GENERAL EXPERIMENTAL TECHNIQUE

CORRECTION OF WAVEFRONT TILT ON THE STAND OF THE ADAPTIVE OPTICAL SYSTEM

© 2025 V. V. Lavrinov*, L. V. Antoshkin, L. N. Lavrinova, A. A. Selin

V.E. Zuev Institute of Atmospheric Optics

Siberian Branch of the Russian Academy of Sciences Tomsk

**e-mail:lvv@iao.ru*

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Abstract. The principles of operation and practical design of the elements of the created experimental stand of the tracking adaptive optical system for the formation and correction of turbulent distortions of laser radiation are described. The stand allows for the implementation ofemulationuatmospheric turbulencewith the ability to replay it to adjust the adaptive system, correct for distortions caused by atmospheric turbulence, and also correct for overall wavefront tilts.The results are giventest results of the developedTip–Tilt-mirrorsas part of an adaptive optical tracking system.

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1. INTRODUCTION

The most common and effective method of improving the quality of the received image under the influence of a turbulent atmosphere is the stabilization of the position of the radiation in the plane of the receiving device of the adaptive system. Stabilization of angular displacements of the image is carried out by compensating for the tilt of the wave front of the received radiation by a high-speed controlled Tip-Tilt mirror [1–3]. Deformable mirrors are used to correct distortions associated with the presence of high-order aberrations [4].

A Tip-Tilt mirror designed for controlling beam tilt angles and stabilizing its image at the input aperture of an optical system has been developed at the IOA SB RAS. The tracking device with a closed-loop control system for general wavefront tilts consists of a high-speed video camera and an angle-controlled Tip-Tilt mirror. The Tip-Tilt mirror includes an electronic control unit that works with digital and analog input signals, and an actuating device created based on piezoceramic actuators and a flat mirror. The original design solutions of the actuating device ensure the preservation of mirror flatness throughout the entire range of correction angles, while the electronic damping system suppresses mirror vibrations during pulsed control signals. Adaptive optics systems with a Tip-Tilt mirror are used in astronomical telescopes, ground-based vision systems in turbulent atmospheres, and laser optoelectronic systems operating on atmospheric paths.

Since the development of an adaptive optical system is a labor-intensive and expensive process, the team of authors developed a test bench for an adaptive optical system to study the correction of turbulent distortions of laser radiation, allowing preliminary testing of techniques, methods, and control algorithms for adaptive optical systems.

2. DESCRIPTION OF THE TRACKING ADAPTIVE OPTICAL SYSTEM TEST BENCH

The main elements of the correcting loop of any adaptive optical system in most cases are a controllable deformable mirror, which allows correcting the shape of the wavefront, and a wavefront sensor as an element that registers wavefront distortions caused by the turbulent atmosphere. The electronic control system closes the feedback between the wavefront sensor and the controlled optical element.

On our test bench (Fig. 1), correction is implemented using two independent loops. The first loop emulates atmospheric turbulence [5, 6], and consists of a Tip-Tilt mirror *3* , which forms wavefront tilts, and a Tip-Tilt mirror *4* , which corrects these tilts. Tip-Tilt mirror *4* is used to correct wavefront tilts at a frequency of 1 kHz. The second loop, built on the basis of a Shack-Hartmann wavefront sensor and a bimorph deformable mirror, is used to correct wavefront aberrations, starting from second-order aberrations and operating at frequencies up to 300 Hz.

Fig. 1. Scheme of the tracking adaptive optical system test bench for studying correction of turbulent distortions in laser radiation:

Software - hardware complex of the test bench (Fig. 2) allows modeling overall wavefront tilts with specified parameters, with the ability to reproduce and repeat any time fragment of the simulated atmospheric turbulence sample. The set of control signals for the Tip-Tilt mirror and deformable mirror can be formed both using a numerical model of the Shack-Hartmann wavefront sensor [7] and previously recorded wavefront distortions. There is a possibility of using the test bench in real time on an atmospheric path under real atmospheric conditions.

