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Design and characterization of a vibrating piezo-membrane deformable mirror for adaptive optics application

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ABSTRACT

Recently, we proposed an inexpensive deformable mirror made of Poly-Vinylidene Fluoride (PVDF), called Vibrating Membrane Mirror (VMM), to compensate for optical atmospheric aberrations [1, 2]. The degree of similarity between the vibration mode shapes of a circular membrane and Zernike polynomials were investigated and VMM was introduced as a promising alternative to the traditional deformable mirrors. The present work deals with technical concepts, design, and surface analysis of the proposed deformable mirror. The mode identification, dynamic range, and time response of the proposed mirror is discussed and important factors that influence these parameters are investigated. To measure the mirror surface motion, a Laser Doppler vibrometer is used. Results show that the mechanical performance of the VMM satisfies the basic requirements of an optical deformable mirror. The mirror performance is optically examined in an interferometer setup and recommendations are provided to improve it.

Keywords: Deformable Mirror, Vibrating Membrane Mirror, Piezoelectric PVDF, Bessel functions, Zernike polynomials, Interferogram, resonant frequency, modal superposition

1. INTRODUCTION

In the second half of 20th century, the idea of real-time deformable mirrors in adaptive optics emerged, and flexible face sheets with reflective surfaces were employed instead of glasses to correct optical aberrations in real time. Thanks to the emergence of digital computation and smart materials in the 1970's, the technology of deformable mirrors went through an impressive evolution. In addition to design and material selection for the mirror face sheet, the actuating technique has been the focus area of researchers over last decades. Traditional deformable mirror systems consist of two main parts: 1) the deformable mirror itself, i.e. a complex electromechanical device that would be very expensive to finish optically and to assemble, and 2) a relatively simple and, unfortunately, expensive electronic driver amplifier array. There is one driver for each actuator and there are some restrictions to using them such as high cost, low temporal frequency response, and rather high weight.

Yellin [3, 4] first proposed membrane mirrors in adaptive optics in 1976 and described the basic implementation of electrostatically deflected membrane mirrors which was positioned between a single transparent electrode and a region of actuators. The membrane's low mass, which results in no hysteresis, low deflection voltages and high resonant frequencies, and its simple and inexpensive fabrication are the reasons that led scientists to focus on membrane mirrors [3]. In spite of the easy fabrication of membrane mirrors, the cost of their production is still high because of their drive and complex control system.

We recently introduced a novel application of the power of mechanical vibration in generating the wavefront shape of optical aberrations on the surface of a Vibrating Membrane Mirror (VMM) [1, 2]. The similarities between the vibration eigenmodes and Zernike polynomials, as the representatives of optical aberrations, was discussed. The piezoelectric Polyvinylidene fluoride or PVDF film introduced as a promising candidate for the proposed mirror and a primary prototype created to visualize mode shapes. The proposed mirror is self-excited and possesses some advantages as, 1) simple control system, 2) low cost of production, 3) capability of compensation of low and high order of aberrations, 4) quick response to the input control signal, 5) lower cost of maintenance and calibrations. However, the mechanical and optical performance of the VMM has not investigated to date. Continuing our study on VMM, this work focuses on the design and surface deflection characteristics of VMM to show its promising application as an affordable deformable mirror. The dynamic range, response time, and superposition of mode shapes are discussed. The quality of the reflected laser light from the mirror surface is optically examined in an interferometer setup and recommendations are provided to improve it.

This paper has been organised in the following way. It begins with details on the mirror prototype design and manufacturing in the section, "Mirror Assembly". It will then go on to the vibration measurement setup in the section, "Measurement Procedure". Modal properties of the mirror are extracted in the section "Modal Extraction". The fifth section, "Surface

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Characterization”, discusses the vibration measurements results. In the section, “Optical Measurements”, the mirror is put in an interferometer system to analyse its optical performance and recommendations are provided to enhance its performance as a deformable mirror. In the last section, results are concluded.

2. MIRROR ASSEMBLY

An Aluminium DM holder with 30 mm diameter is designed in Autodesk Inventor® and machined using CNC equipment, as shown in Figure 1a and c, respectively. The reflective PVDF film is fixed between an Aluminium ring and a back-plate. Figure 1b shows the 3D exploded view of the mirror holder. Aluminium parts are directly connected to the metallized surfaces of the PVDF film and provide a perfect contact in order to apply the electric field to both sides of the film. To firmly hold the PVDF film between Al parts and avoid the short circuit between two electrodes, electrically insulated Nylon bolts are used. Because of the electrical resistivity of the PVDF sheet, which is <3.0 Ohms/square, the quality of the electrical connection is of importance in the application of an even distribution of the electric charge over the surface of the piezoelectric film. Therefore, a perfectly flat surface connection is considered in the setup design. In addition, a proper surface connection prevents the fretting corrosion of electrodes and reduces electrical losses.

