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50. Internationales Wissenschaftliches Kolloquium
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A. V. Shaporin / M. Hanf / W. Dötzel

Efficient MEMS Characterization Technique for Spring-Mass-Damping Systems

ABSTRACT

A novel characterization method for MEMS devices based on the combination of measurement and simulation results is introduced by the example of an electrostatically actuated micro mirror array. The aim of this method is to determine geometrical parameters and built-in mechanical stress on the basis of the measured Eigenfrequencies. A Laser Doppler interferometer and a signal analyzer are used to determine the frequency response function (FRF) of the micro mechanical structure and the Eigenfrequencies are calculated. For the numerical simulation of the micro mirror behavior the finite element (FE) model is used and a series of nonlinear coupled-field analysis and pre-stressed nonlinear modal analysis is performed to obtain the dependence of the Eigenfrequencies on geometrical parameters and built-in mechanical stress. The comparison to the measured frequencies yields values of the searched parameters that are mean values for the entire micro mechanical structure. The presented method is very efficient because it determines several characteristics of a MEMS device on the basis of a single measured frequency response function only. The article demonstrates that a sufficient accuracy is achieved and stress values are calculated which are hardly ascertainable using common measurement methods.

1. INTRODUCTION

At present there is a big demand for efficient methods to characterize micro electro-mechanical system (MEMS) devices during the manufacturing process. Spring-mass-damping systems play a very important role in the field of MEMS. All acceleration sensors, gyros, vibration sensors, micro mirrors etc. are such systems. They can be described by their spectral behavior, that depends on several parameters like material properties, geometry, damping and built-in mechanical stress.

Measurement systems like electronic Speckle pattern interferometer (ESPI) [1] and stroboscopic interferometers [2], [3] are suitable to determine the dynamic deformation of MEMS. Up to now, they have not been implemented in the manufacturing process. A Laser Doppler interferometer (LDI) is preferable to measure the FRF. It utilizes the Doppler effect of light to capture the velocity of an object parallel to the illuminating Laser beam [4]. In contrast to the measurement systems mentioned above the LDI observes only a single point of the object at a time. Scanning the sample yields the dynamic deformation, but now for the whole observed spectral range. It is a robust system that has been already implemented in a probe station. Hence the Laser Doppler interferometer promises a system to characterize spring-mass-damping systems applicable for the MEMS manufacturing. It is known that built-in mechanical stress influences the behavior of micro mechanical structures. Especially Raman spectroscopy [5]-[7] and X-ray diffraction [8] are suitable for mechanical stress measurements, with a resolution of about 10 MPa. But even stress less than 10 MPa can result in strong changes of the behavior of MEMS. The implementation of these measurement systems in the manufacturing process is hardly possible, since they are time consuming, because the structure has to be scanned and they are critical in handling.

The objective of the presented work is to develop a method that utilizes only one measurement system to determine geometrical values and built-in mechanical stress of micro mechanical spring-mass-damping systems. Regarding the MEMS fabrication, this method has to be robust and efficient. The LDI has been already introduced as a sufficient measurement system. In conjunction with a signal analyzer, the obtained measurement results are FRF which makes the determination of the Eigenfrequencies possible. The basis of the developed method is a numerical description of the micro mechanical system. A FE simulation yields the dependence of the Eigenfrequencies on characteristics of the structure, like geometry and built-in mechanical stress. The conjunction of the measured and the calculated Eigenfrequencies results in a set of data which are effective values for the searched parameters.

In the following the method of the indirect parameter determination will be explained by the example of a micro mirror array. The procedure splits in the three main tasks:

(1) creation of the parametric FE model, calculation of the structure's behavior depending on parameters of interest, regression of the simulation results,

(2) measurement of the FRF and precise determination of the Eigenfrequencies,

(3) parameter identification based on the FE simulation and the measurement results.

The results of the FE simulations and the Laser Doppler interferometer measurements are presented and discussed. The developed method is evaluated based on determination of Eigenfrequencies versus temperature.

