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Sub-nanometer Broadband Measurement of Elastic Displacements in Optical Metrology Frames and Other Critical Elements

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ABSTRACT

This paper presents the outline for a real-time nano-level elastic deformation measurement system for high precision optical metrology frames. Such a system is desirable because elastic deformation of metrology frame structures is a leading cause for performance degradation in advanced lithography as well as metrology and inspection equipment. To date the development of such systems was thwarted by the unavailability of sufficiently sensitive and cost effective strain sensors. The recent introduction to the market of the IntelliVibe™ S1 strain sensors with sub nanostrain sensitivity makes it possible to develop a real-time nanometer level elastic deformation monitoring system. In addition to the sufficiently sensitive and cost-effective strain sensor it is necessary to develop the analytical foundation for the measurement system and use this foundation for the development of a signal processing algorithm that will enable the real-time reconstruction of the elastic deformation state of a metrology frame at any given time from data transmitted by a reasonable number of properly placed S1 strain sensors. The analytical foundation and the resulting algorithms are demonstrated in this paper.

KEYWORDS: Metrology, nanostrain, strain sensor, modal decomposition, vibration, real time health monitoring, elastic deformation

1. INTRODUCTION

Manufacturing, inspection, and metrology of nanotechnological devices depend on the alignment accuracy of the illumination source, the focusing system (lens), and the target (wafer or reticle). A critical component in achieving alignment is the optical metrology frame, a rigid structure that supports elements of the feedback metrology for stage positioning, as well as the illumination source and the focusing system. The function of the metrology frame is to provide an inertially stabilized platform for the above-mentioned optical components.

The rigidity requirement of metrology frames carries the penalty of low inherent damping, since typical high-damping materials such as rubber and other polymers cannot be used. Thus even very small dynamic forces acting on the metrology frame can excite elastic displacements that are large enough to significantly degrade optical alignment.

It is virtually impossible to eliminate nano-scale elastic vibration of structural elements. Thus the only remaining strategy is to accurately estimate these dynamic displacements and compensate for them in the active alignment algorithm.

Unfortunately until recently there was no way to measure nano-scale elastic displacement in structural elements. Accelerometers do not have sufficiently good response at low frequencies, where much of the floor vibration energy is concentrated. Furthermore, an accelerometer will measure the sum of rigid body and elastic vibration making it impossible to isolate the elastic component. Finally, a typical high-performance accelerometer with sensitivity of 1 volt per g will yield only 100 micro-volts per 250 nm at 10Hz, a highly deficient sensitivity performance. Relative displacement sensors are inadequate for sensing elastic displacement because they will sense the combined displacement of the metrology frame and the sensors support structure.

Thus non-referenced elastic displacement in structures can only be estimated by a strain sensor. In linear structures (and metrology frames specifically due to their highly rigid nature and extremely small deformations can be safely assumed to be linear) the strain field maps uniquely to the displacement field of the structure. Thus an accurate measurement of

strain and the correct application of well-established linear structural analysis can yield an accurate estimate of elastic deformation at any given point in the structure across a wide frequency band.

However, the nano-level deformations in modern metrology frames yield strain fields that are measured in parts per billion (nano-strain) and cannot be measured with currently available strain sensors. This paper describes the successful development of a cost-effective and simple to use strain gauge that can measure nano-strain levels of elastic deformation leading to a non-referenced measurement of elastic displacements. The enabling technology at the base of this innovation involves the packaging of a large quantity of piezoelectric material in a very small printed circuit board, resulting in a MEMS-like device with a level of performance that exceeds anything currently commercially available. The paper presents experimental validation for the measurement of nanometer levels of vibration in steel structures representative of typical metrology frame elements. The adoption of this technology is expected to be beneficial to the development of semiconductor manufacturing for the 35 nm node and beyond.

