Low Input Voltage Switching Amplifiers for Piezoelectric Actuators

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ABSTRACT

The Inertially Stabilized Rifle is a new stabilized rifle system that can eliminate the disturbances induced by the shooter. Recurve actuator is used in this system to provide the precise movement of the rifle barrel. In such a portable device, only low voltage electrical sources are available yet the piezoelectric actuator needs high voltage to drive the actuator. The actuators consume little real power but a large amount of reactive power. Furthermore, the piezoelectric actuators are present an almost purely capacitive load. In this paper, we describe the development of a low input voltage amplifier for a high voltage piezoelectric actuator. This amplifier is based on switching technology so it efficiently handles the regenerative energy from the piezoelectric actuator. This amplifier consists of two stages. The first stage is a flyback converter which boosts the (low) input voltage to the maximum voltage required by the piezoelectric actuator. The second stage is a half-bridge amplifier which delivers the output voltage to the actuator as commanded by the reference signal. The basic structure of the amplifier is described, and its performance is characterized in terms of bandwidth, distortion, and efficiency.

Keywords: piezoelectric actuator, switching amplifier, flyback, half-bridge, Recurve actuator

1. INTRODUCTION

In order to improve the soldier's marksmanship performance in combat, a new stabilized rifle system demonstrator is being developed. The INertially STabilized Rifle (INSTAR) eliminates aiming error sources by stabilizing barrel assembly, effectively compensating for the small user induced disturbances. This revolutionary gun system will greatly impact the use of small arms in the military. It will enable improvement in aiming and hit performance of all skill levels (expert, sharpshooter, and marksman, etc.) shooters; thereby enabling engagement of targets at greater ranges. It will also enable lesser skilled and trained shooters to meet mission requirements previously assigned to higher skilled/trained personnel. This system will lead to greater soldier survivability with less ammunition expended, reduced training requirements and warfighting with less collateral damage. It will greatly impact the force structure and serve as a force multiplier and change fighting doctrine.

This application represents many challenges that are typical in smart structures. The INSTAR system is being developed for a .308 caliber tactical rifle. The only space for the full actuation system to fit into is the base and stock, which is very space and weight constrained. To make matters even more challenging, the strokes and forces lead to a specific work at the same order of magnitude of the smart material before it undergoes any transformation; thus, space and energy cannot be wasted. This demands an efficient transfer of energy from the power source to the electronics into the material and transformed to be applied to the barrel. Furthermore, the energy source (battery) must be small and light to minimize the weight for the soldier while at the same time, the system must have an acceptable lifetime. In this paper we will describe the power electronics being developed for INSTAR.

Novel to INSTAR is the active suspension system with integrated actuators and sensors enabling controlled motion of the gun barrel muzzle. The critical challenge of this design is that the actuators have to fit into the very confining gunstock dimensions. All of the electronics including the battery, power amplifiers, signal conditioning electronics and

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microprocessor must be contained in the gunstock. Clearly, the idea is to employ active control of the gun barrel to reduce the shooter induced disturbance entering through the shooter interaction with the gunstock. This system would be activated just prior to the trigger pull. To meet the actuation challenge, a Recurve actuator [1] was developed using piezoelectric material. In this paper we describe the development of the drive electronics for this actuator.

While the energy source is clearly constrained to a low voltage battery, the Recurve actuator requires an excitation signal with a peak voltage swing of 200 V. So the first challenge of the power electronics is to boost the voltage.

When designing the driving circuit, PZT actuators operate as capacitive loads, which require almost zero real power and a large amount of reactive power. Using linear power amplifier can have a good frequency response and no voltage noise, but they are usually very bulky and have low efficiency. But when the PZT actuator is a part of portable equipment, the power consumed by both the driving circuit and the PZT actuator is fully supplied by the battery, which can only provide a very low input voltage. Adopting switching technology, the amplifier can be made smaller and it can have higher efficiency. Previous work has been done in this area, like in [2] and [3], but these amplifiers are not suitable for high-voltage PZT actuators. A driving circuit is proposed in this paper, especially suitable for low input DC bus, high-voltage PZT actuators. It is a two-stage circuit, which includes a flyback circuit for the first stage and a half-bridge circuit as the second stage. Both circuits are switching circuits and use PWM technology. This circuit is small, light and highly efficient even when the input is much lower than the output.

