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## 双压电片变形镜的人眼像差拟合能力分析

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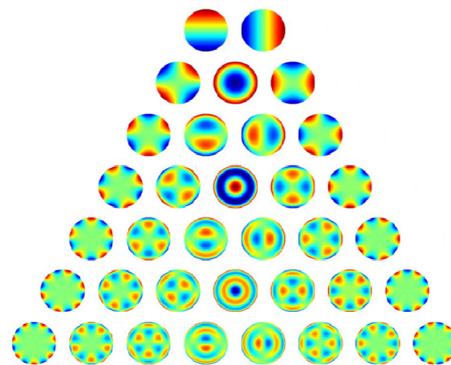
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**摘要:** 针对三种不同空间分辨率的双压电片变形镜(Bimorph DM), 采用仿真实验分析其对 3~35 项 Zernike 静态像差和实际人眼(包括疾病人眼)像差的拟合能力。实验表明, Bimorph 变形镜特别适用于校正低阶像差, 拟合误差小于 0.15, 随着空间分辨率的增加, Bimorph 变形镜对 Zernike 像差和人眼像差的拟合能力总体表现为增强的趋势, 其中, 35 单元的 Bimorph 变形镜的像差拟合能力最优, 对前 20 项 Zernike 像差的拟合误差稍优于传统分立式压电变形镜。通过对 Bimorph 变形镜像差拟合能力的实验分析, 为人眼视网膜高分辨率系统的 Bimorph 变形镜选型提供了分析方法, 也为进一步提升 Bimorph 变形镜的像差校正能力奠定了研究基础。

**关键词:** 自适应光学; 双压电片变形镜; Zernike 像差; 像差拟合; 视网膜成像

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## Analysis on fitting capability to human aberrations of bimorph deformable mirrors

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**Abstract:** This study adapted simulations to analyze the fitting capabilities to human aberration of three kinds of Bimorph Deformable Mirrors (DMs) with different spatial resolutions, especially the capability to fit to 3~ 35th orders of Zernike static aberrations and the human aberrations, including the eye of diseases. It's shown that Bimorph DM is

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well suitable for fitting to low-order aberrations with the error less than 0.15. As the spatial resolution increased, the capability of fitting aberrations enhanced totally. Compared with traditional discrete piezoelectric DM, 35-element Bimorph DM had smaller fitting error on the first 20th Zernike aberration. This simulated analysis provided an analytical method for the selection of Bimorph DMs for high-resolution human eye imaging systems. In addition, it provided a research foundation of further improvement of the Bimorph DM in fitting aberrations capability.

**Keywords:** adaptive optics; bimorph deformable mirror(DM); Zernike aberrations; aberration fitting; retina imaging

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## 1 引言

利用自适应光学技术实时探测人眼像差并完成校正, 可以获取人视网膜近衍射极限的细胞级高分辨率图像<sup>[1-2]</sup>, 已经逐渐成为视觉科学和眼科医学领域的一种前所未有的科学工具和研究手段<sup>[3-4]</sup>, 有助于实现对视觉功能更深入的认识, 以及对眼科疾病的早期诊断<sup>[5-6]</sup>。

变形镜(Deformable mirror, DM)作为自适应光学技术的核心部件, 承担着像差校正的任务<sup>[7]</sup>。传统的分立式压电变形镜变形量行程约  $2\ \mu\text{m}\sim 4\ \mu\text{m}$ , 并且为了保证对人眼像差一定的校正能力, 镜面尺寸通常较大<sup>[8]</sup>。新型的微机电 MEMS 变形镜在很小镜面尺寸范围内都具有很高的校正精度, 其行程却小于  $2\ \mu\text{m}$ <sup>[9]</sup>。据统计<sup>[10]</sup>, 无论是正常人眼, 还是疾病人眼的波前像差组成中, 离焦和像散的低阶像差占比都超过 80%, 绝大部分人眼像差的校正幅值要求至少要达到  $10\ \mu\text{m}$  量级。因此, 在较小口径上构造大行程的变形镜技术将非常有利于自适应光学人眼高分辨率成像技术的产业化发展。