2. SENSING TECHNOLOGY

As previously mentioned, a non-referenced, reliable, ultra-sensitive, and cost effective strain sensor is required for production-level real-time elastic deformation monitoring system. The reason for the non-referenced requirement is that in the nano-level universe there is no sufficiently stable base to which referenced displacement measurements such as capacitive sensors or laser interferometers can be referenced. The only two types of non-referenced sensors that can measure structural deformation are strain sensors and accelerometers; the former because they measure strain as the source of all elastic deformation and the latter due to the inertial nature of acceleration. However, acceleration measurement is not the answer for three main reasons: first accelerometers measure inertial the second time derivative of displacement, which includes the elastic and rigid body components. As a matter of fact, the elastic component may be much smaller than the rigid body one, making it difficult to isolate. The rigid body component, however, does not typically degrade the performance of metrology frames because the relative registration of all components is maintained. Second, acceleration has a high frequency bias, such that a single nanometer displacement at 100 Hz will yield a signal that is 100 times higher than the same displacement at 10 Hz. Thus lower frequency vibration resulting from the particularly dangerous main-body vibration modes will be underestimated by an accelerometer, while the less important high frequency local modes will be overestimated. Finally, currently available accelerometers just don't have the sensitivity needed to resolve nanometer displacements at relatively low frequencies. One nanometer at 100 Hz will yield an acceleration of $1 \times 10^{-9} (2\pi 100)^2 = 0.04 \text{ mg}$. A high-end accelerometer has a sensitivity of 1000 millivolt per g. Thus for 0.04 mg or 40 μg , the accelerometer signal will be 0.04 mV or 40 μV . This kind of signal level will not yield sufficient signal to noise ratio for reliable measurement.

The S1 is a unique strain sensor that relies on patent pending technology to incorporate lead zirconium titanate wafers in a printed circuit board structure. A typical S1 sensor is shown in



Figure 1: The Intellivibe S1 strain sensor

The sensor has a sensitivity of 50 mV/ $\mu\epsilon$ without amplification. With the use of appropriate amplifier sensitivities in the range of 10 mV/ $\mu\epsilon$ have been measured making the S1 sensor ideally suitable for nanostrain measurement.

3. MEASUREMENT ALGORITHM

We start by building a finite element model of the metrology frame and performing a modal run to obtain N_m eigenvectors. The number of eigenvectors is chosen such that the eigenvalue (natural frequency) corresponding to the N_m -th eigenvector is higher than the high end of the desired measurement band.

Next we express the eigenvectors in the form of a planar normal strain in order to determine the number and locations of strain gauges to be used in the measurement. This will require engineering judgment, since there is a tradeoff between the desire to place a large number of sensors and the added cost and computational complexity. A reasonable starting

point would be to place one sensor at each high stress area for a given mode shape. This number final number of sensors is denoted N_s .

Expressing the eigenvectors in the form of deformation (elastic displacement) will determine the number and location of displacement estimation points. Analogously to the choice of measurement points, there is a tradeoff involved; higher number of estimation points will yield a smoother rendition of the structural deformation, however, once the number of estimation points exceeds the number of measurement points there is a loss of estimation accuracy. There is no additional implementation cost, since the estimation points are a mathematical construct and no actual hardware is placed there. It is thus important to place the estimation points at the high displacement areas of the structure and keep a balance between the desire to have a well-resolved picture of the structural deformation and keeping the number of estimation points to within a reasonable ratio to the number of measurement points. A number of special estimation points may be added at specific locations of interest, such as mounting points for optical components or vibration isolation equipment. The total number of estimation points is denoted N_d . Note that each point will have three displacement components.

The next step is to create a modal strain matrix ϕ_s by listing the appropriate planar normal strain at each strain gauge location for each eigenvector in the form of a column vector and setting these vectors side by side. This matrix will have the dimension of $[N_s \times N_m]$.

Three modal displacement matrices – ϕ_x , ϕ_y , ϕ_z – are created by eliminating from each directional eigenvector all the displacement components that belong to nodes that do not contain a chosen displacement estimation point. Each matrix will have the dimension of $[N_d \times N_m]$.

We then attach the IntelliVibe S1 sensors to the chosen sensor locations and using an appropriate A/D converter obtain a discrete time measurement signal for time step j . This signal contains the list of all sensor output voltages at the time step in question and is denoted ε_j . This results in a column vector with N_s rows.