This paper can be divided into following sections: Section II describes the circuit topology. It has two stages: one is flyback circuit to boost the bus voltage; the other is the half-bridge circuit to amplify the reference signal. The detailed design specification and procedure of the flyback circuit is given in Section III. Section IV describes the design for the half-bridge circuit. Section V gives the experimental result of the real hardware. Conclusion is drawn in Section VI as the last part.

2. CIRCUIT TOPOLOGY FOR SWITCHING AMPLIFIER

2.1 Design Specifications

The design specifications for the power electronics are derived from the INSTAR requirements. A simple block diagram of INSTAR is shown in Figure 2.1. In our design, the PZT actuator is to make the precise movement of the rifle barrel against the disturbance induced by the shooter. A sensor on the gun barrel will provide a feedback signal to the controller which will in turn provide a reference signal to the power amplifier. The power amplifier will then provide an appropriate drive signal for the Recurve actuator.

The reference signal will be enlarged to some extent by the power amplifier to supply the voltage high enough to the PZT actuator. To get long battery life, the power dissipation of the driving circuit must be as small as possible. At the same time, the whole circuit should be small and light since it will be used as a part of a portable device. Based on these requirements, switching amplifier is chosen here instead of linear amplifier.

Figure 2.1 Block Diagram of the PZT Actuator System

The input voltage is 9V, which is the voltage level of the common commercial batteries. The maximum output voltage is set to be 200V, which is high enough for the maximum deflection of the PZT actuator. The PZT actuator can be seen as

a 12.15 μ F capacitor for the driving amplifier circuit. The bandwidth of the control loop must be large enough to compensate for user induced disturbance signals. Through ergonomics, the bandwidth is determined as 10 Hz. Here, a sinusoidal signal with the amplitude of 3.3V is chosen to represent the reference signal.

2.2 Circuit Topology

2.2.1 Introduction

In [3], a buck circuit is proposed for the switching power amplifier for a PZT actuator, in which the output voltage is always lower than the input voltage. But according to our design specification, it is quite difficult to boost the reference signal to 100V directly since the input DC voltage is only 9V. Hence, we choose a two-stage circuit to implement the power amplifier. The first stage is a DC-DC converter, increasing the input voltage to a relatively high DC voltage. Then the second stage can be a buck circuit to amplify the reference signal. The complete circuit is shown in Figure2.2.

Figure2.2 Circuit Topology

2.2.2 The First Stage

In the first stage, the input voltage should be amplified for the second stage. As the maximum voltage needed by the second stage is over ± 100 V, the output voltage of the first stage should reach to 300V for spacious design margin. Two commonly used circuits for increasing voltage are boost circuit and flyback circuit. In switching circuits, duty cycle is defined as the fraction of time in which the switch is on. To meet our specification, the duty cycle of the boost circuit will be very high since the output voltage of the first stage will be much higher than the input voltage. Since the efficiency decreases rapidly at high duty cycle for the boost circuit, we choose flyback circuit instead circuit for the first-stage. In addition, flyback circuit can provide multiple outputs using a minimum number of parts. This is a notable advantage for our design because the first-stage circuit must provide both the high DC bus voltage and the ± 15 V voltage for chips of the second-stage circuit.

2.2.3 The Second Stage

The second stage is just a bulk circuit to amplify the reference signal. Since the output voltage varies between negative and positive, original buck circuit cannot be used. Two other choices are half-bridge circuit and full-bridge circuit. Half-bridge circuit uses less switching components and consumes less power, so it is better than the full-bridge circuit for the current design. The following description of the circuit design is divided into these two parts.

3. FLYBACK CIRCUIT

3.1 Theory For Flyback Circuit

The flyback circuit is based on buck-boost converter. Its topology is shown as Figure 3.1. The transformer is used to store and transfer the energy from the input to the output. Unlike the ideal transformer, current does not flow simultaneously in both winding of the flyback transformer. When transistor Q_1 conducts, energy from the dc source V_g is stored in L_m . When diode D_1 conducts, this stored energy is transferred to the load, with the inductor voltage and current scaled according to the 1:n ratio [4].

