Performance Analysis of Micro-Cantilever Beams and Sensor Data Fitting

Bai Yanping , Hao Yilong

Abstract**—**This paper investigates the specimen size influence on bending strength of microstructures cantilever beams. The vertical bending deflection of microfabricated polysilicon beams was evaluated. Because the original data contain noise terms, the data should be processed via wavelets analysis. The experiment results takes into account the effect of device geometry and elastic properties of the specimens, and agrees well with the results obtained by the theoretical line model for small deflection. The vertical deflection increases with increase in the beam length for a fixed beam width and thickness, decreases with increase in the beam width for a fixed beam length and thickness. And when vertical deflections of specimens are about less than 800nm, the relationship of force and deflection are linear. For larger displacements, non-linear terms will appear in the force-displacement relationship.

On the other hand, we used autoregressive models and genetic ARMA model to fit a set of sensor data. Fitting results show following conclusions. In the case of fitting model to determine, the regression model gets only a fitting curve. And yet genetic ARMA model of can get different the fitting parameters by adjusting the parameters of genetic algorithm, which provides an effective method according to different accuracy fitting curve.

Keywords**—** Artificial neural network, Cantilever beam, Micro-electro-mechanical system, Wavelet transformation, data fitting.

I. Introduction

Microelectromechanical System (MEMS) have been a promising technology for twenty years. It is the extension and development of Microelectronics. The recent focus of the MEMS world on optical applications of micromachined devices has pushed the field out of surface micromachining technology [1]-[3]. The mechanical design of MEMS is one of the frontiers of mechanical engineering. Micro mechanical cantilever-based sensors have also been widely used for a variety of optical applications in telecommunications, as well as in biomedicine [4]. The modeling for a micro electromechanical cantilever beam is a challenging task. Reference [5] gave a micro accelerometer configuration with four suspended symmetric beams and a central proof mass. The PZT thin film on each flexural beam is patterned into two transducer elements, thus eight piezoelectric transducers are arranged on four beams symmetrically to form the sensing devices in the structures. The flexible cantilever is the most important component of the strain type displacement sensors with high accuracy and high resolution. The material, structure and working accuracy of the flexible cantilever influence the performance of sensors directly, especially the sensitivity of sensors. Recently, micro accelerometers using piezoelectric thin film have drawn much research interest due to the miniaturization trend of electronic devices, their low cost and their suitability for batch manufacturing. Research has focused on the device's measurement capabilities and structural analysis and modeling to increase the sensitivity of the devices.

This paper investigates the specimen size influence on bending strength of microstructures cantilever beams. The bending deflection of microfabricated polysilicon beams with dimensions of 40-60μm long , 10 ~ 30μm wide , and 80nm thick was evaluated. The result shows that size effect of bending strength of cantilever beams microstructures on the specimens and the relationship of force and deflection are linear for small vertical deflection. For larger displacements, non-linear terms will appear in the force-displacement relationship. And In MEMS most of the parts are strictly nonlinear and finding a proper model is difficult or sometimes impossible. The constraints of this kind of model have motivated the development of artificial intelligent approaches [6]-[8].

In next sections, we organize as following. The structural analysis of cantilever beam is introduced in section 2. Size influence of cantilever beam specimens is presented in section 3. Sensor data fitting is showed in section 4. Finally, conclusions are given in section 5.

II. Structural Analysis of Cantilever Beam

Structural beams are a basic building block of most MEMS devices. A beam is, as the name implies, a long thin piece of material that often serves as the supporting basis for a structure.

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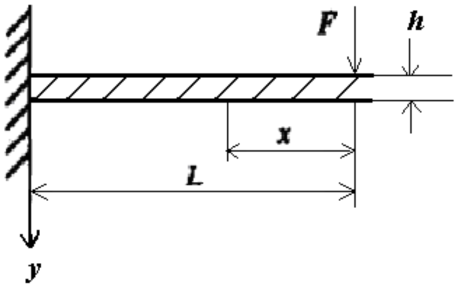


Fig.1 Configuration of a cantilever beam under transverse loading

One issue critical to understanding beams is understanding how they bend under different loadings. Fig. 1 illustrates the concept being described. The most common method to determine this involves the Euler-Bernoulli equation [9]:

$$\frac{d^2y}{dx^2} = \frac{M(x)}{EI} \tag{1}$$

Where x = direction along the neutral axis.
y = direction along the transverse axis.

E = Young's modulus.
I = area moment of inertia,

$$I = \frac{h^3 b}{12} \tag{2}$$

$M(x)$ = the bending moment in the beam, which is usually a function of x.

b = beam width, h = beam thickness, L = beam length, n=beam number.