Now it becomes possible to compute the modal participation vector c_j for time step j . Modal participation vectors are defined as the weighted contribution of all considered modes to the actual transient deformation shape of an elastic structure at a particular moment in time. Thus the actual strain vector can be expressed as the product of the modal participation vector and the modal strain matrix as follows:

$$\varepsilon_j = \phi_s c_j \quad (1)$$

Since we have just measured the strains ε_j using the S1 sensors and we have previously obtained the modal matrix ϕ_s from finite element analysis, we can compute the modal participation vector the modal participation factor vector c_j from its defining equation. Note the dimensionality of that equation to be:

$$[N_s \times 1] = [N_s \times N_m] \times [N_m \times 1]$$

When $N_s > N_m$, c_j does not have an explicit solution. A least squares type fit must be made to solve for c_j .

When $N_s = N_m$, c_j has an explicit solution:

$$c_j = \phi_s^{-1} \varepsilon_j \quad (2)$$

When $N_s < N_m$, the problem is ill conditioned. Fewer modes need to be selected or more sensors added to the system.

We are now ready to compute the displacement vectors for time step j , d_j as

$$\begin{aligned} d_j^x &= \phi_x c_j \\ d_j^y &= \phi_y c_j \\ d_j^z &= \phi_z c_j \end{aligned} \quad (3)$$

Note that because the strain field is a spatial derivative of the deformation field, the displacement and strain modal participation factors must be identical. Thus the vector of modal participation factors found using the modal variant of the modal matrix can be used for deriving the vector of estimated displacements with no transformation required.

The final step is the visualization of the displacement of the metrology frame by plotting the computed displacements in real-time giving the operator a unique picture of the actual state of the elastic deformation of the metrology frame.

4. IMPLEMENTATION EXAMPLE

Prior to investing the resources necessary to implement the proposed measurement system on a real metrology frame, the performance of such a system may be evaluated by simulation. In this case we chose a simple metrology frame such as commonly used in metrology and inspection equipment for semiconductor manufacturing. This is a steel frame structure as shown in Figure 2.

