

"Feedforward" Adaptive-Optic System Identification

Analysis for Mitigating Aero-Optic Disturbances

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As a beam of light traverses through a non-uniform index-of-refraction field, adjacent light rays become advanced or retarded with respect to one another. This in turn creates an aberrated line of constant phase known as an aberrated optical wavefront. Such phase distortions significantly degrade the beam’s far-field intensity pattern resulting in a loss of system performance. Aberrations induced over short propagation lengths, i.e. on the order of the beam’s aperture, are known as “aero-optic” effects. Aero-optic disturbances, such as those created in free shear layers, commonly exceed 1 kHz placing certain sensing and update requirements on the control system used to correct for these aberrations. Frequency response testing was used to perform system identification on one of the key components in an Adaptive-Optic (AO) system. The amplifier used to transfer control signals to the deformable mirror (DM) was shown to have significant slew rate limitations. These results, in conjunction with the DM’s actuator response characteristics, reveal that the conventional AO approach may be limited by sensing and update requirements necessary to correct for aero-optic disturbances. System identification was also used to determine a representative transfer function for the DM amplifier to be used in the analysis and development of an alternative AO controller. The system identification outlined in this paper will also serve as a model for further testing.

I. Motivation

Aberrations imposed on otherwise planar optical wavefronts cause significant degradation to the beam’s far-field irradiance pattern, resulting in a loss of system performance due to the reduction in on-target intensity. These aberrations may be caused by variations in the index-of-refraction field; a field producing additive phase fluctuations to the beam’s wavefront as it traverses the flow. Optical aberrations that amass over long propagation lengths are termed atmospheric disturbances and those that occur over short propagation lengths, on the order of the beam’s aperture, are called “aero-optic” effects; this refers to the flow field near the exit aperture of an outgoing beam or the receiving aperture of an imaging system as shown in Fig. 1.

Due to the dependence of a beam’s maximum irradiance on wavelength, aero-optic effects proved inconsequential until recently with the movement towards near-visible-wavelength laser systems. With the increased use of shorter wavelength lasers, aero-optic disturbances due to separated flows greatly restrict an airborne laser system’s field of regard; in order to recover field of regard it becomes imperative to perform real-time corrections of aero-optic disturbances.1 Adaptive-Optics (AO) is “the control of light in a real-time closed loop fashion”.2 Current AO systems, which sense, construct, and apply conjugate corrections at regular time intervals, successively correct for low frequency disturbances present in atmospheric

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turbulence; however these systems become bandwidth limited with increased frequencies, as is the case in aero-optic disturbances where frequencies commonly exceed 1 kHz.\textsuperscript{1,3} These performance limitations are due primarily to system gain requirements, cutoff frequency, system latency, and “slew rate” limitations as will be discussed in this paper. It is important to recognize that in this paper the term \textit{slew rate} is used in its control context rather than being mistaken for the motion of the beam through the atmosphere. \textit{Slew rate} is used here to describe the maximum rise rate of an output voltage to a step input voltage, which is the common use of this term in control theory.

\textbf{Figure 1. Shear layer formed over a turret/fairing combination.}

The conventional AO system typically consists of a wavefront sensor, reconstructor, and deformable mirror (DM). As shown in Fig. 2, an incoming aberrated wavefront, commonly quantified using optical path difference (OPD), is reflected off the DM used to apply the optical wavefront’s conjugate correction. Since a perfect correction is impossible due to latencies and wavefront approximations, a certain amount of error remains on the reflected beam which is then directed onto the wavefront sensor. The residual error is measured and a signal sent to the reconstructor which approximates a fraction of the error, based on system gain requirements. The wavefront correction is then applied to the DM closing the feedback loop.\textsuperscript{2}

