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A LINEAR HIGH-VOLTAGE HIGH-POWER AMPLIFIER FOR USE WITH PIEZOELECTRIC ACTUATORS

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ABSTRACT

Piezoelectric actuators are increasingly used in smart structures due to their reliability and performance characteristics. However these actuators present highly reactive impedances that make it difficult to design efficient drive amplifiers. This paper presents a high-voltage, high-power amplifier for driving piezoelectric actuators in smart structure systems. A linear amplifier concept has been realized using a combination of operational amplifiers and MOSFETs. The power stage delivers up to 300 mA current with a peak voltage of 280V. Further increases in both current and voltage drive capability can be readily achieved if required by the chosen application. The design and performance characteristics are discussed.

INTRODUCTION

Piezoelectric actuators are well suited to smart structure applications because of their high energy density and adaptability to a wide range of geometrical configurations. The voltage required by piezoelectric devices depends on the thickness of the active layers, and typically ranges from a few tens of volts to a few hundred volts. Current requirements depend on the frequency of operation and both the surface area and thickness of the piezoelectric material. The devices present a highly capacitive load when driven off-resonance and a near resistive load when driven near resonance. The reactive equivalent circuit requires high current with high voltage when the actuator voltage is switched, but a holding current is not required. Special care in the drive circuit design must be used to ensure that voltage and current spikes associated with the switching transient are held within tolerable limits. All of these considerations impose challenging constraints on the electronics design [1].

An attractive approach for analogue voltage drive circuits for piezoelectric actuators is to use a pair of power MOSFETS to charge or discharge the actuator under feedback control [2]. This approach requires suitable protection circuits to attenuate excessive rates of voltage and current change in order to maintain switch operation in the safe operating area [3]. This paper describes a high-voltage amplifier design (SA11) which uses this approach. The amplifier is intended to meet the needs of smart structure systems for such applications as vibration suppression and precision positioning control. The amplifier design configuration is described and performance results when driving reactive loads typical of piezoelectric-based smart structure systems are presented.

CIRCUIT DESCRIPTION

The amplifier contains two high-voltage power operational amplifiers that are configured in a bridge circuit as shown in Fig. 1. The bridge configuration is able to provide an output voltage in the range of –280 to + 280V using a built-in ±150 V power supply. The bridge effectively doubles the maximum output voltage, slew rate and output power while canceling out even harmonics of the output.