为此, 中国科学院光电技术研究所研制出的双压电片变形镜(Bimorph DM)<sup>[11-12]</sup>, 基于横向压电效应的双层压电陶瓷结构, 可以产生超过  $10\ \mu\text{m}$  的大变形量, 并且相对于传统分立式压电变形镜的镜面口径缩小一半。针对光电技术研究所研制的三种不同空间分辨率的 Bimorph 变形镜, 我们选取实测的疾病人眼像差统计数据, 分别分析不同空间分辨率的 Bimorph 变形镜的人眼像差拟合能力, 为高分辨率成像系统的变形镜选型提供依据。

## 2 方法原理

### 2.1 Zernike 人眼像差描述

由于 Zernike 多项式是单位圆上的一组正交基, 从而成为一种描述光学系统瞳面上的像差的常用基函

数<sup>[13]</sup>, 因此现在一般都使用 Zernike 多项式来描述人眼像差  $W(x,y)$  :

$$w(x,y) = \sum_{n,m} C_n^m Z_n^m(x,y), \quad (1)$$

其中  $x,y$  分别为人眼瞳面处的纵横坐标,  $Z_n^m$  为 Zernike 多项式,  $C_n^m$  为相应的 Zernike 系数。注意, 在圆域内的 Zernike 多项式采用极坐标形式, 并且按照美国光学学会(OSA)建议的标准排布方式<sup>[14]</sup>, 从低阶到高阶的顺序排成金字塔形, 如图 1 所示。考虑到人眼像差特性, 采用前 7 阶 35 项 Zernike 多项式描述人眼像差。

### 2.2 Bimorph 变形镜参数

Bimorph 变形镜将两片压电材料薄片按相反的极化方向粘接而成作为驱动层, 将其上粘贴的薄镜面精密抛光后镀膜作为反射面, 驱动层划分为分立的电极驱动反射面, 产生可控变形。图 2 为三种工艺成熟的 Bimorph 变形镜电极排布示意图, 所有 Bimorph 变形镜的有效通光口径均为  $20\ \text{mm}$ , 驱动电极均采用扇形排布方式, 电极数目依次为 9、20 以及 35, 三种 Bimorph 变形镜的具体参数如表 1。Bimorph-9 与 Bimorph-35 变形镜的双压电层均由分立电极驱动, 而 Bimorph-20 变形镜第一层分布着 1~19 号分立电极, 第二层是一整块离焦 20 电极, 可以提供较大的离焦变形。

### 2.3 像差拟合方法

对于给定的某一 Zernike 多项式像差波前  $\Psi(x,y)$ , 遵循变形镜驱动电极影响函数的线性叠加原理, 即可计算出变形镜面形对该像差波前的拟合情况  $\varphi(x,y)$ , 其关系式:

$$\psi(x,y) = \varphi(x,y) + \varepsilon, \quad (2)$$

其中:  $\varepsilon$  定义为变形镜的像差拟合误差。由于:

$$\begin{aligned} \varphi(x,y) &= \sum_i c_i Z_i(x,y), \\ \varphi(x,y) &= \sum_j v_j Z_j(x,y), \end{aligned} \quad (3)$$

