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Research Article

Analysis of Hysteresis-Free Creep of the Stack Piezoelectric Actuator

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A modified log-type creep model without hysteresis of the stack piezoelectric actuator is presented. For high-speed micro-/nanopositioning system, the time scale should be less than one second for creep modeling and control in the stack piezoelectric actuator. But creep effect was studied in the frame of minutes in previous works. Meanwhile, parameters of the classical creep models are hard to be determined. By the proposed model, the hysteresis and the creep effect can be separated. A series of experiments have been performed, where different staircase voltages have been applied to the actuator. There are two clear rules to follow in small duration and different heights to determine parameters. Firstly, L_0 starts from fixed point either in ascending stage or in descending stage and rotates clockwise. Secondly, γ converges to a small vicinity of a constant when the duration is small enough.

1. Introduction

The applications of piezoelectric (PZT) actuators are restricted by their nonlinearities, such as hysteresis [1–3] and creep [4, 5]. Hysteresis has bigger influence on PZT actuators than creep has, but creep deteriorates the positioning accuracy apparently over extended period of time [6].

Two methods were applied to compensate for the creep effect. Firstly, the effect can be suppressed by some complex algorithms in the closed loop [7–9]. But this method requires expensive devices in order to achieve fast data acquisition and high-speed computation. Secondly, creep models and their inverse models were cascaded to compensate for the creep. Some phenomenological creep models were used in the open loop, such as log-type [5, 10, 11] and LTI [6]. However, parameters in these models are complex hysteretic [12]. Considering hysteresis as an accurate nonlinearity, some creep operators coupled with hysteresis were proposed in [13, 14]. To compensate for the time-dependent and voltage-dependent creep effect, Kuhnen and Krejci [15] proposed a complex threshold discrete Preisach operator and its inverse operator, in which the creep was closely related to the hysteresis. Its dynamic property was verified in [16]. Moreover, a creep model with the Prandtl-Ishlinskii (PI) operator was presented in [17]. Other models from the view of materials were presented in [18–20].

Comparing to the voltage control, charge control was used to suppress hysteresis and creep effects to a large extend in [21, 22]. Switched capacitor charge pump control was presented in [23] to reduce the creep as an effective way. However self-discharge, small current in low dynamic positioning, and external misaligning effect limit the application of charge control.

The creep is a slow and smooth process [12]. However the requirement of high-speed nanopositioning propels the control duration down to one second. In other words, control duration has been shortened. Hence it becomes meaningful to find properties of creep in small voltage duration. Krejci and Kuhnen [24] gave a figure to describe the creep effect in the small duration of staircase voltage, but more interpretations should be given. A dynamic electromechanical model [25] was presented to model the dynamic creep, but the coupled model was hard to show the special properties of the creep in small duration.

The paper is organized as follows. Section 2 proposes a modified log-type creep model in order to separate the

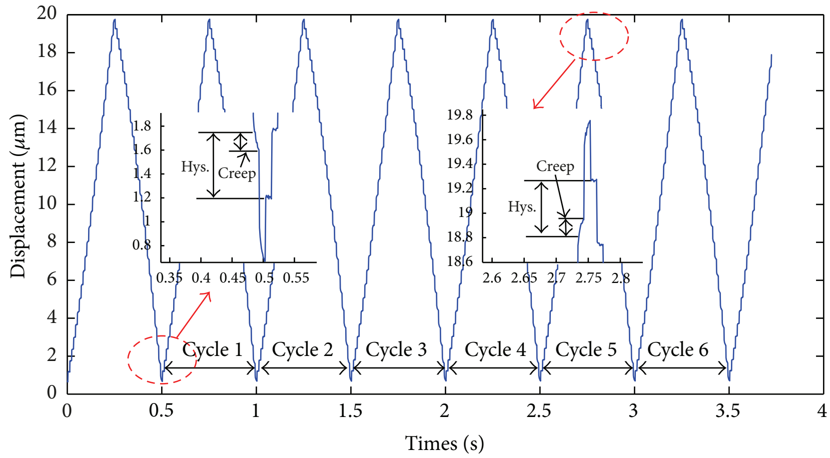
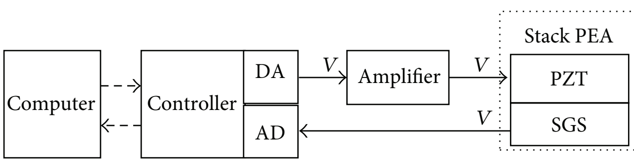
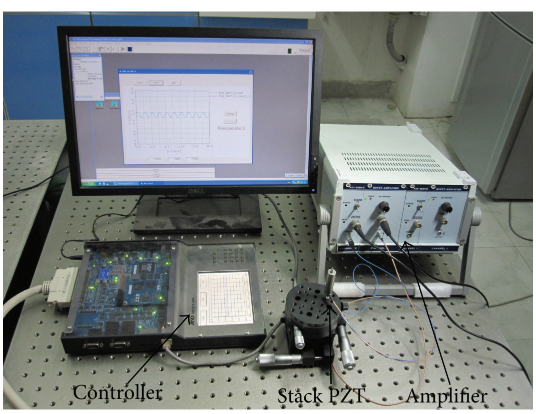


Figure 1: Relation between hysteresis and creep in staircase voltage response.



(a)



(b)

Figure 2: Experimental setup. (a) Structure diagram; (b) experiment devices.

hysteresis and the creep. A series of experiments are designed and performed in Section 3. The section is devoted to observe the influence of the duration and the height of staircase voltages on creep. The identification and the distributing rule of parameters are given in Section 4. Section 5 gives some concluding remarks and discussions.

2. Creep Modeling

Figure 1 illustrates the response of PZT actuators for a series of 3 V staircase input voltages with 0.01 s duration. The embedded figures show the responses of the maximum step voltage (75 V) and the minimum step voltage (0 V). In spite of not having knowledge on the occurring time of hysteresis and transient procedure, creep is defined as a much slower response that happens finally. PZT actuators, with high resonant frequency, are in creep procedure if its response curve under fixed voltage changes smoothly. The descriptive equation of classical log-type creep is given [1].

$$L(t) = L_0 \times \left[1 + \gamma \times \log_{10}\left(\frac{t}{0.1}\right)\right], \tag{1}$$

where $L(t)$ is the displacement of PZT actuators for any fixed input voltage, L_0 is a nominal constant displacement value, and γ is the creep factor that determines the rate of the logarithm. In the experiment, under 0.001 s sampling interval, a dynamic transient was not observed. According to [1], the creep effect continues until the next step voltage is applied. The response of applied staircase voltage after 0.001 s is the one corresponding displacement of hysteresis.