For a cantilever beam, which is one of the most structural beams in MEMS, with the boundary conditions of $y(L)$=0 and $y'(L)$=0 and a force, F, applied at one end, the equation yields:

$$y(x) = \frac{F}{EI}\left(\frac{x^3}{3} - \frac{L^2 x}{2} + \frac{L^3}{3}\right) \tag{3}$$

Since Equation (3) describes a linear force-deflection relationship at a fixed point x, it is essentially describing a spring reacting to an applied load. This means that it is possible to extract a spring constant, k, from this expression. Evaluating y(x) at a specific point will determine the spring constant. For the specific point x=0, we have following formulation from equation (3):

$$y_{\max} = y(0) = \frac{FL^3}{3EI} = \frac{4FL^3}{Eh^3 b} \tag{4}$$

Rearranging this equation yields:

$$\frac{F}{y(0)} = \frac{Eh^3 b}{4L^3} = k \tag{5}$$

While this expression is useful for predicting displacement under a given load , there are some limitations to it that must be understood. Hooke's law only applies for small displacements. For larger displacements, non-linear terms will appear in the force-displacement equations, as in [9]. The degree to which this equation applies thus depends largely upon how large force is applied to the structure. Often, to simplify the development of devices, designers will construct structures that will operate solely within the linear regime. However it is important to understand that the linear force-displacement equation is only a first order approximation of the actual relationship between force and displacement.

III. Size Influence of Cantilever Beam Specimens

We consider an array of Polysilicon silicon cantilever beams configuration. . These beam arrays, which are designed by Fan Wei at the Institute of Microelectronics of Peking University, contain cantilever beams of four, eight, twelve suspended symmetric with various lengths and widths and a central proof mass. An example array is shown Fig. 2. These beams were designed to study vertical deflections of Micro-cantilever under

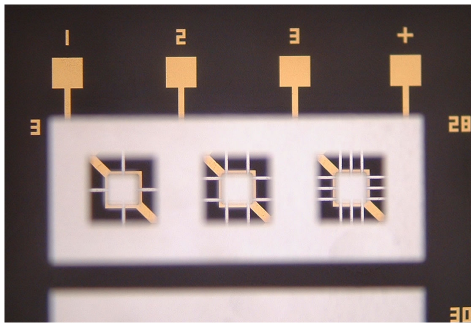


Fig.2 Micro-cantilever beams configuration

transverse loading. When the central mass is subjected to vertical vibration (force), the suspending beams can produce bend. One issue critical to understanding beams is understanding how they bend under different loadings. Because of the symmetry of the device structure, we have following formulation for small displacements by equation (4):

$$y_{\max} = \frac{4FL^3}{nEh^3 b} \tag{6}$$

Where n=beam number.

When the central mass is subjected to vertical force, the suspending beams can produce bend. We investigate the relationship of force and deflection on the mass under different loadings and analysis how large force applied to the structure can get the linear force-displacement relationship. For a set of experiment results, we approximate the data of force and deflection for small deflection by least-squares linear fitting curves algorithm. Fig. 3 gives the experiment results. When vertical deflections of specimens, which are arrayed with 4-24 symmetric beams number and various lengths and widths, are about less than 800nm, the relationship of force and deflection are linear. The mean of absolute errors of least-squares linear fitting are less than 8 nm for each data. Component dimensions of specimen configuration are marked in Fig. 3.

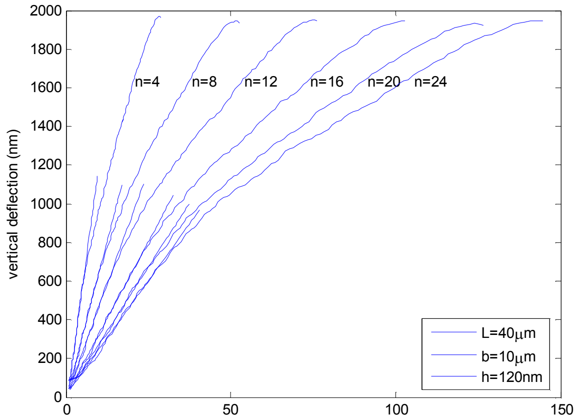


Fig. 3-1 vertical force (μN))

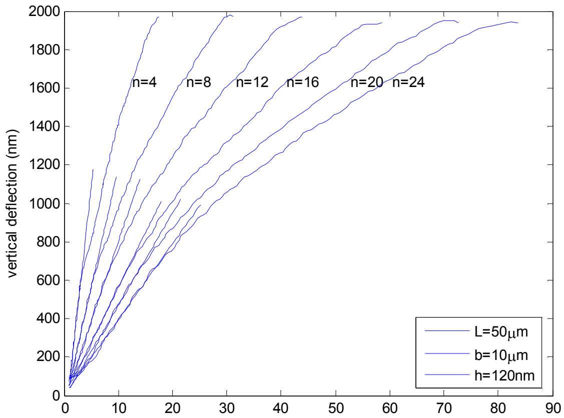


Fig. 3-2 vertical force (μN))

