PROTOTYPE SMALL FOOTPRINT AMPLIFIER FOR PIEZOELECTRIC DEFORMABLE MIRRORS

K. Caputa[1,a], G. Herriot[1], J. Niebergal[2], A. Zielinski[2]

[1]NRC – Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria British Columbia, V9E 2E7, Canada
[2]University of Victoria, Dept. Electrical and Computer Engineering, P.O. Box 3055 STN CSC, Victoria British Columbia., V8W 3P6, Canada

Abstract. Adaptive Optics (AO) systems of the Extremely Large Telescopes (ELT) will incorporate deformable mirrors with an order of magnitude larger number of piezoelectric actuators than the AO systems currently deployed. Simply scaling up the drive electronics offered commercially would substantially drive up the AO cost, pose unacceptably high demands for the supply power, and occupy large volume. We are progressing on the design of a compact high voltage amplifier with the goal to have a Deformable Mirror (DM) drive density of 1200 channels per 6U VME crate. Amplifiers will be driven by multichannel D/A converters, consume no more than 0.5 W power each, be slew rate limited in hardware, and be short-circuit protected. In addition, the cost per amplifier is expected to be drastically lower compared to the integrated circuit amplifier currently used in smaller scale AO systems. Several suitable circuits using inexpensive components have been conceived and investigated by computer simulation and built. In this paper we present experimental results of prototype circuits exposed to both normal operating conditions and foreseeable fault conditions. The performance is evaluated against the AO requirements for the output range and bandwidth as well as the DM actuator operational safety requirements.

1. Introduction

AO systems of the ELTs will operate deformable mirrors with an order of magnitude larger number of actuators than in previously deployed AO systems. Currently available DM Electronics (DME) systems cannot accommodate large numbers of actuators efficiently. Specifically, these DME systems cannot meet power and volume requirements and at a reasonable cost. This prompted the necessity to develop a small footprint, high-voltage amplifier which can meet AO performance requirements at low cost. The proposed system will be based on a low-power, high-voltage amplifier, of a compact construction to allow a very high channel density.

A target power dissipation of ≤500 mW per amplifier is postulated such that an increase in number of channels on the order required for ELT AO systems will still maintain acceptable total power consumption. By using off-the-shelf components, the goal is to achieve parts cost

[a] e-mail : Kris.Caputa@nrc-cnrc.gc.ca

of less than $20 per amplifier. We have developed a prototype DME amplifier meeting these requirements, and are now in the process of testing compliance with other AO DME performance specifications.

The proposed amplifier circuit is based on small, discrete, high-voltage MOSFET transistors. To achieve the output voltage range of -400 to +400 V the circuit requires the N and P-channel devices with hard to find V_{DS} rating of 850 V and -850 V respectively. A number of candidate transistors were eventually chosen, and their corresponding SPICE models were used in simulations. The simplified schematic of the DME amplifier test circuit is shown in Figure 1 without proprietary circuits for voltage slew rate limiting and short circuit protection.

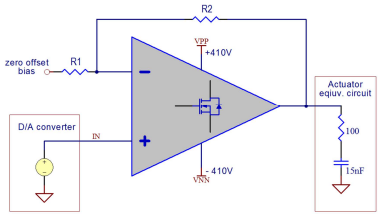

Fig. 1. Simplified schematic of DME amplifier.

Considering the substantial 820 V rail-to-rail voltage of the proposed amplifier, the quiescent current draw must be kept to a minimum to limit power dissipation. By careful selection of active components and fine tuning of circuit biases we have achieved a quiescent current of 500 µA per amplifier. The circuit has an active output range of ±400 V and is tolerant to short circuit faults. To ensure safe operation of the piezoelectric actuators, slew rate limiting is incorporated into the circuit. Bias voltages common to all channels will determine positive and negative slew rate limits and output offsets.

To put this design in perspective, consider a commercial DME system deployed in several AO installations of 10 m class telescopes with up to 400-actuator mirrors. This system is based on the PA95 operational amplifier from Cirrus Logic [1], shown in Figure 2. Although convenient to drive the DM actuators due to programmable current limit and controllable frequency response, several factors make this integrated circuit impractical for large scale DME systems. First of all an individual PA95 draws a 1.6 mA quiescent current from the ±410V rails which implies 5.2 kW power needed for a 4,000 actuator ELT DME system compared to only 1.6 kW for our proposed design.