2. MICRO MIRROR ARRAY AND NUMERICAL SIMULATION

A micro mirror array has been developed which is applied as the encoding mask in a Hadamard transform spectrometer [9] the Chemnitz University of Technology. Fig. 1 shows a SEM image of the fabricated array. Its whole length is about 7 mm. The array contains 48 equal mirror elements, driven by electrostatic forces. This is achieved by a plate capacitor arrangement where the mirror plate is the moveable electrode and an underlying aluminum area is the fixed driving electrode. For the design process a FE model of a micro mirror is used to calculate and optimize its characteristics. As to be seen from Fig. 2, the mirror plate is asymmetrically supported by two flexures. This design is preferable to achieve large tilt angles, when using a single electrode for each micro mirror. The micro mirror array is fabricated by standard silicon bulk micromachining techniques. Three double-side polished single crystalline wafers are necessary. The micro mirrors are released by dry and wet etching. The three wafers are assembled by two silicon fusion bonding processes. To increase the reflectivity of the micro mirrors they are coated with 40 nm thick aluminum layer by sputtering. The fabricated micro mirror arrays are investigated for the first resonant frequency and strong deviations (up to 20 %) are found. The main reasons for this are differences of the flexure's cross sections and the variation of the built-in mechanical stress that is mostly induced by the bonding processes. Because of the small geometrical dimensions of the flexures optical measurement methods do not meet the requirements on resolution. The characterization of the built-in mechanical stress by Raman spectroscopy yields no sure results. Hence the stress is close to or less than 10 MPa. It will be shown, that the novel method of MEMS characterization gives an opportunity to determine these parameters exactly.

The most important part of the MEMS characterization method is an accurate theoretical description of the micro mechanical system. For more than ten years finite element method (FEM) [10] was used for MEMS simulation. Comprehensive FEM algorithms enable one getting a precise behavioral description of each single energy domain of multifield problem including domain interactions, like electrostatic softening [11].

To perform the multiparametric FE analysis an exact FE model of the investigated micro mechanical system needs to be created. The parameters of interest must be defined as variables. Now one calculates the Eigenfrequencies for all possible combinations of variables.

For the sake of an analytical description the dependence of Eigenfrequencies on parameters needs to be fitted, for instance by a polynomial. In the following multiparametric FE analysis is demonstrated based on the micro mirror. As mentioned, above the most interesting parameters of the micro mirror are the dimensions of the flexure's cross section (thickness and width) and the built-in mechanical stress.

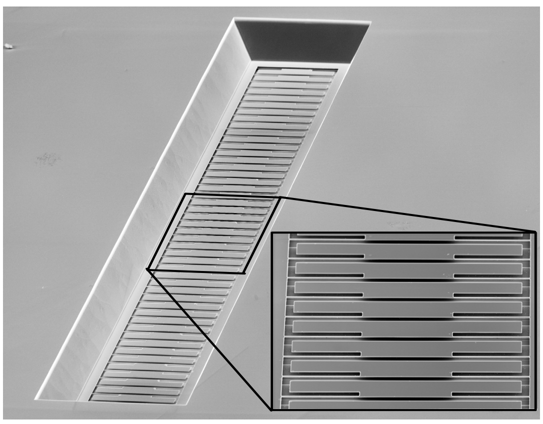


Fig. 1: SEM image of the realized micro mirror array.

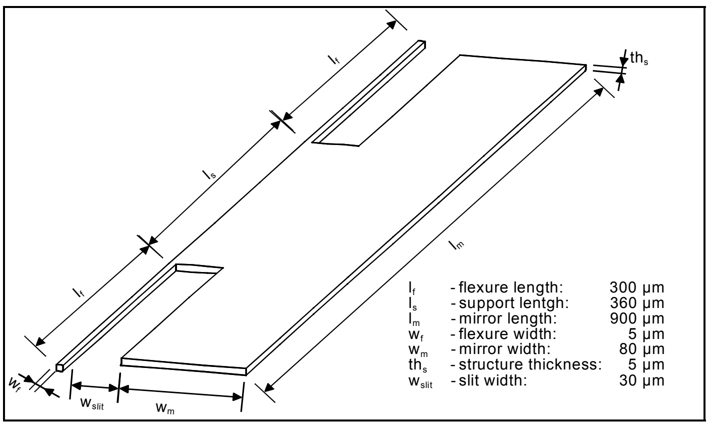


Fig. 2: Scheme of one micro mirror including all geometrical dimensions.

The FE model is created in ANSYS 8.1 (Fig. 3) in order to investigate the influence of these three parameters on the Eigenfrequencies. The flexures are assumed to be cuboids. Consequently, inhomogeneities of the real flexure's cross section, e. g. a wedge like shape, are not considered. The nodes at one end of the flexures are fixed in all directions, while the nodes at the opposite end are moved along the y-axis but fixed for the remaining directions to simulate the mechanical stress. One can induce either compressive or tensile stress in flexures depending on the direction of this shift. A static analysis leads to the stress distribution as shown in Fig. 4. The stress distribution in the flexures is homogeneous. The average over flexure's volume gives the mean stress. Consequently, all assumed values for flexure's cross section geometry and built-in mechanical stress are effective parameters.