Figure 1. The mirror prototype, a) the perspective view b) the exploded view c) the Al version created by CNC machine

The PVDF film can be excited by a shaker, speaker, or by itself. A mounting table is designed to attach the mirror holder to a vibration shaker. The holder has the capability to be attached to an optical stand and the cage system of the adaptive optics system as well. A threaded piston is screwed behind the PVDF film in order to apply an initial in-plane tension in the film to avoid wrinkles on the mirror surface and to stabilize it. The piston stretches the film evenly in the radial direction that is of importance in the orientation of mode shapes and resonant frequencies. It aids to control the initial tension using the designed piston.

2.1 PVDF Properties

Today, PVDF thin films are manufactured in a wide range of thickness and piezoelectric properties. The company, Measurement Specialties Inc. (MSI) manufactures the PVDF film that is used in this study. It is a uniaxial polarized PVDF film with $110\ \mu\text{m}$ thickness is sputtered with $800\ \text{\AA}$ Copper and Nicle on each surface. The typical properties of PVDF films provided by this manufacturer are listed in Table 1. However, the values do not come with any guarantee of exact data by the manufacturer because of inconsistencies existing in manufacturing and poling process of PVDF thin films.

Table 1. Typical properties of piezoelectric films manufactured by MSI [5]

Parameter	Symbol	Quantity	Unit
Thickness	t	9, 28, 52, 110	μm
Piezo Strain Constant	d_{31}	23	10^{-12}m/V
	d_{33}	-33	
Young's Modulus	E	2-4	GPa
Permittivity	ϵ	106-113	pF/m
Relative Permittivity	ϵ/ϵ_0	12-13	—
Density	ρ	1780	kg/m^3
Max operating Voltage	—	750(30)	V/mil(V/ μm), DC, @ 25°C
Breakdown Voltage	—	2000(80)	V/mil(V/ μm), DC, @ 25°C

In reality, polarized PVDF films, particularly the uni-oriented piezoelectric films, behave the same as orthotropic materials. Manufacturers, including MSI, provide either a rather wide range of Young's modulus of elasticity in both in-plane directions or separate ranges for the machine and transverse directions. In spite of extensive scientific studies, the electromechanical properties of PVDF films are reported with a wide range of discrepancies. The most likely reasons are listed as follows:

- 1- Variations happening in the poling process
- 2- Randomness in the semi-crystalline structure of PVDF [6]
- 3- The Operating condition including the temperature and frequency [7]
- 4- Inaccuracies associated with the property measurement of very thin films [7]

The formation of eigenvectors greatly depends on the orientation of material properties of the PVDF film. Since the Bessel modes, which are the radial closed form solution of a vibrating isotropic membrane, bear a great resemblance to the Zernike polynomials [2], an isotropic piezoelectric PVDF film should ideally be used in manufacturing the VMM to replicate the Bessel modes. However, a small degree of the orthotropic behaviour of the film would aid to separate identical modes, i.e. avoiding degeneracy condition. It will be discussed later in the section "Modal Extraction".

3. MEASUREMENT PROCEDURE

Figure 2 shows the schematic of a vibration measurement setup prepared to measure the mirror surface vibration using the Laser Doppler vibrometer. An external signal generator or the built-in signal generator of the vibrometer can be used to drive the PVDF film. The output of the signal generator is amplified by 20 times and applied both sides of the mirror. The scanning head measures the velocity signal of vibration and sends the collected data to the junction box. The post-processing of the velocity signal gives the displacement and acceleration of vibration at the measured point(s).

Figure 2. The schematic of vibration measurement setup. A Laser Doppler vibrometer is manufactured by Polytec.

4. MODAL EXTRACTION

The piezoelectric PVDF film is fabricated in a way that its stretching direction, i.e. direction 1, is in the vertical direction of the image, as shown in Figure 3a. The transverse direction is perpendicular to the machine direction and is called direction 2. The mirror surface is meshed by 43×43 points, as shown in Figure 3b. Since some points are located on the nodal lines and nodal circles of the vibration mode shapes, four specific points are considered as the measurement points of the Frequency Response Function (FRF) spectra to identify the natural frequencies. They are named CP (Center Point), N (North), NW (North West), and W (West).