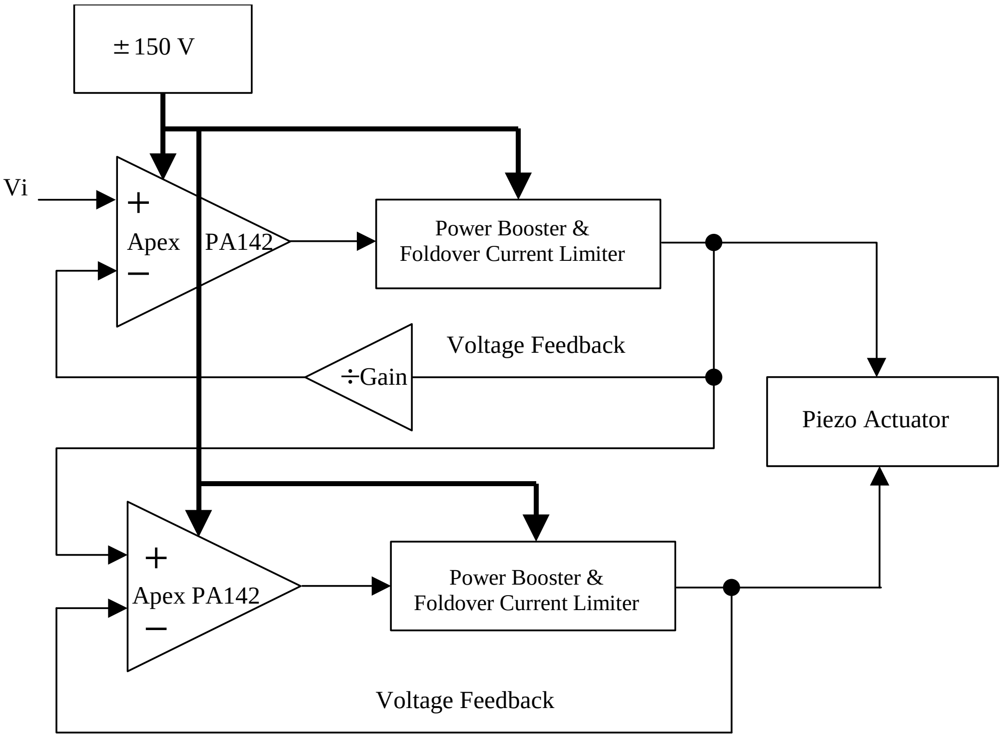

Figure 1. Basic configuration of the SA11 high-voltage amplifier.

Each arm of the bridge in the SA11 uses a high-voltage operational amplifier and a power booster with current limiting circuitry in the feedback loop. Fig. 2 shows a single arm with details of the power booster section and current limiting circuitry. The single mode gain is 15 and the bridge mode gain is 30. The circuit retains the excellent DC characteristics of the op-amp as well as the good dynamic performance of the MOSFET power booster. It is able to provide high-precision, high slew rate dV/dt, high power density and a wide safe operating area, all of which are required for driving piezoelectric actuators. The current limit is determined by R_c and is chosen to correspond to the rated current capability of the 150 V supply.

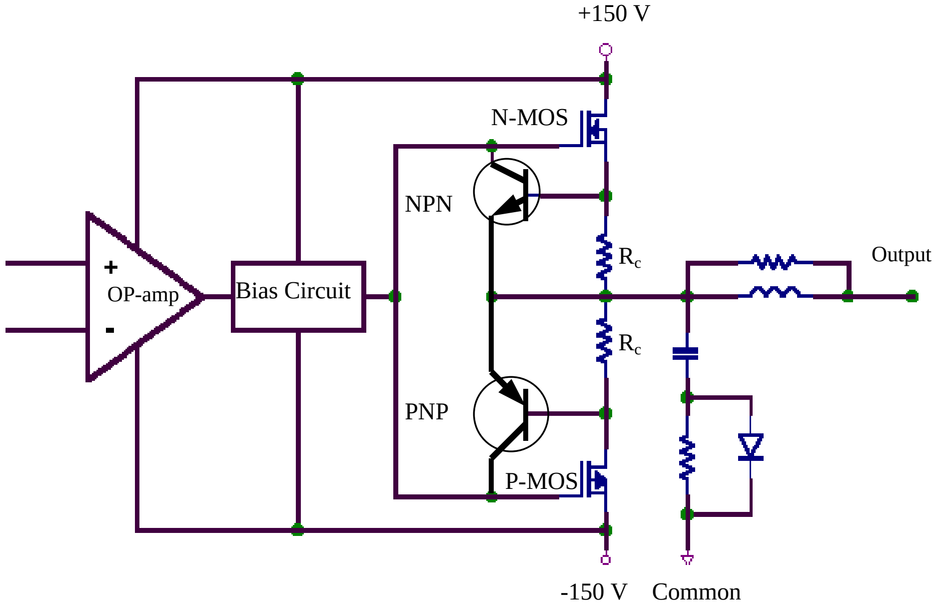

Figure 2. Detail for single arm of SA11 bridge circuit.

PERFORMANCE CHARACTERISTICS

The frequency response of the amplifier is shown in Fig. 3 for the case of a 10 nF load. This load is typical of a BM500 (Navy type II) piezoelectric patch actuator with 300 mm^2 area and 0.5 mm thickness. Such a load can be easily driven at frequencies well in excess of 1 kHz. Fig. 4 shows the frequency response for case of loads up to 3 μF. The largest of these loads can be driven at frequencies up to about 100 Hz which is adequate for many applications in vibration control of low frequency modes.