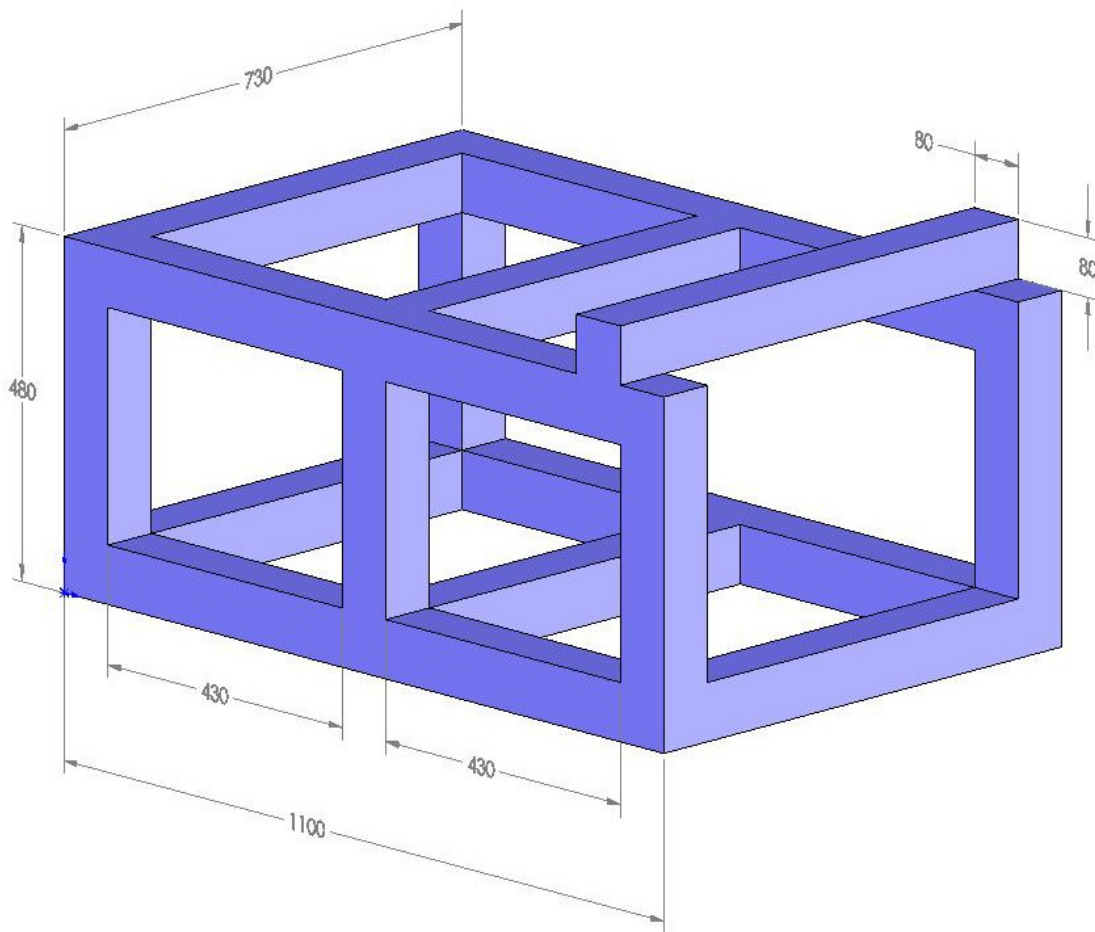


Figure 2: A typical metrology frame, dimensions in millimeters (mm). All beams are same thickness.

A finite element model of this structure was constricted to eliminate rigid body motion and run to obtain 12 modes with frequencies ranging from 189.5 Hz to 888.7 Hz. The first principal strain mode shape for Mode 1 is shown in Figure 3. The same information for Mode 12 is shown in Figure 4.

Maximum Principal Elastic Strain
Type: Maximum Principal Elastic Strain
Frequency: 189.5 Hz
Unit: m/m
1/30/09 6:39 PM

0.10153 Max
0.05
0.042856
0.035713
0.028569
0.021426
0.014282
0.0071396
-4.0328e-6 Min
-5e-6

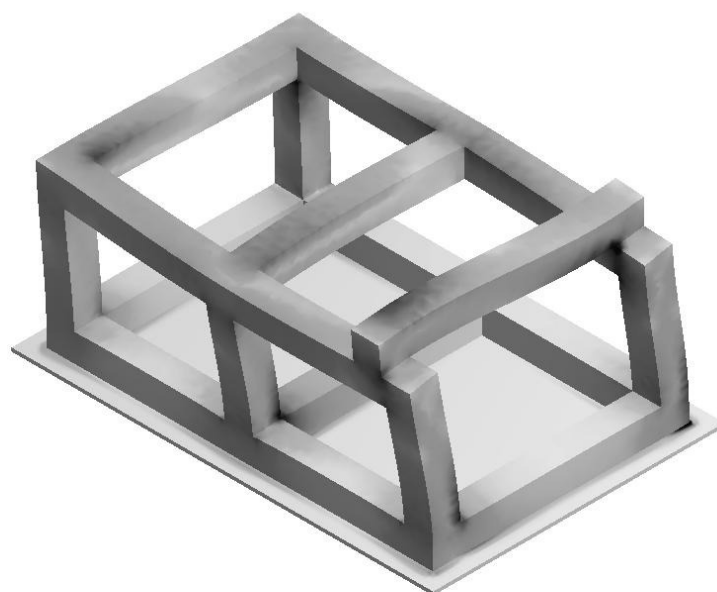


Figure 3: First mode deformation shape of the metrology frame colored by first principal strain intensity.