A modified model of creep is given as the following equation:

$$L_{ik}(T_d) = D_{ik}(T_d) - H_{ik} = L_{ik0} \times \left[1 + \gamma_{ik} \times \log_{10}\left(\frac{t}{0.1}\right)\right], \quad i = 1, 2;\ t \in [0, T_d], \tag{2}$$

where i is 1 when voltage is in ascending stage and i is 2 when voltage is in descending stage, $L_{ik}(T_d)$ is creep for ith fixed input voltage in T_d duration, $D_{ik}(T_d)$ is measured displacement for kth fixed input voltage in T_d duration, H_{ik} is the measured displacement of kth step input voltage after 0.001 s, L_{ik0} is the creep initial response of kth stair, and γ_{ik} is the creep factor, then the displacement of hysteresis is equal to $|H_{2k} - H_{1k}|$. The real creep maybe occurs before 0.001 s after the applied voltage; it has an influence on displacement of creep but not on the variation rules of the creep.

3. Experimental Setup

The experiments are performed according to the experiment setup as shown in Figure 2. There is a stack-type

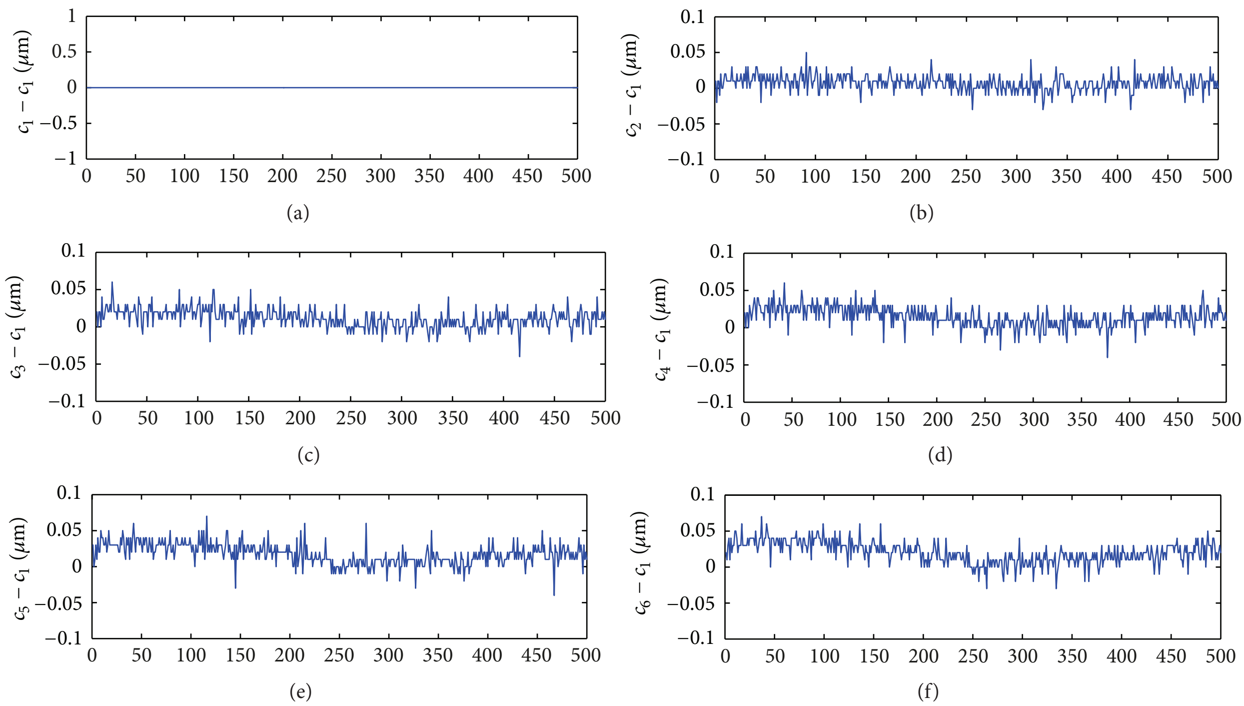


Figure 3: Creep relation with different cycles. (a) cycle 1–cycle 1; (b) cycle 2–cycle 1; (c) cycle3–cycle 1; (d) cycle 4–cycle 1; (e) cycle 5–cycle 1; (f) cycle 6–cycle 1.

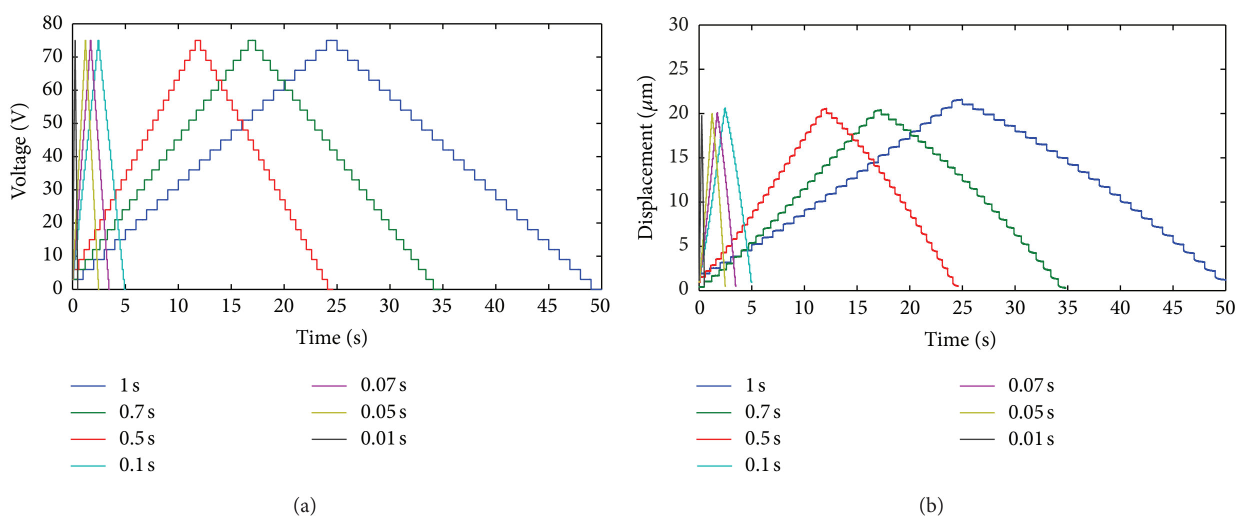


Figure 4: Different input voltage durations T_d, where $T_d \in (1\,\text{s}, 0.7\,\text{s}, 0.5\,\text{s}, 0.1\,\text{s}, 0.07\,\text{s}, 0.05\,\text{s}, 0.01\,\text{s})$. (a) Staircase input voltage; (b) the response.

