Optical Measurement Methods to Study Dynamic Behavior in MEMS

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ABSTRACT

The maturing designs of moving microelectromechanical systems (MEMS) make it more-and-more important to have precise measurements and visual means to characterize dynamic microstructures. The Berkeley Sensor&Actuator Center (BSAC) has a forefront project aimed at developing these capabilities and at providing high-speed Internet (Supernet) access for remote use of its facilities. Already in operation are three optical-characterization tools: a stroboscopic-interferometer system, a computer-microvision system, and a laser-Doppler vibrometer. This paper describes precision and limitations of these systems and discusses their further development. In addition, we describe the results of experimental studies on the different MEMS devices, and give an overview about high-speed visualization of rapidly moving MEMS structures.

Keywords: MEMS, MEMS testing, MEMS characterization, stroboscopic interferometer, microvision system, vibrometer

1. INTRODUCTION

Advanced testing methods for the dynamics of microdevices are necessary to develop reliable, marketable microelectromechanical systems (MEMS) [1]. The main purpose for MEMS testing is to provide feedback to the design-and-simulation process in an engineering development effort. This feedback should include device behavior, system parameters, and material properties. An essential part of a more effective microdevice development is high-speed visualization of the dynamics of MEMS structures. The growing number of MEMS related projects at Berkeley have lead to the essential need for advanced testing and characterization facilities for microdevices. We are establishing an optical MEMS-metrology laboratory for the increasingly diverse types of micromechanical devices developed at Berkeley or by the industrial partners of BSAC. At this time we have assembled three setups to measure and characterize the motions of MEMS microstructures:

- One setup is a Stroboscopic Microscopic Interferometer System that has been developed at BSAC. The system can measure both in-plane and out-of-plane motions in a single experiment. In-plane motions are measured with subpixel resolutions better than 5nm. Out-of-plane deflections are recorded with nm accuracy for structures either at rest or vibrating at frequencies up to 1MHz. Stroboscopy and digital-image processing are employed to determine in-plane motions with sub-pixel resolution. Stroboscopic interferometry is used to determine out-of-plane deflections at defined phases for a periodically moving structure. We have developed this system to study the excitation of complex mechanical modes in micromachined devices.
- A second system was developed at MIT and is called a "Computer-Micro-Vision System". It employs stroboscopy and image-processing techniques to track the motions of moving rigid-body structures. Through a focus variation, this system can measure out-of-plane as well as in-plane motions. Frequencies up to 100kHz have been investigated in our laboratory.
- A third system is a commercial Laser-Doppler Vibrometer (Polytec PI), which can be used to measure transient out-of-plane motion on one spot. With a microscope adaptor, the measuring laser beam is coupled into a microscope and is focused to a spot smaller than 1 μ m in diameter. This system measures the Doppler shift of the reflected laser beam and, therefore, the velocity of a moving microstructure. The laser-Doppler instrument can measure out-of-plane motions having frequencies as high as 1.5MHz.

Different MEMS devices, for example: micromirrors, read/write heads for hard disks, acceleration sensors, and electroacoustic high-frequency elements have been studied using the three different experimental facilities. In addition, we use the white-light interferometer (Wyko NT3300) from Veeco Instruments for accurate static-profile characterizations of complex structures.

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We have begun work on a system that will connect the measuring equipment to a new high-speed Internet (SuperNet) that will make the BSAC test facilities accessible at sites remote from Berkeley. The SuperNet testbed is supported by DARPA's Next-Generation-Internet program [2]. The goals of this program (Matisse) [3] are: (1) The development of advanced technologies that enable up to 10Gigabit-per-second streams between end systems over a shared, wide-area infrastructure; (2) the development of automated-network monitoring and a network management and planning tool. The Matisse project will extend the capabilities of the BSAC-optical-characterization facilities for dynamic and static behavior of MEMS to users across the country through their use of the new Gbit/s SuperNet in a "Virtual-Laboratory" environment with SuperNet connection to advanced MEMS CAD and Simulation tools.

2. BERKELEY STROBOSCOPIC MICROSCOPIC INTERFEROMETER SYSTEM

In reference [4] we demonstrate a stroboscopic, computer-controlled, phase-shifting interferometer for high-resolution full three-dimensional motion characterization. The schematic of the new three-dimensional Stroboscopic Microscopic Interferometer System (SMIS) is shown in Figure 1.