The input sinusoidal signal to the piezoelectric film is swept from 0.1 to 8 kHz with a constant $80 V_{pp}$ amplitude. To assure that the steady state condition is attained before starting each measurement, the excitation frequency is increased slowly over 20.48 seconds. The input voltage drives the PVDF film and vibrometer measures the velocity of vibration as the output.

Figure 3. Fabricated PVDF mirror a) arrows show the stretching direction of the film during the poling process (direction 1), b) Scan points and four single points to measure FRFs

Figure 4. The coherence function between the applied voltage and response signal measured at CP

In signal processing, it is important to know how much of the output power is caused by the input force. The coherence function represents the relationship between the output and input signals. The coherence between two signals generally indicates the degree of linear correlation between them at a specific frequency. This function is limited between 0 and 1 where 0 shows no correlation between signals and 1 indicates a perfect linear correlation between two signals. The values close to unity also show the good quality of signals, i.e. a high signal-to-noise ratio.

In the case of PVDF film, Figure 4 presents the coherence between the input and output signals measured at point CP. The output signal is averaged three times to calculate the coherence. It is clear that the coherence function is very close to 1 and confirms that all the output power is caused by the input signal. However, there are leakages at specific frequencies, which are resonant or anti-resonant frequencies. In practice, the resonance and anti-resonance influence the excitation and response signals, respectively, and cause errors in the coherence calculation [8]. Figure 4 shows the measurements have been well made and confirms the fact that the excitation force and response are linearly related. It is very important when we are talking about the superposition of mode shapes and vibration control of the mirror.

To identify the resonant frequencies, frequency response functions at four mentioned points are compared. Figure 5 illustrates the mobility spectra, i.e. the ratio of velocity response to the input voltage, at four points. Because of the low dissipation of energy in the vibration of thin films, the extreme values represent the most likely candidates of resonant frequencies. The fundamental frequency of the film clearly generates a resonance peak at 1.07 kHz in all point FRFs. The mode shape corresponding to this frequency is a concave shape, i.e. Mode (0, 1), where 0 and 1 represent the number of nodal lines and nodal circles in the mode shape, respectively.

Figure 5. Mobility Frequency Response Function (FRF) at four points in logarithmic scale (dB). The extreme values likely represent the resonance zones of the mirror.

Figure 6. The experimental mode shapes and resonant frequencies of 110 μ m PVDF film measured using the Laser Doppler vibrometer, PSV-400.

The second resonance peak happens around 1.88 kHz, as shown in the FRF at point N in Figure 5. Surface scanning shows that this frequency is corresponding to mode (1, 1), which represents the Bessel mode corresponding to the Vertical Tilt aberration or Z_3 . Since CP and W points are located on the nodal line of this mode, their FRF show very small peaks at 1.88 kHz. Scanning the mirror surface at 2.02 kHz reveals that this frequency belongs to the counterpart of mode (1, 1) that is corresponding to the Horizontal Tilt aberration or Z_2 . The CP and W points are located on the nodal line of this mode so that they do not show this resonant frequency in their spectra. In theory, mode shapes such as identical Modes (1, 1) are called the degenerate mode shapes of an isotropic membrane, which means that the two natural frequencies of that pair are equal. In this case, since the natural frequencies of the same modes are split, we conclude that the PVDF film is in-plane anisotropic and possesses different stiffness (or tension) in the machine and transverse directions. The sources of anisotropic behaviour of the PVDF film are the inconsistency of stiffness in the poling process, sputtering, and pushing the PVDF film. In general, the higher the discrepancy of natural frequencies, the higher the degree of anisotropy. Since the nodal line of the mode with lower frequency, i.e. 1.88 kHz, is in the horizontal direction, we can conclude that the film is stiffer in the transverse direction, or direction 2, rather than the machine direction, i.e. direction 1. In the optical mirror application, avoiding the degeneracy of mode shapes helps to generate more atmospheric wavefront shapes on the vibration mirror surface.

The mirror surface is scanned at the other candidates of resonant frequencies, and results are illustrated in Figure 6. 11 mode shapes are extracted from the FRFs. It is evident that some identical modes are separated because of the anisotropic properties of the film. It is true for modes with a 90-degree rotation, i.e. Mode (1, 1) and Mode (1, 2). The resonant frequencies of modes (2, 1), (3, 1), (4, 1), and (2, 2) are close to their counterparts. It causes missing the pair of these modes in experimental FRFs. The closeness of the resonant frequencies along with the damping of the PVDF film and the high level of vibration of the consecutive resonance are the most likely reasons of missing the pairs of identical modes. However, measurements around the only frequencies obtained from FRFs show that the missed modes can be captured but their motion is modulated with a rotating frequency. This fact can be explained by the conservation of averaged mechanical energy.