Figure 3.1 Flyback Circuit Topology

It has two operation modes: continuous-current-mode (CCM) and discontinuous-current-mode (DCM). In the discontinuous mode, all the energy stored in the primary during the on time is completely delivered to the secondary and to the load before the next cycle, resulting in small transformer size. To reduce the weight and size of the driving circuit, the flyback circuit should work in DCM in this circuit. Another advantage of operating in DCM is that it can avoid the heavy output diode recovery stress by the very high output voltage.

The switching frequency of the flyback circuit is chosen to be 100kHz, which is a typical value. There are two main designs in the flyback circuit: one is the transformer and the other is the control loop for the duty cycle of Q_1 . These two designs will affect the amplitude and the stability of the output voltage of the flyback circuit.

3.2 Design Procedure

3.2.1 Transformer Design

The transformer of the flyback circuit should be designed first. If the value of the inductor L_m is smaller than a certain value L_{mth} , the circuit will operate in DCM, which can be written as

$$L_m \leq L_{mth} = \frac{V_{in}^2 \cdot D^2}{2 \cdot P_o \cdot f_s} \quad (1)$$

In this equation, D is the duty cycle of the flyback circuit. P_o is the output power of the flyback circuit. Since PZT actuator consumes little real power, the real power consumed by the second stage is just the power loss of the switching amplifier, which can be roughly estimated as 10W. As the duty cycle is unknown yet, we first chose the value of L_m to 10μH.

When operating in DCM, the output voltage of the flyback circuit can be expressed as

$$V_{out} = D \cdot V_{in} \cdot \sqrt{\frac{R}{2L_m \cdot f_s}} \quad (2)$$

In equation (2), R is the load of the flyback circuit looking from the secondary side. When V_{out} is 300V and P_o is 10W, the load equals to 9kΩ. So the duty cycle D can be calculated from this equation, which is 0.5. Checking the inductor in (1) and it can be seen that if L_m is 10μH the circuit is still operate in DCM.

On the secondary side, the turns ratio n can be written as

$$n = \frac{V_{out}}{V_{in}} \cdot \frac{D_2}{D} \quad (3)$$

where D_2 is the conducting period for the diode D_1 . When in DCM, D_2 must be smaller than $(1-D)$. So the maximum turns ratio is 34. But when n gets smaller, the peak current must become larger for a constant average output current. Here we chose n to be 25 as the trade-off value.

3.2.2 Control Loop Design

Another essential design for the flyback circuit is the control loop design, which is to make the output voltage stable. Here we use a dual loop control scheme: a voltage control loop as the outer loop and a peak current control loop as the inner loop in Figure 3.2. V_{sense} is the sensed voltage of V_{out} , which is around 2.5V and I_{sense} is the sensed current. In

voltage control loop, the feedback components, R_c and C_c , add a pole to the loop transfer function at $f_p = \frac{1}{2\pi R_c C_c}$. R_c and C_c are chosen so that this pole cancels the zero of the output filter capacitor equivalent series resistance (ESR) in the flyback circuit[5]. The output filter capacitor of the flyback circuit is 4.7 μ F to limit the voltage ripple within 0.05%. Assuming its ESR is 10m Ω , if R_c is 4.7k Ω , C_c should be 100pF. The output of the voltage control loop is the reference for the current control loop. When I_{sense} exceeds the output of the voltage control loop, V_c will go to high, which will block the circuit. If I_{sense} is below that value, the control loop operates. Using this kind of control, it can have current limiting as well as output voltage control.

Figure 3.2 Control Loop for Flyback Circuit

Figure 3.3 is the simulation result of the flyback circuit. From the simulation result, it is clear that the flyback circuit operates at DCM and it can provide 300V DC voltage for the second-stage circuit.