Fig. 2. External view of the adaptive optical system test bench.

The test bench enables measurements in several modes: by image using the correlation algorithm of the Shack-Hartmann wavefront sensor [8]; by energy centers of gravity of the Hartmannogram [9] and by the energy center of gravity of the entire beam [10].

3 DESIGN PRINCIPLES AND TEST RESULTS OF THE TIP-TILT MIRROR

The specifics of modern adaptive optical systems with phase measurements of the wavefront [11] require from the Tip-Tilt mirror increased accuracy in transmitting the reflected wavefront incident on the mirror; maintaining the flatness of the mirror surface throughout the entire range of working angles; increasing the operating frequency of mirror rotation; and enhanced accuracy and stability. The DP series models implement design solutions that meet the requirements specified above. The device is protected by two patents of the Russian Federation [12, 13].

The Tip-Tilt mirror contains an electronic control unit that works with digital and analog input signals, which expands its application possibilities. The actuator based on a flat mirror mounted on piezoceramic actuators is shown in Fig. 3.

Fig. 3. Design of the optical head of the DP-04 deflector:

The optical head includes a flat mirror *1* , which is glued to supports *2* , fixed on a movable platform *3* . The platform moves on steel balls *5,* placed in sockets *4* of flanges *6,* fitted on piezoelectric actuators *7* . The entire optical head is fixed by tensioning a string *10* , secured at the central point *11* of the movable platform *3. The* rotation of the platform occurs relative to the base *9* with a cage *8*.

Control signals, after being formed by a digital-to-analog converter (DAC) in analog form, have a stepped shape with a wide frequency spectrum. With each step change in the control voltage at the outputs of the amplifiers, linear deformation of the piezoceramic actuators occurs, which causes rotations of the mirror *1* mounted on them. The mirror *1* rotates around the central point *11* with oscillations at the frequency of its mechanical resonance.

The settling time and amplitude of mirror oscillations *1* (Fig. 3) depend on the mechanical characteristics of the Tip-Tilt mirror. The two-channel electronic damping unit (damper) is designed to prevent oscillations of mirror *1* (Fig. 3) when step changes occur in the control signals from the DAC.

Fig. 4 shows the diagram of the piezoelectric drive control unit.

Fig. 4. Diagram of the piezoelectric drive control unit with electronic damper.

The operation of the electronic damper unit with a step control signal is shown in the timing diagram (Fig. 5a). Fig. 5b shows the measurement results of the Tip-Tilt mirror rotation angles in the optical path at minimum control signals.

Fig. 5. a - Oscillogram of flat mirror *1* (Fig. 3) oscillations when applying a step control signal: curve 1 - without damping, 2 - damper on; **b** - oscillogram of the minimum tilt angle of 0.05" of the optical beam (curve 1), incoming control signal (curve 2).

The design solutions of the control unit and the actuator (Fig. 6) allow maintaining the flatness of mirror *1* (Fig. 3) throughout the entire range of corrected wavefront tilt angles, which is necessary for phase measurements.

Fig. 6. External view of the two-coordinate optical deflector DP-04.

Technical characteristics of the Tip-Tilt mirror DP-04: corrector mirror diameter 76 mm, mirror rotation angle ±115", angular resolution 0.05", maximum control frequency 1000 Hz, mirror settling time not more than 1 ms, mirror resonant frequency 1500 Hz, hysteresis value not more than 4%.

The application areas of DP series Tip-Tilt mirrors are as follows**:** adaptive optical systems in astronomy, vision systems in turbulent atmosphere, laser beam control in optical systems.

To expand the scope of application and increase the precision of adjustment in optical schemes, the Tip-Tilt mirror has a built-in two-coordinate mechanical high-precision angular adjustment unit using microscrews.

The Tip-Tilt mirror DP-04 is maximally adapted for operation on experimental research stands for the purpose of creating and testing algorithms and software, for example, for testing algorithms that emulate atmospheric turbulence.