其中:  $Z_j(x,y)$  和  $v_j$  分别为实测的第  $j$  个驱动器影响函数及加到该驱动器上的电压, 式(2)中的拟合误差可以被

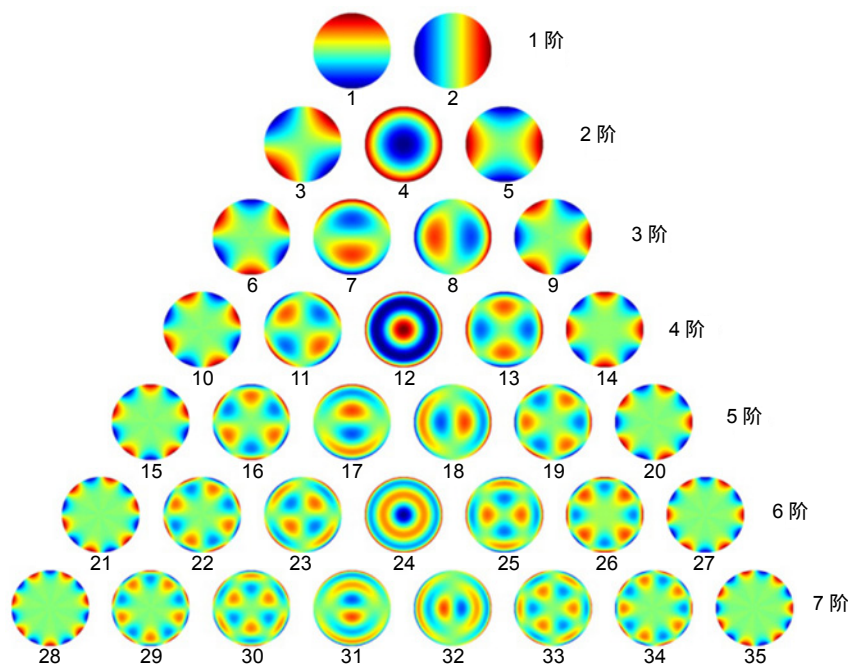


图 1 标准 Zernike 排布(OA 推荐)

Fig. 1 Standard Zernike distribution(OA 推荐)

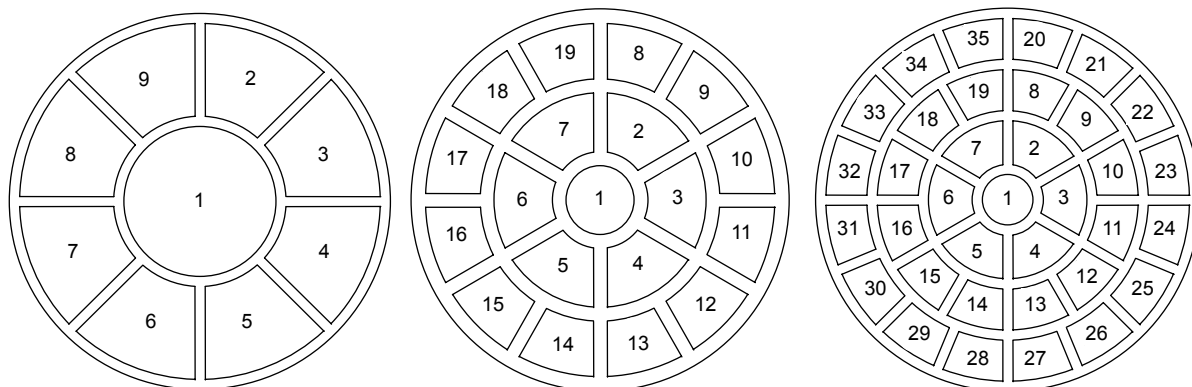


图 2 三种 Bimorph 变形镜电极排布

Fig. 2 Distribution of discrete electrodes of the three types of Bimorph DMs

定义为

$$\varepsilon = \frac{RMS_{\varphi(x,y)-\psi(x,y)}}{RMS_{\psi(x,y)}} = \frac{\sqrt{\iint [\varphi(x,y) - \psi(x,y)]^2 dx dy}}{\sqrt{\iint [\psi(x,y) - \bar{\psi}]^2 dx dy}} \quad (4)$$

表 1 三种 Bimorph 变形镜参数

Table 1 Parameters of three types of Bimorph DMs

型号	驱动电极数目	最大行程量/ $\mu\text{m}$	初始面形 RMS 值/nm	动态响应频率/kHz
Bimorph-9	9	$\pm 14$	25	2.8
Bimorph-20	20	$\pm 20$	<20	4
Bimorph-35	35	$\pm 17$	13	>3

因此，参数  $\varepsilon$  表征着变形镜对给定像差的拟合精度， $\varepsilon$  越小拟合精度越高。Zernike 多项式第 1 项和第 2 项分别代表像差波前的平移和倾斜，在自适应光学系统中，变形镜是无法对波前平移与倾斜进行校正。因此，在分析 Bimorph 变形镜的人眼像差拟合能力时，只考虑第 3~35 项 Zernike 像差。