\textbf{Figure 2. Closed-loop depiction of the conventional AO system, consisting of a wavefront sensor (WFS), reconstructor, and deformable mirror (DM).}
Each component of the closed-loop feedback system shown above in Fig. 2 possesses its own bandwidth limitations. Given current technology, the wavefront sensor typically creates the bottleneck within the system. Figure 3 gives wavefront sensor capture rate requirements assuming a system gain of approximately 0.1, which seems to be characteristic of most conventional systems, including the AO system owned by Notre Dame. The disturbance frequency along the abscissa in Fig. 2 is presumed to be the Greenwood frequency for atmospheric propagation, but may be taken here as the disturbance frequency under the presumption that the DM is capable of fitting the disturbance both in form and amplitude. Further, this plot assumes an initially reduced on-target intensity of less than 10% the diffraction limited intensity, or maximum achievable intensity. Three reference lines indicate the factor at which the capture rate must exceed the disturbance frequency based on desired on-target intensity; the bold solid line shows capture rate requirements needed to achieve 80% of the diffraction limited intensity, the solid line represents 50% of the diffraction limited intensity, and the dotted line shows requirements based on achieving 30% of the diffraction limited intensity.

Therefore, given a disturbance frequency of 1 kHz, a wavefront sensor capture rate of approximately 100 kHz is needed to maintain system stability while achieving approximately 80% of the diffraction limited intensity through AO corrections. Such a capture rate exceeds the capabilities achievable by current wavefront sensor technology. Moreover, if wavefront sensor limitations were overcome, yet another component of the feedback system would inhibit the ability to apply real-time corrections in the case of aero-optic disturbances. This has been the impetus for Notre Dame’s efforts in combining flow control with an alternative approach to AO correction using a combination of “feedforward” and feedback architecture. This paper presents frequency response results for the Notre Dame’s AO system amplifier used to transfer control signals to the DM actuators. The results obtained here may be used to further express limitations set forth by the conventional approach as well as provide a means of constructing independent transfer functions for components studied in the future. These transfer functions will be used in the analysis and development of our alternative AO approach described in detail by Nightingale et al. and demonstrated experimentally using a “person-in-the-loop”. Finally, performance implications based on frequency response data for the DM amplifier along with frequency characteristics of individual actuators will be discussed.

II. Frequency Response Analysis

In order to characterize the DM amplifier’s bandwidth limitations and create an appropriate model to be used in a feedback control system, frequency response analyses were performed. The AO system located in the Hessert laboratory at the University of Notre Dame, was developed by Xinetics and consists of two different control loops; a DM performs conjugate corrections and a tip/tilt mirror removes the average slope, or tilt, across the beam’s aperture. Each feedback loop contains various components possessing frequency response characteristics crucial to overall system performance. Experimental tests...
were conducted to determine key operational features, such as cutoff frequencies, latencies, and slew rate limitations of the DM amplifier. The experimental procedure and system identification analysis described below will be used to study remaining AO system components in future work.

A. Experimental Method

The conjugate correction feedback loop, as a part of Notre Dame’s AO control system, consists of 5 NI-PXI (National Instruments) boards each containing 8 channels corresponding to the 37 DM actuators where three channels are unused. Control signals are relayed from each of the NI-PXI board channels through an amplifier which amplifies each signal by 3X the input voltage. The amplified signals are then sent directly to each of the DM actuators which may be modeled as a capacitor.

Experimental tests were conducted to determine the frequency response of the DM amplifier. Bode diagrams were constructed depicting the amplifier’s behavior as a function of input frequency. Sinusoidal input signals ranging in amplitude from 1 Volt to 8 Volts and ranging in frequency from 100 Hz to 20 kHz were sent into the amplifier. The input and output signals were measured simultaneously using a data acquisition system with a sampling rate of 500 kHz. Data was acquired over twenty-five consecutive time periods, i.e. $25T$ where $T$ is the time period associated with the sinusoidal input frequency. Two amplitude measurements and two phase delay measurements were taken from each of the twenty-five time periods resulting in 50 amplitude measurements and 50 phase delay measurements for each frequency test. Amplitude was measured as the maximum and minimum peak value over a time period and phase delay was measured as the phase shift between the input and output signals at the zero cross-over points. Phase delay was measured after the signal’s mean or DC bias was removed. The data was then averaged and plotted on a frequency response diagram showing magnitude and phase response characteristics where the magnitude data was determined by normalizing the output amplitude by the averaged input amplitude. The range of values obtained at each input frequency was used to determine the signal’s uncertainty for each measurement.