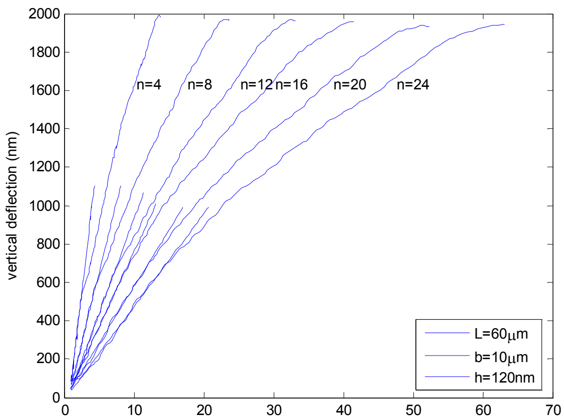


Fig. 3-3 vertical force (μN))

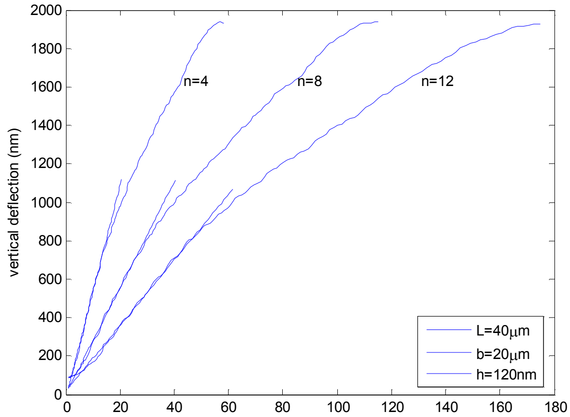


Fig. 3-4 vertical force (μN))

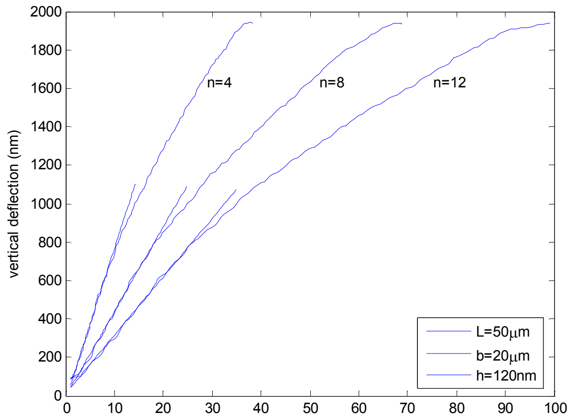


Fig. 3-5 vertical force (μN))

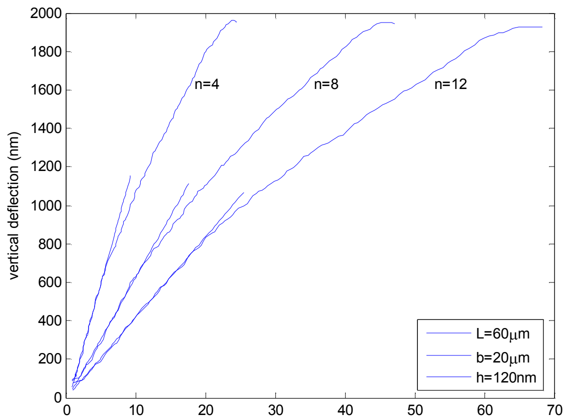


Fig. 3-6 vertical force (μN))

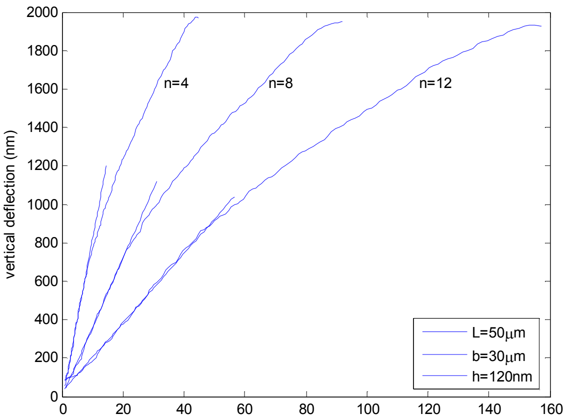


Fig. 3-7

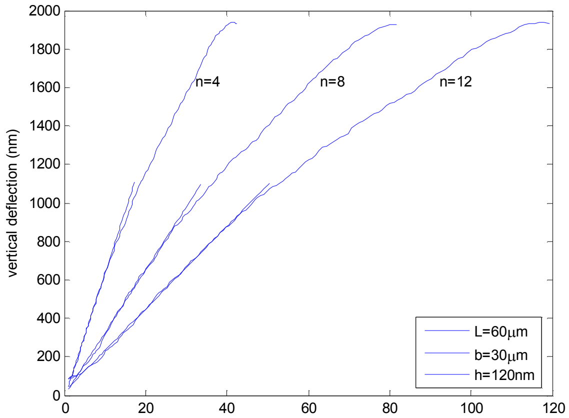


Fig. 3-8

Fig.3 The linear force-displacement relationship for small vertical deflection

Fig.4 gives the length influence. The vertical deflection increases with increase in the beam length for a fixed beam width and thickness with 4-24 beams number, respectively. In the analysis, it is found that both analytical model (6) and experiment results give very close results for small deflection about less than 800nm.