### 3 仿真实验与结果

#### 3.1 静态 Zernike 像差拟合实验

常规地，变形镜能够校正的像差类型由“校正到第  $N$  项 Zernike 像差，拟合误差小于  $X$ ”来表述。给定第 3~35 项静态 Zernike 各项像差，每项像差的均方根值为 1 倍波长( $\lambda=820 \text{ nm}$ )，分别计算三种不同空间

分辨率的 Bimorph 变形镜对各项像差的拟合误差  $\varepsilon$  , 图 3 为三种 Bimorph 变形镜对 Zernike 像差的拟合误差仿真实验结果。

从图 3 可见,三种 Bimorph 变形镜对这些 Zernike 像差都有一定的校正能力,对低阶像差的校正能力都表现得很好,仿真实验结果可知:

1) 随着空间分辨率的增加,Zernike 像差拟合能力总体表现为增强的趋势,以对 Zernike 像差校正误差 15%的为限,Bimorph-9 有 3 项,Bimorph-20 有 7 项,Bimorph-35 有 14 项,因此空间分辨率最高的 Bimorph-35 变形镜的像差校正能力在三种变形镜中最强。

2) Bimorph-20 变形镜在对离焦(第 4 项 Zernike 像差)和二次球差(第 15 项 Zernike 像差)的校正能力较 Bimorph-35 变形镜有所增强,是因为前者增加了一个全局的离焦驱动器,使得更适合校正这种旋转对称的像差。

### 3.2 人眼像差拟合实验

静态 Zernike 像差的校正拟合能力分析,只能说明 Bimorph 变形镜对单一像差的拟合校正精度,在实际人眼高分辨率成像系统中,人眼像差不仅有低阶项,还有很多高阶项,是不同系数的 Zernike 多项式组合。为了更真实地反映变形镜的实际像差校正能力,我们采用实测的人眼像差数据,包括正常人眼和疾病人眼,开展对三种 Bimorph 变形镜的像差拟合能力分析。

人眼像差数据来源于温州医科大学门诊病人和实验室工作人员,像差采集由光电技术研究所的人眼像差测量仪(与日本 Topcon 公司的 KR-1W 人眼像差仪对标,像差测量精度约为 4 nm)完成。图 4 为三种 Bimorph 变形镜对实际人眼像差的拟合结果。

活体人眼像差包括正常人眼,以及葡萄膜炎(uveits)、黄斑变性(MD)、视网膜静脉阻塞(RVO)、青光眼(glaucoma)、视网膜色素变性(RP)、视网膜糖尿病病变(DR)、中浆(CSC)、黄斑水肿(CME)等八种眼科常

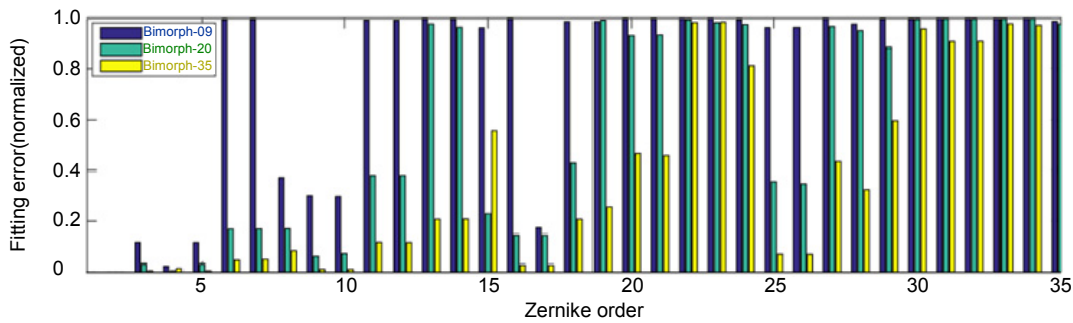


图 3 三种 Bimorph 变形镜的 Zernike 像差校正拟合能力  
Fig. 3 Zernike aberration fitting ability of three types of Bimorph DMs