Figure 1. Schematic of Stroboscopic Interferometer System. The Abbreviations used are as follows: L – $\lambda/2$ - Wave-Plate, P – Polarizer, PBS – Polarization Beam Splitter, f_c – Condenser Lens, f_i – Imaging Lens, and f_m – Microscope Objective for Imaging, LD – Laser Diode, M – Reference Mirror

The SMIS system can also be conveniently used as conventional light microscope if the light beam that goes to the reference mirror is shadowed with shutter S (Figure 1). Through the stroboscopic visible-light illumination, a set (set 1) of images is taken of the periodic motion without forming an interference pattern. We have developed an algorithm to extract the in-plane motion from this sequence with a subpixel resolution of the motion amplitude better than 5nm. After the system has taken a set of images (set 1) without interference fringes, the shutter is moved out of the laser beam. Now the system is an interferometer and a set of images (set 2) is taken. The interferometer forms an image of the MEMS device that is crossed by bright and dark fringes that can be interpreted as a contour map of object surface heights. The optical arrangement is that of a Twyman-Green interferometer and is described in detail in [5,6].

To measure the shape of a static specimen or that of a moving specimen, "frozen" by the strobe light, phase-shifting interferometry (PSI) is used. A five-step PSI algorithm (Hariharan's Algorithm) in which the fringe pattern of a specimen is visualized five times for five different reference-mirror positions is used [6]. The translation data extracted from set 1 are then used to recalculate the in-plane motion from the images of set 2. Finally, the out-of-plane motion is calculated with nm resolution using the five-step-PSI algorithm. Set 2 contains five images for every single time point where the surface-height map is measured because of the five-step-PSI method. Therefore, to investigate the three-dimensional deflection at 10 phases

of the periodic motion the systems saves 10 images for the in-plane-motion extraction and 5 times 10 images for the out-of-plane-motion computation. Hence, a full sequence for a measurement at 10 time points contains 60 images. The structure of the algorithm, which computes full three-dimensional motion, is presented using analysis software written with MATLAB[®] (The MathWorks, Inc) and is shown in Figure 2.

Figure 2. Structure of the Analysis Software

We number the columns of each picture with i_n and the rows with j_n ($i_n, j_n \in \mathbb{N}$). $j_n=1$ is the number for the row at the bottom of the image. Column number $i_n=1$ is at the first column at the left side. Therefore, the coordinates i and j ($i, j \in \mathbb{R}$) coincide for integer values with the numbers of the columns i_n and rows j_n . The displacements di and dj are computed using digital-image processing.

The Progressive-Scan-CCD camera captures 8-bit gray-level images that are saved on the hard disk. The sampled-image matrix $\underline{M}$ with components $I_s(i_n, j_n)$ is the image and the resampled image $I_r(i, j)$ is the continuous gray-level distribution function that can be calculated from the sampled image by employing the Nyquist-Sampling Theorem. Equation 1 demonstrates this for a sampled image with n columns and m rows.

$$f(i, l) = \sum_{k=1}^n \frac{\sin(\pi(k-i))}{\pi(k-i)} I_s(k, l)$$

$$I_r(i, j) = \sum_{l=1}^m \frac{\sin(\pi(l-j))}{\pi(l-j)} f(i, l) \quad (1)$$

The in-plane-motion algorithm calculates the shift di and dj between image I_1 and image I_2 using the least-square-optimization criterion

$$\min(\|I_{1,s}(i_n, j_n) - I_{2,r}(i_n - di, j_n - dj)\|_2), \quad (2)$$

where

$$\|A(k, l)\|_2 = \sqrt{\sum_{k,l} A_{k,l}^2}$$

is the L_2 norm [7]. The least-square problem in (2) is solved by employing the Nelder-Mead algorithm [8] that is implemented in MATLAB[®]. This algorithm is very robust in finding the global optimum so that displacements over several

pixels are calculated with subpixel resolution. However, the direct employment of the Nyquist-Sampling Theorem is not applicable because the computation time is too long. Therefore, we have developed an algorithm that translates and resamples an image with linear interpolation in one step. The algorithm is published in [4]. The restriction for this algorithm is that rotations cannot be computed, but the displacement between two images can be extracted in less than a second using a Pentium II computer. We measured displacements of a device up to $2\mu\text{m}$ between 2 images.

