Influence Function Measurement Technique Using the Direct and Indirect Piezoelectric Effect for Surface Shape Control in Adaptive Systems

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Influence Function Measurement Technique Using the Direct and Indirect Piezoelectric Effect for Surface Shape Control in Adaptive Systems

James M. Muganda, Bas Jansen, Erik Homburg, Yoeri van de Burgt, and Jaap den Toonder

Abstract—Since the introduction of adaptive systems for corrective measures, static and dynamic disturbances have been reduced through the manipulation of surface shape in a well-controlled manner. One important application where adaptive systems are highly needed is in the future photo-lithography machines, particularly the wafer table where disturbances affect overlay and focus performance. To reduce overlay and focus errors, a dense array of actuators must be integrated into the wafer table to apply both in- and out-of-plane corrective deformations to the wafer surface. To realize a certain wafer shape, influence functions are linearly superimposed. Accurate models of the influence functions result in an accurate prediction of the final wafer shape. To reduce calibration errors, the influence function of every actuator needs to be determined. Here, we propose a technique to rapidly measure the influence function: the influence function measurement (IFM) technique. Using the actuate-sense property of piezoelectric materials, the influence function is determined by activating one piezo-actuator and measuring the charge induced on the neighboring piezo-actuators. The measured charges are compared to the results of finite element simulations and the absolute difference of 0.3 % is reported for the inter-actuator charge coupling parameters. This clearly indicates the potential of the proposed technique.

Note to Practitioners—A critical step during the integrated-circuit lithographic fabrication process is the exposure. A particular practical challenge in this step is to correct for the mismatch between the optical image plane and the wafer surface, caused by wafer deformations. The mismatch negatively impacts the overlay and focus performance. To reduce the mismatch, actuators can be embedded into the wafer table to counteract wafer deformations, where the overall wafer surface shape is a superposition of each actuator’s influence function. As part of the calibration for the embedded actuators, their influence functions are measured and stored. However, errors arise when influence functions are not measured for every actuator. Additionally, for different wafers, the influence functions vary hence the calibration should be done per wafer. This calibration process takes time and should not influence throughput. Our paper presents a viable approach that reduces the calibration time of active wafer tables, which is also relevant for other adaptive systems such as deformable mirrors. Since the technique requires the actuators to be mechanically coupled, it is limited to continuous surfaces. The proposed technique is numerically tested and experimentally verified to demonstrate performance.

Index Terms—Actuators, charge amplifier, focus, influence function, manipulators, overlay, piezoelectric effect, shape control, throughput, wafer.

I. INTRODUCTION

Surface shape control is the act of manipulating the surface of materials in a well-controlled manner using embedded active elements [1]. Its importance has been documented ever since the advent of adaptive optics in addressing atmospherically induced wavefront aberrations using deformable mirrors [2]. The principle involves actuating the mirror surface in the out-of-plane direction to produce a conjugated mirror surface to the aberration. Optical wavefront sensors are used to measure the aberrated wavefront and corrections are done in real-time. Upon the success of deformable mirrors, the same principle was applied to the correction of eye-induced wavefront aberrations [3].

Another emerging application for surface shape control is in wafer tables used in photo-lithographic machines. A photolithography machine is a tool used in the production of microchips in a process called the exposure step, see Fig. 1. During exposure, a wafer is clamped tightly to the wafer table and the mask patterns are optically transferred to the wafer with the help of a photo-sensitive layer. For a successful transfer, the image plane should be matched to the wafer surface since any mismatch introduces so-called focus errors (out-of-plane) and overlay errors (in-plane) resulting in an incorrect image on the wafer [4]. The main causes of the mismatch are local and global deformations on the wafer surface due to wafer heating, wafer-table contamination, and other fabrication processes such as etching and chemical mechanical polishing. To reduce the mismatch and keep the focus and overlay errors minimal, actuators can be embedded within the wafer table capable of applying both in-plane and out-of-plane corrective deformations to the wafer surface; this concept is called the active wafer table [5]. Thus, for many practical applications, research into surface shaping systems is essential.
Calibration of the complete surface shaping system involves measuring the influence function of each actuator and storing it in an influence function matrix. The influence function quantitatively describes the effect of activating one actuator while the rest of the actuators are connected to a common offset voltage, usually zero volts [6]. For open-loop systems, high accuracy in measuring the influence function is required in order to predict the final shape and hence the real performance of the system. For multiplane systems, the accompanying influence functions for each plane are required hence the influence function matrix is plane-dependent.