Figure 3.3 Simulation Result of the Flyback Circuit

4. HALF-BRIDGE CIRCUIT

4.1 Theory For Half-Bridge Circuit

Half-bridge circuit is the main circuit of the switching power amplifier. Its topology is shown in figure 4.1. When Q_1 is ON and Q_2 is OFF, the loop is from the positive side of power V_g through Q_1 , inductor L , load C_o and capacitor C_2 to the negative side of power V_g . When Q_2 is ON and Q_1 is OFF, the loop is from the positive end of power V_g through capacitor C_1 , load C_o , inductor L and Q_2 to the negative end of power V_g . Through turning ON and OFF of these switches Q_1 and Q_2 , the voltage on this resonant tank, namely voltage on a and b, is a square wave with expected duty cycle. Then through filtering function of load C_o and suitably chosen inductor L , the expected output voltage on load C_o is a sinusoidal waveform with required frequency and amplitude.

Figure 4.1 Topology of Half-bridge Circuit

In this topology, the energy can flow back through diodes paralleled with switches to the flyback circuit and will be stored in the output capacitors of the flyback circuit. The resonant tank, which is composed of C1, C2, L, and Co, has a role of storing the energy temporarily. This configuration allows the energy to circulate between the actuator and the bus capacitors with the battery replacing only the dissipated energy. Hence, this circuit is very efficient.

Compared with the switching frequency, the frequency of the reference signal is so low that the reference signal can be treated as a DC signal in each switching period. Then the half-bridge acts just like a buck converter with PWM technology.

4.2 Design Procedure

For this inverter, the switching frequency f_s should be much higher than the frequency of the output voltage so that the duty cycle can be seen as a constant one during each switching cycle. But if the switching frequency is too high, it will cause more power dissipation and its implementation in hardware will become more difficult. In this circuit, f_s is chosen to be 100kHz. Two main components to be designed in this circuit is the inductor L and the control loop for the duty cycle of Q1 and Q2.

4.2.1 Inductor Design

The inductor L and the load Co compose the output filter of the circuit. The bandwidth of the filter should be around 1kHz to get rid of the high frequency noise of the switches. Then the frequency of the resonant tank should be

$$800\text{Hz} \leq f = \frac{1}{2\pi\sqrt{LC_o}} \leq 1200\text{Hz} . \quad (4)$$

which means the inductance should satisfy $1.45\text{mH} < L < 3.25\text{mH}$

Figure 4.2 Current and Voltage Waveforms of the Inductor

The current ripple $\Delta I_{L,\max}$ is set to 0.3A. According to the operation theory of the half-bridge, the current and voltage waveforms of the inductor L are shown in Figure 4.2. V_{out} is the output voltage, which can be expressed as $d \cdot V_g$ in buck converter. Then

$$\Delta I_{L,\max} = \frac{V_g - V_o}{L} \cdot d \cdot T_s = \frac{(1-d) \cdot V_g}{L \cdot f_s} \cdot d. \quad (5)$$

So L can be calculated as

$$L = \frac{(1-d) \cdot d \cdot V_g}{f_s \cdot \Delta I_{L,\max}}. \quad (6)$$

Since d is not a constant one, we need to find out the largest value of L. From above equation, we can see that L is maximum when d equals to 0.5

$$L = \frac{(1-0.5) \cdot 0.5 \cdot 300}{100k \cdot 0.3} = 2.5mH. \quad (7)$$

We choose toroidal core for convenient hardware design. Since the value of the inductor is quite large, we must choose a higher inductance rating with smaller volume. Here we choose: Toroidal Core T400-26 with A_L equals 131 nH/N². To prevent the inductor from saturating, we use three paralleled together. The number of wires for this inductor should be

$$n = \sqrt{\frac{2.5mH}{131nH}} = 138. \quad (8)$$

4.2.2 Control Loop Design

The main task of the controller here is to design a suitable control system so that through adjusting duty cycle $d(t)$, $V_o(t)$ can reach the expected output waveform voltage.

Before designing the control loop, we must derive the transfer function of the half-bridge circuit. The nonlinear components in the circuit are the switches, which must be made into linear components to derive the transfer function. So a single-pole-double-throw (SPDT) can be used to substitute the Q_1 and Q_2 and it be described as the following function

$$S(t) = \begin{cases} 1 & \text{when } Q_1 \text{ is ON, } Q_2 \text{ is OFF} \\ 0 & \text{when } Q_2 \text{ is ON, } Q_1 \text{ is OFF} \end{cases}. \quad (9)$$

Finally we arrived at the small signal model of the half-bridge circuit in Figure 4.3.