high resonant frequency PZT actuator (Pst 150/7/40 VS12, Piezomechanik) with 40 μm nominal displacement for 150 V. Controlled signal and data acquisition flow diagram are obtained from the Simulink and then compiled, and downloaded to the controller (AD7011, A & D). Measured displacement voltage from SGS is transformed linearly.

3.1. Periodic Relation. To investigate whether creep curve has some relation with periodic input voltage, a series of staircase voltages are applied to the PZT actuators. The staircase voltages are of the magnitude of 3 V and the duration of 0.01 s, and one complete voltage cycle consists of 3 V-75 V-0 V. In Figure 3, six cycles' displacements are subtracted from the first cycle's displacement.

By using the xcorr function of MATLAB, it is found that cross-correlation of the six cycle curves in Figure 1 are all 1 as lag is 0. This means that any cycle can stand for the whole properties of creep effect. In order to find the rule of small difference of the six cycles in Figure 3, the mean of these differences is shown in Table 1.

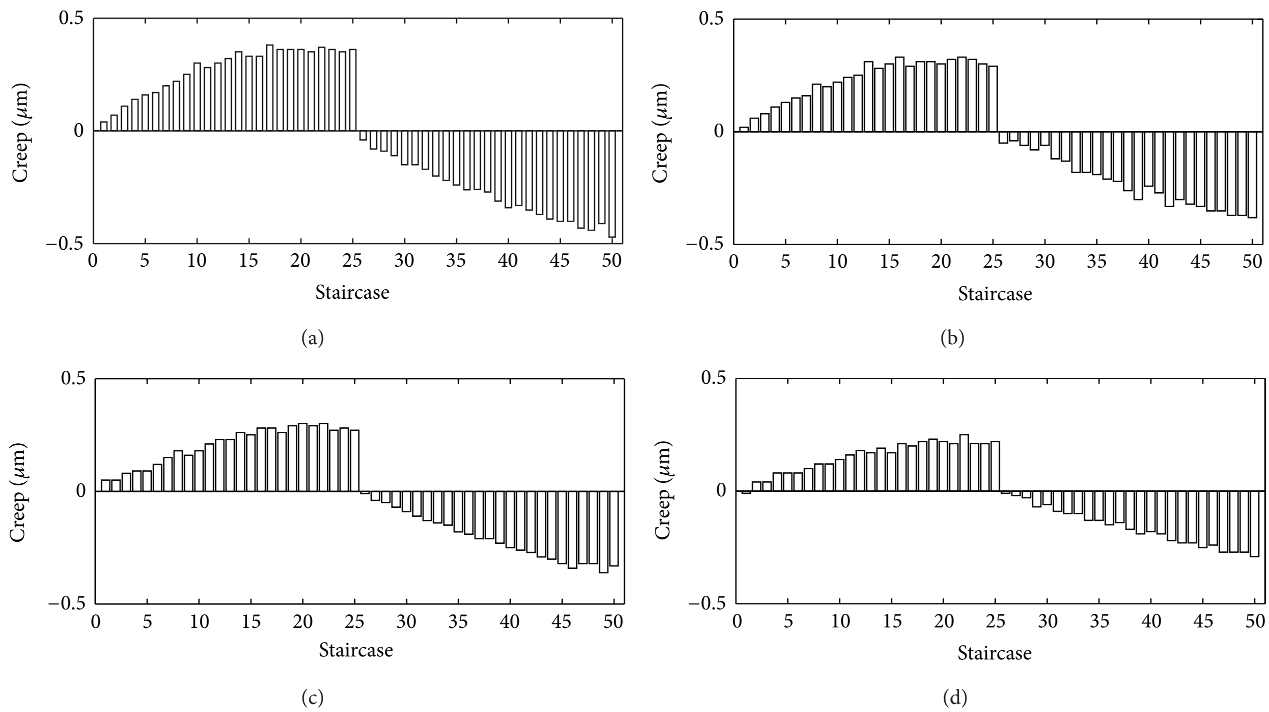


FIGURE 5: Creep increment of 3 V staircase input voltage with different durations. (a) 1 s; (b) 0.1 s; (c) 0.05 s; (d) 0.01 s.

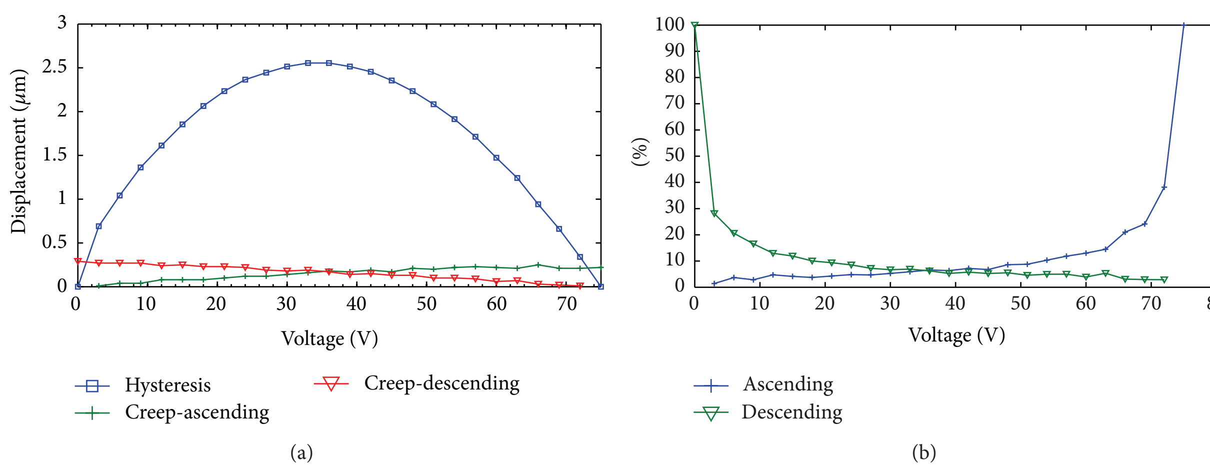


FIGURE 6: The input step voltage has 3 V height and 0.01 s duration. (a) Hysteresis and creep; (b) ratio of creep to hysteresis.