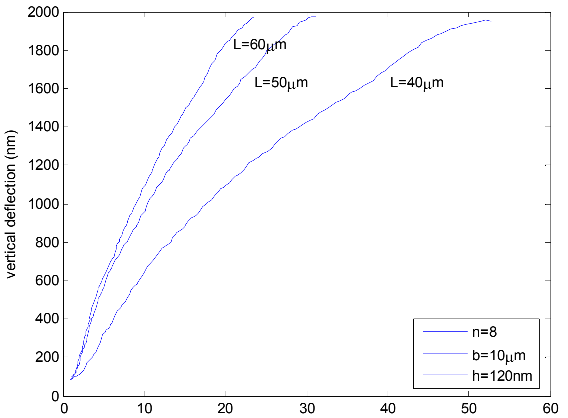


Fig. 4-1

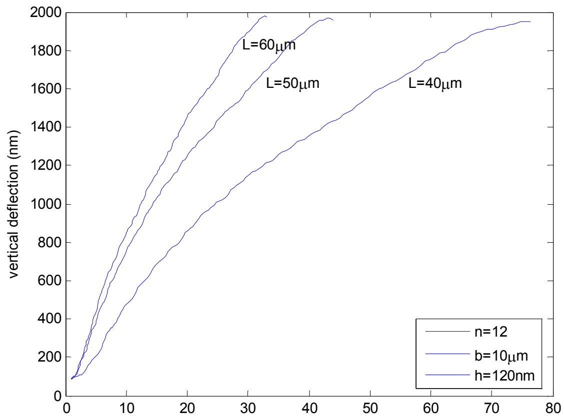


Fig. 4-2

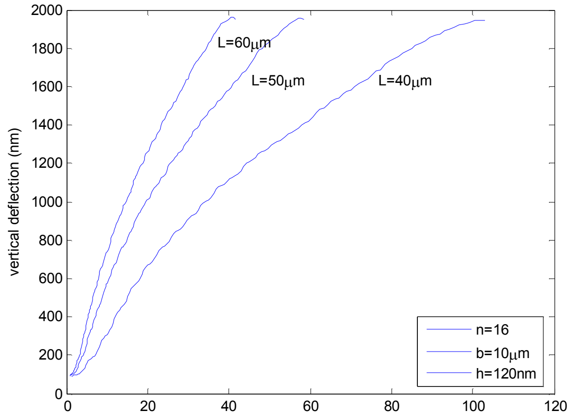


Fig. 4-3

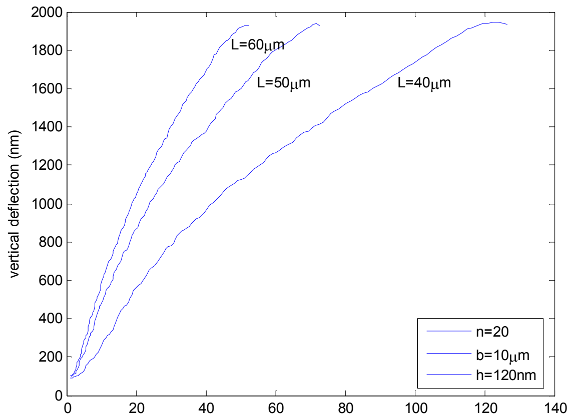


Fig. 4-4

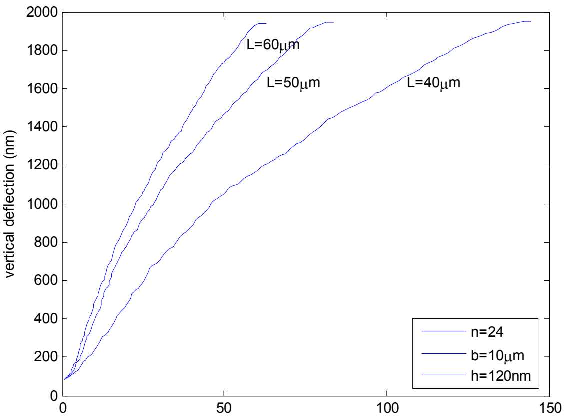


Fig. 4-5

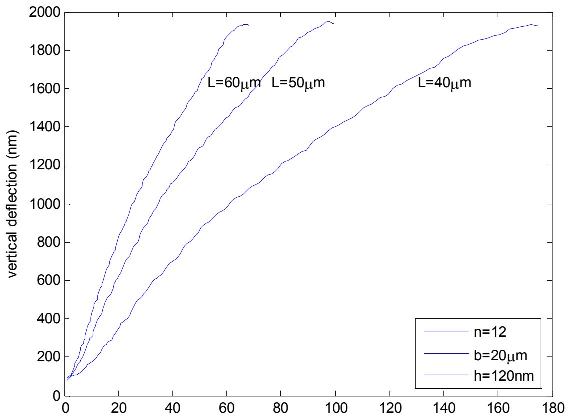


Fig. 4-8

Fig. 4 The length influence of vertical deflection

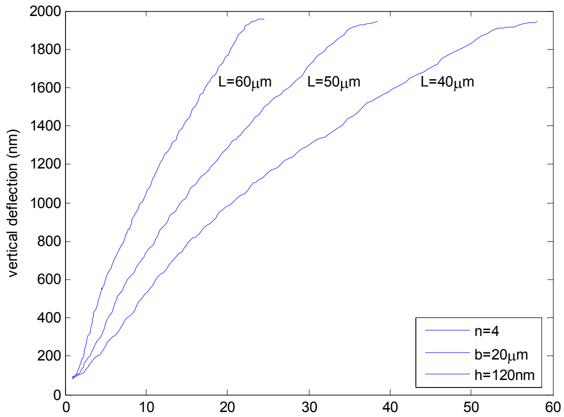


Fig. 4-6

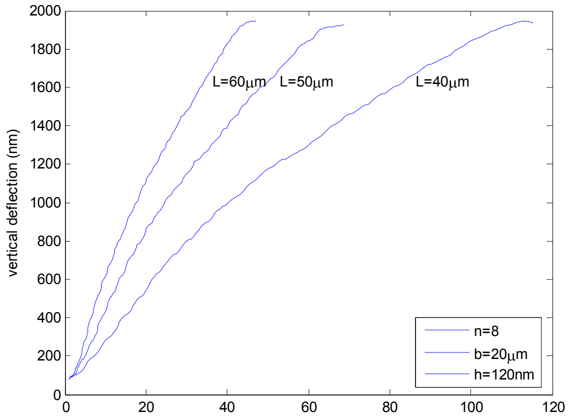


Fig. 4-7

Fig.5 gives the width influence. The vertical deflection decreases with increase in the beam width for a fixed beam