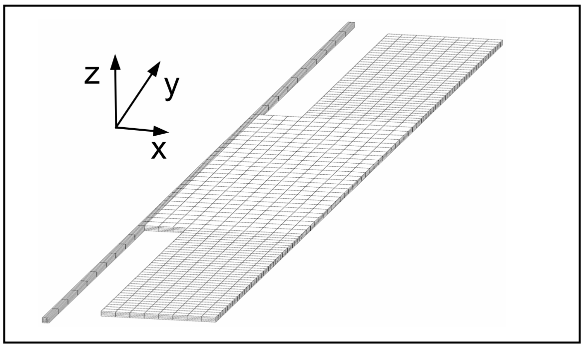


Fig. 3: Meshed FE model of a micro mirror.

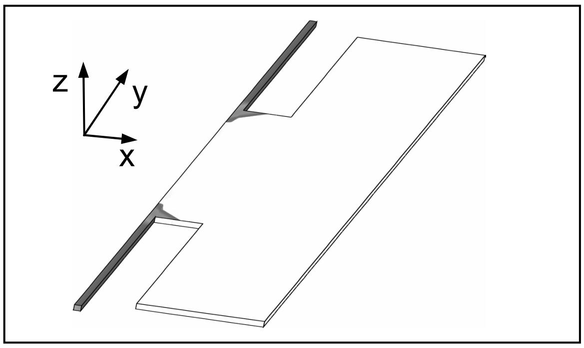


Fig. 4: Stress state in the flexures after first analysis step.

The stress σ is varied from -10 to 10 MPa in steps of 2.5 MPa for the multiparametric analysis. Furthermore the flexure's thickness th_s and the flexure's width w_f (compare to Fig. 2) are changed from 3 to 6 μm in steps of 0.5 μm. For all possible combinations of flexure's cross section and built-in mechanical stress the first 9 Eigenfrequencies are calculated within loops by a pre-stressed modal analysis. The first four out-off plane modes are shown in Fig. 5.

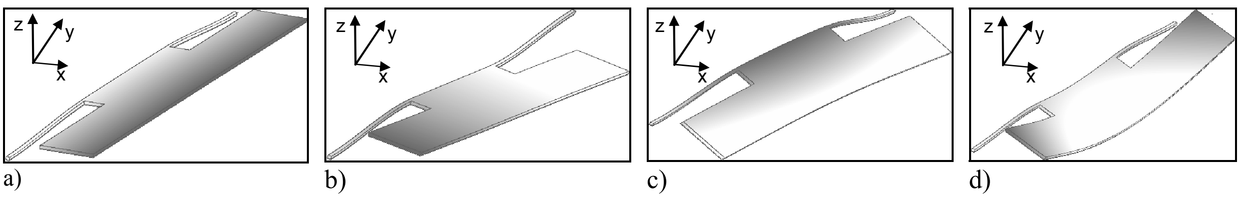


Fig. 5: Simulated out-off plane mode shapes of a micro mirror:

a) 1^{st} mode, superimposition of the rotation around the y-axis and the translation in z-direction,

b) 3^{rd} mode, rotation around the x-axis,

c) 5^{th} mode, rotation around the y-axis placed closed to the centre of the mirror plate,

d) 6^{th} mode, half sine wave like shape of the mirror plate.

Depending on the ratio of the flexure's thickness and its width the order of the modes can interchange. The result of the FEM calculation is a (n×7) matrix (Table 1). The first three columns contain the variables flexure thickness, flexure width and built-in mechanical stress (th_s, w_f, σ). The subsequent four values are the corresponding out-off plane Eigenfrequencies and n depends on the numbers of FEM runs. The time to establish this data set is about 3 hours.

The graphs in Fig. 6 a) and b) illustrate the dependence of the first and the sixth Eigenfrequency respectively on the flexure's geometry. Therefore the stress is set to zero. Up to the fifth mode the frequencies are influenced by the width and the thickness, while all next modes are mostly defined by the structure's thickness. A similar situation is obtained for the graphs in Fig. 6 c) and d).

In this case the flexure's width is held constant at 5 µm while stress and thickness vary. As to be seen, even here the frequencies of the higher modes are less dependent on the mechanical stress. The reason for this behavior lies in the different mode shapes – for the first five modes large motion of the flexures occurs whereas for the next modes mostly mirror plate deformations take place. A multivariate regression of the data for each Eigenfrequencies leads to the analytical description of their dependence on thickness, width and stress:

$$fo_N = f(th_s, w_f, \sigma), \quad (1)$$

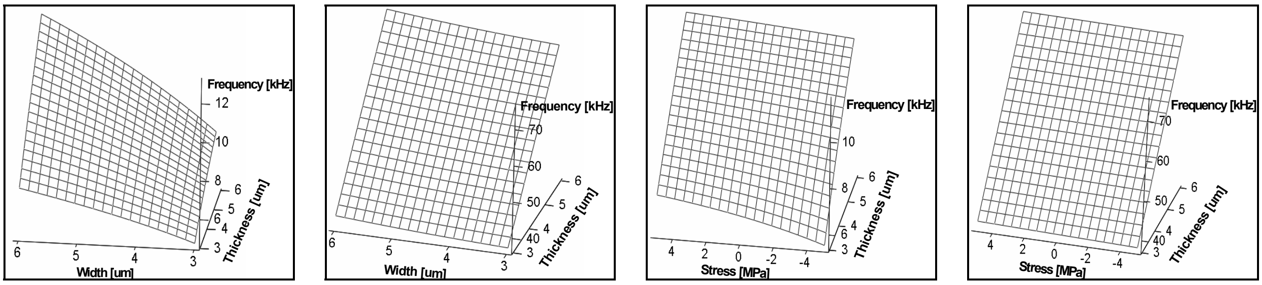
where fo_N is the Eigenfrequency of the mode number N.

As result the coefficients of a fourth order polynomial are obtained and one can construct the equations for the particular Eigenfrequencies (2). The error of this regression is less than 0.05 %.

$$fo(th_s, w_f, \sigma) = a_{000} + a_{001} \cdot \sigma + a_{010} \cdot w_f + \ldots + a_{132} \cdot th_s \cdot w_f^{\,3} \cdot \sigma^2 + \ldots + a_{444} \cdot th_s^{\,4} \cdot w_f^{\,4} \cdot \sigma^4 \quad (2)$$

Parameters			**Eigenfrequencies [Hz]**			
th_s [µm]	**w_f [µm]**	**σ [MPa]**	**1st mode**	**3rd mode**	**5th mode**	**6th Mode**
3.00	3.00	10.1000	5263.478	10735.55	23465.23	36737.52
3.00	3.00	7.5748	5148.956	10258.98	22664.28	36631.51
…	…	…	…	…	…	…
5.00	4.50	-9.7863	8310.260	15161.34	35499.24	61236.00
…	…	…	…	…	…	…
6.00	6.00	-9.5237	11929.780	21406.51	49045.71	75373.62

Table 1. FEM simulations results for given problem.



a) b) c) d)

Fig. 6: Dependence of Eigenfrequencies on geometry and stress:
a) 1st mode Eigenfrequencies vs. flexure's width and thickness,
b) 6th mode Eigenfrequencies vs. flexure's width and thickness,
c) 1st mode Eigenfrequencies vs. flexure's thickness and built-in mechanical stress,
d) 6th mode Eigenfrequencies vs. flexure's thickness and built-in mechanical stress.

3. DETERMINATION OF EIGENFREQUENCIES

The determination of the eigenfrequencies splits in two tasks. In the first step one measures the FRF of the micro mechanical structure. In the second part the extractions of the eigenfrequencies out of the FRF follows. Fig. 7 shows the used measurement setup. The microscope with the implemented optical fiber of the LDI focuses the Laser beam to a spot with a diameter of 3 µm. Furthermore it makes alignment of Laser spot on the micro mechanical structure possible. The arbitrary function generator supplies the investigated mirror with the voltage, used for the electrostatic driving. Different signals are useful, like the falling edge of a rectangular pulse, a chirp signal or noise. The disadvantage of using a rectangular signal is the decreasing amplitude at rising frequencies.

For the developed parameter identification method even the higher Eigenfrequencies, up to