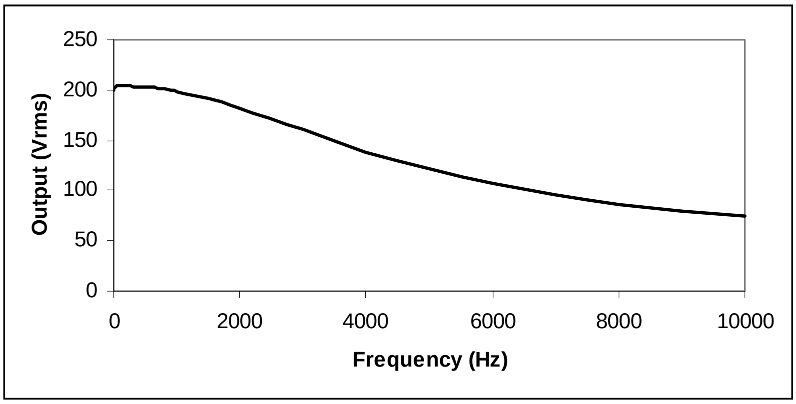

Figure 3. Frequency response of SA11 high-voltage amplifier with 10 nF load.

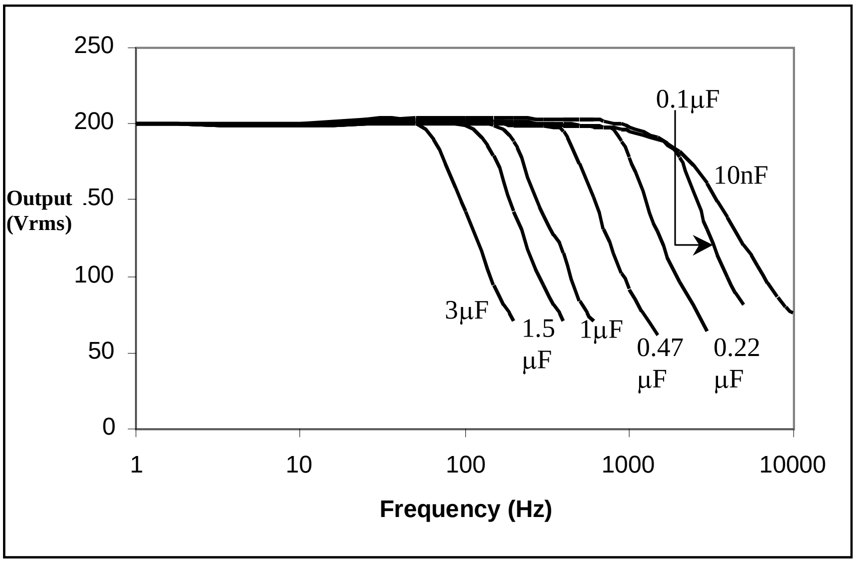

Figure 4. Frequency response of SA11 high-voltage amplifier with load ranging from 10 nF to 3 μF.

Each arm of the SA11 is an inverting amplifier that produces a phase shift of 180° at low frequencies. The phase shift increases with frequency as shown in Fig. 5. This curve was measured under open circuit conditions with maximum input and output voltage. The slope in the low frequency region is approximately 0.01 degree/Hz.

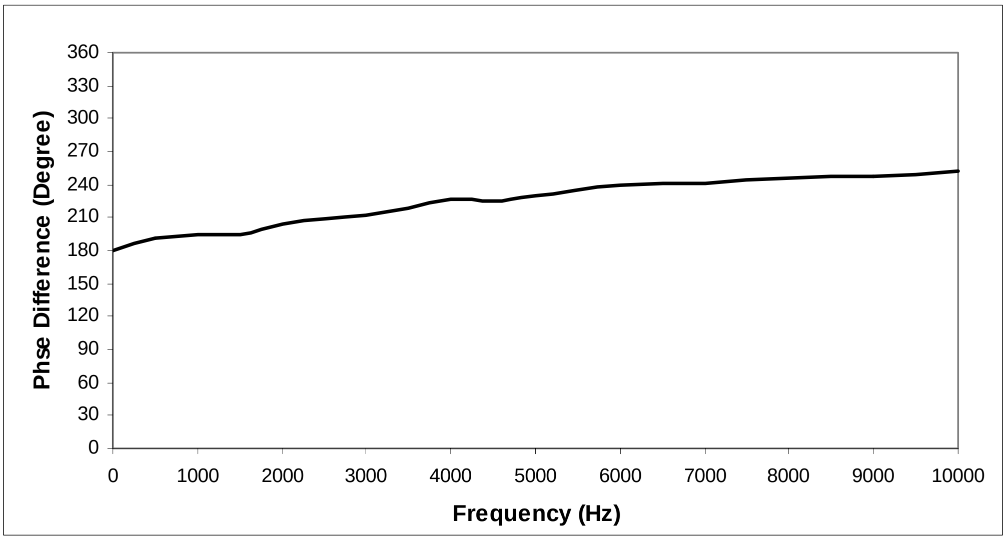

Figure 5. Phase shift vs. frequency for single arm of SA11 HV amplifier.