length and thickness with 4-24 beams number, respectively. In addition, it is found that the experiment data in fig.5-1 are little different with analytical model for small deflection. The results of this study can be applied to sensitivity analysis of piezoelectric microaccelerometer. Appropriate geometrical dimensions of structural beams can achieve high accelerometer sensitivity

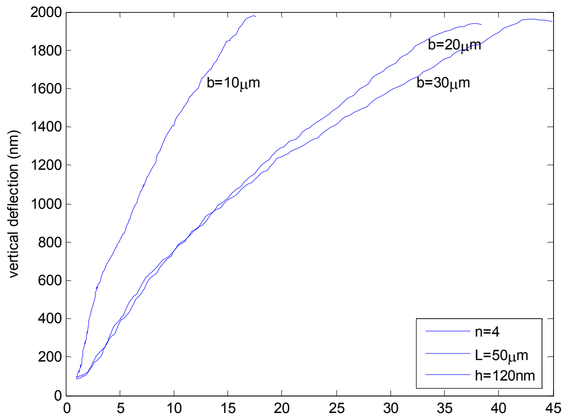
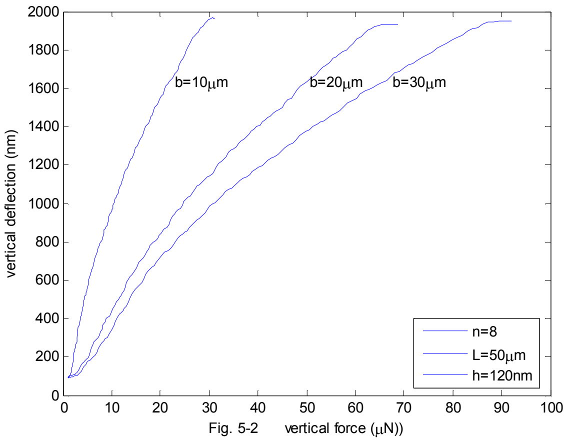
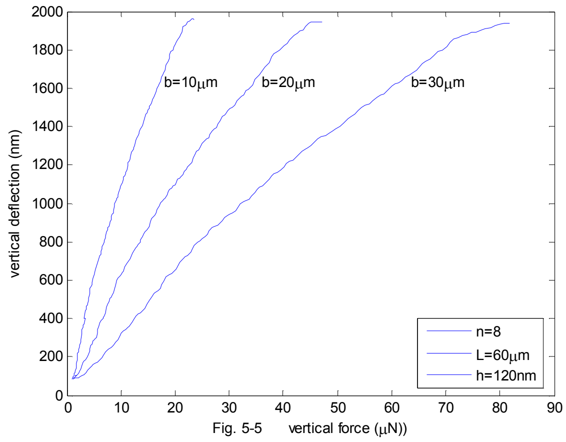
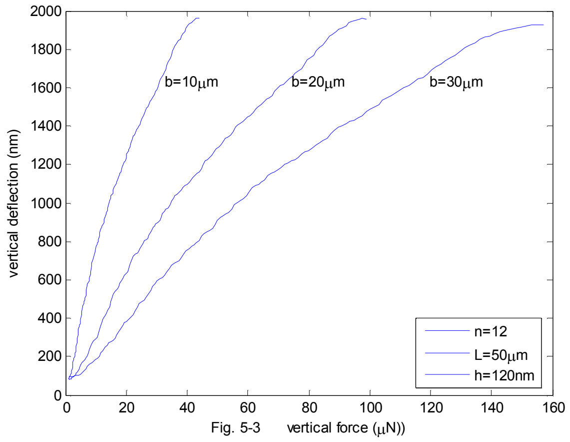
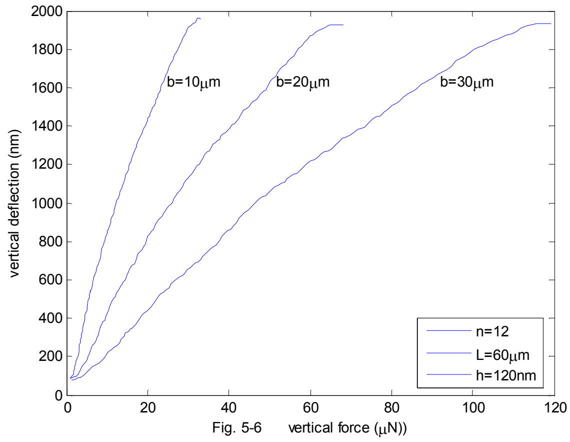