The raw signals were also transformed into the Fourier domain for further analysis using Matlab’s discrete Fourier transform commands. The output signal’s amplitude and phase delay were determined from the signal’s Fourier transform at the input frequency as a means of verifying the measurements described previously. The frequency spectrum obtained from the Fourier transform was also used to locate any harmonics present in the output signal which would indicate harmonic distortion. Square wave inputs were also used to study the DM amplifier’s response to step changes in voltage. This data was used to determine any slew rate limitations of the component. The frequency response measurements were then used to model and describe the component’s characteristics through system identification based on robust control theory.

B. System Identification

System identification, the process of constructing a model based on experimental data, measurements, and observations, is an important aspect of this effort. The alternative AO control system, mentioned previously, will consist of several different components including optical sensors, mirrors, electrical circuitry, etc. It becomes necessary to model system response characteristics for each of the individual components to properly analyze and design the AO controller. The frequency response measurements, obtained through methods described in the previous section, were used to identify and construct a transfer function as well as determine corresponding bandwidth limitations for the DM amplifier. The system identification procedure applied in this paper is based on robust control theory. The component is modeled with an unstructured multiplicative uncertainty model given by,

$$G(s) = G_o(s)[I + \Delta(s)]$$  \hspace{1cm} (1)$$

where $G_o$ represents the nominal plant and $\Delta$ the uncertainty associated with the actual plant, or model, $G$. The average magnitude and phase response data is plotted versus input frequency, where each averaged data point contains an associated range of values corresponding to its uncertainty. The nominal plant, $G_o$, can then be determined by finding a transfer function which most closely models the average magnitude and phase response characteristics. Step response data will also be used to illustrate the primary source of uncertainty for the amplifier.
In order to access the uncertainty of both magnitude and phase in conjunction with one another, phasor notation must be used. Therefore, a Nyquist plot may be generated from the nominal plant’s transfer function and uncertainty regions constructed using the maximum and minimum values of experimentally-measured magnitude and phase for a given input frequency. Uncertainty circles are then constructed, centered along the nominal plant’s Nyquist plot and encompassing the corresponding uncertainty regions. Given the multiplicative model expressed in Eq. (1), the radius of each circle corresponds to the magnitude of the nominal plant multiplied by the uncertainty as shown in Fig. 4. Therefore, the uncertainty is determined by multiplying the radius values for each respective input frequency by the inverse of the nominal plant’s magnitude.

![Figure 4. Example of a Nyquist plot given a multiplicative uncertainty model.](image)

Over bounding the uncertainty with a stable proper rational transfer function is one method of modeling system uncertainty.\(^7\)\(^8\) In this approach, a multiplicative bound, \(W(s)\), is constructed such that

\[
\|W^{-1}A\|_\infty < 1
\]

where the \(\mathcal{H}_\infty\) norm is the supremum of the maximum singular value of a complex valued matrix, or in this case a single complex valued function. This type of model accounts for uncertainties within the plant and provides a useful form for further robust control analysis.\(^7\)\(^8\)

### C. Nonlinear Characteristics

Many electronic devices and components such as amplifiers exhibit nonlinear characteristics which can significantly affect both its magnitude and phase response. Two such nonlinear features are harmonic distortion and slew rate. Harmonic distortion refers to the process of harmonics being added to a signal as it passes through a device due to nonlinear effects. The output signal being altered or distorted results in a more complicated transfer function. Slew rate is the maximum rate of change that a signal can achieve placing limitations on its response characteristics. This can lead to nonlinear effects given a sinusoidal input if the slew rate, \(SR\), does not meet the following condition:

\[
SR > 2\pi f A
\]

where \(f\) refers to input frequency and \(A\) is the peak amplitude of the signal. Each of these effects will be explored and consequences discussed in the subsequent sections.