4. EFFICIENCY OF CORRECTION OF GENERAL WAVEFRONT TILTS WITH A TIP-TILT MIRROR

To assess the efficiency of optical radiation stabilization by the Tip-Tilt mirror, it is sufficient to evaluate the residual errors resulting from the correction of tilts, obtained based on the simulation of optical radiation jitter in the focal plane of the system.

For the model of optical beam jitter at the input aperture of the system, general wavefront tilts were used, calculated based on a numerical turbulence model [10], illustrated by general tilts of a random phase screen in the form of Phase profiles, corresponding to data from a row in a two-dimensional array of phase distribution numbers (Fig. 7a).

Fig. 7. a - Wavefront profile: curve 1 corresponds to phase distribution without general tilt, 2 - with a tilt of 0.32", 3 - with a tilt of 0.64"; **b** - root-mean-square error between the values of the general wavefront tilt modeled by the Tip-Tilt mirror *3* , and the values of the correcting Tip-Tilt mirror *4* .

The calculation of the response signal by the Tip-Tilt mirror *4* (Fig. 1) was performed at various values of the transverse component of wind velocity V_x, which was set by varying the time between analyzed frames.

From Fig. 7b it follows that the root-mean-square error does not exceed 2%, in other words, the values of the modeled wavefront tilts of a random phase screen moving under the action of wind transfer in the plane of the system's input aperture [10], practically coincide with the tilt angle values representing the control signals for the correcting Tip-Tilt mirror *4* (Fig. 1).

5. CONCLUSION

A modern adaptive optical system today represents a two-mirror adaptive optics system [2, 3], which includes a stabilizing optical radiation tilt correction loop [14, 15].

To evaluate the effectiveness of stabilizing optical radiation with a wavefront tilt corrector, it is sufficient to assess the residual errors resulting from the correction of tilts obtained based on the emulation of atmospheric turbulence that simulates the trembling of the optical radiation image in the focal plane of the system. The emulation of atmospheric turbulence represents a repeatedly reproducing inhomogeneities of the light field tool for testing optical elements. Light field inhomogeneities can be modeled based on a numerical turbulence model, as well as represent previously measured values on an atmospheric path [16].

The novelty of the conducted scientific research is confirmed by the obtained Patents of the Russian Federation for the technical implementation of the Tip-Tilt mirror and the atmospheric turbulence emulation unit in the tracking adaptive optical system circuit [14-16].

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FIGURE CAPTIONS

Fig. 1. Scheme of the tracking adaptive optical system test bench for studying the correction of turbulent distortions of laser radiation: *1* – point source or test image, *2* – system of rotating mirrors, *3* – Tip-Tilt modeling mirror, *4* – correcting Tip-Tilt mirror, *5* – wavefront tilt sensor, *6* – deformable mirror, *7* – video camera, *8* – wavefront sensor.

Fig. 2. External view of the adaptive optical system test bench.

Fig. 3. Design of the optical head of the DP-04 deflector: *1* – mirror, *2* – support, *3* – movable platform, *4* – sockets on the movable support, *5* – steel balls placed in sockets, *6* – flanges interacting with the balls, *7* – piezo actuators, *8* – frame for mirror mounting, *9* – frame base, *10* – string securing the mirror to the frame, *11* – attachment point of the string on the mirror, relative to which the platform rotates.

Fig. 4. Control circuit of piezoelectric drive with electronic damper.

Fig. 5. **a** – Oscillogram of flat mirror *1* oscillations (Fig. 3) when a step control signal is applied: curve 1 – without damping, 2 – with damper enabled; **b** – oscillogram of the minimum tilt angle of 0.05" of the optical beam (curve 1), incoming control signal (curve 2).

Fig. 6. External view of the two-coordinate optical deflector DP-04.