Fig. 5-1









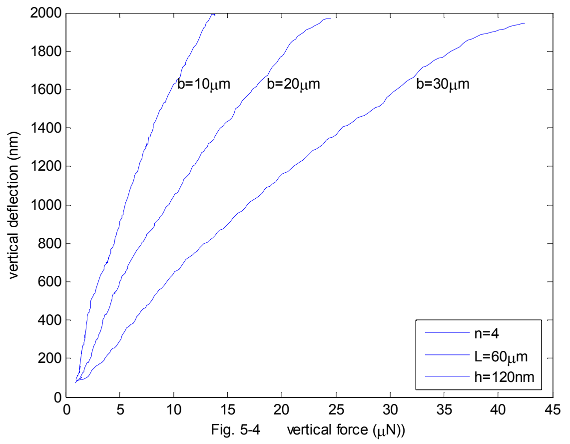


Fig. 5 The width influence of vertical deflection

IV. SENSOR DATA FITTING

We used autoregressive models and genetic ARMA model to fit a set of sensor data. ARMA model is a more mature model, which is used Short-term forecasting and data fitting[10].

A. AR Model

AR model is also known as self-regression model. It is through the prediction by the linear combination of observations value in the past and the interference at present. The mathematical formula for the regression model as following:

$$Y_t=\Phi_1 Y_{t-1}+\Phi_2 Y_{t-2}+\cdots+\Phi_p Y_{t-p}+e_t \tag{7}$$

Where p is the order of autoregressive model;

Φ_i $(i=1,2,\ldots,p)$ is the coefficients for the model;

e_t for the error;

Y_t as a time series.

B. MA Model

MA model is also known as the moving average model. It is through the forecast by the linear combination of the interference value in the past and present. The mathematical formula for the moving average model as following:

$$Y_t = e_t - \theta_1 e_{t-1} - \theta_2 e_{t-2} - \cdots - \theta_q \ e_{t-q} \tag{8}$$

Where q is the order of autoregressive model;

θ_j (j=1,2,…,q) is the coefficients for the model;

e_t for the error;

Y_t as a time series.

C. ARMA Model

Combination of the regression model and moving average model constitute the autoregressive moving average model (ARMA Model), which is used to describe stationary random process. The mathematical formula for ARMA model as following:

$$Y_t = \Phi_1 Y_{t-1} + \Phi_2 Y_{t-2} + \cdots + \Phi_p Y_{t-p} + e_t - \theta_1 e_{t-1} - \theta_2 e_{t-2} - \cdots - \theta_q \ e_{t-q} \tag{9}$$

D. Genetic ARMA Model

Genetic Algorithm (Referred to as GA) was first put forward by the United States Professor John H. Holland and his students of University of Michigan in the 60 years of the 20th century [11]. GA is also known as simulated evolutionary optimization algorithm, which basic idea is to simulate biological and human evolution method to solve complex optimization problems [12]-[13]. Genetic algorithm can not rely on any external knowledge of the search space, only the fitness function to guide and optimize the search direction. This flexibility makes it possible that the genetic algorithm is used in design of autoregressive, which can overcome the shortcomings of traditional training algorithm [14]. Genetic algorithm in the application of autoregressive model is mainly a fixed regression structure and only the coefficient optimized in regression model. The specific applications of genetic ARMA model as follows:

(1) Code and population generation, training parameters are given; This article describes the model will use floating-point encoding. The initial parameter values and the initial population are gotten by GAOT initialization function in Genetic Toolbox. The initialization of the initial range of parameter values can be selected in the interval [-1,1].