From Table 1, the mean error of creep displacement is less than 0.020 μm, and the absolute maximum error is less than 50 nm. The mean is increasing continuously and slightly; it is not clear whether the creep effect or thermal drift has an influence on it.

3.2. Different Durations. From Figure 4, creep displacement is increasing both in ascending stage and in descending stage. So the extreme displacement occurs in the first stair and the last stair to different stages. The absolute maximum creep displacement only occurs at the top or bottom of a staircase, where the controlled input step voltage changes direction in the next step. When controlled voltage changes direction, the direction of creep also changes. Then the changing direction of input voltage resets the creep effect, and the creep displacement will increase from small creep again. With duration decreasing, the frequency of input voltage becomes higher at the same time.

The changes of the extreme displacement are shown in Table 2, in which the height of staircase voltage is 3 V. Although both the minimum displacement and the maximum displacement are decreasing in Table 2, the amount of reduction does not have an apparent rule. In order to find the rule of creep in one cycle, every stair displacement is preprocessed according to (2), in which all those displacements are subtracted by the displacement of 0.001 s. The variations are shown in Figure 5. One cycle, 3 V-75 V-0 V, is divided into 50 staircases.

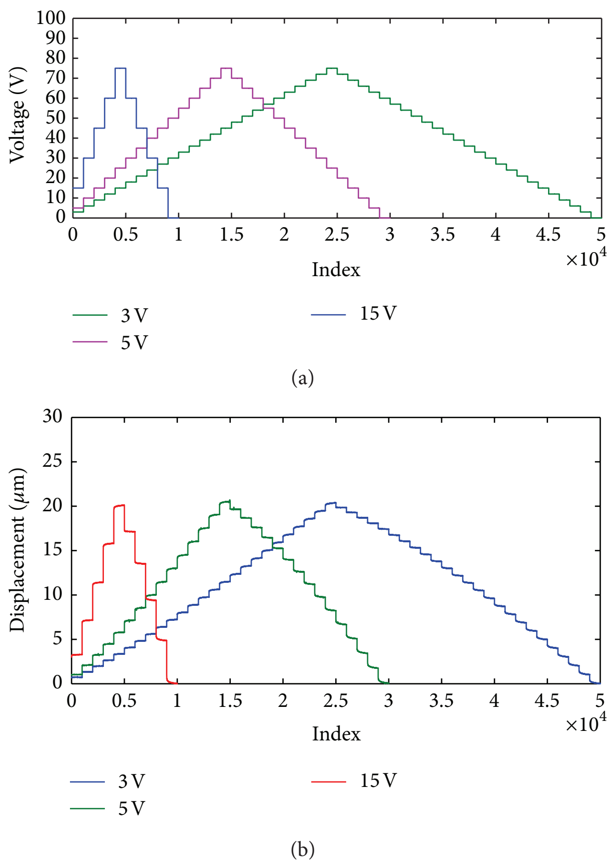


Figure 7: Relationship between input voltage and output displacement. (a) Input voltage; (b) displacement response.

Table 1: Mean of difference.

No.	Figure 3	Mean (μm)
1	(a)	0
2	(b)	0.007
3	(c)	0.011
4	(d)	0.015
5	(e)	0.018
6	(f)	0.020

Table 2: Extreme displacement with different durations.

No.	Duration (s)	Minimum displacement (μm)	Maximum displacement (μm)
1	1	1.191	21.892
2	0.7	0.259	20.419
3	0.5	0.490	20.580
4	0.1	0.911	20.650
5	0.07	0.490	20.088
6	0.05	0.450	19.998
7	0.01	0.640	19.767