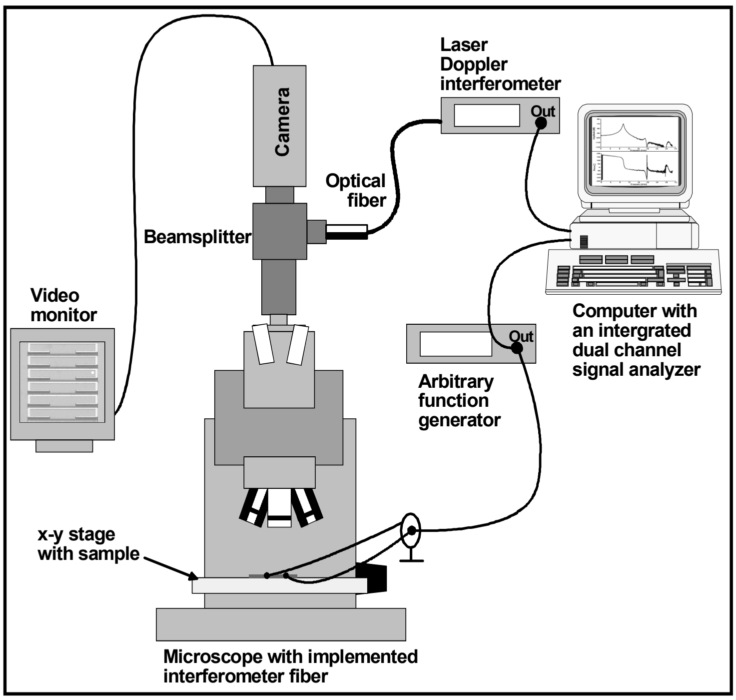


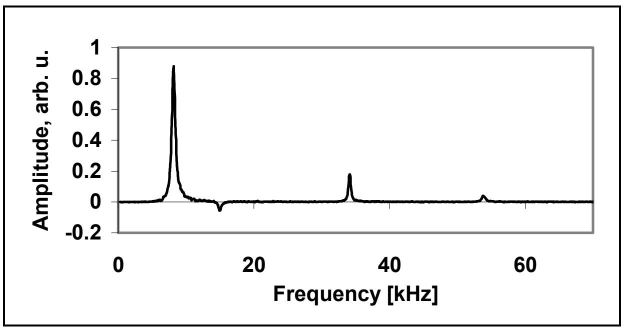
Fig. 7: Scheme of the measurement setup for FRF determination.

150 kHz, have to be determined. The Fourier analysis of the used signal analyzer has a spectral resolution of 3200 lines. It is advantageous to generate a signal containing only these frequencies but with a constant amplitude. This offers a specific discrete noise that consists of 3200 different sinusoidal signals at the frequencies corresponding to the frequency lines of Fourier analysis. They are superimposed that way that a noise like signal results. As mentioned above the LDI captures the velocity of the out-off plane motion of the observed measurement point. The obtained response signal and the discrete noise are recorded by a computer with a dual channel signal analyzer card. It calculates the fast Fourier transform. The resulting FRF of a micro mirror is shown in the Bode plot in Fig. 8 a) and b) as real and imaginary part, respectively. For an efficient Eigenfrequencies determination one should use an automatic method that finds the amplitude maxima of the real part. In the first step it has to select the frequency ranges, where they occur. Therefore the phase vs. frequency is calculated, because it strongly changes at resonant frequencies.

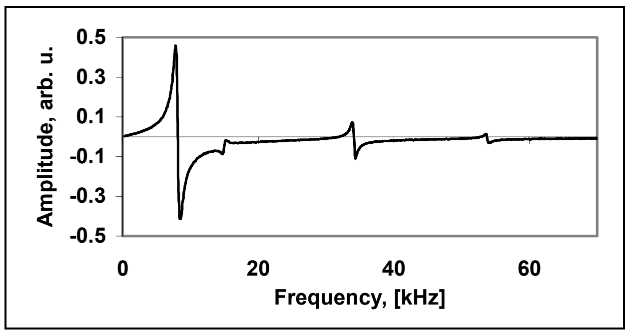
The grey bars in Fig. 8 c) illustrate the recognized frequency ranges. In the second step of the Eigenfrequencies determination the automatic method extracts the recognized frequency ranges from the real part and determines the local maximum. The measured FRF has a frequency resolution of about 38 Hz that is not sufficient. That’s why the data are fitted by the Lorentzian equation [12]:

$$L(f) = \frac{\alpha}{\alpha^2 + \left(f - fo_N\right)^2}, \tag{3}$$

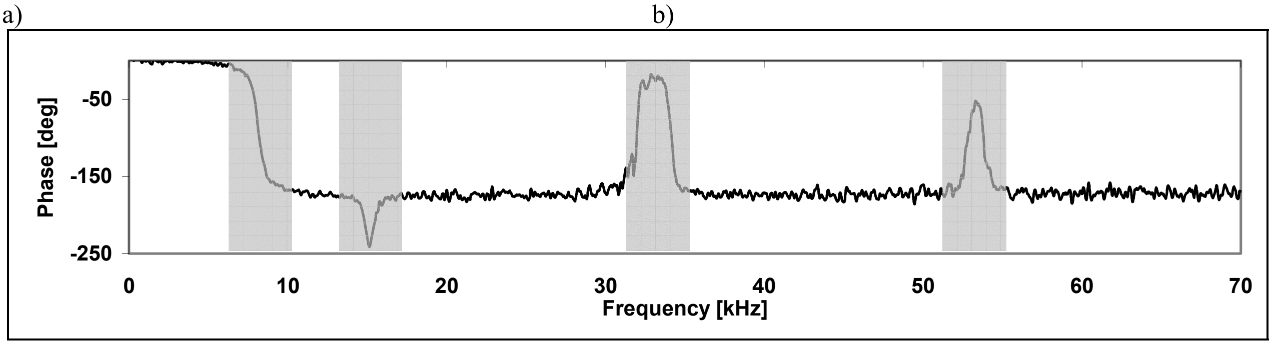
where α is a parameter depending on the amplitude, f is the frequency and fo_N are the desired eigenfrequencies.



a)



b)