The in-plane-displacement data between the images is used to calculate the in-plane motion from the interferograms of image set 2. This is necessary to make sure that out-of-plane deflection is computed in respect to points on the device surface. To measure the shape of a static specimen or that of a moving specimen “frozen” by the strobe light we use a five-step PSI algorithm in which the fringe pattern of a specimen is visualized five times for five different reference-mirror positions. The PSI algorithm calculates a wrapped-phase map and is known as Hariharan’s Algorithm [5]. The algorithm calculates the wrapped phase $\phi(i, j)$ from the five intensity amplitudes $I_1(i, j) \dots I_n(i, j) \dots I_5(i, j)$ using the formula

$$\phi(i, j) = \arctan \left[\frac{2(I_2(i, j) - I_4(i, j))}{2I_3(i, j) - I_5(i, j) - I_1(i, j)} \right]. \quad (3)$$

Inputs to this algorithm should change phase by approximately $\pi/2$ in each data-acquisition step. The surface under test is assumed to be smooth and continuous; abrupt steps are removed by software. Our single-wavelength system measures wave-front-phase modulo 2π and, therefore, calculates a “wrapped” phase map from the interferogram sequence. The unwrapped phase map $\varphi(i, j) = \phi(i, j) + 2n(i, j)\pi$ is determined from the wrapped-phase function $\phi(i, j)$ and describes the phase difference of the measurement beam and the reference beam at every pixel of the CCD sensor. The spatially varying integer $n(i, j)$ is present because the optical phase can only be measured modulo 2π in a single-wavelength interferometer.

Finally, the surface-height map $h(i, j)$ can be found using

$$h(i, j) = \lambda \cdot \varphi(i, j) / 4\pi \quad . \quad (4)$$

This procedure is repeated for different strobed-light delays. In addition a time unwrapping algorithm is employed to enable the system to measure pure piston motion.

Our system can measure in-plane motion as well as out-of-plane profiles and deflections. The spatial in-plane resolution of the system is defined through the optical resolution of the imaging optics. With high quality microscope objectives we achieve optical in-plane resolution better than $1\mu\text{m}$. Spatial out-of-plane resolution is limited by constant wavefront aberrations (approximately $20\mu\text{m}$).

The measurement of displacements has much higher resolutions and is limited by noise of the camera sensor. The motion resolution is better than 5nm (amplitude of a harmonic motion) for in-plane measurements and better than 1nm for out-of-plane measurements. The in-plane measurement range is the field of view imaged on the CCD sensor and depends on the magnification, e.g. 600 times $800\mu\text{m}$ for 10X microscope objectives. The out-of-plane measurement range depends on the depth of focus of the imaging optic and is defined through the magnification (numerical aperture). For 10X microscope objectives the out-of plane-range is more than $20\mu\text{m}$. Slightly unsharp images can still be used for high-resolution, out-of-plane-profile measurements. The maximum measurable tilt of highly reflective surfaces depends on the numerical aperture of the imaging optics. We are able to measure tilts of $\pm 12^\circ$ with our interferometer.

The time resolution is defined by the shortest possible width of the strobe pulse, which is 100ns for our system. The width of the strobe pulse (exposure time) and the interframe time (duration of phase delay between two exposures) are not related. To capture unblurred images the exposure time (minimum 100ns) has to be smaller than the time, which the imaged object needs to move the distance of one pixel of the image sensor. The resulting velocity limit for in-plane motion is for example 12.5m/s for 10X objectives (8 times magnification and $10\mu\text{m}$ square sensor pixels. It is more critical to capture out-of-plane motions because during the exposure the specimen must not move more than half of the wavelength in out-of-plane direction. The limit for out-of-plane velocity is 3.3m/s . The highest frequency we can investigate is defined through our electronic. Frequencies up to 1MHz can be studied.

A limitation of our system is that we can only investigate periodic or periodically repeatable dynamic processes, which can be synchronized with the strobed illumination.

3. MIT COMPUTER-MICRO-VISION SYSTEM

The Computer-Micro-Vision System (CMVS) is a video microscope with stroboscopic illumination [9,10] (see Figure 3). Therefore, CMVS can also measure periodic or periodically repeated processes. The determination of in-plane motion with CMVS is similar to the determination of in-plane motion with SMIS. For both setups the in-plane displacement is extracted from a sequence of images showing a translating object.