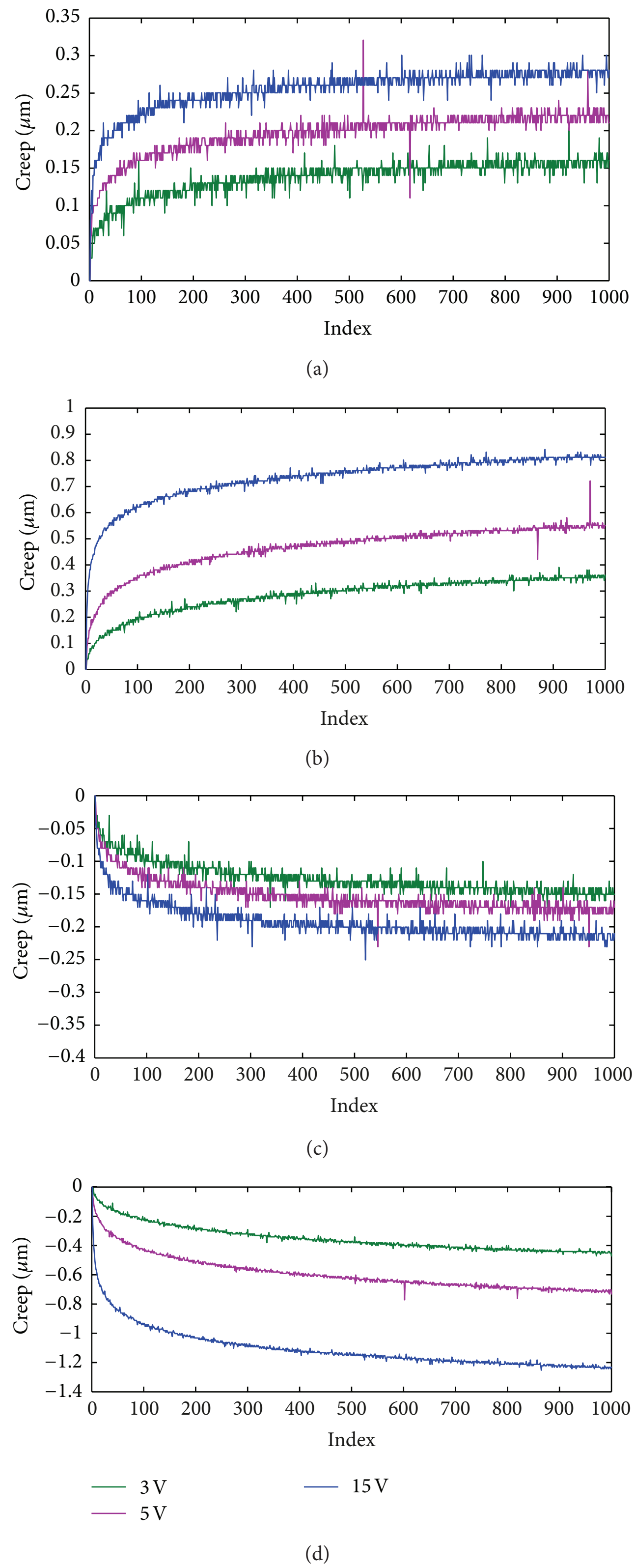


Figure 8: Response of different staircase voltages with different heights influence on the creep: (a) 15 V in ascending stage; (b) 75 V in ascending stage; (c) 60 V in descending stage; (d) 0 V in descending stage.

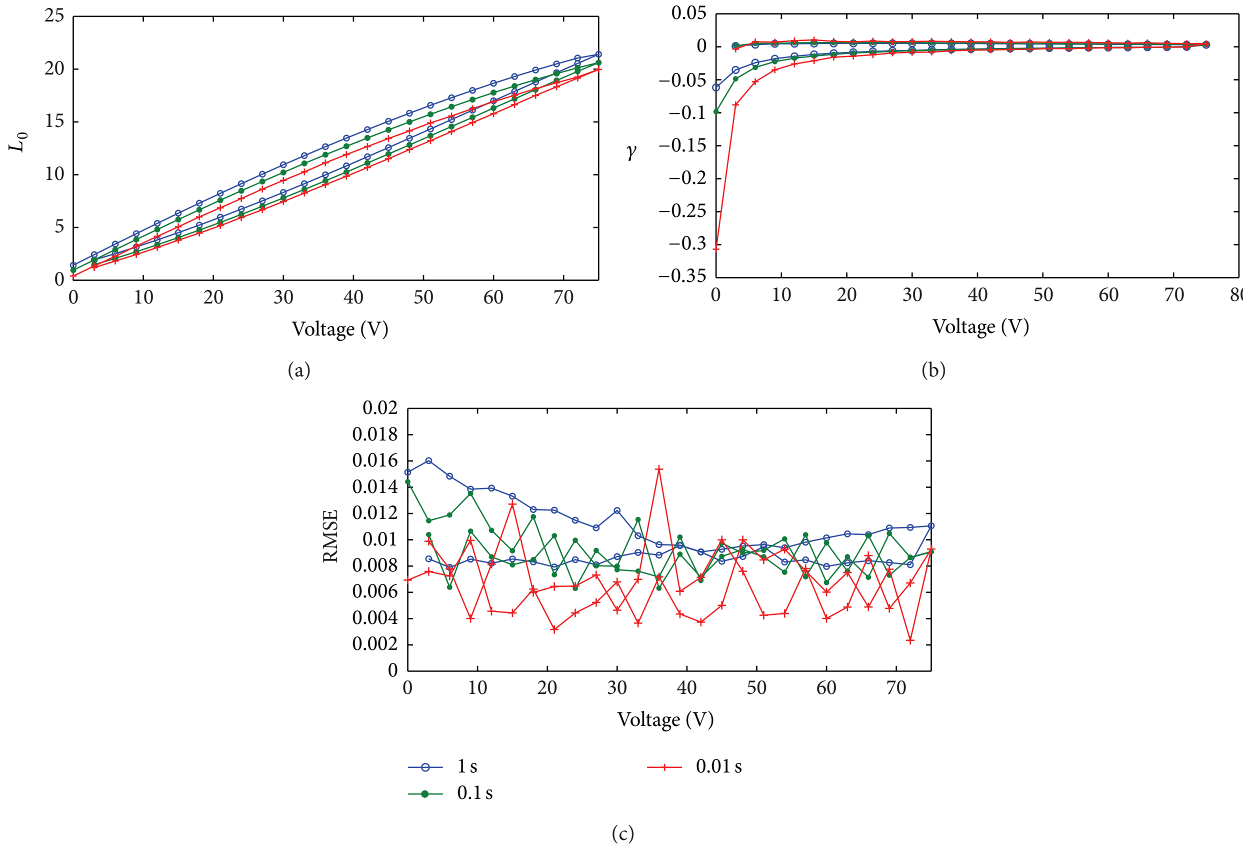


Figure 9: Parameters distribution of classical log-type creep with 3 V height and different durations T_d, $T_d \in (1\,\text{s}, 0.1\,\text{s}, 0.01\,\text{s})$; (a) L_0; (b) γ; (c) RMSE.

It is seen from Figure 5 that the creep increment changes with different rates. It is apparent that the smaller duration results in the smaller increment. The creep increment is decreasing, but it obviously exits. The rule of creep increment in ascending stage is different from that in descending stage. The absolute maximum increment of creep is 0.471 μm, 0.381 μm, 0.331 μm, and 0.291 μm with the duration of 1 s, 0.1 s, 0.05 s, and 0.01 s, respectively. The absolute maximum increment of creep all occurs in descending stage. The sum of absolute increment in ascending stage is smaller than that in descending stage when the duration is 1 s, 0.05 s, and 0.01 s; however, it is not right when the duration is 0.1 s. Since the sum of absolute increment in ascending stage is smaller than that in descending stage when the duration is 0.01 s, it seems that the mean of one cycle becomes negative after some cycles. It is in contradiction with the result in Figure 3. In fact, the difference between the sum of absolute increment in ascending stage and that in descending stage is smaller than periodic increment.

From (2), hysteresis is zero when input voltage reaches the maximum value and the minimum value, as illustrated in Figure 6(a). The maximum creep displacement is at two endpoints, and at the same time the hysteresis displacement is zero. The hysteresis curve is not symmetric and has faster increasing ratio when input voltage is smaller than 36 V. The ratio of creep and hysteresis is shown in Figure 6(b). The proportion of creep increases drastically when input voltage is close to the two endpoints.