Fig. 7. **a** – Wavefront profile: curve 1 corresponds to the phase distribution without general tilt, 2 – with a tilt of 0.32", 3 – with a tilt of 0.64"; **b** – root-mean-square error between the values of the general wavefront tilt modeled by the Tip–Tilt mirror *3* , and the values of the correcting Tip–Tilt mirror *4* .

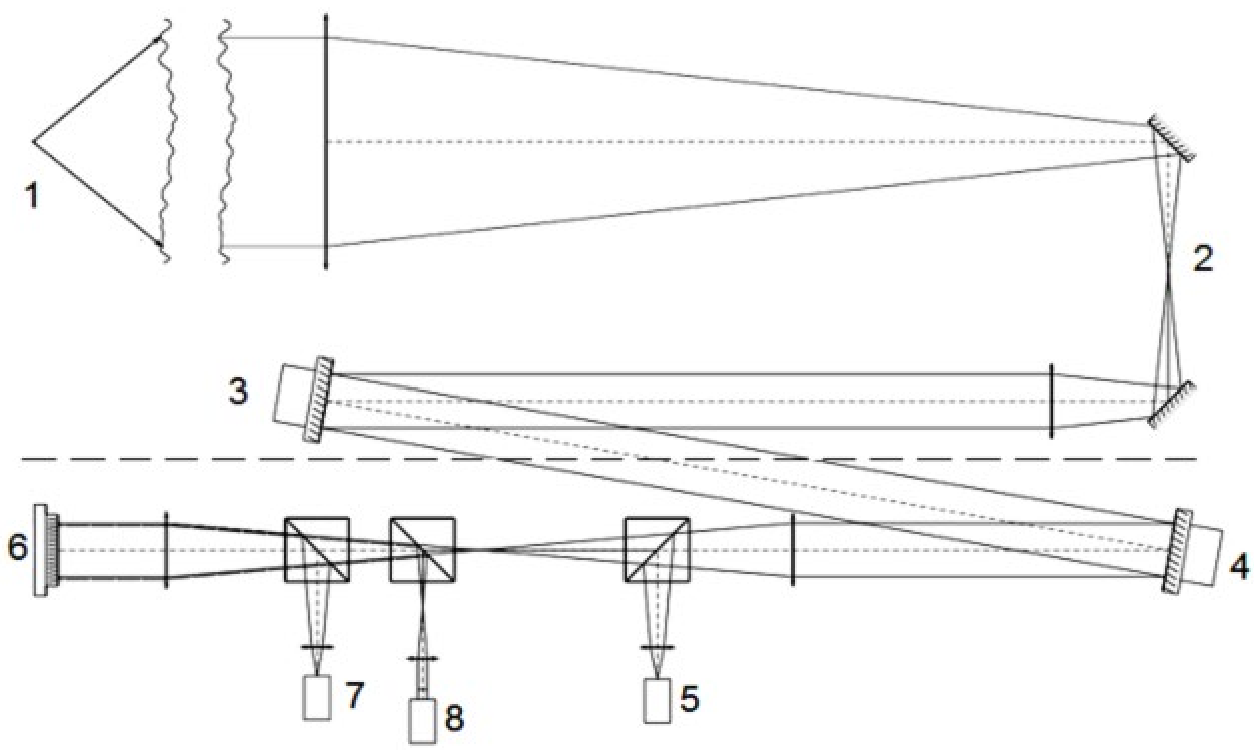

Fig. 1

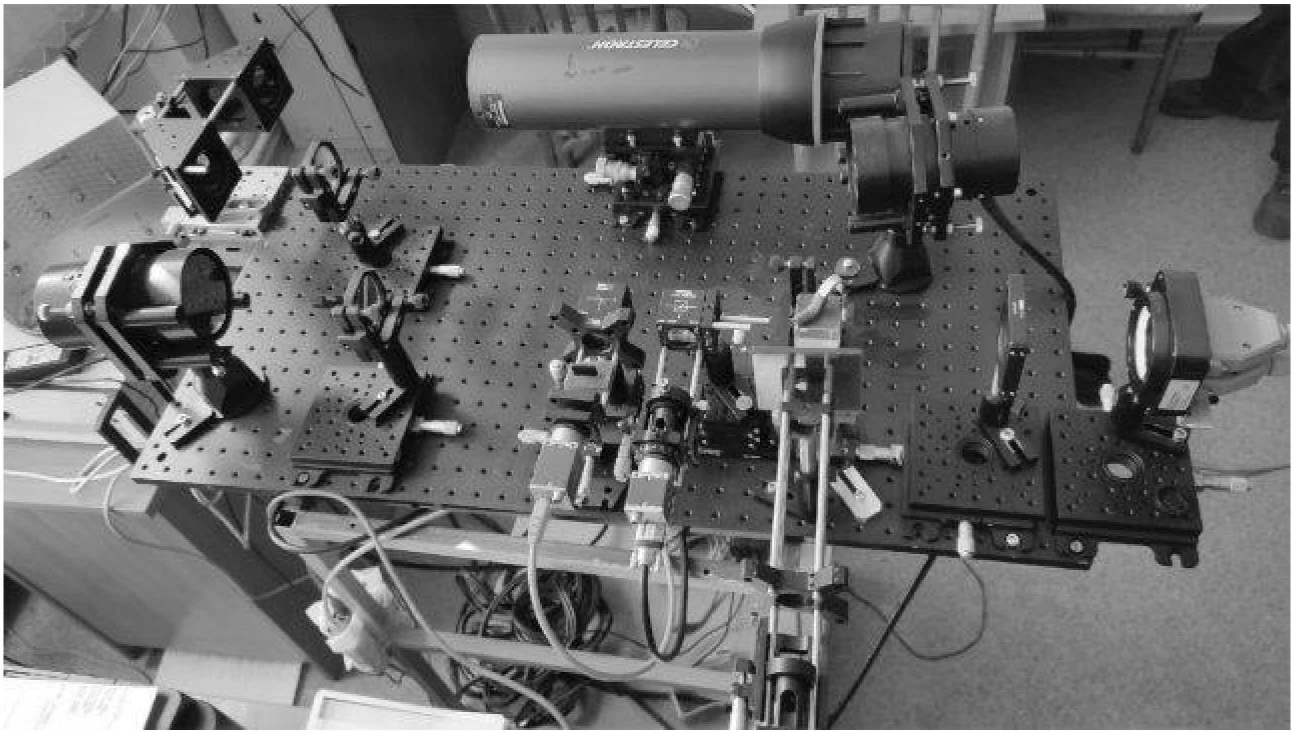