Maximum Principal Elastic Strain 2
Type: Maximum Principal Elastic Strain
Frequency: 888.71 Hz
Unit: m/m
1/30/09 6:38 PM

0.45152 Max
0.25
0.21429
0.17857
0.14286
0.10714
0.071429
0.03571
-5e-6
-1.7966e-5 Min

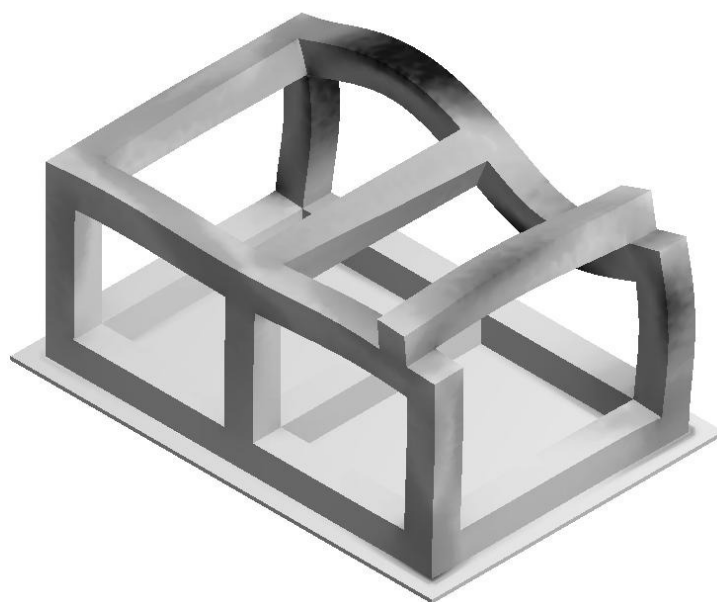


Figure 4: Twelfth mode deformation shape of the metrology frame colored by first principal strain intensity.

Based on this information, sixteen (16) were selected to be placed at the locations denoted by the red squares in Figure 5. Twenty-eight (28) estimation points were chosen to be located at the points denoted by spheres in Figure 6. The displacement of the dark blue sphere is point #8 and will be analyzed in particular.

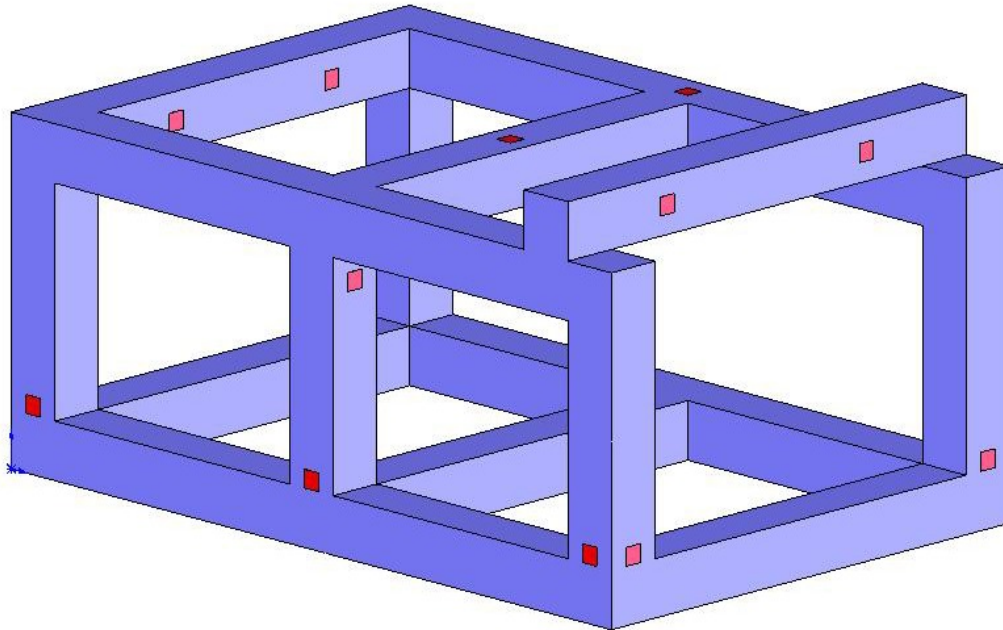


Figure 5: Locations of S1 strain sensors. Four (4) sensors are located on the lower legs, hidden from view