Fig. 2. High-power operational amplifier, PA95 [1].

Second factor is the cost - an individual PA95 linear amplifier costs $120 in quantity and a 4,000 channel DME system would require $480k just to purchase the amplifier parts. By contrast the amplifier of our design will cost less than $20 per channel or $80k for all amplifier parts of a 4,000 channel DME.

Although other commercial DME systems exist based on switch-mode amplifiers that require less power; such systems are offered at a cost much higher than the PA95 based systems. It was our goal in designing this amplifier to achieve simultaneously the low-cost, low-power and small size required for application in ELT AO systems, which is something not currently commercially available.

1.1. Characterization of piezoelectric actuator load

For testing of our design, the actuator load is represented by an equivalent electrical circuit. A general equivalent circuit for piezoelectric actuator consists of a series LCR resonant branch to represent the mechanical vibrating system connected in parallel with the static capacitance of the actuator. This electrical model is valid for operation at frequencies near the resonant frequency. Typical unloaded piezoelectric actuators can have a resonance as high as 100 kHz [2]; however the loaded DM piezoelectric actuators typically have a resonant frequency on the order of 10 kHz. AO systems typically operate at frequencies below 1 kHz and the actuator resonance and therefore the electrical equivalent model can be simplified since the inertia (L) and friction (R) are negligible at these frequencies. We have adopted a static capacitance of 15 nF and series resistance of 100 Ω to represent a typical DM actuator driven with a 20 m multiconductor cable.

2. Results

During the winter and spring of 2011, the initial stages of design testing and verification were performed. This involved extensive simulation, followed by assembly and testing of physical circuits built on single channel PCBs. Test results are positive and are outlined in this paper, along with plans for further improvement and testing. A single channel driver board was developed for validating individual amplifier configurations. Provisions for multiple circuit configurations were made by means of multiple PCB layouts. One of the prototypes assembled on a printed circuit board is shown in Figure 3. A separate mother-board with support circuitry accommodates this amplifier board with quick disconnect receptacles.

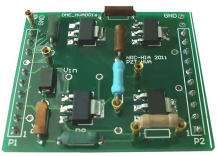

Fig. 3. Single channel piezoelectric actuator amplifier prototype assembled on a PCB.

2.1. Open-loop response

The closed-loop gain of the amplifier can be set arbitrarily and be approximated well by $1/F = 1+R_2/R_1$ provided that a large open-loop gain (A_{OL}) is available. Since open-loop gain is difficult to measure, a combination of measurement and simulation was used to characterize

the open-loop gain (A_{OL}) as a function of frequency. Two poles are determined at 10 Hz and 4 kHz. The DC open-loop gain is found to be sufficiently large, ~10000, thus the closed-loop gain approximation holds. The second order transfer function of the open-loop gain is of the form given by (1). The corresponding frequency response is shown in Figure 4 for simulated and measured results.

$$A_{OL}(s) = \frac{K}{\left(\frac{s}{p_1}+1\right)\left(\frac{s}{p_2}+1\right)}$$

$$where\ \ K = 10000, \qquad p_1 = 10 \cdot 2\pi, \qquad p_2 = 4000 \cdot 2\pi \tag{1}$$

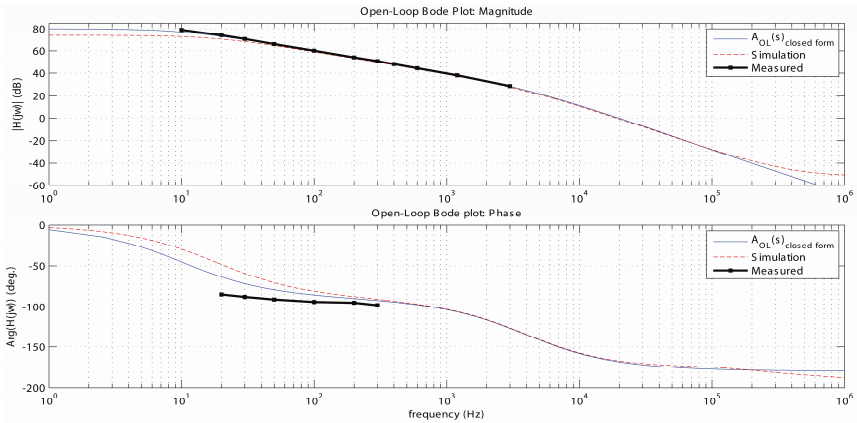

Fig. 4. Open-loop gain (A_{OL}) Bode plots.

