended to the linear measurement system of other passive sensors in principle [20], such as transformer sensor [21], capacitive sensor [22], inductive sensor [23] or non-contact magnetic induction resistance tomography system [24].

For the actual linear measurement system, the input signal of the signal processing circuit often contains the interference of high frequency and power frequency from outside and the DC bias from the front circuit. Therefore, the signal processing circuit connected with ADC should contain high-order band-pass filter circuit to minimize the influence of interference and noise, thereby maintaining the proportional relationship between the ADC input signal and the strength of the measured parameter. Similarly, for the conversion circuit that directly takes signal from the excitation source, when it is very close to the excitation source, the interference in the input signal is mainly the DC bias of the excitation source. The DC bias should be compensated before providing the ADC with the reference voltage, thereby ensuring the proportional relationship between the reference voltage and the amplitude of the excitation signal.

In the sensor measurement system, it is generally desirable that the output characteristic of the sensor is linear, which can make its sensitivity consistent throughout the measurement range, thereby facilitating the analysis and processing of the system. However, the input-output characteristics of the sensor is often nonlinear, which makes the calibration of the sensor more complicated, but does not affect the use of the systematic proportional method. For the nonlinearity problem of the sensor [25]–[28], there are several ways to solve it: approximate substitution method, calculation method, look-up table method, interpolation method, hardware circuit compensation method, etc.

V. CONCLUSION

The systematic proportional method is proposed in this paper. In this method, the DC voltage converted by the excitation signal is taken as the reference voltage of the ADC. The proportional relationship between the measured signal and the excitation signal is established by using the transmission characteristics of the ADC, therefore, the amplitude fluctuation of the excitation signal is compensated in a proportional manner. The method can greatly suppress the measurement error caused by the amplitude fluctuation of the excitation signal and the fluctuation of the ADC reference voltage, thereby effectively improving the measurement accuracy of passive sensor measurement system without increasing the system cost. To verify the effectiveness of the proposed method, the Wheatstone bridge measurement circuit with AC excitation is designed. The precision full-wave rectifier circuit and the second-order low-pass filter circuit of voltage-controlled voltage source are used to convert the AC excitation voltage into a stable DC voltage, which is used as the reference voltage of the ADC. And then the effect of the amplitude change of the excitation signal on the measurement result is observed. The experimental results show that when the amplitude of the excitation signal changes 50%, the measurement result of the systematic proportional method only change about 1%. In order to further improve the measurement accuracy of the systematic proportional method, the DC bias voltage compensation circuit is added in the system, and the maximum measurement error after compensation is only 0.3%. For general linear measurement system including excitation source or reference source, this method can also improve its measurement accuracy without adding any economic burden.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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