(2) Calculation of individual fitness; Here individual fitness function is the error sum of squares. We are seeking squared error (objective function) of the minimum.

(3)Genetic operations (crossover, mutation, selection); Produce a new generation of individuals out of the individual of parent; Up to the maximum evolution generation or generate the optimal solution. This step is the ARMA model trained with genetic algorithms, which obtain the initial model parameter values.

(4) Iterative computation (specified times) until the specified accuracy; If you do not achieve the accuracy, transfer (1) re-training of the network structure and initial weights and thresholds.

(5) Output parameter values at this time, the end of training.

E. Sensor Data fitting

We fit a set of sensor data by using autoregressive models and genetic ARMA model. The blue curve represents the set of data in Fig. 6.2. That τ is horizontal axis. σ 2 is Vertical axis. In accordance with the theoretical analysis, We need the data fitted the following function:

$$\sigma^2 = k_1\tau^2 + k_2\tau + k_3 + k_4\tau^{-1} + k_5\tau^{-2} \tag{10}$$

We used autoregressive model fitting this data set. The fitting coefficient as following:

K= (-0.00010378 0.92733 -114.84 2918.1 -910.06)

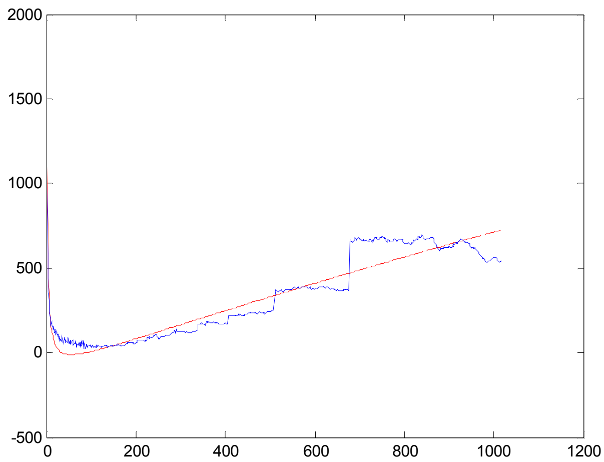


Fig. 6 The curves of Cartesian coordinates fitted by autoregressive model

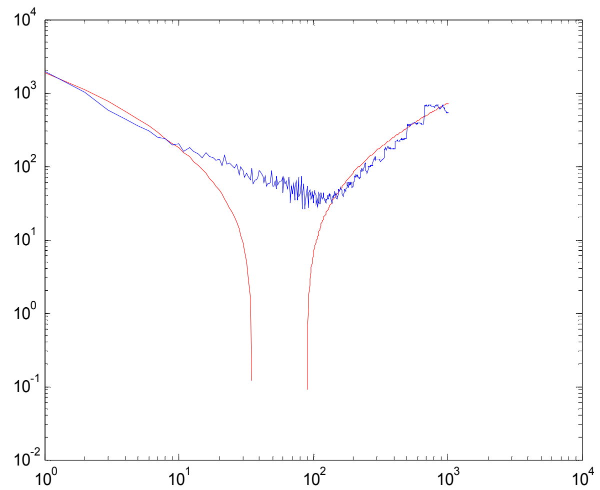


Fig. 7 Autoregressive model fitting the log-log curve

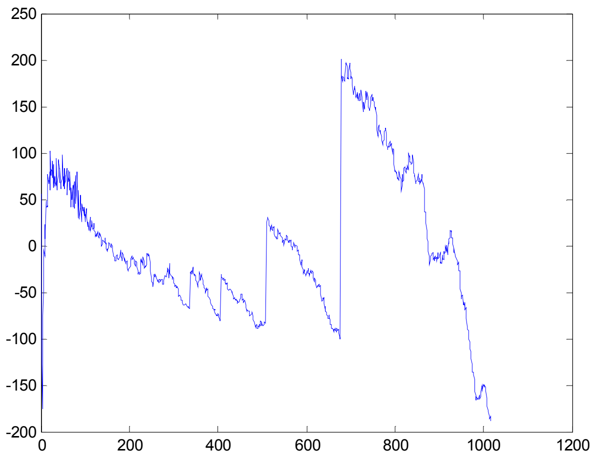


Fig. 8 The error curve fitted by autoregressive model

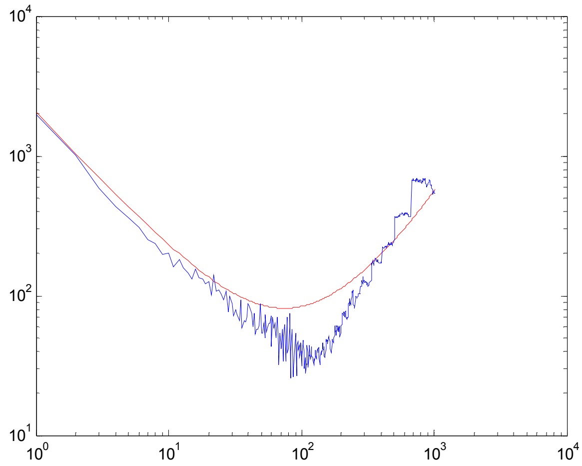


Fig. 10 Genetic ARMA model fitting the log-log curve

The fitted curves of Cartesian coordinates is represented in Fig. 6. Fitting log-log curves is shown in Fig. 7. Figure 8 that is the error curve.