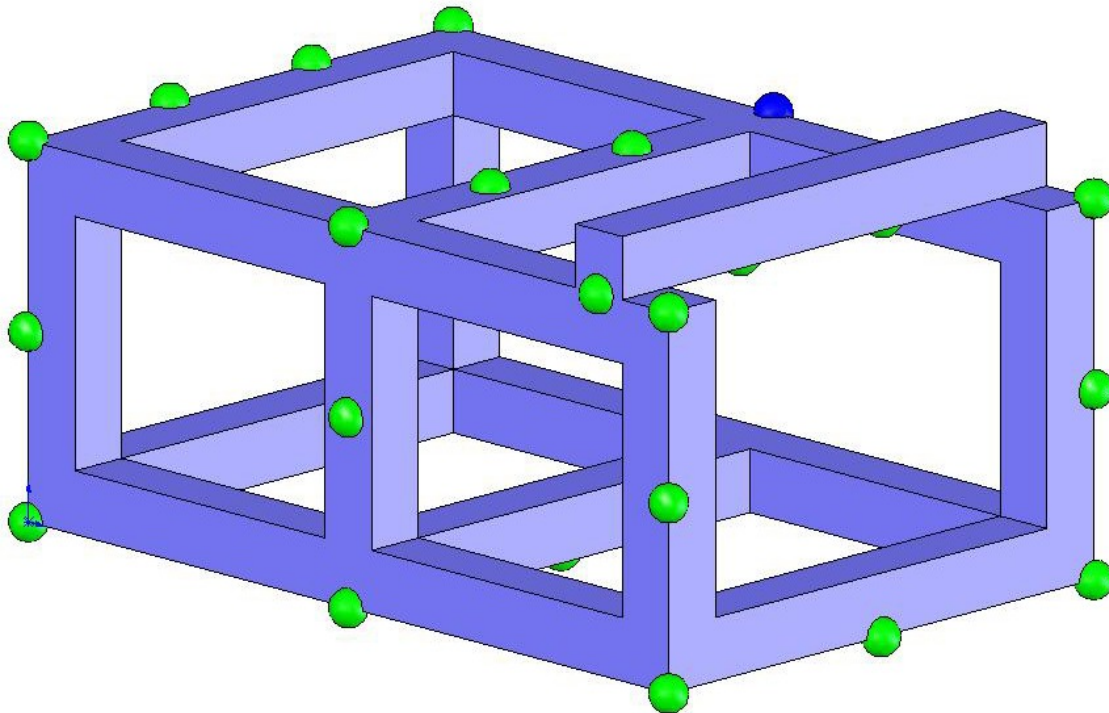


Figure 6: Locations of displacement estimation points.

Since this is a simulated approach to performance evaluation, finite element analysis was used to simulate the actual operating conditions of the metrology frame. A transient solution was obtained by giving a step displacement impulse of $1\mu\text{m}$ in the y (up) direction to a plate fixed to the bottom of the frame. The sampling frequency was 5000Hz (0.2ms time step), which is greater than 10 times higher than the sixth mode (456Hz), which is the highest mode considered here. The strain seen in this simulation is $0.6\text{ n}\epsilon$ to $400\text{ n}\epsilon$.

Once the simulation was completed, the strain data at selected time steps was exported to a MATLAB program that computed the modal participation vectors and the resulting deformation shape. This deformation shape was then compared to the “actual” deformation shape from the finite element run.

5. RESULTS

Figure 7 through Figure 9 show a comparison of the “actual” frame deformation (from the full scale FEA result, simulating the actual frame deformation) in red dashed lines and the “measured” frame deformation (obtained from processing the local strain obtained from FEA at the sensor locations) in blue solid lines at three different times during the frame operating cycle. Figure 10 shows the time domain “actual” and “measured” deformation at estimation point # 8, shown in Figure 6 as the blue sphere. Good agreement between the actual and estimated deformation is observed in all cases.

The standard deviation and mean were found for the total error of every node in the simulation, and averaged across all times. The mean error displacement was 193nm, and the standard deviation was 183 nm.