4.1 Modal Assurance Criterion (MAC)

To identify the mode shapes and indicate the consistency of them, Modal Assurance Criterion (MAC) is considered for the experimental modes that represent optical aberrations wavefront. This criterion is a statistical indicator that measures the least square deviation of the scanned points of two sets of mode shape data from the straight-line correlation. Although the MAC shows the degree of consistency between mode shapes [9], it does not exhibit the orthogonality of mode shapes since the mass matrix is not used in MAC calculation. However, the extended version of the concept to the mass-normalized version is considered in automatic correlation procedures [10]. The following equation represents the MAC formula:

$$MAC_{ij} = \frac{|\sum_{k=1}^n \varphi_{k,i} \varphi_{k,j}|^2}{\sum_{k=1}^n \varphi_{k,i} \varphi_{k,i} \sum_{k=1}^n \varphi_{k,j} \varphi_{k,j}} \quad (1)$$

where φ denotes the mode shape vector and n is the number of modes. Similar to the coherence definition, MAC values are limited between zero and one. A value near zero indicates a low resemblance between two comparing modes. It is likely because of non-linearity in material, noise in measurement, or variation in parameters during the test and measurement. Perfectly correlated modes give a MAC value of unity. Non-diagonal values indicate the resemblance of different modes together.

There are two common versions of MAC, AutoMAC and CrossMAC. The AutoMAC version exhibits the correlation between a set of mode shapes with themselves. It checks whether the Degree of Freedoms (DOFs), or the number of scan points, considered to show the mode shapes are adequate to avoid spatial aliasing problem or not [10]. The AutoMAC assists to introduce experimental mode shapes to the control system of the proposed mirror by automatic selection of correlated mode pairs in correlation packages. In details, outputs of a wavefront sensor in the AO system can be imported to a MAC calculator program to distinguish the actual mode shapes of the proposed VMM from their superposition modes. The second version, CrossMAC, examines the degree of similarities of a set of mode data with another set, for instance, the correlation between finite element modes and experimental modes can be checked to update the numerical model.

Table 2 represents the AutoMAC values of comparing experimental mode shapes calculated using a generated MATLAB code. The symmetric AutoMAC matrix with unit diagonal values of identical modes verifies the calculations. All diagonal components of AutoMAC table, which are highlighted with green colour, are identically unity since each mode perfectly correlates itself. The non-diagonal cells show that the measured modes are largely consistent and do not significantly overlap each other. However, the yellow background cells highlight that of non-diagonal MAC values which are more than 1%. It is clear that the maximum overlap of modes is 2.76% that happens in experimental Mode (0, 3) and Mode (2, 2) (corresponding to Secondary Astigmatism). The reason is this that these modes happen consecutively and their energy of vibration influence on each other. Moreover, there is a degree of inaccuracy in extracting the resonant frequencies using the FRFs, hence a bit changing the frequencies will result in identifying the exact resonant frequencies. It is expected that the integration of an AutoMAC calculator with a vibrometer can minimize the overlaps.

To conclude, the AutoMAC matrix shows the consistency of experimental mode shapes very well, evaluates the DOF of the measured mode shapes, and helps to find the overlaps between them. This criterion can also be used to identify the mode shapes and their corresponding frequencies as a reference to control the vibrating deformable mirror.

Table 2. AutoMAC values (in %)