### III. DM Amplifier

The DM Amplifier represents a key component in Notre Dame’s AO control system. The amplifier is used to transfer the conjugate correction signal to the DM actuators. It provides an amplification of 3X the input voltage resulting in an output signal of +/- 30 Volts peak to peak riding on a 70 Volt bias signal, i.e.
when the input is 0.0 Volts the output is 70 Volts. The amplifier accepts a maximum input signal of +/- 10 Volts; therefore frequency response testing was conducted using sinusoidal waveforms with amplitudes ranging from 1 Volt to 8 Volts. Input frequencies ranged from 100 Hz to 20 kHz. In order to test the amplifier under conditions similar to those experienced during normal operation, a 2.2 μF capacitor was connected to the output of the amplifier, simulating the effects of an individual piezoelectric actuator. Sinusoidal signals were input into the amplifier using a function generator and the output voltage was measured across the simulated actuator (capacitor). The input and output signals were acquired at a 500 kHz sampling rate. Figure 5 shows the ratio of output to input amplitude versus frequency for eight different input amplitudes. Figure 6 shows the corresponding phase delays encountered between the input and output signals over the same range of input amplitudes and frequencies. As evident from Figs. 5 and 6, the DM Amplifier exhibits linear characteristics to approximately 1 kHz, at which point both the magnitude and phase begin to significantly fall off for large input amplitudes; the exception to this linear response for frequencies below 1 kHz is the linear negative slope on the Fig. 6 phase plot, which is an indication of a pure time delay discussed later.

Figure 5. Magnitude response for the DM Amplifier.
Examination of the raw signal response provides further insight into the source of the amplifier’s nonlinear response. Step inputs were applied at four different amplitudes to determine any slew rate limitations. Figure 7 shows four different step response tests overlaid with one another for both rising (left) and falling (right) edge response, revealing a positive slew rate of 0.18 Volts/μs and a negative slew rate of 0.15 Volts/μs. Note that the output signal has been scaled by a factor of 1/3 so as to remove the DM amplifier’s amplification rate aligning the final values of the input and output signals.

The amplifier’s slew rate limitations may also be seen in the frequency response data shown below in Fig. 8. The left plot in Fig. 8 represents a case where the slew rate limit has not yet been reached, whereas the middle and right plots show two different cases in which the output signal experiences nonlinear effects due to slew rate limitations. For the given range of input frequencies tested, the amplifier displayed positive slew rates between 0.15 and 0.158 Volts/μs and negative slew rates between 0.13 and 0.137 Volts/μs. Again, the output signals have been scaled by 1/3 to more clearly show the slew rate effects.
Figure 8. Frequency response tests performed on the DM Amplifier showing slew rate limits ranging between 0.13 and 0.16 Volts/μs (after rescaled by 3X) given an input amplitude and frequency of 2 Volts and 4 kHz (left), 4 Volts and 5 kHz (middle), and 4 Volts and 20 kHz (right), respectively.

Using the data given above, an approximation to the DM amplifier’s magnitude and phase response may be derived. Negligible nonlinear effects were observed in the frequency response data given an input amplitude of 1 Volt. Therefore, a transfer function was fit to the +/- 1 Volt peak to peak magnitude response data points shown in Fig. 5. The best fit corresponded to a transfer function consisting of a low pass filter with a cutoff frequency of 7.5 kHz and an additional pure time delay of 25 µs. The response characteristics from this transfer function were then applied in conjunction with slew rate limitations, noting that there exists a maximum output amplitude restriction given by,

$$|A_o|_{\text{max}} \equiv \frac{SR}{4f_d},$$

(4)

based on the amplifier’s slew rate, $SR$, and the input or disturbance frequency, $f_d$. These characteristics were used to estimate or model the magnitude response data measured experimentally. The good agreement between the measured data and the modeled response shown in Fig. 9 indicates that the nonlinear effects are due primarily to slew rate limitations and the pure time delay referred to above imposed by the amplifier.