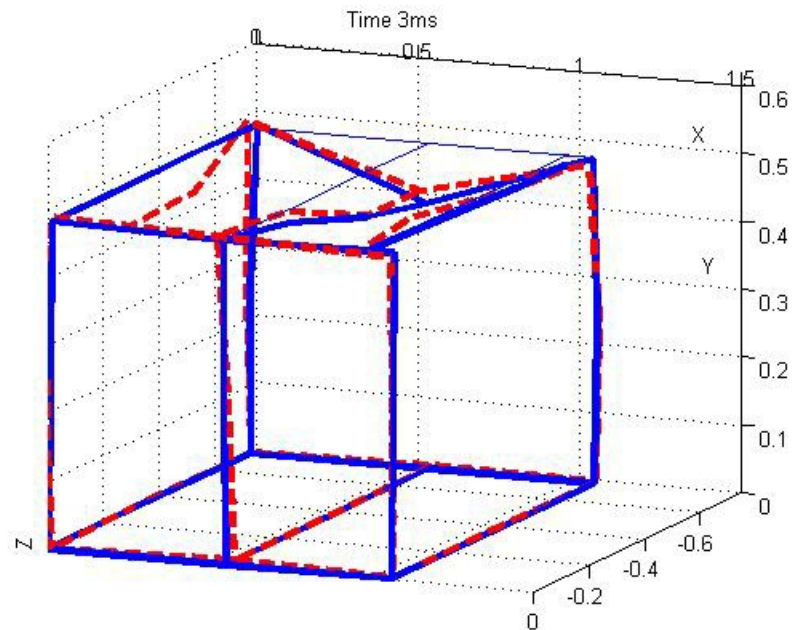


Figure 7: Actual (red dashed) and measured (blue solid) frame deformation at t= 3ms

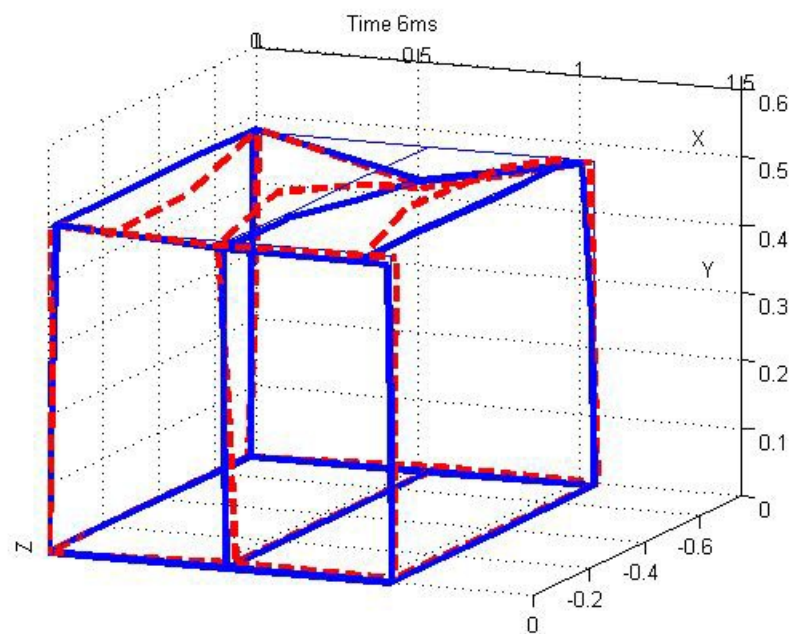


Figure 8: Actual (red dashed) and measured (blue solid) frame deformation at $t = 6\text{ms}$