AutoMAC	Experimental modes #									
	Mode 2 V (1,1)	Mode 3 H (1,1)	Mode 4 (2,1)	Mode 5 (0,2)	Mode 6 (3,1)	Mode 7 V (1,2)	Mode 8 H (1,2)	Mode 9 (4,1)	Mode 10 (2,2)	Mode 11 (0,3)
Mode 2 (1877 Hz)	100.00	0.09	0.00	0.04	0.00	0.06	0.00	0.00	0.00	0.00
Mode 3 (2023 Hz)	0.09	100.00	0.58	1.10	0.04	0.00	0.09	0.02	0.01	0.07
Mode 4 (2768 Hz)	0.00	0.58	100.00	0.15	0.17	0.12	0.05	0.08	0.00	0.02
Mode 5 (3207 Hz)	0.04	1.10	0.15	100.00	0.02	1.17	0.01	0.03	0.07	0.06
Mode 6 (3659 Hz)	0.00	0.04	0.17	0.02	100.00	0.21	0.01	0.34	0.14	0.06
Mode 7 (4002 Hz)	0.06	0.00	0.12	1.17	0.21	100.00	0.03	0.34	0.41	0.26
Mode 8 (4194 Hz)	0.00	0.09	0.05	0.01	0.01	0.03	100.00	0.03	0.19	0.03
Mode 9 (4611 Hz)	0.00	0.02	0.08	0.03	0.34	0.34	0.03	100.00	0.76	0.72
Mode 10 (5237 Hz)	0.00	0.01	0.00	0.07	0.14	0.41	0.19	0.76	100.00	2.76
Mode 11 (5691 Hz)	0.00	0.07	0.02	0.06	0.06	0.26	0.03	0.72	2.76	100.00

5. SURFACE CHARACTERIZATION

5.1 Mode shapes decomposition

To show the similarity of the experimental mode shapes to the optical aberrations, they are decomposed into the Zernike modes and results are shown in Figure 7. The left y-axis represents the Zernike expansion coefficients of the experimental mode shapes. The decomposition of experimental modes is compared with that of the closed form solution for the eigenvectors of a unit-radius membrane. The exact solution of the mode shapes of a circular isotropic membrane is expressed as follows [11]:

$$w(r, \theta) = J_m(\omega r) e^{im\theta} \quad (2)$$

where J_m is the Bessel function of first kind, and ω is frequency. r and θ are the radius and angle, respectively. The Zernike expansion coefficients of the Bessel modes are shown on the right y-axis of each plot. It is clearly evident that the masked mode shapes follow the Bessel modes' decomposition.

Figure 7. The decomposition of vibration mode shapes and Bessel modes into the Zernike modes. The Zernike expansion coefficients of the Bessel modes are shown on the right y-axis of each plot. The shapes of dominant Zernike modes are placed on the top of each bar. The Zernike mode numbering is in accordance with the Noll's index scheme. Plots are sorted in accordance with the increase of resonant frequencies.

Figure 7. (Continued)

The associated radius of the masked area of mode shapes, r_{eff} , is formulated as follows:

$$r_{eff} = R_c r \quad (3)$$

Where R_c is the reduction coefficient of the membrane radius, r , and is listed in Table 3 for each mode.

The plots in Figure 7 give invaluable information that can help to design the control system of the VMM. While the amplitude of excitation voltage is the same for all modes, the decomposition plots show a different level of Zernike coefficients for each mode, even for identical modes. To attain the same magnitude of Zernike expansion coefficients for all modes, we must customize the amplitude of the input voltage of individual modes. To do that, it is needed to normalize the excitation voltage to the $|z_i|_{exp}$. It will be shown in the section, "Effects of excitation signals", that the amplitude of vibration is in linear relation to the input voltage. Therefore, the input voltage of the i^{th} mode, V_i , corresponding to the desired Zernike expansion coefficient, z_i , can be calculated as follows:

$$V_i = z_i \frac{V_{ref}}{|z_i|_{exp}} \quad (4)$$

where $|z_i|_{exp}$ is the experimental Zernike coefficient of the i^{th} mode when the reference voltage, V_{ref} , is applied to identify the mode shapes of the PVDF film. For example, Figure 7 represents the experimental Zernike coefficient of mode shapes when $V_{ref} = 80V_{pp}$. The normalized voltage constant of each mode for the present mirror is listed in Table 3.

5.2 Maximum Stroke and Reduction Coefficient

The dynamic range of deformable mirrors is defined as the maximum stroke or deflection of the mirror surface. In the case of the vibrating deformable mirror, the maximum deflections happen at resonance, and fortunately, the desired mode shapes for optical wavefront compensation are created at the resonance. The dynamic range of the PVDF VMM depends on the following non-intrinsic factors that can be modified in the design stage and operation:

1. *Initial stretch*: the in-plane tension stiffens the film and reduces the amplitude of vibration.
2. *The power of the input voltage*: the amplitude and shape of the input signal determine the pocket of energy that drives the PVDF film. The deformation of the PVDF film under application of different input signals is discussed in Section "Effects of excitation signal".
3. *Piezoelectric properties of the film*: the piezoelectricity increases the stiffness of the film [12] and consequently decreases the dynamic range of the mirror. The mode shapes that their nodal lines are in the direction of stretching of the PVDF film possess the maximum amplitude of the motion. For instance, the Horizontal Mode (1, 1) possess higher stroke rather than the Vertical one, as shown in Table 3.
4. *Boundary conditions*: more degree of freedom at the edges causes lower constraints and restrictions against the film deflection. Hence, simply supported edges are associated with higher stroke rather than the fully clamped boundary conditions.
5. *The thickness of the PVDF film*: as the thickness of the film increases, the behaviour of the film approaches to the plates. Therefore, the film's stiffness increases and consequently the amplitude of vibration declines.
6. *Electrode thickness*: The Young's modulus of elasticity of PVDF is 2-4 GPa, while it is tens of GPa for common electrodes such as Nickel (~200GPa), Copper (~117GPa), and Aluminum (~70GPa). Therefore, as the thickness of the deposited electrode increases, the film stiffness increases and consequently it prevents the film deflection.

The Peak-to-Valley (PV) deflections of the current vibrating film at resonant frequencies are listed in Table 3. The effective stroke, S_{eff} , represents the overall magnitude of deformation of the effective area, not the whole mode shape. The Zernike expansion coefficients, $|z_i|_{exp}$, for each mode and its twin show to what extent the vibrating mode shapes represent the shape of optical wavefront errors. The reduction coefficients of the film's radius are presented in the last column.

Table 3. The characterization of mode shapes under 80 V_{pp} sine signal

Aberration	Twin Mode	ω_{nm} (Hz)	S_{eff} (μ m)	$ z_i _{exp}$	Twin's $ z_i _{exp}$	$\frac{V_{ref}}{ z_i _{exp}}$	R_c
Vertical Tilts	Vertical Coma	1877	3.93	2.41	0.62	33.20	0.59
Horizontal Tilts	Horizontal Coma	2023	8.62	5.31	1.46	15.07	0.58
Astigmatism	Sec. Astigmatism	2768	17.31	11.63	3.66	6.88	0.65
Defocus	Spherical	3207	5.22	2.17	0.91	36.87	0.60
Trefoil	-	3659	1.64	1.18	-	67.80	0.76
Vertical Coma	Vertical Tilts	4002	1.69	0.86	0.27	93.02	0.69
Horizontal Coma	Horizontal Tilts	4194	5.97	3.30	0.54	24.24	0.69
Quadrafoil	-	4611	1.31	0.85	-	94.12	0.77
Sec. Astigmatism	Astigmatism	5237	7.65	4.43	0.19	18.06	0.70
Spherical	Defocus	5691	3.85	1.49	0.2	53.69	0.69

5.3 Effects of excitation signals

In this section, the effects of the shape and amplitude of the input signal on the magnitude of the mirror deflection are compared. Three types of periodic excitation signals are examined: sinusoidal, square, and ramp. In theory, the square signal possesses the maximum energy rather than the sinusoidal and ramp signals. Figure 8a illustrates the cross-section of the fundamental response of the PVDF film to the excitation signals. Once the amplitude of input signals is constant, the maximum displacement happens under the square signal. It is notable that the configuration of mode shapes are independent of the excitation but the energy carried by the signal determines the amplitude of modes.

Figure 8. Effects of the input signal on the mirror's dynamic range measured by vibrometer, a) The cross section displacement of the PVDF film under different signal shapes at fundamental mode shape, b) Amplitude of vibration vs amplitude of input voltage at the center point

In addition to the signal form, the amplitude of the input signal will influence the response function. Since almost the whole input signal power is used for the output signal in this system, it is expected that the higher the input power, the higher the amplitude of vibration. To find their relation, the PVDF film is driven by different amplitudes of the input signal and the response function is measured at the centre point of the film. It is interesting that there is a linear relationship between the input signal amplitude and the amplitude of vibration, as shown in Figure 8b for the first and second modes. This linearity is considered to be an excellent feature in controlling the stroke of the mirror by changing the voltage of the excitation signal.

5.4 Time Response of Mirror

How quick a deformable mirror reacts to a control signal is of importance in AO systems. Unfortunately, the definition of the mechanical response time of deformable mirrors is a controversial topic in the market. The reported temporal response values are for example microseconds for MEMS-based DMs, few milliseconds for bimorph piezoelectric DMs, and few

seconds for thermal DMs. It generally depends on their actuating technique and application. The input power, initial condition, and the final shape of the mirror surface are the important factors in measuring the time response while they are not reported clearly in technical data sheets. Here, the temporal response of the VMM to a changing the frequency of vibration is presented. At a constant signal amplitude, the frequency changes from 4 to 1.07 kHz, i.e. from Mode (1, 2) to the fundamental mode (0, 1), and the response signal in time domain is captured. Figure 9 shows that the transition time is approximately 11 ms. Moreover, it is common in control design to report the time to reach 68% of the target value. It is below 11 ms for the VMM.