Figure 9. Experimental magnitude response data (‘*’s) and the modeled magnitude response (solid lines) using an estimated transfer function along with the amplitude restrictions placed on the output due to the DM amplifier’s slew rate limitations.
Due to the triangular output signal there does exist a higher order harmonic at a frequency three times that of the input, however its associated power is approximately $1/100$ of the fundamental and therefore only a slight amount of harmonic distortion occurs. Although the approach shown by Fig. 9 seems to model the experimental data very well, it must be noted that these data points correspond to pure sinusoidal inputs free of any harmonics. Since the actuators may be driven using signals consisting of several frequencies and amplitudes to correct for an actual optical wavefront induced by aero-optical effects, it becomes necessary to model the nonlinear effects using an uncertainty model.

The experimental magnitude and phase data shown in Figs. 5 and 6 were averaged and a transfer function was fit to the set of nominal data points. Figure 10 displays the averaged magnitude and phase data (x’s in Fig. 10) for the DM amplifier along with the bode plot for the associated nominal plant (solid line in Fig. 10) given by,

$$G_o(s) = 3.2 \frac{2\pi(3000)}{s + 2\pi(3000)}.$$  (5)

A low pass filter with a cutoff frequency of 3 kHz was first determined to be the best fit for the averaged magnitude data. The larger phase delays observed in the averaged data at higher frequencies will be modeled using the uncertainty analysis described below.

The next step involved modeling the measurement uncertainty. Although the nominal plant shown above (Fig. 10) seems to model the averaged magnitude data points very well, there remains a certain amount of uncertainty between the averaged data points and actual system response (Fig. 5 and Fig. 6). A Nyquist plot was generated for the nominal plant to access the frequency response of both the magnitude and phase data in combination. Figure 11 shows the Nyquist plot for $G_o$. 

![Figure 10. Averaged magnitude and phase response data for the DM Amplifier plotted against the bode diagram for its associated nominal plant or model.](image)
Figure 11. Nyquist plot of the nominal plant given in Eq. (5) (solid curve) and uncertainty circles bounding the ranges of magnitude and phase (dotted boxes) at each input frequency.

The range of experimental values associated with each data point for varying input amplitudes have been swept out by dotted lines. Circles were then constructed, centered along the nominal plant’s Nyquist plot and encompassing the corresponding uncertainty regions. These circles represent the DM amplifier’s uncertainty present at a given frequency. As described under the System Identification section, the radius of each circle represents the magnitude of the nominal plant multiplied by the uncertainty at a given frequency, $|G_o(j\omega)\Delta(j\omega)|$. Given the nominal plant described in Eq. (6) and the radius values of the uncertainty circles shown in Fig. 11, the uncertainty of the amplifier was determined and plotted versus input frequency. Figure 12 is a plot of the uncertainty values along with the gain-magnitude response of the transfer function,

$$W(s) = 0.75 \left[\frac{31.43(s + 2\pi(350))}{s + 2\pi(11,000)}\right],$$

representing the multiplicative bound. The DM Amplifier may therefore be conservatively modeled as,

$$G(s) = 3.2 \frac{2\pi(3000)}{s + 2\pi(3000)}[1 + \Delta(s)],$$

where

$$|\Delta(s)| < |W(s)|.$$

This uncertainty model will be used in the design and construction of our alternative AO controller.5
IV. Deformable Mirror (DM)

The Xinetics DM consists of 37 piezoelectric actuators mounted to the back of a flexible membrane. Seven evenly spaced (separated by 7 mm) rows of actuators, with each of the three corner actuators removed, makes up an approximate 42 mm diameter circular aperture used for corrections (Figure 13). Each actuator has a stroke length of ±4 μm given an input signal of ±10 Volts.