3.3. Different Heights. In order to investigate the influence on creep with height of input voltage, three staircase voltages with different heights are applied to the PZT actuators. The staircase number is smaller when the height is bigger. To minimize the periodic influence, the second cycle is chosen. Meanwhile all chosen cycle displacements are added to or subtracted from the last sampling displacement of 0 V in order to keep the same initial displacement. There is no influence on creep by this linear translation. The relation between input voltage and displacement is as shown in Figure 7.

The same voltages, (15 V, 30 V, 45 V, 60 V, 75 V) in ascending stage and (60 V, 45 V, 30 V, 15 V, 0 V) in descending stage, and the corresponding displacement are used to investigate the influence on creep with different heights of input staircase voltages. According to (2), Figure 8 only has creep displacement.

From Figure 8, the height of input voltage has deep influence on the creep. With the height increasing, creep becomes lager. When input voltage is 15 V, the maximum creep displacement reaches 0.200 μm, 0.220 μm, and 0.301 μm as the height of staircase voltage is 3 V, 5 V, and 15 V, respectively. The difference of the step response between 3 V and 5 V, and that

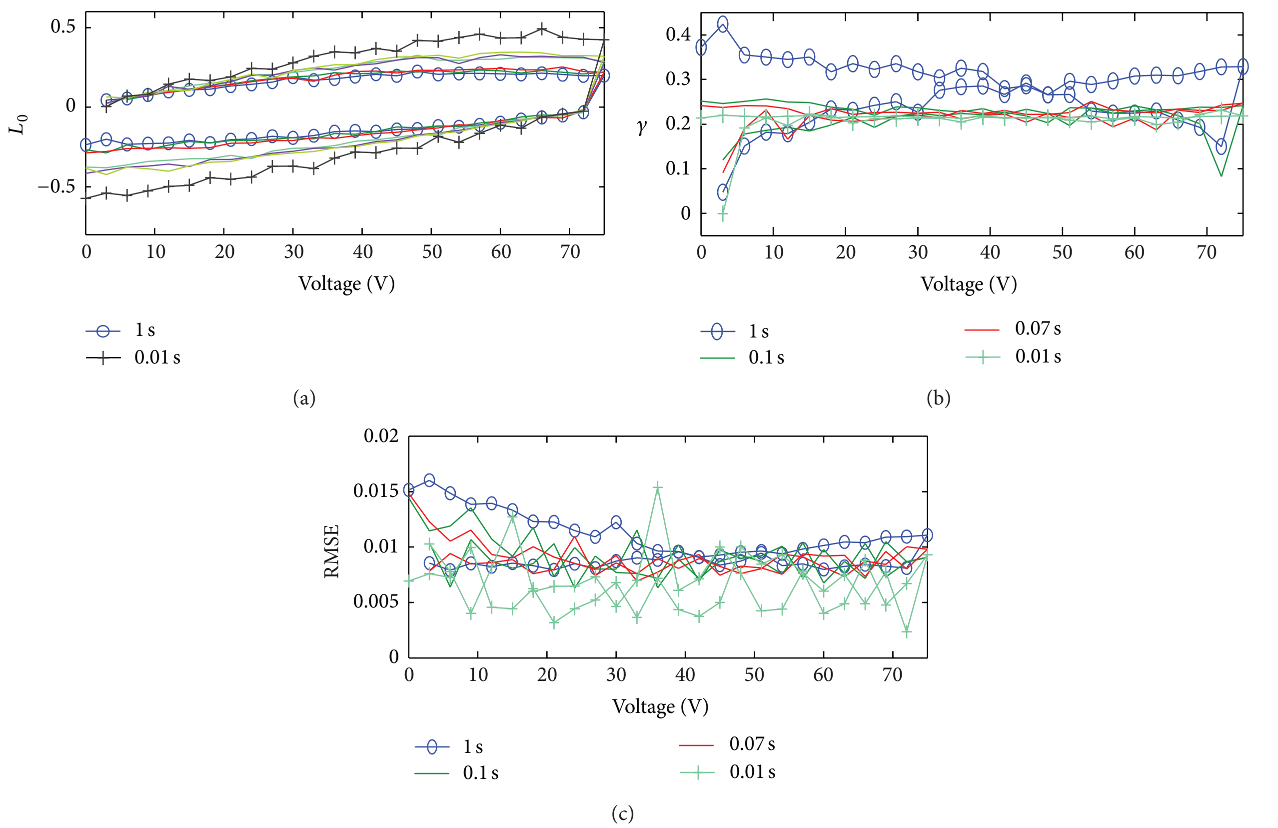


FIGURE 10: Parameters distribution of the proposed log-type creep as the height is 3 V and different durations T_d, $T_d \in$ (1 s, 0.7 s, 0.5 s, 0.1 s, 0.07 s, 0.05 s, 0.01 s); (a) L_0; (b) γ; (c) RMSE.

between 5 V and 15 V seems likely equal. However, this difference changes when input voltage is 75 V. Creep displacements vary from 0 μm to 0.361 μm, from 0 μm to 0.551 μm, and from 0 μm to 0.842 μm as the heights of staircase voltage are 3 V, 5 V, and 15 V, respectively. Due to the change of direction or reset function, creep varies insignificantly when input voltage is 60 V. The minimum creep displacement is −0.150 μm, −0.180 μm, and −0.220 μm as the heights of staircase voltage are 3 V, 5 V, and 15 V, respectively. As the same thing in the ascending stage, absolute creep displacement becomes larger when input voltage decreases in descending stage. When input voltage is 0 V, creep displacements vary from 0 μm to −0.451 μm, from 0 μm to −0.731 μm, and from 0 μm to −1.232 μm as the heights are 3 V, 5 V, and 15 V, respectively.

4. Parameters Identification

To compare (1) with (2), both equations are used in parameters identification.

4.1. Different Duration. The corresponding displacement data are chosen from one staircase input voltage cycle, 3 V-75 V-0 V. The staircase voltages are set 3 V height with different durations. In (1), L_0 is a real displacement and kept positive and γ is either positive or negative in the procedure of identification. The result is shown in Figure 9.

It is observed that different durations are the same as different input voltage frequencies, and then different durations make the hysteresis curve rotate clockwise as shown in Figure 9(a). The absolute maximum values of γ increase fast with the step duration decrease as in Figure 9(b) and γ is −0.3069 when duration is 0.01 s.