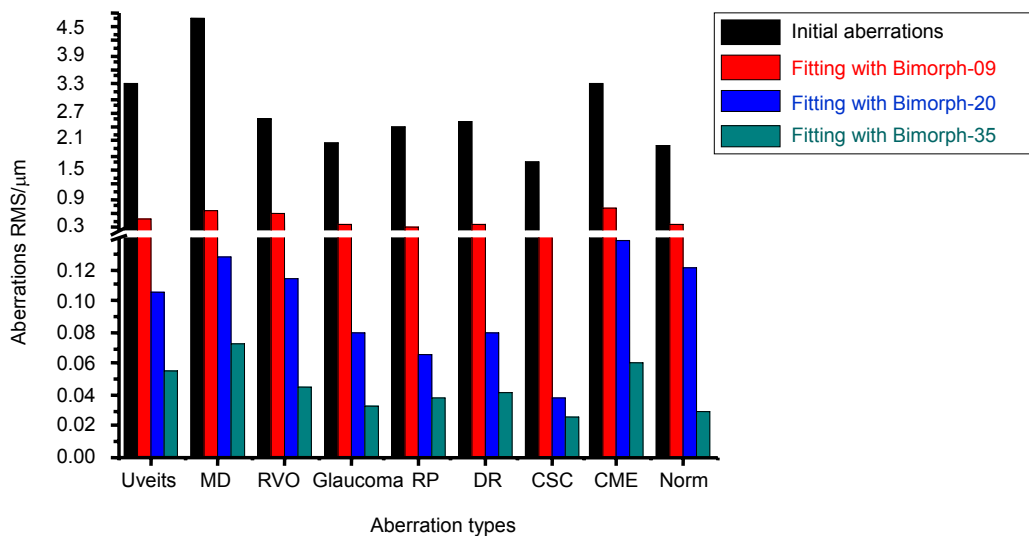


图 4 三种 Bimorph 变形镜对实际人眼像差的拟合能力  
Fig. 4 Human aberrations fitting ability of three types of Bimorph DMs

见疾病人眼。从拟合结果可看出,三种不同空间分辨率的Bimorph变形镜对各种人眼像差都有一定的校正能力,由仿真实验可知:

1) Bimorph-9变形镜对人眼像差的校正残差RMS值均大于 $0.2\ \mu\text{m}$ ,校正效果并不明显;Bimorph-20和Bimorph-35变形镜随着空间分辨率的提升像差校正能力也明显增强。以像差残差RMS值 $0.1\ \mu\text{m}$ 为限,Bimorph-20对四种疾病人眼的像差校正有效。

2) 对于三种不同空间分辨率的Bimorph变形镜,Bimorph-35对人眼像差的校正幅值是最高的,基本上都能将人眼像差校正至接近衍射极限( $\lambda/14$ )。

## 4 结论

针对第3~35项静态Zernike像差和实际人眼(包括疾病人眼)像差,分别详细分析了三种不同空间分辨率Bimorph变形镜对它们的校正拟合能力。空间分辨率最高的Bimorph-35变形镜的像差拟合能力综合而言是最优的,Bimorph-20变形镜对于旋转对称性像差的拟合能力最强,因此,可以得出以下结论:

1) 若只采用单个Bimorph变形镜完成人眼像差校正,Bimorph-35变形镜是最优选择,将来可以继续以减小通光口径和缩小驱动电极尺寸来提高空间分辨率,可以进一步提高像差拟合能力。

2) 排除研制工艺难题,可以给Bimorph-35变形镜增加第36个电极,作为独立离焦电极层,类似于Bimorph-20的电极结构,可以有效提升对旋转对称性像差的拟合能力。