The dynamic capabilities of the mirror depend on the frequency response of the amplifier and actuators presented above, the number of cycles that can be accurately formed across the mirror’s aperture, as well as the bandwidth constraints for applying discrete time control commands to the amplifier and DM. This section studies the effect that each of these limitations has on the AO system’s correction capabilities.

Based on the number of actuator rows as well as the spacing between them, the DM is limited by the number of full cycles that it can accurately form across the aperture. Since a bi-quadratic fit represents a good model for the DM’s shape and given seven rows of actuators, the mirror is capable of constructing one full cycle of disturbance very well. However, as the number of cycles of disturbance across the aperture increases so does the error. Figure 14 gives the requirements needed to produce an acceptable AO correction based on the number of actuators per disturbance wavelength given various aperture sizes. It is
clear from these results that at least three actuators per disturbance wavelength are necessary to achieve any amount of correction. Furthermore, as the DM aperture size increases with respect to the disturbance wavelength the number of actuators needed to attain the same amount of correction also increases.

![Figure 14. Requirements for the number of actuators needed to apply an acceptable correction.](image)

In addition to the number of actuators per disturbance wavelength, the slew rate limitations discussed previously place another constraint on the amount of correction attainable. Moreover, if the AO system uses discrete time updates to control the DM actuators, yet another variable is introduced. Figure 15 shows two different simulations of an individual actuator’s “response” given five updates per quarter disturbance wavelength. It should be noted that the mirror itself has its own response characteristics which have not been introduced here, but will be addressed in a subsequent paper. Thus the “response” in Fig. 15 really represents the voltage pattern that will be felt by the piezoelectric actuators and the “response” plotted in Figs. 16 represent only the mirror displacement that would occur if the mirror responded with no time delays, overshoot, etc. introduced by the mirrors own response characteristics. The first case (Fig. 15, left) demonstrates the actuator’s “response” when the slew rate limitation given by Eq. (3) is satisfied. In this example the actuator rises and falls at the maximum slew rate yet is still able to achieve the target stroke height over each discrete update period. The second case (Fig. 15, right) shows the actuator’s “response” when the slew rate limitation given by Eq. (3) is not satisfied. In this case, the actuator is unable to reach the target stroke height during each discrete time period therefore causing the actuator to maintain the maximum slew rate from peak to peak. Note that this simulation agrees with the experimental data for the amplifier’s response shown in Fig. 8 (middle and right plots).
The next logical question is how the “response” of an individual actuator translates to the overall wavefront correction capabilities. Figure 16 shows three different time series of OPD, again not including the mirror’s own response characteristics. The far left plot shows the progression in time of a one-dimensional aberrating wavefront. This waveform then becomes the input signal used to produce the middle plot showing a one-dimensional OPD given the actuator “response” from Fig. 15 (left). Using the DM waveform (Fig. 16, middle) to correct for the aberrating wavefront (Fig. 16, left) resulted in the one-dimensional time evolution of OPD shown in the far right plot of Fig. 16. This example shows a significant reduction in OPD; however, as would be expected, a similar analysis of the case shown in Fig. 15 (right) produces a far less desirable outcome.

Correction capabilities were then quantified using the root-mean-squared of the difference between an actuator’s ideal temporal surface, $\Omega_{\text{ideal}}$, and its “actual” temporal surface, $\Omega_{\text{actual}}$, (i.e. absent the mirrors own characteristics) described as,

$$\delta_{\text{rms}} = \sqrt{\frac{1}{T_d} \sum (\Omega_{\text{ideal}} - \Omega_{\text{actual}})^2},$$

(9)

where $T_d$ is the disturbance time period. Since the aberrations for this analysis are given by sinusoidal functions, the following equation may also be used in replacement of Eq. (9),

Figure 15. Simulated time response of an individual actuator plotted against the input waveform given discrete time updates where $SR > 2\pi f_A$ (left) and $SR < 2\pi f_A$ (right).