It is found that the relation between L_0 and staircase voltage is conic in ascending stage and the radius of conic becomes larger with the decreasing duration of staircase voltage; however, the relation between L_0 and staircase voltage is more linear than conic in descending stage. The mean squared error is $4.406e-4$ by fitting a line with the least square criterion in descending stage.

γ is a butterfly-shape complex hysteretic parameter in Figure 10(b), when the duration is 1 s; however, its range decreases rapidly. The mean of γ also decreases when duration decreases. γ has a very clear rule that it converges to around 0.21 when the duration is 0.01 s.

The maximum RMSE is 0.016 in Figure 10(c) when staircase duration is 1 s, and it is 0.015 when staircase duration is 0.01 s. As the staircase duration is descending, the RMSE ranges from 0.016 to 0.002. This means that modeling precision varies a little in different durations. Comparing RMSE in Figure 9(c) with that in Figure 10(c), there are only little different RMSE points. This means both models have the same modeling precision.

4.2. Different Height. Just as that in Section 4.1, the same procedure is done in this subsection. In (1), L_0 is a real

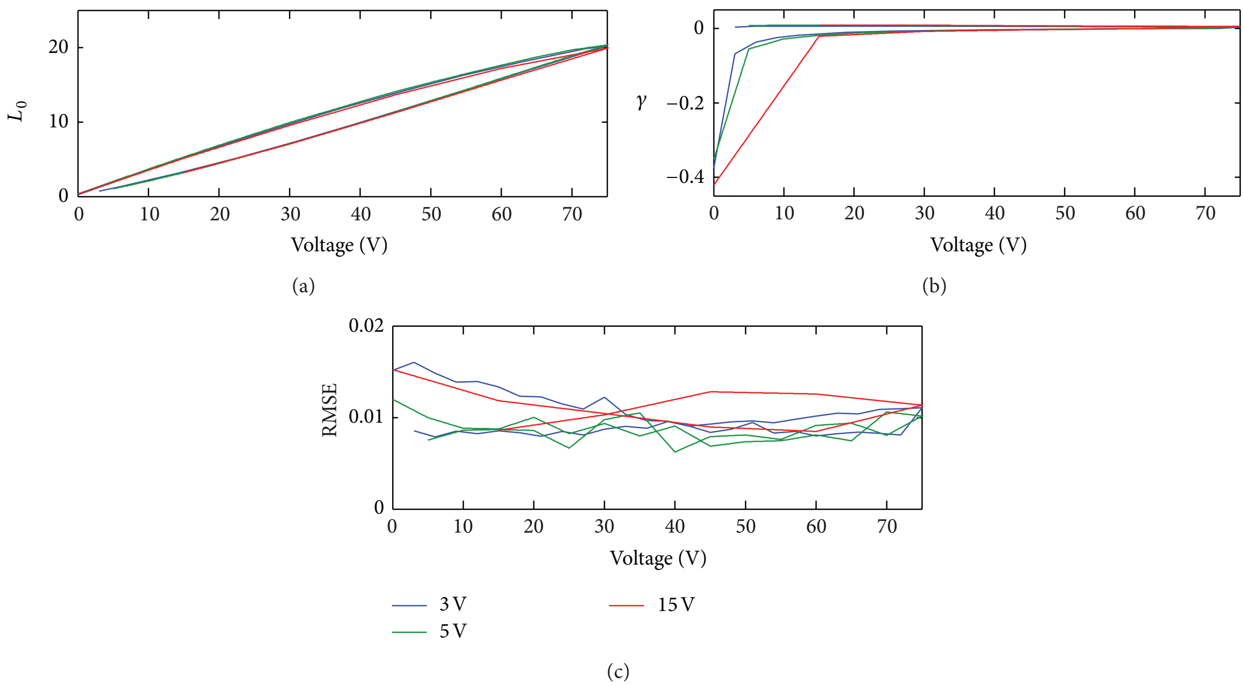


Figure 11: Parameters distribution of classical log-type creep with 1 s duration and different heights H_d, $H_d \in (3\,\mathrm{V}, 5\,\mathrm{V}, 15\,\mathrm{V})$; (a) L_0; (b) γ; (c) RMSE.

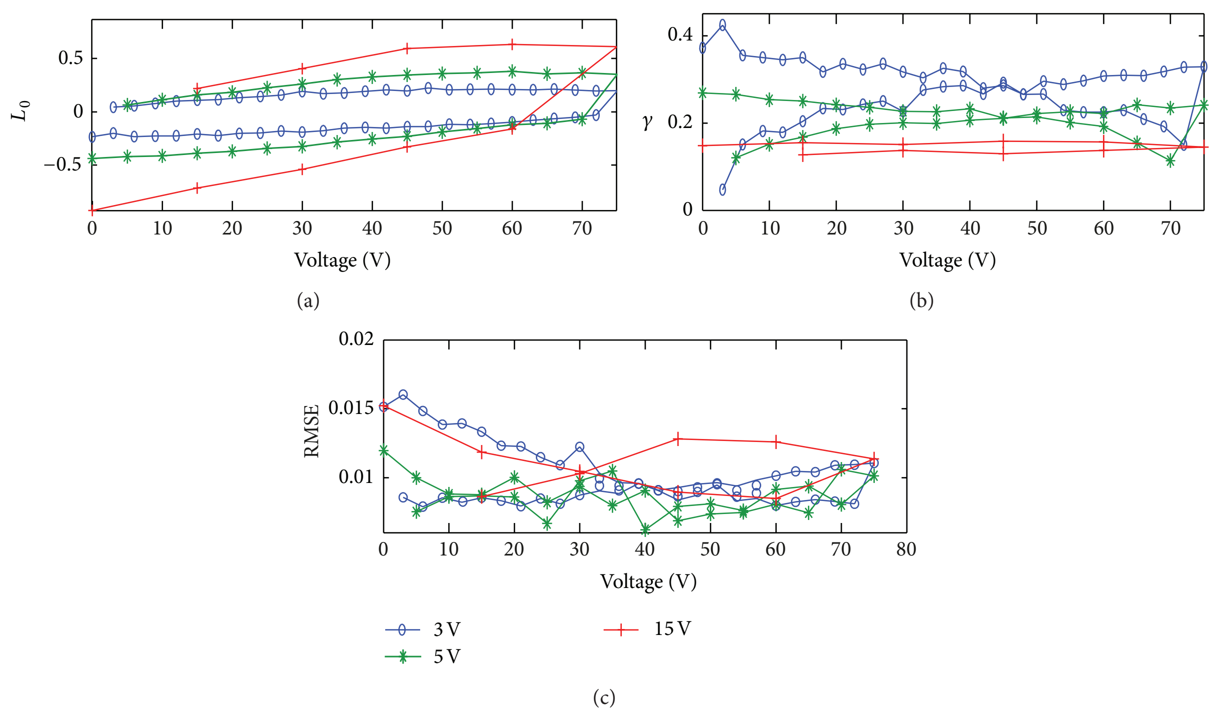


Figure 12: Parameters distribution of creep with different heights of staircase voltage. (a) L_0; (b) γ; (c) RMSE.