In a vibrating mirror, the time response extensively depends on the frequency range and damping. At high frequencies, the mirror surface profile varies swifter than low frequencies. In addition, although the damping ratio aids to stabilize the oscillation, it causes delays in mirror's reaction to the control signal.

Figure 9. Mechanical time response of VMM to transition from Mode (0, 2) to Mode (0, 1)

5.5 Superposition of Mode Shapes

If a mechanical system is linear, the principle of superposition of mode shapes can be used. Based on this principle, the response of a linear system, $w(r, \theta, t)$, to any input excitation frequency is the linear combination of mode shapes as follows:

$$w(r, \theta, t) = \sum_{i=1}^n \eta_i \varphi_i(r, \theta) T(t) \quad (5)$$

where η_i is the participation factor of the mode shape φ_i , and $T(t)$ is the temporal response. In the mirror case, the coherence function showed that the relationship between the input signal and output response is linear. In addition, because of the low damping ratio of the thin films, the effective bandwidth of each mode is limited to the range between its prior and former resonant frequencies. It means that the transition from one mode to its following mode is a combination of two modes. For example, Figure 10 shows the transition from vertical Mode (1, 1) to the horizontal one. It is clear that these two modes contribute to constructing the deformation of the film at $\omega_{V(1,1)} < \omega < \omega_{H(1,1)}$.

Similarly, Figure 11a-f show the transition from the mode shape corresponding to the Astigmatism mode, i.e. Mode (2, 1), to Mode (0, 2) that is corresponding to the Defocus mode. To show how the transition happens, it is interesting to decompose the deformation fields into the Zernike modes. It is evident from Figure 12 that by getting away from the resonant mode (2, 1), the height of bar Z_6 that is corresponding to the Astigmatism aberration is declined and, in contrary, the contribution of Z_4 , which is corresponding to the defocus mode, increases. This fact can be used in a control system to combine sequential modes to correct optical wavefront aberrations.

Figure 10. Superposition and phase shift of Tilt mode by frequency. Plot (a) represents the V Tilt and by increasing the excitation frequency it rotates towards the H Tilt, Plot (f). The amplitude of vibration is shown below each mode.

Figure 11. The transition from Mode (2, 1) to Mode (0, 2). The corresponding frequency and amplitude of vibration are shown below each mode.

Figure 12. Decomposition of the transition modes into Zernike modes. Transition is happening from the corresponding mode of Astigmatism (Z_6) to the Defocus one (Z_4) by increasing the excitation frequency.

6. OPTICAL MEASUREMENTS

The aim of this section is to examine the optical performance of the vibrating PVDF film as a deformable mirror. The 110 μm PVDF is sputtered with 700 $\text{\AA}$ of Copper covered with 100 $\text{\AA}$ of Nickle on each surface. The flatness and deflection of the mirror surface are visualized using interferometric measurement techniques. To freeze the oscillating mode shapes at a specific phase, the laser beam can be strobed on the mirror surface using an Acousto-Optic Modulator (AOM) excited by a step signal with 1% duty.

Figure 13 shows a Michelson Interferometer setup that one of its arms is the reflected light from the VMM. A monochromatic laser beam, radiated from a He-Ne laser class 2 source, passes through an acousto-optic switch to strobe the light through the system. A Gaussian beam exits from the spatial filter and its diameter is tuned using an iris. The coherent beam is expanded to reach the desired diameter and then collimated. The parallel beam is directed into the beam splitter, the transmitted beam is incident on the DM surface and the reflected beam from the splitter strikes a flat mirror. The reflected beams from two mirrors are brought back together to create an interference pattern. A PixelINK Camera is used to visualize the patterns where fringes are separated by $\lambda/2$ deformation.

The interferometric measurement of the surface of the unpowered mirror is shown in Figure 14a. The Tilt between the beams is adjusted to maximise the number of beams visible on the camera. Poor quality of the PVDF film surface causes the diffraction of light in a way that the produced fringes are irregular in lieu of equal inclined. The manufacturing defects on the PVDF mirror surface can also be seen at the bottom of the interferogram. To visualize the dynamic displacement of the PVDF mirror, the laser beam is strobed on the mirrors with a frequency slightly bigger than the vibration frequency. Therefore, we are able to capture the mirror motion, as shown in Figure 14b-c. Figure 14b represents the vertical Mode (1, 1). The sole nodal line of this mode can be seen at the middle. Mode (2, 1), the corresponding mode of Astigmatism aberration, is also shown in Figure 14c. The crossed lines are the nodal lines of this mode.