Figure 16. Simulated time series of OPDs corresponding to an aberrated wavefront (left), twice the DM wavefront (middle), and the resulting wavefront error (right) where $SR > 2\pi f_A$. 
\[
\overline{OPD_{\text{residual}}} = \sqrt{\frac{1}{A_p} \sum (OPD_{\text{ideal}} - OPD_{\text{actual}})^2}
\]  

(10)

where \(A_p\) represents the mirror’s aperture and the overbar indicates a time-averaging over one disturbance time period, \(T_d\). The same results are produced using either Eq. (9) or Eq. (10) since time-averaging the OPD error at any location along the mirror’s aperture looks the same as one full-disturbance time period elapses.

Figure 17 shows several different sets of simulation results for various ratios of slew rate to \(2\pi f_d A\). As indicated by the range of plots shown below, there exists a limit on the amount of achievable correction independent of the number of updates per disturbance period when the slew rate drops below half of the limit given in Eq. (3).

![Figure 17. Correction restrictions due to the optical disturbance and slew rate limitations.](image)

Finally, the spatial restrictions shown in Fig. 14 must be combined with the temporal restrictions from Fig. 17 along with the frequency response characteristics for the mirror and each of the other system components to develop an overall understanding of the AO system’s correction limitations.

V. Wavefront Sensing

As described previously, wavefront sensing rates are dependent upon both system gain requirements in order to maintain system stability along with the number of full corrections needed to attain a specified increase in on-axis intensity. The ability of the conventional AO system to accurately sense and correct a disturbance depends upon system latencies, \(\tau_2\), disturbance frequencies, \(f_d\), and update frequencies, \(f_u\), as shown below in Fig. 18.\(^9\)
As an example, the latency of 25 µs determined from the DM Amplifier’s experimental data alone would require 5.6 kHz of full corrections given an 800 Hz disturbance to achieve a 50% reduction in the residual OPD \( \text{rms} \) (i.e. -3 dB); this in turn would require a 56 kHz wavefront frame rate in real time given a system gain of 0.1. The latency issue of the amplifier alone exceeds the limitations set by current technology; therefore an alternative AO approach is necessary in a case such as this.

VI. Conclusions

Conventional AO systems are currently being used to successively correct for low frequency disturbances such as those found during atmospheric propagation. However, in the case of aero-optic disturbances, where frequencies commonly exceed 1 kHz, current technology becomes limited due to system latencies, frequency response characteristics, slew rate limitations, and wavefront sensing rates as discussed in this paper. Each AO system component provides a source of magnitude response reduction and a phase delay as shown in the frequency response data for the DM amplifier. The amplifier tested for this paper displayed significant reductions in magnitude and phase beyond 1 kHz in addition to nonlinear effects. Slew rate limitations were also shown to play a critical role in the system’s ability to perform acceptable corrections. A positive slew rate limit of approximately 0.15 Volts/µs and a negative slew rate limit of approximately 0.13 Volts/µs was determined for the amplifier given the range of tested input frequencies. This in turn restricts the system’s ability to apply satisfactory corrections. Finally, the combination of system latencies due to the aforementioned causes along with the disturbance frequency creates a minimum update rate needed to achieve a desired amount of correction. Although the latency is presented here as almost an aside, it is clear that latency of the amplifier alone poses a major limitation on the use of AO correction in the conventional sense. On the other hand, a combined “feedforward” and feedback approach, as described in a previous paper, is essentially unaffected by latency because by its very nature it is correcting for all phase errors introduced in the entire system. These findings further support the need to use an alternative approach to solve the real-time AO problem of correcting aero-optic disturbances.

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