Fig. 2

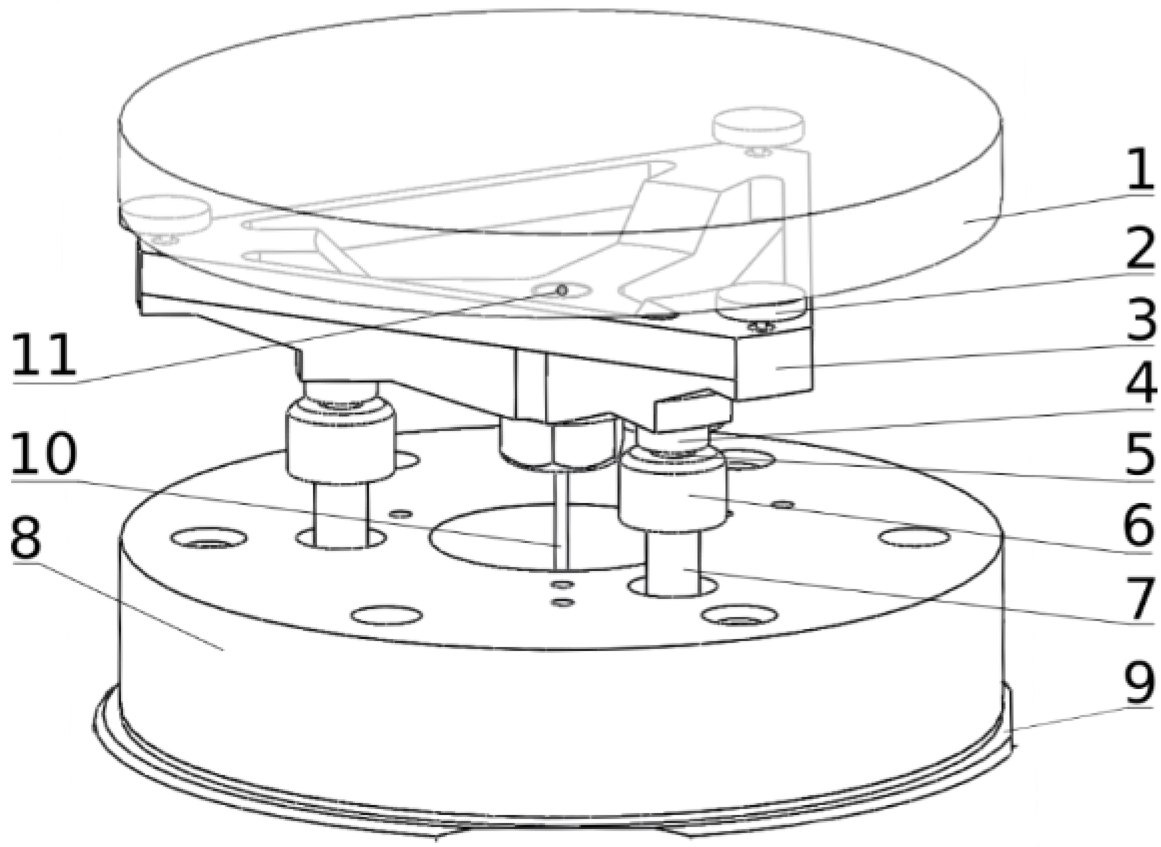

Fig. 3

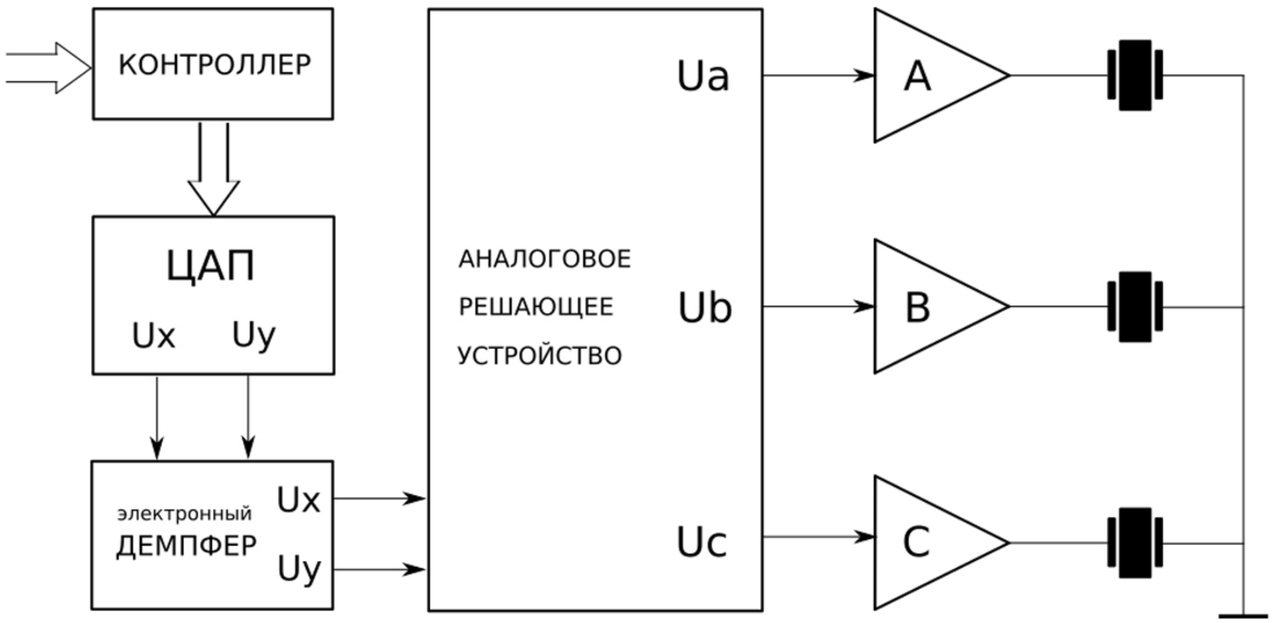

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Fig. 4

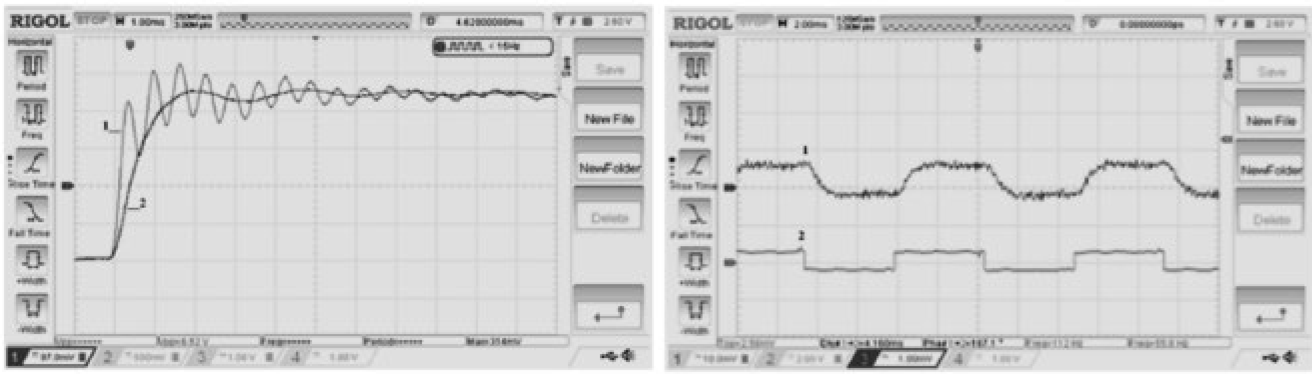