For deformable mirrors (single-plane actuation), influence functions are measured during the calibration process using external optical wavefront sensors such as the Shack–Hartmann [7] and interferometer-based sensors [8]. Both sensors have a limited sampling frequency from 30 Hz up to 2 kHz [9], [10] depending on the measurement area. The sampling frequency is inversely proportional to the measurement area [11]. In addition, the influence function matrix is assumed to be invariant throughout the operation of the deformable mirror since the mirror thickness is fixed. Hence, the influence function measurement (IFM) procedure is carried out only once.

For wafer tables (multiplane actuation), the influence function matrix is wafer-dependent. This dependence occurs because the actuators are embedded in the wafer table, onto which the wafer is clamped and every wafer is different from another due to wafer fabrication processes [12]. Hence the influence function matrix for each wafer needs to be determined for each exposure step, preferably without compromising machine throughput. Additionally, both in-plane and out-of-plane influence functions are needed. It is challenging to use conventional optical wavefront sensors since they are limited to out-of-plane sensing. Alternatives are other position sensors such as strain gauges and capacitive sensors; however, given the limited space and the large number of actuators, it becomes complex and costly to add external sensors in the wafer table.

In most cases, due to the high number of actuators (in the order of thousands), only a few strategically chosen actuator’s influence functions are measured in order to reduce the calibration time. For the remaining actuator’s influence functions, either the rest of the influence functions are assumed identical, or influence function fitting models are used. Among the fitting models, a widely employed method is the Gaussian influence function fitting [13]. Zernike polynomials have also been used for fitting the influence function due to their enhanced flexibility [14]. However, both cases introduce errors in the influence function matrix as the influence function might differ due to inhomogeneous actuator distribution, varying actuator stiffness, different actuator sensitivities to the driving signal, and actuator clamping conditions. The errors from fitting also affect the accuracy of the influence function matrix.

The IFM technique, we propose here, overcomes these issues by rapidly measuring all in- and out-of-plane influence functions for every wafer and before each exposure step. This allows the wafer table to have an influence function matrix best suited for the particular wafer being exposed, throughout the process. We focus on the ability of piezoelectric elements to actuate and sense [15]. In fact, piezoelectric elements are a popular choice because of their high stiffness, fast response time, low power dissipation, and virtually unaffected performance after many cycles [16].

For piezoelectric elements, the typical response time for a well-clamped element is in the order of microseconds (∼30 μs) resulting in sampling frequencies around 12 kHz; a factor of six faster than the conventional sensors.

A drawback of piezoelectric elements is their nonlinearity due to hysteresis, creep, and they often require hundreds of volts to achieve several micrometers of stroke [17]. To circumvent hysteresis, piezo-actuators are charge-driven [18]. To reduce the high voltages required for actuation, stacked piezo-actuators are used [19]. In this study, finite element simulations are used in the design process and the simulations are validated experimentally. The main purpose of this article is to present the findings of the IFM concept for a simple 1-D setup. The main purpose of the experiments is to verify and validate the IFM concept by comparing experimental results with numerical simulations.

Organization: The outline of this article is as follows. Section II explains the influence function, the direct, and indirect piezoelectric-effect. Section III describes the IFM technique, the finite element model, and the measurement setup. In Section IV, the finite element simulations are experimentally validated. Section V contains discussions about the IFM. Section VI discusses the conclusion and future work on the IFM technique.

II. BACKGROUND

A. Influence Function

In practice, the influence function is obtained by measuring the surface displacements when a given voltage is applied to one actuator while another common offset voltage is applied
The force per unit length \( q \) modulus of the foundation is the distributed in meters, positive downward as in Fig. 2. The constant \( k \) per unit length \( p \) is the Young's modulus of the beam and has dimensions N/m². Assuming that the length \( L \), and a width \( w \) that is supported along its entire length in the \( x \)-direction at a pitch \( p \) and with spring constant \( K \), see Fig. 2. The force per unit length \( q \) that resists the displacement of the beam is equal to \( ky(x) \). Here \( y(x) \) is the beam deflection in meters, positive downward as in Fig. 2. The constant \( k \) is the distributed modulus of the foundation and is given by \( k = K / p \) and has dimensions N/m². Assuming that the length of the beam is much greater than its thickness and width, the structural model can be modeled using the Winkler model [22].