We used genetic ARMA model 1 fitting this data set. The fitting coefficient as following:

K= (0.25253 0.21642 0.004625 0.00218 1.1107e-008)

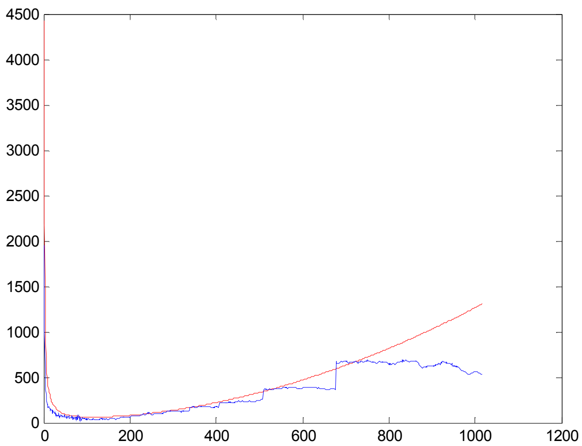


Fig. 9 The curves of Cartesian coordinates fitted by genetic ARMA model

The fitted curves of Cartesian coordinates is represented in Fig. 9. Fitting log-log curves is shown in Fig. 10. Figure 11 that is the error curve.

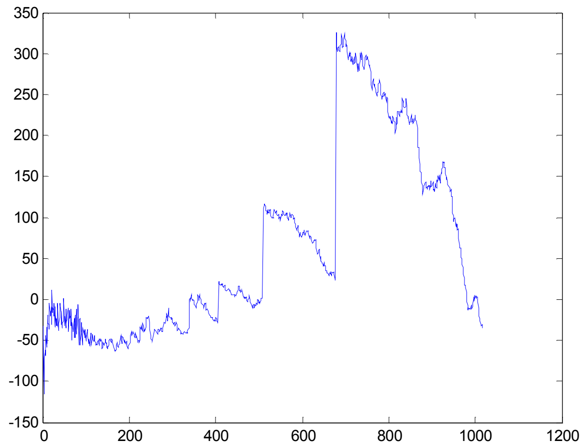


Fig. 11 The error curve fitted by genetic ARMA model

From the above fitting curve we can get following conclusions. In the case of fitting model to determine, the regression model gets only a fitting curve. And yet genetic ARMA model of can get different the fitting parameters by adjusting the parameters of genetic algorithm, which provides an effective method according to different accuracy fitting curve.

V. Conclusion

In this paper, we present a theoretical model and neural networks modeling of an array of micro-cantilever beams configuration, which contain 4-24 symmetric beams with various lengths and widths and a central proof mass. These beams were designed to study static deflections of Micro-cantilever under transverse loading and size influence. The experiment results takes into account the effect of device geometry and elastic properties of the specimens, and agrees well with the results obtained by the theoretical model for small deflection. When vertical deflections of specimens are about less than 800nm, the relationship of force and deflection are linear. The mean of absolute errors of least-squares linear fitting are less than 10 nm for each data. This study shows that the vertical deflection increases with increase in the beam length for a fixed beam width and thickness and the vertical deflection decreases with increase in the beam width for a fixed beam length and thickness with 4-24 beams number, respectively. The results of this study can be applied to sensitivity analysis of piezoelectric microaccelerometer.

This paper also describes the regression model and the genetic ARMA model used data fitting. Genetic algorithm has Global search ability. Search does not rely on gradient information. It is using individuals, containing of the groups of the solution in the specific issue, selection, crossover and mutation operations to simulate the biological evolution. Because the genetic algorithm has a high implicit parallelism the search efficiency is significantly. we used autoregressive models and genetic ARMA model to fit a set of sensor data. Fitting results show following conclusions. In the case of fitting model to determine, the regression model gets only a fitting curve. And yet genetic ARMA model of can get different the fitting parameters by adjusting the parameters of genetic algorithm, which provides an effective method according to different accuracy fitting curve

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F. A. Author Thanks Fan Wei, which is a graduate student of Institute of Microelectronics of Peking University in China. He designed an array of Micro-cantilever beams which contain 4-24 symmetric beams with various lengths and widths and a central proof mass and provided experimental data.

F. A. Author Thanks Chi Xiaozhu, which is a postdoctoral fellowship of Institute of Microelectronics of Peking University. She provided a set of sensor data.

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