To prove the stability of the amplifier; the loop-gain ($A_{OL}F$) is examined, where feedback factor F is given by $R_1/(R_1+R_2)$ = 1/80 or -38 dB. The frequency response of the loop-gain can be obtained by scaling the magnitude response of Figure 4 by F while the phase response remains unchanged. From this, the gain and phase margins can be found to be 78 dB and 76 ° respectively which demonstrates the unconditional stability of the circuit.

2.2. Bandwidth

It is desirable for the AO DME to have a low-pass characteristic with a cut-off at 1.5 kHz or lower so as to not excite resonant modes in the DM at frequencies above 1.5 kHz. Typically a low-pass response with arbitrarily cut-off frequency could be generated with reactive feedback impedance; however this amplifier uses only the intrinsic capacitances of the transistors and the actuator load to produce the desired frequency characteristic. This is attractive because it eliminates a need for large high voltage capacitors which would otherwise be required in the feedback path. However, this means that adjusting the cut-off frequency via modifying resistor values also has an effect on the DC response of the circuit. Using SPICE simulation, the closed-loop frequency response of the amplifier was determined and tuned. Simulation demonstrated that a bandwidth as high as 1.7 kHz could be reached with a gain of 38 dB (80), and any prescribed bandwidth less than this can be attained easily with little modifications to

the circuit. The response follows a second order roll-off at -40 dB/decade. Subsequently the frequency response was captured in hardware prototype and demonstrated to adhere closely to simulation result. From the characterization of the open-loop in (2.1), the transfer function of the closed-loop system is given by (2). The corresponding closed-loop Bode plots are as shown in Figure 5 for the simulated and measured results as well as for the transfer function representation of (2). An important result is the repeatability of the frequency response, which is found to display little variation when measured on multiple amplifier boards.

$$A_{CL}(s) = \frac{A_{OL}(s)}{1 + A_{OL}(s)F} = K_{DC} \cdot \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \cong 80 \cdot \frac{14{,}100^2}{s^2 + 25{,}100s + 14{,}100^2} \tag{2}$$

$$where\ \ K_{DC} = \frac{K}{1+KF} \cong 80, \qquad \omega_n = \sqrt{p_1 p_2 (1+KF)} \cong 14{,}100\frac{rad}{s}, \qquad \xi = \frac{p_1 + p_2}{2\omega_n} \cong 0.893$$

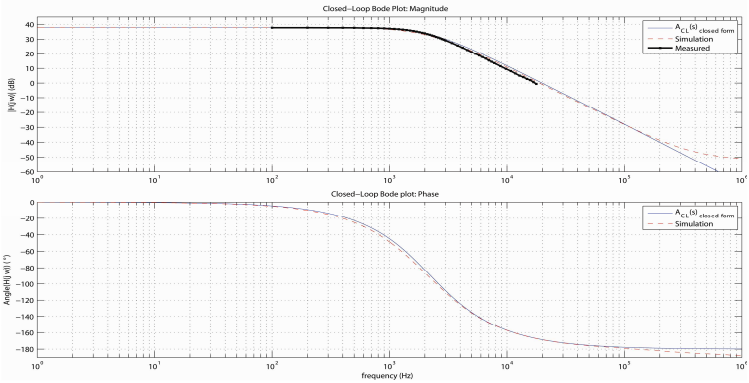

Fig. 5. Closed-loop Bode plots.

2.3. Output range and linearity

In addition to sufficient gain and bandwidth, the amplifier is required to produce a linear DC response capable of reaching ±400 V output span. This requirement was satisfied both in simulation and in hardware; the measured DC response is plotted below in Figure 6.

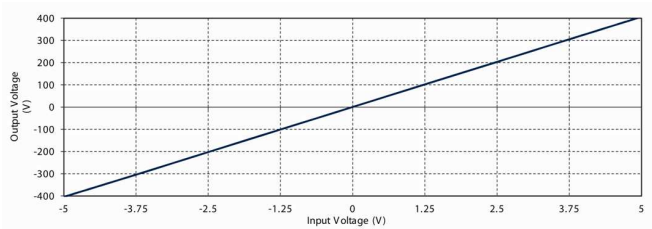

Fig. 6. DC response (measured).