In the literature of deformable mirrors, the commercial PVDF films as the active layers are stuck into a reflective silicon or glass substrate to create the mirror surface on the PVDF film [13]. Since adding top layers on the PVDF film increases its stiffness, this method is not suitable for the flexible VMM. However, it is possible to sputter coat reflective surface while being careful with deposition thickness. Fortunately, new technologies to produce ultra-smooth thin polymers are recently introduced that facilitate manufacturing high-quality mirrors using a single layer of PVDF thin film[14]. They are promising candidates to increase the optical performance of our proposed VMM. Study on this topic is left for future work.

Figure 13. Michelson Interferometer setup for optical measurement of the mirror surface

Figure 14. Interferometric measurements. The defects on the PVDF mirror surface are visible at the bottom of images. a) Unpowered film b) Vertical Tilt c) Astigmatism modes. Nodal lines can be seen in the interferograms.

7. CONCLUSION

A prototype of the PVDF vibrating membrane mirror was created and its surface motion was characterized using the Laser Doppler vibrometer and Interferometric setup. It was shown that the VMM is a linear system, and there is a linear relationship between the input voltage signal and the dynamics of the mirror. Therefore, the principle of superposition of mode shapes is valid for the mirror to approximate the motion at any frequencies. The Modal Assurance Criterion (MAC) was introduced as a useful tool to identify the eigenmodes in the control system of the VMM. It was shown that the dynamic ranges of the mode shapes of VMM, which represent the optical wavefront errors, are orders of magnitudes higher than the light wavelength. In addition, the response of the mirror to the input control signal is fast, a few milliseconds for mode transition. To show the performance of the VMM in an optical system, one of the flat mirrors of the Michelson interferometer setup was replaced with the VMM and the mirror surface quality visualized. In spite of the low quality of the PVDF film surface, the mode shapes could be captured. The results of this paper pave the way for designing a control system for the VMM and improving its optical quality.

REFERENCES

- [1] Hadipour, M., Tahtali, M., and Lambert, A., "Dynamics of Vibrating Piezo-Membrane Mirror," OSA Technical Digest (online). Imaging and Applied Optics 2016, AOT1C.3 (2016).
- [2] Hadipour, M., Tahtali, M., and Lambert, A. J., "Vibrating Membrane Mirror Concept for Adaptive Optics." SPIE Astronomical Telescopes + Instrumentation (2016).
- [3] Yellin, M., "Using Membrane Mirrors In Adaptive Optics." SPIE Imaging Through the Atmosphere 75, 97-102 (1976).
- [4] Grosso, R. P., and Yellin, M., "The membrane mirror as an adaptive optical element*," Journal of the Optical Society of America, 67(3), 399-406 (1977).
- [5] [Measurement Specialties (MEAS): Piezo Film Sensors-Technical Manual], USA(1999).
- [6] [Precision Acoustics: PVDF Properties and Uses].
- [7] Roh, Y., Varadan, V. V., and Varadan, V. K., "Characterization of all the elastic, dielectric, and piezoelectric constants of uniaxially oriented poled PVDF films," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 49(6), 836-847 (2002).
- [8] Ewins, D. J., [Modal Testing: Theory, Practice and Application] RESEARCH STUDIES PRESS LTD, Hertfordshire, England(2000).
- [9] Pastor, M., Binda, M., and Harčarik, T., "Modal Assurance Criterion," Procedia Engineering, 48, 543-548 (2012).
- [10] Ewins, D. J., "Model validation: Correlation for updating," Sadhana, 25(3), 221-234 (2000).
- [11] Rao, S. S., [Vibration of Continuous Systems] John Wiley & Sons, Inc., (2007).
- [12] Hadipour, M., Tahtali, M., Lambert, A. J., and Pota, H. R., "Study on a hybrid model for the vibration control of flexible piezoelectric thin films," (submitted).
- [13] Patterson, K., and Pellegrino, S., "Ultralightweight deformable mirrors," Applied Optics, 52(22), 5327-5341 (2013).
- [14] The Fraunhofer Institute, 'New technology for ultra-smooth polymer films ' (Media Release: 27 June 2018)