3) 若采用双变形镜组合校正人眼像差,Bimorph-9与分立式压电变形镜的组合最优,Bimorph-9结构简单、成本低、稳定性高,大行程非常适合校正低价像差。

据文献[15],Bimorph-35变形镜的Zernike像差拟合能力与37单元的分立式压电变形镜相当,除第31~33项之外,Bimorph-35变形镜的拟合精度更优,特别是对于前20项Zernike像差。因此,通过对几种不同空间分辨率的Bimorph变形镜像差拟合能力分析,特别是针对活体人眼像差的拟合,Bimorph变形镜是用于人眼视网膜高分辨率成像切实可行的波前校正器之一,其优势在于对低阶像差的拟合精度高。相比于分立式压电变形镜,Bimorph-35变形镜口径缩小,像差拟合能力稍优,是能够实现对人眼像差有效校正的最优选择,但还需要进一步完善结构实现对旋转对

称性像差的校正。

## 参考文献

- Jiang W H. Adaptive optics techniques investigations in institute of optics and electronics[J]. *Opto-Electronic Engineering*, 1995, **22**(1): 1-13.  
姜文汉. 光电技术研究所的自适应光学技术[J]. *光电工程*, 1995, **22**(1): 1-13.
- Rao C H, Zhu L, Zhang L Q, et al. Development of solar adaptive optics[J]. *Opto-Electronic Engineering*, 2018, **45**(3): 170733.  
饶长辉, 朱磊, 张兰强, 等. 太阳自适应光学技术进展[J]. *光电工程*, 2018, **45**(3): 170733.
- Liang J Z, Williams D R, Miller D T. Supernormal vision and high-resolution retinal imaging through adaptive optics[J]. *Journal of the Optical Society of America A*, 1997, **14**(11): 2884-2892.
- Dai Y, Xiao F, Zhao J L, et al. Ocular aberrations manipulation with adaptive optics and its application[J]. *Opto-Electronic Engineering*, 2018, **45**(3): 170703.  
戴云, 肖飞, 赵军磊, 等. 自适应光学人眼像差调控及其应用[J]. *光电工程*, 2018, **45**(3): 170703.
- He Y, Wang Z B, Wang Y Y, et al. In vivo imaging of mice auricle vessels using adaptive optical confocal fluorescence microscope[J]. *Chinese Optics Letters*, 2015, **13**(11): 111702.
- Wang Y Y, He Y, Wei L, et al. Bimorph deformable mirror based adaptive optics scanning laser ophthalmoscope for retina imaging in vivo[J]. *Chinese Optics Letters*, 2017, **15**(12): 121102.
- Jiang W H. Overview of adaptive optics development[J]. *Opto-Electronic Engineering*, 2018, **45**(3): 170489.  
姜文汉. 自适应光学发展综述[J]. *光电工程*, 2018, **45**(3): 170489.
- Wang Z B, Wei D, Wei L, et al. Aberration correction during real time in vivo imaging of bone marrow with sensorless adaptive optics confocal microscope[J]. *Journal of Biomedical Optics*, 2014, **19**(8): 086009.
- Zhang Y H, Poonja S, Roorda A. MEMS-based adaptive optics scanning laser ophthalmoscopy[J]. *Optics Letters*, 2006, **31**(9): 1268-1270.
- Liang J Z, Williams D R. Aberrations and retinal image quality of the normal human eye[J]. *Journal of the Optical Society of America A*, 1997, **14**(11): 2873-2883.
- Ning Y, Jiang W H, Ling N, et al. Response function calculation and sensitivity comparison analysis of various bimorph deformable mirrors[J]. *Optics Express*, 2007, **15**(19): 12030-12038.
- Dai Y, Zhao L N, Xiao F, et al. Adaptive optics vision simulation and perceptual learning system based on a 35-element bimorph deformable mirror[J]. *Applied Optics*, 2015, **54**(5): 979-985.
- Thibos L N, Applegate R A, Schwiegerling J T, et al. Standards for reporting the optical aberrations of eyes[J]. *Journal of Refractive Surgery*, 2002, **18**(5): S652-S660.
- Thibos L, Applegate R A, Schwiegerling J T, et al. Standards for reporting the optical aberrations of eyes[M]//Lakshminarayanan V. *Vision Science and Its Applications*. Santa Fe, New Mexico United States: Optical Society of America, 2000: 232-244.
- Zhou H, Guan C L, Dai Y. Bimorph deformable mirrors for adaptive optics of human retinal imaging system[J]. *Acta Optica Sinica*, 2013, **33**(2): 0211001  
周虹, 官春林, 戴云. 用于自适应光学视网膜成像系统的双压电片变形反射镜[J]. *光学学报*, 2013, **33**(2): 0211001.