The DC response of amplifier was found to display a high degree of linearity. By simulation, the amount of nonlinearities can be determined across the range of output. The magnitude of

the nonlinear components of the response were determined by fitting the DC response to a polynomial and solving for all the terms with exponents greater than one. These nonlinear terms are given in (3) by $NL(V_i)$, where $V_0(V_i)$ is the response of the amplifier to the full range of input, similar to Figure 6. The magnitude of the non-linear components of the DC response was determined as being within ±0.5 % of full-scale output, as is shown in Figure 7.

$$\begin{aligned} V_O(V_i) &= \cdots + c_5 Vi^5 + c_4 Vi^4 + c_3 Vi^3 + c_2 Vi^2 + c_1 Vi + c_0 \\ V_O(V_i) &= NL(V_i) + c_1 V_i + c_0 \\ NL(V_i) &= V_0(V_i) - c_1 V_i - c_0 \end{aligned} \tag{3}$$

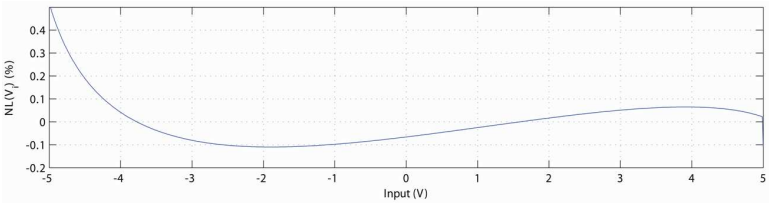

Fig. 7. Nonlinearities in the DC response as a percent of full-scale output, gain of 38 dB.

2.4 Actuator expansion rate limiting

One of the characteristics of piezoelectric actuators is that when subjected to a drive voltage changing too rapidly the piezoelectric material may shutter due to build-up of mechanical strain. To prevent such damage the drive electronics must limit voltage slew rate below the safe maximum which is typically ±100 kV/s. In our prototype the slew rate protection is handled strictly in hardware by proprietary circuits imposing limits on the current inflow and outflow at the output. Simulation using SPICE was performed to evaluate this operation. The transient response of the amplifier is plotted in Figure 8, whereby a ±300 mV, 250 Hz square wave input signal is driving the output at a current limit. By tuning the bias voltages in the simulation, the positive and negative slew rates were set at an appropriate value of 30 kV/s and -50 kV/s respectively. During constant slewing, the charge/discharge current is limited and is approximately constant.

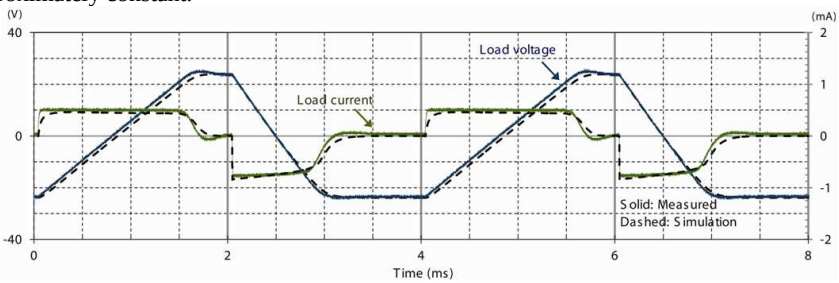

Fig. 8. Output slew rate limiting; measurement and simulation.

Upon verifying a proper limiting function in simulation and determining the required component/bias values, an identical amplifier was built in hardware and tested. The resultant circuit response is very close to the simulated behaviour as shown in Figure 8, and exhibits only very slight overshoot as compared to the simulated result.

2.5 Output offset

The un-driven output offset from 0 V is controlled by a bias voltage (Figure 1) common to all channels. Ideally, all channels sharing the common bias should have identical output offsets, however our experiments revealed larger than desired output offset variation. The variation is measured at up to 15 V between three amplifiers built. Since only one channel operation at a time is currently possible, the measurement was done separately for each amplifier while maintaining all bias voltages unchanged. A multi-channel board capable of operating many channels upon the same bias voltages simultaneously is the next step to better identify the amount of offset variance between multiple instances of identical circuits. In any case, individual channel offsets are provided within the AO control system in order to compensate for mechanical non-uniformities across the mirror surface due to surface imperfections and actuator variations. The process of DM flattening by the AO control will also absorb output voltage variations between amplifier channels, provided that sufficient actuator stroke can still be achieved after the flattening.