Figure 4.3 Small Signal Model of Half-bridge Circuit

The transfer function of the output voltage and the duty cycle is

$$G_{vd} = \frac{\hat{V}_o}{\hat{d}} = \frac{\overline{V_g}}{1 + sC_o(R_s + R_{esr}) + s^2LC_o}. \quad (10)$$

We also choose the dual loop control for this project. The current control loop is the average current proportional control for damping; the voltage control loop is proportional-integrate control. The output of the voltage control loop is the reference of the current control loop, which is the same as the flyback circuit. The whole control loop diagram is shown as Figure 4.4.

Figure 4.4 Control Block Diagram

In the above figure, G_{ci} is the transfer function of PWM comparator, which is the reciprocal of the magnitude of the triangular waveform. In this circuit, it is set to 0.1. H_i is the value of the current sensor, which is chosen to be 1 in our design. H_v is the value of the voltage sensor. Since the gain of the amplifier is 30, H_v should be 0.033. G_{cv} is the compensation function of the voltage control loop. In this design, the voltage compensator is chosen to be two-poles-one-zero compensator of the form

$$G_{cv} = \frac{K_v(s + w_z)}{s(s + w_p)} \quad (11)$$

The first pole “ $s=0$ ” is to make the DC gain of the open loop to be infinite so that the DC gain of the closed loop to be as close to 1 as possible. The second pole here is to eliminate the high frequency noise. Since the high frequency noise comes mainly from the switches (switching frequency 100kHz), we set the second pole to be 50kHz. The zero should be put near the resonant frequency of L and Co, which is 400Hz. K_v should be chosen to give enough bandwidth. From simulation, we give its value to be 300,000. Using the compensation network as Figure 4.5, we can realize the function of G_{cv} .

Figure 4.5 Compensation Network for Voltage Control Loop

In real hardware, UC3637 is used as the control chip with the above compensation network. Figure 4.6 shows the frequency response of loop gain.

Figure 4.6 Voltage control open-loop gain with current control loop closed

From Figure 4.6, it is clear that the crossover frequency is 1.2kHz. For the closed loop, the bandwidth of the system is then also 1.2kHz. Its phase margin is 70.8°, which means the system is quite stable.

Figure 4.7 shows the whole circuit of the half-bridge circuit. The reference signal can be amplified 30 times by the half-bridge circuit.

Figure 4.7 Half-bridge Circuit

5. EXPERIMENTAL RESULT

The flyback circuit and the half-bridge circuit were fabricated and tested. Using 9V DC power supply as the input, 12.15 μ F capacitor as the PZT actuator, 10Hz sinusoidal signal with the magnitude of 3.3 as the reference signal, the supply voltage to the load is shown in Figure 5.1.

Figure 5.1 Output Voltage of Power Amplifier (frequency is 10Hz)

From the above figure, we can see that the output voltage has little distortion with 93V as the maximum output voltage.

Figure 5.2 shows the frequency response for this switching amplifier. The gain is 30 well beyond the required bandwidth.

Figure 5.2 Frequency Response for Power Amplifier

Figure 5.3 shows the power loss of the driving circuit. When the frequency of the reference signal goes high, the current of the load will be increased proportional to frequency, which will consume more power. However, the whole power consumption will be under 10W when the frequency is below 50Hz. . Since there is a transformer in the flyback circuit, the flyback circuit consumes more power than the half-bridge circuit.

Fig 5.3 Power Loss vs. Frequency

6. CONCLUSION

In this paper, we propose a switching amplifier to drive the PZT actuator. The amplifier is composed of a flyback circuit and a half-bridge circuit. The flyback circuit can boost the bus voltage from 9V to 300V and the reference signal can be amplified 30 times by the half-bridge circuit. Both circuits use PWM technology for switches. The output voltage ripple is very small and it has little distortion. The real board is built and tested. Measurements show that the power loss is below 10W when the frequency is under 50Hz.

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