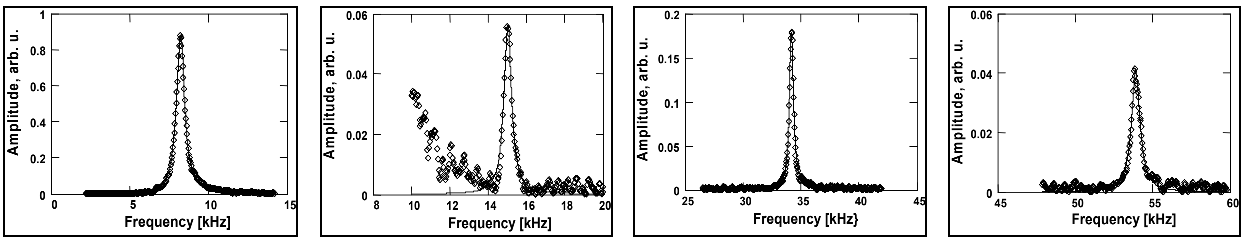
c)

Fig. 8: Measured FRF as a) real part, b) imaginary part and c) phase with selected frequency ranges.

The used function for the Lorentzian fit is given in equation (4).

$$L(f) = \frac{1/\left(A_{max} - A_{min}\right)}{\left(\frac{1}{A_{max} - A_{min}}\right)^2 + \left(\frac{f - fo_N}{bw}\right)^2} + A_{min}\,, \tag{4}$$

where A_{max} denotes the maximum value of the extracted real part, A_{min} the minimum value of the real part, bw the bandwidth and fo_N are the desired eigenfrequencies. An ordinary generalized regression algorithm performs fitting procedure. Fig. 9 shows the extracted frequency ranges from the real part and the according Lorentzian fit. These eigenfrequencies correspond to mode shapes presented in Fig. 5. The interchange of these modes is excluded by measurements of FRF at various points on the micro mirror.



a) b) c) d)

Fig. 9: Extracted frequency ranges from the real part (dots) and Lorentzian fits (solid line):
a) 1st mode at fo_1= 8172.25,
b) 3rd mode at fo_2= 14977.11,
c) 5th mode at fo_3= 34113.90,
d) 6th mode at fo_4= 53852.06.

4. PARAMETER IDENTIFICATION

The parameter identification is the last step of the presented characterization method for MEMS devices. Also here the micro mirror array is used to explain the procedure. The results of the theoretical analysis and the eigenfrequencies determination are combined to determine the flexure's thickness and width as well as the built-in mechanical stress. Applying the least square error method one has to minimize the following function:

$$ResErr\left(th_s, w_f, \sigma\right) = \sum_{N=1}^{m}\left(fo\left(th_s, w_f, \sigma\right)_N - fo_N\right)^2\,, \tag{5}$$

where $fo(th_s, w_f, \sigma)_N$ denotes the polynomial for N-th eigenfrequency obtained from the numerical simulations, fo_N is the measured N-th eigenfrequency and m the number of determined eigenfrequencies. The obtained values for flexures thickness, width and built-in mechanical stress are effective parameters, valid for the whole micro mirror.

The verification of the calculated result one can perform by calculating the corresponding sets of geometrical parameters for the obtained stress value for every mode and plotting them as shown in Fig. 10. Now all curves must intersect in one point that gives the thickness and the width of the flexures. Table 2 lists the measured eigenfrequencies and the calculated parameters of two micro mirrors.

In order to validate the method the following experiment was performed. The micro mirror array was heated up from room temperature to 120 °C. It is obvious that no change of geometry but only of stress can occur. At certain temperatures the FRF were measured and eigenfrequencies calculated. The parameter identification yields the results shown in Fig. 11. As to be seen the built-in mechanical stress rises at increasing temperatures (Fig. 11 a) and b)). Fig. 11 c) and d) show geometrical parameters vs. temperature for the two investigated micro mirrors. One can see that the thickness remains nearly constant over the whole temperature range. The obtained maximum deviation is 0.09% for the first and 0.02 % for the second micro mirror. The flexure’s width varies up to 1.88 %. The reason for the higher deviation is that only out-off plane eigenfrequencies were measured which are mostly influenced by thickness and stress variation but less by the width variation.