displacement and kept positive, and γ is either positive or negative in the procedure of identification. The results are shown in Figure 11. Comparing with different durations, there are small impacts on L_0 under different heights of staircase voltages as illustrated in Figure 11(a). However, γ in Figure 11(b) is sensitive to different heights, especially when the input voltage is low in descending stage. Model validity can be verified by Figure 11(c).

L_0 is a series of anticlockwise curves with height increasing as in Figure 12(a). As the height is larger, the increment of L_0 is larger. Then when input voltage is 0 V or 75 V, the absolute L_0 in the response curve of 15 V is bigger than that in the response curve of 3 V. Just as the curves in Figure 10(a), those anticlockwise curves can be replaced by conics in the ascending stage and by straight lines in descending stage. Apparently, these lines do not have fixed start point. From Figure 12(b), γ seems like being congruent to a constant with the height increasing. This can be interpreted as follows: when the height is 75 V, there is only a log-type creep curve. As that in Figure 10(c), model validity is illustrated in Figure 12(c).

5. Conclusion

Based on the experimental data of the stack-type piezoelectric actuator, a modified log-type model is used to describe the creep effect within voltage duration of less than a second. In the model, the hysteresis and the creep effect can be separated and tackled, respectively. Because input signal is discretized into staircase DC voltage in digital control, it is necessary to study the effects of different durations and heights of staircase voltages on creep. A number of experiments have been designed and performed to observe the variation of creep. Firstly, with different durations and different heights of staircase voltage, either decreasing duration or increasing height makes γ converge to a constant. Secondly, the relation of L_0 with input staircase voltage is conic in ascending stage, and it is linear in descending stage when duration is small enough. Furthermore, L_0 has its own constant endpoint in ascending stage and in descending stage.

Acknowledgments

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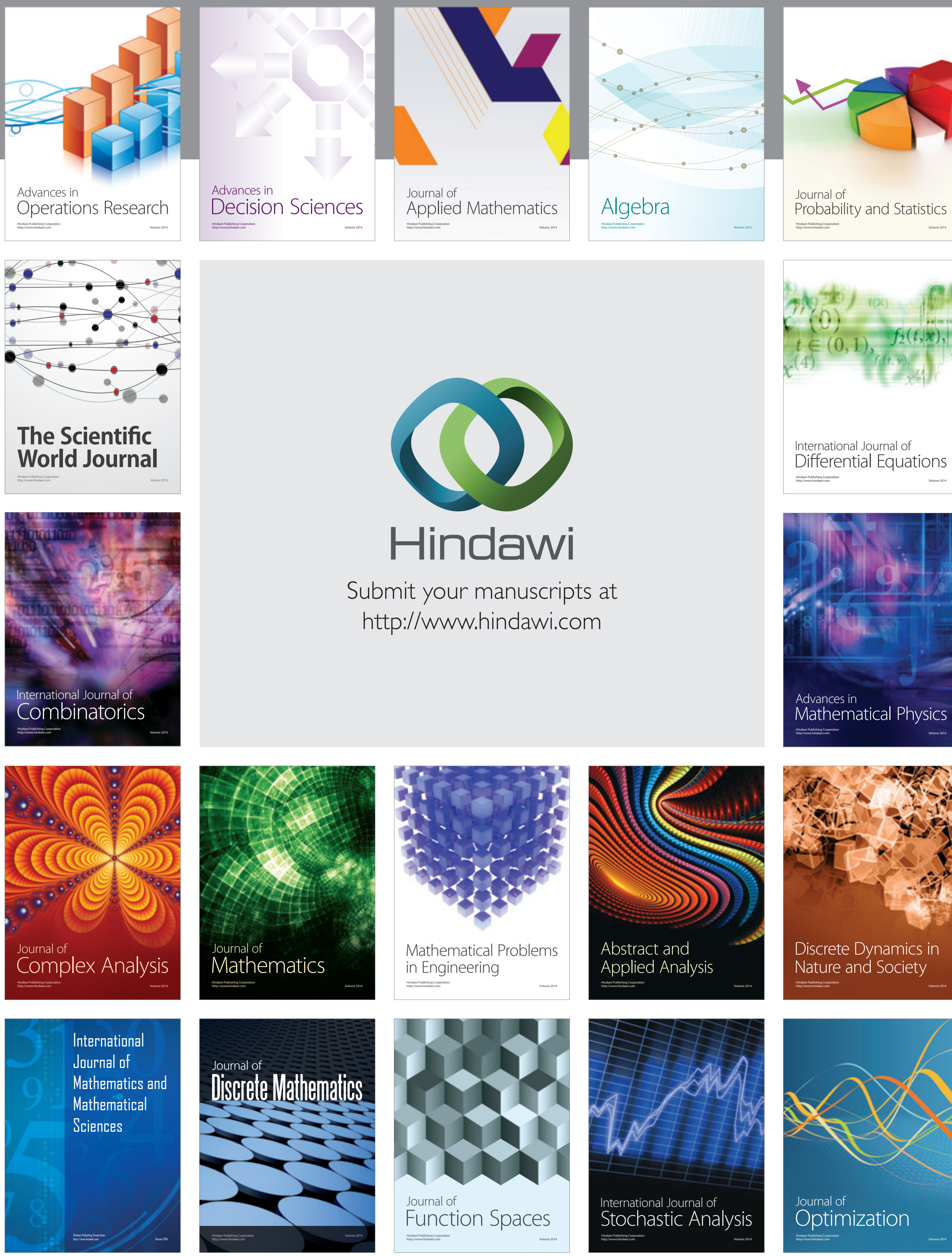
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