The deflection \( y(x) \), subject to a reaction \( q \) and applied load per unit length \( p \), for a condition of small slope must satisfy the beam equation

\[
EI \frac{d^4y(x)}{dx^4} + ky(x) = p
\]

where \( E \) is the Young's modulus of the beam and \( I \) is the area moment of inertia of the beam. For those parts of the beam for which \( p = 0 \), (1) takes the form

\[
EI \frac{d^4y(x)}{dx^4} + ky(x) = 0.
\]

The general solution may be written as

\[
y(x) = -\frac{e^{\beta x}}{\beta} (A_1 \sin \beta x + A_2 \cos \beta x) + e^{-\beta x} (B_1 \sin \beta x + B_2 \cos \beta x)
\]

where \( A_1, A_2, B_1, \) and \( B_2 \) are constants and

\[
\beta = \left( \frac{k}{4EI} \right)^{\frac{1}{2}}.
\]

Assuming an infinite beam with a concentrated load \( P \) at the center of the beam, the particular solution is

\[
y(x) = -\frac{\beta P}{2k} e^{-\beta x} (\sin \beta x + \cos \beta x).
\]

The concentrated reactions \( F_i \) are replaced by equivalent uniform distributed forces given by

\[
F_i = K \cdot y_i
\]

where \( i \) represent the spring location and \( y_i \) is the beam deflection at the corresponding spring location. Equation (6) is crucial to the operation of the IFM technique. Next, we replace the springs with the actual elements and in our case, piezoelectric elements.

### B. Piezoelectric Elements

The microscopic nature of some materials and in particular piezoelectric elements renders them useful as energy converters. Piezoelectric elements have the ability to convert mechanical energy into electrical energy and vice versa. Examples of such materials are barium titanate, lithium niobate, and lead zirconium titanate. Their applications are found in sonar devices for detection and ranging, gas lighters, airbag sensors, and parking sensors [16].

### C. Direct and Indirect Piezoelectric Effect

When piezoelectric elements are subjected to mechanical stresses, they generate a charge proportional to the stress applied. This is called the direct piezoelectric effect and it allows piezoelectric elements to be used as force sensors. Conversely, piezoelectric elements become mechanically strained when subjected to an external electric field and the strain is proportional to the applied electric field. This is called the indirect piezoelectric effect and it allows the piezoelectric elements to be used as actuators [23].

Equation (7) is the constitutive set of equations in matrix form that guide both the direct and indirect piezoelectric effect according to the IEEE notation given in the strain-charge form [24]

\[
\begin{bmatrix}
S \\
D
\end{bmatrix} =
\begin{bmatrix}
\varepsilon & d' \\
d & \varepsilon^T
\end{bmatrix}
\begin{bmatrix}
T \\
E
\end{bmatrix}.
\]

\( S \) and \( T \) are the vectors containing the mechanical strain and mechanical stress, respectively, \( s \) is the elastic compliance tensor, \( d \) is the piezoelectric coefficient matrix, \( \varepsilon \) is the relative permittivity matrix of the piezoelectric material, \( D \) and \( E \) are the vectors containing electric displacement and electric field, respectively. The superscripts \( E \) and \( T \) refer to constant electric-field and mechanical stress boundary conditions, respectively.

The linear and quasi-static physical representation of the piezoelectric transducer acting on a load with dominant electric and mechanical behavior, see Fig. 3. These behaviors are coupled with the piezoelectric coefficient \( d \). The electrical behavior comprises of three parallel components, a capacitance \( C \), internal charge source \( Q \), and internal voltage sensor \( u_p \).