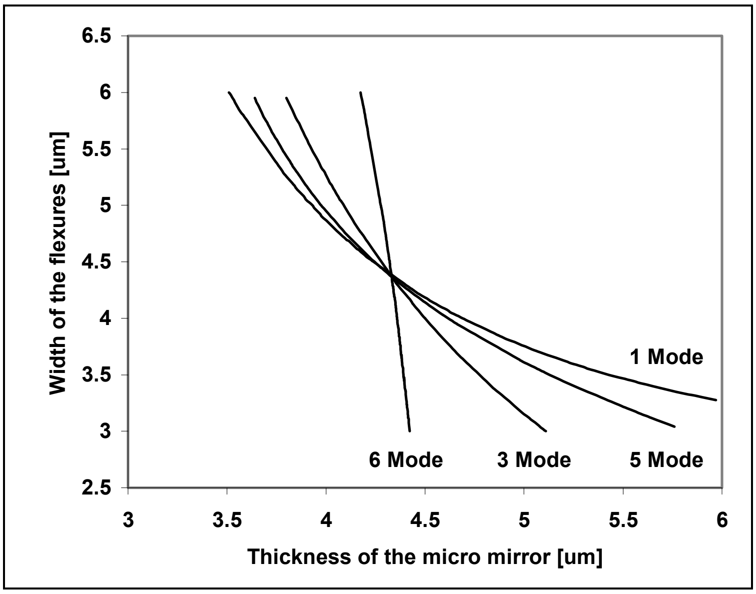
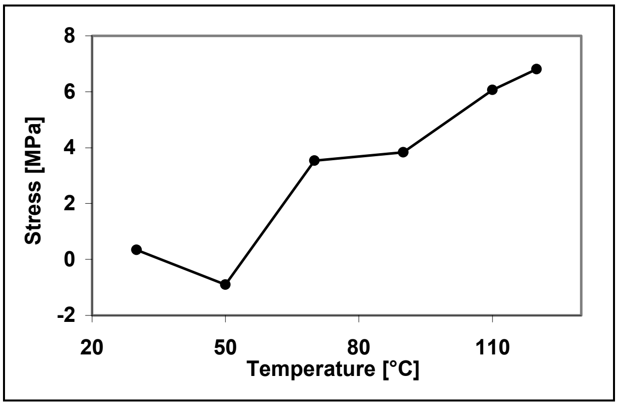


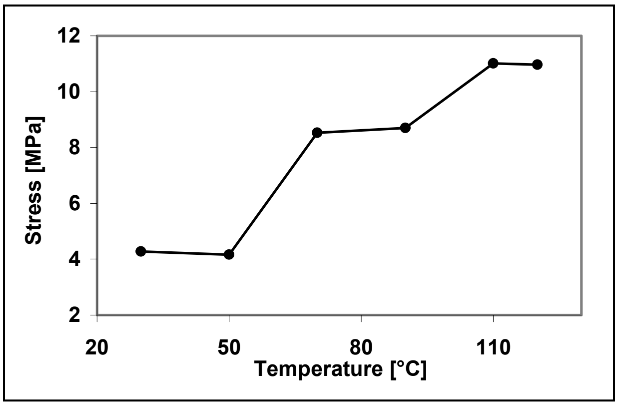
Fig. 10: Verification plot of geometrical parameters for given stress.

Table 2: Determined Eigen-frequencies and micro mirror parameters.

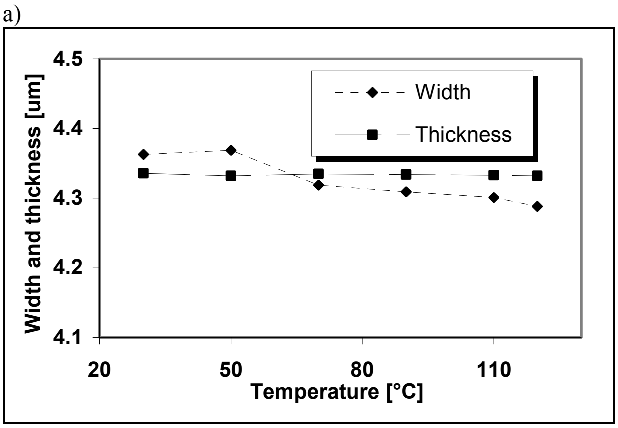
	Mirror 1	Mirror 2
fo_1 [Hz]	8172.25	8411.31
fo_2 [Hz]	14977.11	15662.23
fo_3 [Hz]	34113.90	34951.71
fo_4 [Hz]	53852.06	54059.29
th_s [µm]	4.336	4.343
w_f [µm]	4.363	4.296
σ [MPa]	0.350	4.275



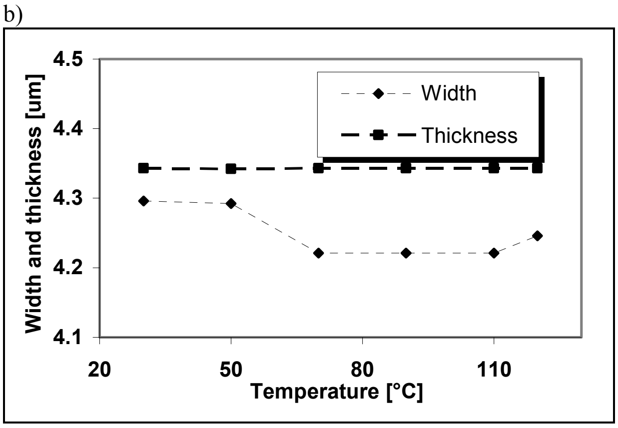
a)



b)



c)