Figure 3: Schematic of the Computer-Micro-Vision System.

Instead of employing a combination of Nyquist-sampling theorem, image translation algorithm, and least square algorithm as it is used for SMIS, CMVS uses a gradient method in combination with least square optimization. The image displacement is approximated by a Taylor expansion and only linear terms are considered [10].

$$\min\left(\left\|I_1\left(i + \frac{di}{2}, j + \frac{dj}{2}\right) - I_2\left(i - \frac{di}{2}, j - \frac{dj}{2}\right)\right\|_2\right) \approx \min\left(\left\|I_1(i, j) - I_2(i, j) + \frac{di}{2} \frac{\partial I_1}{\partial i} + \frac{dj}{2} \frac{\partial I_1}{\partial j} + \frac{di}{2} \frac{\partial I_2}{\partial i} + \frac{dj}{2} \frac{\partial I_2}{\partial j}\right\|_2\right) \quad (5)$$

In addition images and their partial derivatives are approximated by their points midway between pixels. The estimated parameters are the displacements di and dj . The cost function in (5) is linear dependent on di and dj . Therefore, the L_2 solution of (5) can be expressed in closed form with one matrix inversion.

The estimate using (5) is incorrect for large displacements. Thus, an iterative refinement algorithm is applied to compute larger displacements between two images. If the displacement is more than a pixel the second image is shifted about a full-pixel displacement closest to the estimate. When the displacement between the images is subpixel the remaining displacement is estimated using (5). The total displacement results from the sum of the full-pixel shifts plus the sub-pixel displacement estimate. The algorithm (5) used in CMVS is probably faster than the algorithm used in SMIS where the L_2 optimization is performed numerically with the Nelder-Mead algorithm. The SMIS algorithm is probably more robust for large displacements but we have not tested the algorithms under comparable conditions as yet. We were not able to obtain accurate displacement measurements using CMVS studying motions with amplitudes larger than roughly $5\mu\text{m}$ (using 8 strobe-phase delays and a 20X microscope objective). By increasing the number of strobe-phase delays or by decreasing the motion amplitude we were able to acquire the displacement measurements. Higher amplitudes can be studied with a lower-magnification microscope objective.

CMVS can also extract out-of-plane motions by taking a set of images for different distances between the specimen and the microscope objective at every investigated phase of the periodic motion. Several images are taken for different focus adjustments. The out-of-plane displacement is extracted through the varying blur of the images. The gray level at every camera pixel is changing characteristically through the blur when the distance between object and objective is shifted. Therefore, such a set of images with different focus adjustments can be understood as three-dimensional image. Out-of-plane displacements between two three-dimensional images can be extracted with the same method as in-plane displacements.

An out-of-plane resolution of less than 5nm and an in-plane resolution of less than 2.5nm have been reported by the MIT group [9, 11] headed by Dennis Freeman. CMVS has the capability to define a list of frequencies and the system can obtain automatically a frequency response of the specimen. We have measured frequencies with CMVS up to 100kHz. CMVS measures full three-dimensional, rigid-body motions on single spots that the user has to define, while MSIS measures rigid-body in-plane motion and out-of-plane deflections and profiles for every captured time point. Therefore, we use CMVS to measure frequency responds on single points of a microdevice while we use MSIS to measure surface profiles and complex mechanical modes, which are excited at a given input signal. Latest improvements of CMVS are referenced in [11]. [12] shows the www-link to a company commercializing the system.

4. POLYTEC LASER-DOPPLER VIBROMETER

SMIS and CMVS can only be used to characterize MEMS motions when the dynamic processes are periodic or periodically repeatable. In addition, there must be a possibility to synchronize the strobe light with the device motion. Therefore, SMIS and CMVS are not applicable to measure noise or not repeatable transient motions. To measure such processes we use a commercially available Laser-Doppler Vibrometer (LDV) OFV-501 [13] from Polytec [14] that we have attached to a probe station microscope with the manual microscope scan unit OFV-075. This setup can measure the out-of-plane velocity v of a spot in real-time. The LDV consists of a Mach-Zehnder interferometer and an electronic controller (See Figure 4). The microscope scan unit is attached with a standard C-mount to the microscope. Scan unit and interferometer are connected via a glass fiber.