The mechanical behavior comprises of internal actuator stroke \( x_{int} \), actuator stiffness \( K \), damping coefficient \( b \), internal force sensor \( f_p \), the force \( F \) generated by acting on mass \( M \), and \( X \) is the external displacement. With this representation, (7) can be replaced by a new set of equations that describes this specific case given in the form

\[
\begin{bmatrix}
X \\
Q
\end{bmatrix} =
\begin{bmatrix}
K^{-1} & d' \\
d & C
\end{bmatrix}
\begin{bmatrix}
F \\
U
\end{bmatrix}
\]
where $U$ is the external driving voltage. This form will be used throughout this article.

III. IFM TECHNIQUE

A. Principle

The IFM technique employs the actuate and sense ability of piezoelectric elements to determine the influence function. Assume a simple case that consists of two actuators (A and B) that are mechanically coupled by a beam fixed on both ends, see Fig. 4. If actuator A is activated by applying a voltage $U$, it generates a mechanical force $F_{A \rightarrow B}$ that is transmitted through the beam to actuator B causing the beam to deflect. Actuator B senses the mechanical force $F_{A \rightarrow B}$ and through the direct effect, a charge $Q_B$ is generated and at the same time it deforms by an amount $X_B$. By measuring $Q_B$ using a charge amplifier, we can work backward to measure the force $F_{A \rightarrow B}$ and ultimately $X_B$. Although the overall study goal is to estimate the beam deflection, in this article we consider the charge measurements necessary for estimating the beam deflections.

We demonstrate the IFM technique for the measurement of the out-of-plane charge influence function of a beam that is being actuated in the out-of-plane direction. We consider a beam that is supported by nine equidistantly distributed piezoelectric actuators ($a_1, a_2, a_3, \ldots, a_9$), see Fig. 5. We assume the actuators to be able to push and pull the beam. When the centermost actuator $a_5$ is activated (by supplying it with a high voltage $U$ – green components in Fig. 5), while the rest of the actuators are connected to the charge amplifiers, the beam deflects resulting in influence function of actuator $a_5$. Consequently, forces $F(x)$ are transmitted through the beam to the rest of the actuators given by (6) resulting in charge generation on the rest of the actuators.

When $F(x)$ is evaluated at the 8 neighboring actuator locations, the charges generated are given by

$$Q_i = d \cdot F_i$$

where $i$ is the location of the actuator. We define the set of $Q_i$ as the charge influence function. Strictly, if we assume symmetry, $i$ is limited to only half of the actuators. We focus on measuring the charge influence function indicated in Fig. 5 by $Q_6, Q_7, Q_8$, and $Q_9$. In practice, charge amplifiers are used to convert the generated charge to voltage (indicated in Fig. 5 by the sensing charge amplifiers with output voltages $V_{o6}, V_{o7}, V_{o8}$, and $V_{o9}$).

B. Finite Element Model

A finite element package is used to investigate the IFM technique. The model consists of a beam connected to the actuator layer and which is in turn connected to the base. Table I shows the dimensions of the beam, actuators, and base, along with the materials used.

Table II shows the piezoelectric material properties used in the model. A total of nine actuators is used, at an actuator pitch of 18.55 mm. Actuator properties are modeled using the available XYZ piezoelectric actuators that are supplied by PI Ceramics. Actuator properties are adapted from the specifications provided by the supplier. Table III shows the actuator properties used.
The electrical behavior of the IFM technique is modeled using the Electrostatics Module, whereas the mechanical behavior is modeled using the Structural Mechanics Module within the COMSOL Multiphysics® environment. In practice for charge generation to occur, a dynamic excitation is required. Hence, a time-dependent study is employed. The centermost actuator was activated with a sinusoidal input with a frequency of 100 Hz and an amplitude of 50 V. During actuation, the neighboring actuator electrodes are probed for charge measurement and this charge will be compared to the experimental charge.

### C. Measurement Setup

1) Mechanics: The components described in Section III-B are used to construct the physical device with the same dimensions and materials. First, the actuators are glued to the beam using two-component adhesive with the help of an aligner to accurately position the actuators, see Fig. 6(a). Next, the beam-actuators part is glued to the base that is already secured to a fixed table, see Fig. 6(b). The glue is allowed to cure for 24 h before experiments can be done.