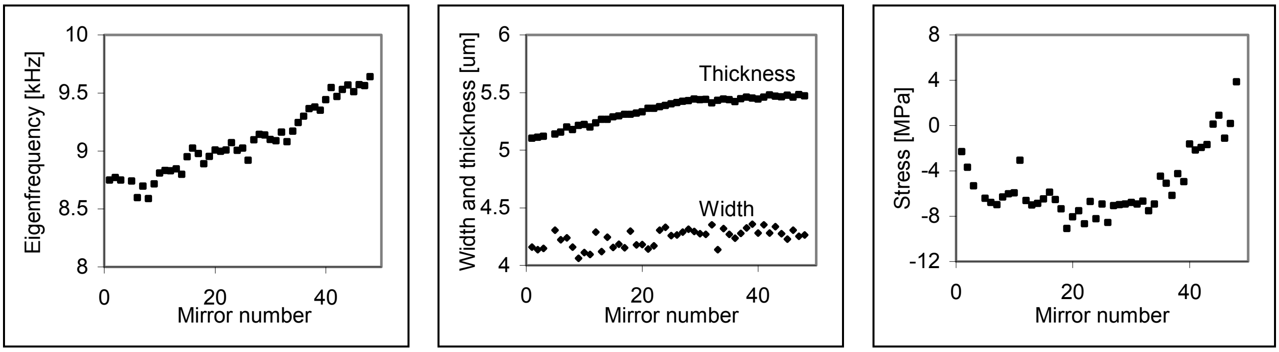


d)

Fig. 11: Determined geometrical parameters and built-in mechanical stress for the two selected micro mirrors:
a) built-in mechanical stress vs. temperature for the first micro mirror,
b) built-in mechanical stress vs. temperature for the second micro mirror,
c) thickness and width vs. temperature for the first micro mirror,
d) thickness and width vs. temperature for the second micro mirror.

5. RESULTS

The chosen micro mirror array is a very good example to demonstrate the performance of the developed method. Investigations regarding the first eigenfrequency yield strong deviations within an array. Fig. 12 a) illustrates the distribution of the first eigenfrequencies along array length. The maximum deviation amounts 1.05 kHz. It is expected, that the main reasons for this are differences of the flexure's cross sections and the variation of the built-in mechanical stress. In order to separate the influence of these three effects and to specify the contribution of each effect the characterization of the micro mirror array was performed. Fig. 12 b) shows obtained geometrical parameters of flexures. One can see thickness increases along the array from 5.1 µm up to 5.4 µm. According to the FEM simulation results this 0.3 µm change leads to 0.5 kHz change of the frequency. The width remains almost constant with respect to lower resolution. Using trend analysis the change estimates to 0.15 µm that corresponds to 200 Hz frequency change. The stress distribution in Fig. 12 c) shows strong variation along array. For the obtained maximum stress deviation of about 13 MPa the according frequency shift calculates to 0.9 kHz. Based on these results one can derive the influence of fabrication technology on properties of the micro mechanical system. Therefore the technological processes have to be known. For the investigated micro mirror array the calculated thickness variations are mainly caused by chemical mechanical polishing. Based on the obtained change of 0.3 µm over the array length of 7 mm the total thickness variation of the used 4 inch wafer estimates to 4.2 µm. This value is typical for commercially distributed wafers. The width variation is defined by lithography. The observed deviation is very low and caused by inhomogeneities of photo resist. The stress distribution in Fig. 12 c) can be explained by silicon fusion bonding and aluminum coating of micro mirrors. Both processes induce mechanical stress, but up to now they can not be separated.



a) b) c)

Fig. 12: Determined geometrical parameters and built-in mechanical stress for the micro mirror array.

6. SUMMARY

A novel characterization method for MEMS devices based on the combination of measurement and simulation results is introduced on the example of an electrostatically actuated micro mirror array. It enables determination of geometrical parameters as well as material properties like built-in mechanical stress. The base forms an exact numerical analysis of structure's behavior dependent on searched parameters. The advantage is that only the dependence of eigenfrequencies is calculated. They can precisely and time efficient be measured by a LDI. The combination of the calculated and the measured eigenfrequencies by the described parameter identification finally yields the results with sufficient accuracy. For MEMS fabrication trend analysis of the obtained data enables observation of technological processes. This novel characterization method gives an opportunity to develop an automatic measurement system for robust and efficient parameters determination in MEMS manufacturing.

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