Figure 4: Schematic of the LDV setup. The Abbreviations used are as follows: LED – Light emitting diode, BS – Beam splitter, PD – Photo detector

A HeNe Laser ($\lambda=632.8\text{nm}$) is used as coherent light source. The frequency of the reference beam is shifted through an acousto-optical modulator (Bragg cell). The direction of the motion is acquired through this heterodyne technique. The measurement beam is frequency shifted by Doppler-shift through the motion of the specimen under test. A quarter-wave plate ensures that the light is parceled to the photo detector instead of turning back to the laser and that measurement beam and reference beam have the same polarizations at the photo detectors. Every photo detector measures the oscillating intensity with the frequency $f_s=f_R+f_D$ plus a dc bias, where f_R is the frequency shift of reference beam and $f_D = 2v/\lambda$ is Doppler shift of

measurement beam. The ac intensity oscillations of the two detectors are π rad out of phase because the sum of the signals is constant because of energy conservation. Therefore, the difference of both detector signals is the pure ac part without dc bias. A controller acquires a real-time, velocity-dependent voltage signal from the ac signal after the differentiation. The direction of the motion is determined through the sign of the voltage.

5. COMPARISON OF THE SYSTEMS

Table 1 gives an overview about the different features of our systems. Due to the test-rig properties the main applications for our systems are: (1) measuring static profiles and mechanical modes with MSIS, (2) measuring in-plane and out-of-plane frequency responds for rigid-body motion with CMIS, and (3) measuring out-of-plane frequency responds as well as transients and noise at one spot with our LDV.

	SMIS (BSAC)	CMVS (MIT)	LDV (Polytec)
Static measurement	possible	possible	not possible
Measurable motions	periodic and repeated transient	periodic and repeated transient	transient and periodic
DOFs measured	in-plane, rigid-body motions; out-of-plane deformations	3D rigid-body motion of spot	out-of-plane motion of spot
Max. out-of-plane displacement	20 μ m		10cm (Polytec results)
Max. in-plane displacement	~500 μ m * **		not possible
Out-of-plane motion resolution	1nm	5nm (MIT results)	~0.01nm (Polytec results)
Out-of-plane profile resolution	20nm	not possible	not possible
In-plane motion resolution	5nm	2.5nm (MIT results)	not possible
Spatial in-plane resolution	500nm	500nm	500nm
Frequency sweep	not realized	possible	possible
Frequency range	0-1MHz	0-100kHz (BSAC measured)	0.5Hz-1.5MHz (Polytec results)
Velocity range (in-plane)	0~20m/s *	0~20m/s *	not possible
Velocity range (out-of-plane)	0-3.3m/s		500nm/s-10m/s (Polytec results)

* Dependent on microscope objective. ** We measured 2 μ m displacements with 2 images.

Table 1: Features of BSAC dynamic MEMS characterization facilities.

6. NETWORKED STROBOSCOPIC MICROSCOPIC INTERFEROMETER SYSTEM

The connection of the BSAC MEMS test facilities to the SuperNet is a major goal of our present work. SMIS and CMVS are already attached to the SuperNet. Thus far, we have developed a Java-based network client and a network protocol to use as the interface to the new global high-speed network. We are developing a C++ network-server program to automate the interferometer system. When these two programs are in operation, we will make our setup accessible from outside (see Figure 5). Our network protocol acts as a specification to be used for packaging the data to be sent between client and server. It is implemented as a network interface, which will act as an abstraction layer between client and server. The interface allows programmers to send and receive data using predefined methods. The network protocol provides [15] a standardized way of transferring information. The protocol does not interpret the actual data, unless it receives a request from the client application. It is up to the end-user to define when and how the data is to be interpreted.