2.6 Output drift

Output voltage drift is also a concern. A certain amount of output voltage drift is present over a long timescale; the amount of drift increases with the closed-loop gain. With a gain of 38 dB, the output voltage drift is measured at ±600 mV over a 24 hour span, as shown in Figure 9. However this is a small fraction of the overall output span, 0.15 % of full scale, however it is yet to be determined if this amount of drift will affect the AO performance.

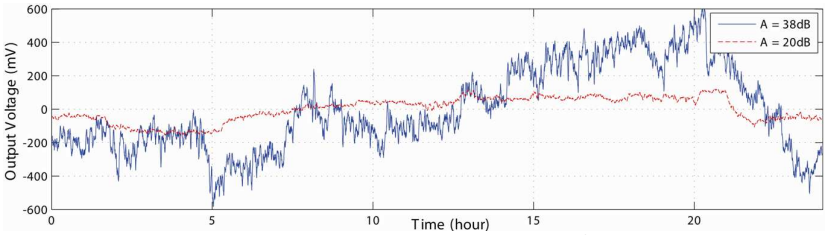

Fig. 9. Long timescale output voltage drift.

Offset and drift can be reduced by operating at a lower gain as shown in Figure 9, this would require a higher voltage drive signal from the D/A converter to compensate. It was found that the output offset variation and drift can be reduced to 2 V and ±200 mV respectively with a gain of 20 dB.

3. Future goals

Currently, individual amplifier circuits have been fully characterized and the next step is to investigate a multi-channel board with tightly packed amplifiers utilizing only surface mount components. A 32 channel board was chosen as it is one third the scale of the anticipated final design and will fully populate the outputs of one 32-channel Digital to Analog Converter (DAC), see Figure 10.

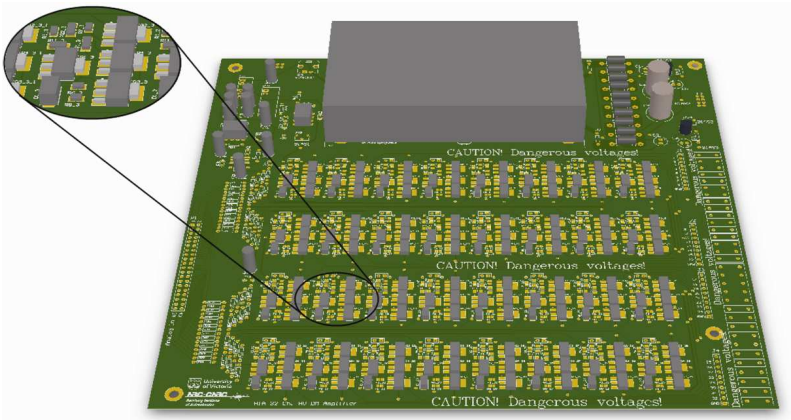

Fig. 10. 32-channel DME prototype board.

Aside from being a proof of concept by demonstrating that all channels can be driven by a multi-channel D/A converter controlled by a computer interface, other experimental objectives of the multichannel prototype board also exist. These include further investigation of the gain, bandwidth and offset variation between channels due to component parameter variability, detecting crosstalk and EMI between closely spaced amplifiers and developing measures to prevent channel interaction. The next step after successive characterization of a 32-channel board will be prototyping of a 96-channel DME board on a 6U Eurocard to realize a DME system with 1152 output channels in a 6U VME crate.

4. References

1. Cirrus Logic. PA95: Very High Voltage 900V, Very Low Standby Current 1.6mA Power Amplifier [Online], (2011 Sept 20). Available at: http://www.cirrus.com/en/products/pa95.html
2. K. Uchino, “Piezoelectric and Related Materials for Actuator Applications” in *Piezoelectric Actuators and Ultrasonic Motors*. Kluwer Academic Publishers, Massachusetts, pp. 101-102, (1997)