2) Electronics: For actuation, a commercial voltage amplifier from PI Ceramic is used. A low voltage sinusoidal signal is generated by a data acquisition board (DAQ) from National Instruments. The analog output channel of the DAQ board is connected to the input of the amplifier where it is amplified ten times. The amplified signal is fed to the longitudinal electrode of the center-most piezoelectric actuator. This is the actuator whose charge influence function is to be measured. For sensing, a custom-made charge amplifier board is employed based on the LTC6241 voltage amplifier from Linear Technologies®. The voltage amplifier is chosen based on its very low input bias current. The charge amplifier circuit is shown in Fig. 7(a). The feedback capacitor $C_f$ is chosen to fix the gain resulting in

$$U_{out} = \frac{1}{C_f} \cdot Q_i \quad (10)$$

where $U_{out}$ is the output voltage of the charge amplifier and $Q_i$ is the charge generated by the piezoelectric actuator. Notably, a charge amplifier has a similar frequency response to high-pass filters and the cutoff frequency $f_c$ is determined by the feedback resistance $R_f$ in such a way that

$$f_c = \frac{1}{2\pi C_f R_f} \quad (11)$$

Table IV shows the values used in the charge amplifier board.

### IV. RESULTS AND ANALYSIS

#### A. Charge Amplifier Characterization

The first step in the measurement procedure is to characterize the response of the custom-made charge amplifier board in terms of linearity and frequency response. The board consists of a total of four individual charge amplifiers.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$\rho$</td>
<td>kg/m³</td>
<td>7800</td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>$\varepsilon_{31}/\varepsilon_0$</td>
<td></td>
<td>1750</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_{33}/\varepsilon_0$</td>
<td></td>
<td>1650</td>
</tr>
<tr>
<td>Piezoelectric charge coefficient</td>
<td>$d_{31}$</td>
<td>$10^{-12}$ C/N</td>
<td>-180</td>
</tr>
<tr>
<td></td>
<td>$d_{33}$</td>
<td>$10^{-12}$ C/N</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>$d_{15}$</td>
<td>$10^{-12}$ C/N</td>
<td>550</td>
</tr>
<tr>
<td>Elastic compliance coefficient</td>
<td>$S_{11}^E$</td>
<td>$10^{-12}$ m²/N</td>
<td>16.1</td>
</tr>
<tr>
<td></td>
<td>$S_{33}^E$</td>
<td>$10^{-12}$ m²/N</td>
<td>20.7</td>
</tr>
<tr>
<td>Coupling factor</td>
<td>$k_p$</td>
<td></td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>$k_t$</td>
<td></td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>$k_{31}$</td>
<td></td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>$k_{33}$</td>
<td></td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>$k_{15}$</td>
<td></td>
<td>0.66</td>
</tr>
</tbody>
</table>

The following tables provide material properties of the PIC255 piezoelectric element and actuator properties:

#### TABLE II

**Material Properties of the PIC255 Piezoelectric Element**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$\rho$</td>
<td>kg/m³</td>
<td>7800</td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>$\varepsilon_{31}/\varepsilon_0$</td>
<td></td>
<td>1750</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_{33}/\varepsilon_0$</td>
<td></td>
<td>1650</td>
</tr>
<tr>
<td>Piezoelectric charge coefficient</td>
<td>$d_{31}$</td>
<td>$10^{-12}$ C/N</td>
<td>-180</td>
</tr>
<tr>
<td></td>
<td>$d_{33}$</td>
<td>$10^{-12}$ C/N</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>$d_{15}$</td>
<td>$10^{-12}$ C/N</td>
<td>550</td>
</tr>
<tr>
<td>Elastic compliance coefficient</td>
<td>$S_{11}^E$</td>
<td>$10^{-12}$ m²/N</td>
<td>16.1</td>
</tr>
<tr>
<td></td>
<td>$S_{33}^E$</td>
<td>$10^{-12}$ m²/N</td>
<td>20.7</td>
</tr>
</tbody>
</table>