The abstraction layers of the network communication are as follows:

- Server/Client: the implementation dependent application
- Interpreter/Parser: the user-defined, server-language specification
- Network Protocol: BSAC user-independent protocol
- TCP/IP (Transmission Control Protocol/Internet Protocol): standard Internet communication protocol

In addition we will use the SuperNet to save interferometer images with information about the experiment on the Distributed, Parallel-Storage System (DPSS) developed and placed at LBL (Lawrence Berkeley National Laboratory). We will use the ftp protocol to transfer the data to LBL. The structure of the planned networked interferometer is shown in Figure 3. Our image-evaluation software has been developed in MATLAB®. We plan to develop a C++-based, networked, stand-alone application of this software and will provide it to Sarnoff (Princeton). Sarnoff will develop an advanced version of evaluation software, which will be performed on computational engines located in Princeton, New Jersey. Our final goal is to demonstrate the stroboscopic interferometer in a “Virtual Laboratory” environment connected to advanced storage and computational engines.

Figure 5: Schematic of networked Microscopic Stroboscopic Interferometer System.

7. CHARACTERIZATION OF MEMS: EXAMPLES

We conclude with a brief summary of MEMS characterizations performed at BSAC. These results give a feeling of what kinds of measurements are possible. Optical MEMS characterization started at BSAC with the study of surface quality of scanning micromirrors for displays with a self-developed interferometer. By freezing motions with a strobed laser diode we were able to investigate dynamic micromirror deformations for the first time. This allowed us to test if mirror stiffness were high enough for a given scanning frequency. Mirror deformation is critical for many applications because it influences directly the wavefront shape of the reflected light beam. Figure 6a shows a SEM photograph of a surface-micromachined mirror and Figure 6b demonstrates the measured mirror deformation at 3120Hz (at 0rad phase delay compared to the input signal). Details of BSAC investigations of micromirrors have been published in [5,6,16,17].

Figure 6: SEM photograph [16] of surface-micromachined scanning mirror (a) and mirror deformation at 0rad (b) and π rad (c) phase at 3120Hz measured with MSIS (courtesy M. Hart and R. Conant).

The first full three-dimensional motion characterization with MSIS was performed to study a hard-disk drive [18]. Figure 7a shows a SEM photograph and Figure 7b the computed in-plane motion (1250Hz) [4]. The out-of-plane deflection maps at 0 and π rad phase delay of the strobe pulse are demonstrated in Figure 7c.

Figure 7: SEM photograph [18] (courtesy L. Muller) of read/write head with gimbaled actuator (a) and in-plane motion data (b) and out-of-plane deflection (c) at 0 and π rad measured with SMIS.

The hard-disk drive changes its dynamic behavior when a dc bias is applied to the input voltage signal. The input frequency responses measured for different voltage offsets have been recorded with the LDV by shining the measurement laser beam on

the sidewall of the read/write disk head. The frequency was swept for the experiment and data was registered with a spectrum analyzer (HP 35665A). The spectrum analyzer provided also the ac input signal. The amplitude response is shown in Figure 8a and the phase response in Figure 8b [4].

Figure 8: Amplitude response (a) and phase response (b) of the read/write-head actuator measured with the LDV (courtesy L. Muller).

The in-plane frequency magnitude response (Figure 9a) of a microgyroscope [19] (an angular resonator for out-of-plane rotation measurements shown in Figure 9b) has been taken with CMVS. The measurement points of the frequency axis are specified in a list before the experiment is performed. CMVS extracts amplitude and phase responses (Bode plots) from the image data for the specified frequencies.

Figure 9: Photograph of gyroscope (a) and amplitude response (b) measured with CMVS (courtesy W. Davis).

8. CONCLUSIONS AND OUTLOOK

We have established a laboratory for MEMS dynamic testing using optical measurement techniques. We employ stroboscopic interferometry, computer-micro-vision methods and laser-Doppler vibrometry to characterize dynamic events in MEMS using the optical characterization facilities described in this paper. A variety of different devices developed at BSAC have been analyzed by using these methods. Currently we are investigating the possibilities of SuperNet access for remote control and for connection to advanced CAD and simulation tools. Some demonstrated results of this project are described in this paper. Future work will include an automated feedback of SMIS to SUGAR [20,21]. SUGAR is a BSAC-developed simulation tool for MEMS that has roots in SPICE [22] developed at Berkeley for integrated circuits. The goal of this new project is to couple the image-evaluation software for SMIS with SUGAR to derive automated parameter identification and

mathematic model verification. In addition, we want to automate the recording of motion at different frequencies to obtain a frequency response with SMIS. The development of systems employing high-speed cinematography [23,24] to study non-repetitive transient motions is also planned.

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