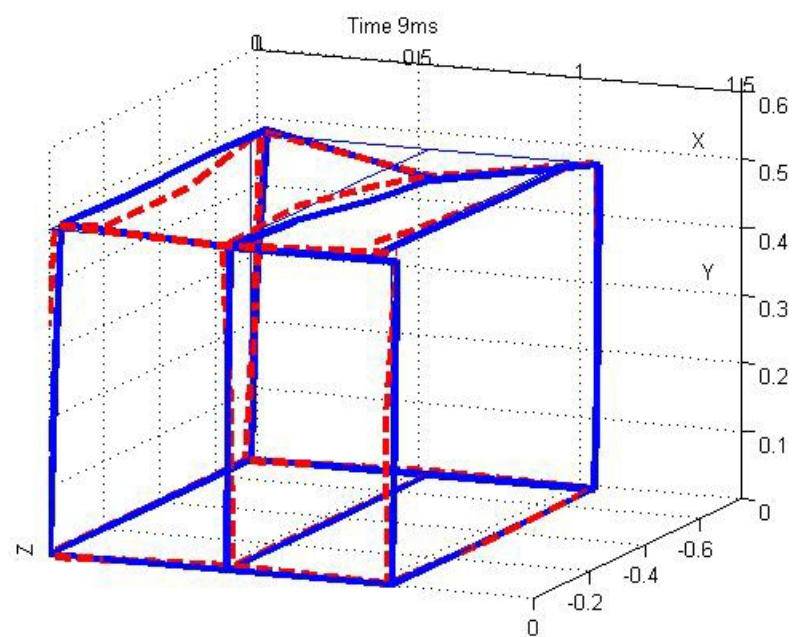


Figure 9: Actual (red dashed) and measured (blue solid) frame deformation at $t = 9\text{ms}$

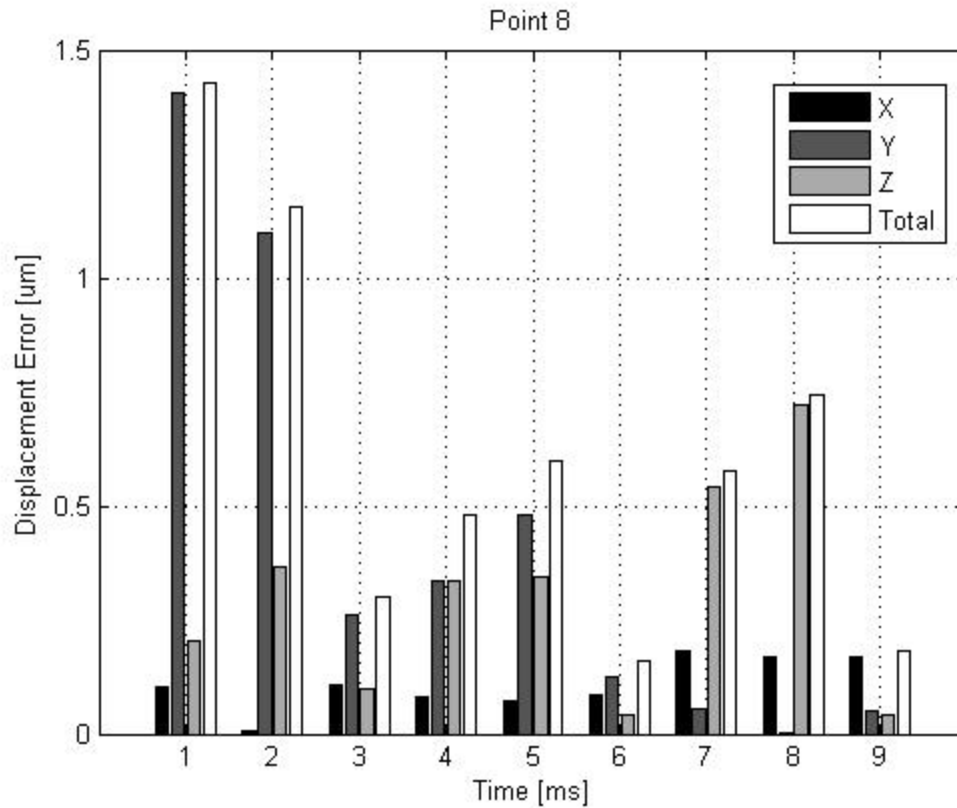


Figure 10: Directional and total displacement error for estimation point 8.

6. CONCLUSIONS

For the first time ever a cost effective system for the real-time measurement based estimation of elastic deformation in optical metrology frame has been proposed and shown to have good potential for success. The system relies on the revolutionary IntelliVibe™ S1 strain sensor with nanostrain sensitivity and resolution as well as a newly developed signal processing algorithm for providing real-time measurement based estimate of metrology frame vibration.

Future development of this project will include investigating the effect of more or fewer modes and more or fewer strain and displacement points. In addition, other frame shapes and more realistic disturbance, such as white noise, will be investigated.