#### TABLE III

**Actuator Properties**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer thickness</td>
<td>$TH$</td>
<td>µm</td>
<td>500</td>
</tr>
<tr>
<td>Capacitance</td>
<td>$X$-plate</td>
<td>nF</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>$Y$-plate</td>
<td>nF</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>$Z$-plate</td>
<td>nF</td>
<td>2.9</td>
</tr>
<tr>
<td>Number of layers</td>
<td>$X$-plate</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Y$-plate</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Z$-plate</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Maximum displacement</td>
<td>$X$-direction</td>
<td>µm</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$Y$-direction</td>
<td>µm</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$Z$-direction</td>
<td>µm</td>
<td>1</td>
</tr>
<tr>
<td>Axial stiffness</td>
<td>$K$</td>
<td>$10^6$ N/m</td>
<td>90</td>
</tr>
</tbody>
</table>

Fig. 6. (a) Gluing the PIC 255 piezoelectric actuators to the beam with the help of an aligner. (b) Completed IFM mechanics.
Fig. 7. (a) Charge amplifier based on the LTC6241 chip. The feedback capacitor is used to set the gain, whereas the feedback resistor is used to modify the frequency behavior of the circuit. (b) For characterization of the charge amplifier, the piezoelectric charge $Q_i$ can be modeled by a voltage source in series with a capacitor (components in the dashed box).

*TABLE IV CHARGE AMPLIFIER BOARD COMPONENTS AND THEIR VALUES*

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedback capacitance</td>
<td>$C_f$</td>
<td>nF</td>
<td>1</td>
</tr>
<tr>
<td>Feedback resistance</td>
<td>$R_f$</td>
<td>MΩ</td>
<td>1000</td>
</tr>
<tr>
<td>Cutoff frequency</td>
<td>$f_c$</td>
<td>mHz</td>
<td>160</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>$V_{ss}$</td>
<td>V</td>
<td>5</td>
</tr>
<tr>
<td>Reference capacitance</td>
<td>$C_{ref}$</td>
<td>nF</td>
<td>1</td>
</tr>
</tbody>
</table>

arranged as in Fig. 5. To mimic the charge generated by the piezoelectric elements, a voltage source $U_{ref}$ in series with a known capacitor $C_{ref}$ is employed, see Fig. 7(b). The value of $C_{ref}$ is shown in Table IV.

1) **Linearity and Frequency Response:** First, the amplitude of the sinusoidal input $U_{ref}$ is varied from 0 to 2.5 V with the frequency fixed at 100 Hz and the output of the four charge amplifiers is recorded, see Fig. 8(a). There is a linear response in all charge amplifiers as characterized by an $R^2$ value greater than 0.99 for all the amplifiers. The results are in good agreement with the SPICE simulations as well. Fig. 8(a) also shows the mean and standard deviation (SD) for repeated measurements ($N = 100$). The reason for the variation is due to the tolerance values of the feedback capacitance.

Next, the frequency of the sinusoidal input is varied from 0.1 Hz to 1 kHz while the amplitude is kept at 1 V and the frequency response of the charge amplifier is recorded, see Fig. 8(b). The frequency response of the four charge amplifiers agrees with the SPICE simulations. The cutoff frequency of the amplifiers is 160 mHz, close to the SPICE simulation value of 159 mHz. For the next set of experiments, the frequency of operation is set to 100 Hz.

![Fig. 8. (a) Linearity of the custom-made charge amplifiers. (b) Frequency response of the charge amplifiers compared to SPICE simulation.](image)

Fig. 9. Lack of symmetry for the actuators that lie on the LHS and RHS of the activated actuator.

B. **IFM**

The inputs of the four charge amplifiers are connected to the piezoelectric actuators. Following Fig. 5, actuator $a_6$ is connected to charge amplifier 1, $a_7$ to charge amplifier 2, $a_8$ to charge amplifier 3, and $a_9$ to charge amplifier 4.

1) **Symmetry and SD:** The setup is assumed to be symmetrical about actuator $a_5$. To verify this, the response of actuators that lie on the left-hand side (LHS) of actuator $a_5$ is compared
to the response of the actuators that lie on the right-hand side (RHS). Fig. 9 shows the asymmetry between the LHS and RHS actuators for the same dynamic excitation of actuator $a_5$ calculated as

$$\text{Asymmetry} = |1 - Q_{\text{LHS}} / Q_{\text{RHS}}|$$

where $Q_{\text{LHS}}$ and $Q_{\text{RHS}}$ are the actuator charges (per actuator pair) of the LHS and RHS, respectively. The maximum asymmetry recorded is 0.23 and it is found at the furthest actuators owing to a low signal-to-noise ratio. However, the symmetrical behavior implies that the actuators are properly glued to the beam and the base.