# Analysis on fitting capability to human aberrations of bimorph deformable mirrors

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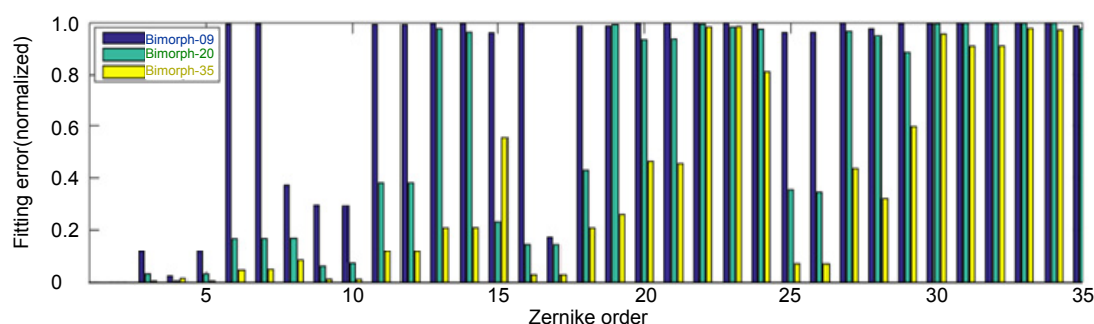
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Zernike aberration fitting ability of three types of Bimorph DMs

**Overview:** For the three kinds of bimorph deformable mirrors (DM) with different spatial resolutions developed by the Institute of Optics and electronics, CAS, a numerical simulation is used to analyze the fitting ability of 3~35 Zernike static aberration firstly in this article. The numerical results shown that all those Bimorph DMs have a certain ability to correct the Zernike static aberrations and perform well for the correction of low-order aberrations particularly. With the increase of the spatial resolution of the Bimorph DM, the aberration fitting capability appeared to increase as well. According to the limitation to 15% of the normalized error of the Zernike aberration fitting, there are 3 items of Zernike aberrations which can be fitting well by Bimorph-9, and 7 items by Bimorph-20, and 14 items by Bimorph-35; Therefore, Bimorph-35 DM with the highest spatial resolution has the strongest aberration correction ability among the three kinds of Bimorph DMs. Next, we analyzed the aberration correction of the human eyes (including the diseased eyes) and found that three kinds of Bimorph DMs have a certain ability to correct aberrations in human eyes with different types of diseases. The Bimorph-9 DM didn't correct human eye aberration obviously, and Bimorph-35 has the strongest aberration correction ability for human eye aberrations, nearly reaching to the diffraction limit ( $\lambda/14$ ). Therefore, the Bimorph DM is one kind of feasible wavefront correctors for high-resolution imaging of human retina through the aberration fitting analysis of Bimorph DMs, especially for human eye aberrations fitting analysis. The Bimorph DM has the advantage of high precision in fitting low-order aberrations. Compared to the conventional discrete piezoelectric DM, the Bimorph-35 DM has a better fitting precision except for the 31~33 item of Zernike aberrations, especially for the first 20 Zernike aberrations. In conclusion, if only a single Bimorph DM is used to correct human eye aberrations, the Bimorph-35 DM is the best choice. In the future, the spatial resolution of Bimorph-35 DM can be further improved by reducing the optics aperture, reducing the size of the driving electrode, and adding an independent defocusing electrode layer to improve the fitting ability of the rotation symmetry aberration. If double DMs are used to correct the human eye aberrations, the combination of the Bimorph-9 and the discrete piezoelectric DM is an optimal choice, with the simplest structure, low cost, high stability and large stroke for the Bimorph-9 DM.

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