The rms value of the electrical noise was measured at the output terminals with the input terminals short circuited and different loads connected to the output. The results are shown in Fig. 6. The noise level was higher for bridge mode, but even in this case was less than 10 mV for loads up to 3 μF. Instability or oscillation was not observed for the amplifier even for loads as high as 30 μF. Table 1 summarizes these and other performance specifications of the SA11.

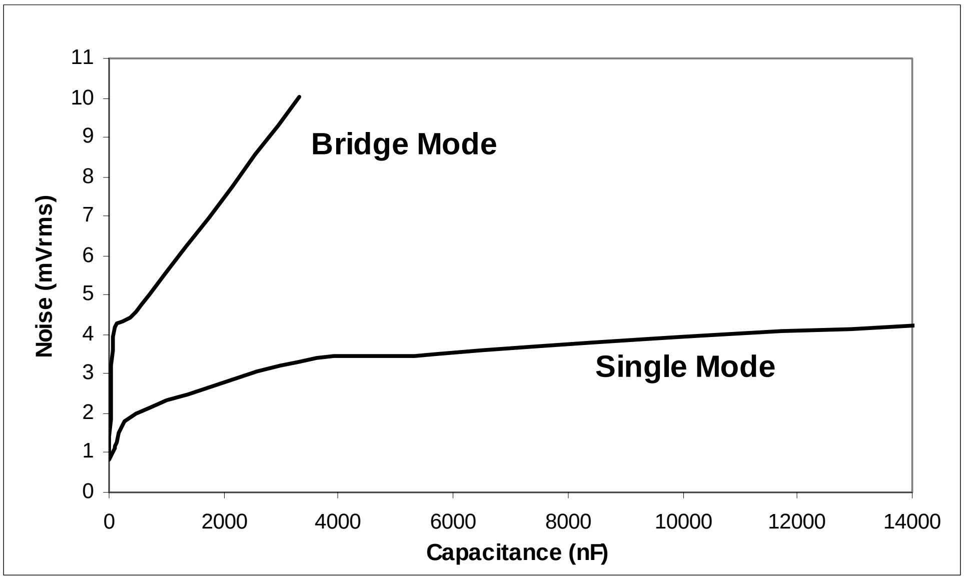

Figure 6. Noise measured at output terminal as a function of load capacitance with input terminals shorted.

Table 1: Performance specifications of SA11 high-voltage amplifier.

Maximum Voltage	Bridge Mode: ±280 Volts Single Mode: ±142 Volts
Maximum Current	±300mA
Output Power	84Watts peak
Frequency Range	DC to ~ 10KHz
Stability	Maximum 33μF
Voltage Gain	Single Mode: -15 Bridge Mode: ± 30
Slew Rate	40 Volts/μs
Maximum Input Voltage	±9.5 Volts peak
Input Coupling	DC only
Input Impedance	20kΩ
Output Coupling	DC Coupling
AC Power Source	120VAC or 220VAC 50/60Hz
Circuit Protection	Overload, short circuit and thermal protection

ANALYSIS AND DISCUSSION

Piezoelectric patch actuators used in typical vibration control applications often have capacitances in the nF range for each square centimeter of area. In a recently described application, 24 patch actuators covering a total surface area of 150 cm^2 were used to suppress vibration of the first three modes of a smart fin [4]. These actuators had a total capacitance of about 0.5 μF and the frequency of the highest of the first three modes was approximately 70Hz. The SA11 could easily meet the needs of this application as well as those involving larger loads and drive frequency.

It is worth noting that the n and p-channel MOSFETs used in the output circuit of Fig. 2 can handle up to 800 V and 500 V respectively, and the maximum current for both MOSFETs is 10 A. This implies that increases in output power could be readily achieved by replacing the 150V supplies shown in Fig. 2 with supplies having higher voltage and current limits.

REFERENCES

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