2) Charge Influence Function: By applying a dynamic excitation to $a_5$ with the characteristics as in finite element simulations, the RHS actuators are used to measure the charge. The measurement is repeated 100 times and averaged out and compared to the finite element simulated charge, see Table V.

To compare the finite element and experimental results, we define two inter-actuator charge coupling parameters, $C_1$ and $C_2$ given by

$$C_1 = \frac{Q_{a_7}}{Q_{a_6}}$$

and

$$C_2 = \frac{Q_{a_8}}{Q_{a_7}}$$

where $Q$ is the charge generated by the corresponding actuator. Table VI shows the values of charge coupling parameters as a percentage.

To compare the results graphically a piecewise cubic interpolation is used to connect the data points resulting in Fig. 10, which is by definition the charge influence function.

The coupling parameters define the relative movement of two-neighboring actuators with respect to each other and they are independent of the actuation signal. The results indicate that a slight mismatch in the experimental results and finite element simulations.

V. DISCUSSION

The main goal of the IFM technique is to measure the influence function of one actuator by measuring the charge that is generated by the piezoelectric elements near to that actuator and convert the measured charges into the associated beam deflection (positional influence function). In this study, we have only considered the charge influence function.

We found the experimental results to be in agreement with finite element simulations as given by the values $C_1$ and $C_2$. The maximum absolute difference in the inter-actuator charge coupling parameters is 0.3%. In terms of charge influence function, the maximum absolute discrepancy is 5.1 pC between experimental results and finite element simulations. The non-zero discrepancy is due to the observation that from the actuator $a_6$ (closest actuator) to actuator $a_9$ (furthest actuator), finite element simulations predict that the charge decreases from 1609 to 3 pC resulting in a dynamic range of 55 dB. In practice, this poses a challenge in measuring the charge generated by the furthest actuators because there is a possibility that the signals are buried in noise. This explains why the discrepancy is higher for the actuator $a_9$. To improve the signal-to-noise ratio, noise-canceling techniques such as filtering are required. However, in our case, this discrepancy is within the acceptable range.

The calibration time of the surface shaping systems depends on several factors such as the actuator response time and reading rate of sensors. For conventional sensors, the resolution of the sensor depends on the measurement range. For high-resolution measurement of nanometer displacements, only a small area can be measured at once and it requires either the sensor or the surface to be moved around (and wait till it settles) in order to measure the entire surface. This increases the calibration time. The IFM setup has no moving sensor parts and the response time of the sensor is the same as the actuator response time hence the calibration time is decreased.

VI. CONCLUSION

In summary, we have presented the IFM technique as a means of measuring influence functions and experimentally validated the IFM finite element simulations. By utilizing one piezoelectric element as an actuator under a dynamic
excitation and the rest of the piezoelectric elements as sensors, experimental results have demonstrated the effectiveness of the proposed technique in measuring the charge influence function. Moreover, the discrepancy between the experimental results and finite element simulation is minimal.

The IFM concept has been demonstrated in a 1-D setup (linear array) though its application in the actual wafer table is 2-D (grid array). In the wafer table, the piezoelectric elements are geometrically arranged either in a hexagonal or rectangular pattern. Still, in all cases, the IFM concept is applicable since all the piezoelectric elements are mechanically coupled to each other by the wafer which ensures a pathway for force distribution amongst the piezoelements. The main difference between the setup presented in this article and the real wafer table is that for the latter the wafer is electrostatically clamped to the actuator grid. Consequently, the actuator force should not exceed the clamping forces, hence further research is required to evaluate the measured IFM concept under clamping conditions. In addition, a more intricate design of actuators is required as the piezoelements need to be scaled down to wafer table dimensions.

The proposed technique has the potential to improve the accuracy and efficiency of surface shaping systems. In future research, we will use the measured charge influence function to construct the positional influence function and compare the results with the actual displacement of the beam. Following that, we will expand the IFM technique to measuring in-plane influence functions.

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REFERENCES

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