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Fig. 5

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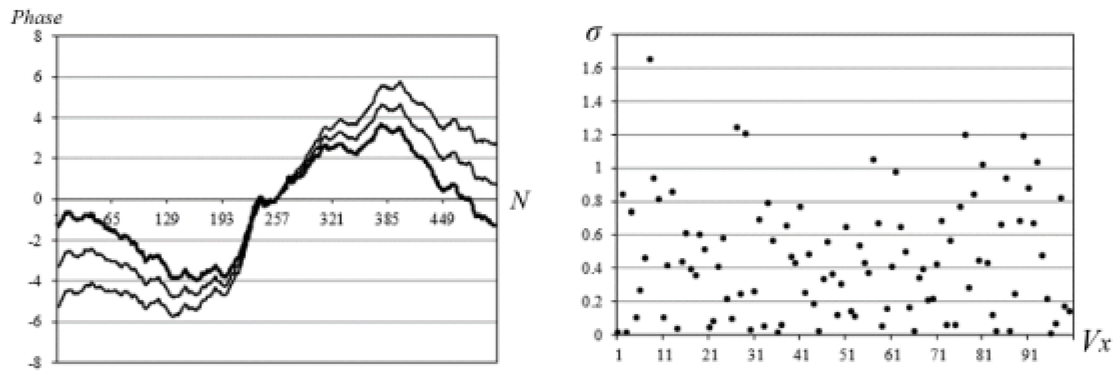
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Fig. 7