Shared inductor hybrid topology for weight constrained piezoelectric actuators

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Abstract. This paper presents a new circuit topology designed to minimise the weight of the control circuit required to actuate multiple piezoelectric actuators. It can independently set the phase and bias voltage on each piezoelectric actuator through the use of a single inductor. This is highly desirable in weight constrained applications such as unmanned aerial vehicles as the ferroelectric material required for the inductor is heavy. Furthermore, the circuit topology can also use the same inductor to generate the high bias voltage required to drive the actuators. The full system has been verified in PSpice and a pair of piezoelectric actuators have been successfully driven using off the shelf components.

1. Introduction
Unmanned aerial vehicles (UAVs) have dramatically increased in popularity since the combined development of lightweight high density batteries, small efficient DC brushless motors and improved control and stability algorithms. However as the desired size and weight of UAVs continues to decrease, electromagnetic become increasingly difficult to efficiently operate, thus biologically inspired flapping lift mechanisms (e.g. flies) have been analysed in order to generate the required lift [1]. This has led to the development of flapping based UAV designs (Figure 1) driven by piezoelectric actuators [2, 3, 4].

Piezoelectric actuators are extremely lightweight and can be designed to mechanically resonate in the hundreds of hertz frequency range, however they require large bias voltages. Power electronics are therefore required to both step-up the voltage from a typical lightweight battery used in UAVs [5] and efficiently bias the piezoelectric actuators with the high voltage.

In [6], two approaches to meet the requirements of the power electronics were considered. The first is to use a two-stage design which steps the voltage converter to produce a constant DC voltage then switches between multiple actuators to apply the desired bias. The second is to use a single-stage design where the voltage is both simultaneously stepped up and applied to a single actuator. The two-stage design is capable of sharing it’s high voltage bias between multiple piezoelectric actuators, however [6] notes that this would have a high component count thus negatively impacting on the weight. The single-stage design approach should use less components however the bias voltage cannot be shared which will increase inefficiencies in driving the actuations [6].

In this paper, a new biasing circuit called the Shared Inductor Hybrid Topology (SIHT) is presented which combines the low component count of a single-stage design with the ability to...
Figure 1. (Left) Structure to drive two wings using four piezoelectric actuators to achieve 4 degrees of freedom (130 mg) [2]. (Right) Two wing flapping UAV driven by a single piezoelectric actuator with passive wing rotation (60 mg) [3, 4].

share the same generated bias voltage of a two-stage design, all with the use of a single inductor. Therefore it will improve both the drive efficiency and minimise the weight associated with the power electronics. This work first analyses the current approaches to the power electronics which drive piezoelectric actuators then presents the design and implementation of the new SIHT circuit. Computer simulation and experimental verification are then presented and further recommendations to improve the design are given.

2. Previous biasing techniques

Two types of biasing drive circuits were evaluated in terms of size, control and power consumption. The first was use of a linear haptic drive for piezoelectric actuators from Texas Instruments, DRV8662 [7]. The second was a bidirectional switching amplifier circuit by [6] which uses resonant charge transfer to achieve high biasing efficiency.

2.1. Linear haptic driver

The linear haptic driver (Texas Instruments DRV8662) is a piezoelectric drive with an integrated boost converter. It samples an analog differential input voltage signal, amplifies it by a set gain then drives a differential output to bias the piezoelectric actuator. Thus an arbitrary waveform can be applied to the actuator. The output can vary between ±100 V at 300 Hz into a 100 nF load. A typical implementation of the DRV8662 can be seen [7].

2.2. Dual stage switching amplifier driver

Figure 2 is the bidirectional switching amplifier technique from [6]. The circuit operates as follows. Switch $S_1$ is closed resulting in the voltage in between the two piezoelectric actuators, $V_{\text{mid}}$, being connected to the biasing voltage, $V_{\text{bias}}$, via an inductor. This results in the voltage bias across $P_1$ decreasing and whilst the voltage bias across $P_2$ increases and energy being stored in the inductor. When the $S_1$ is then opened, $D_2$ provides a free wheel path for the energy stored in the inductor. The inverse operation occurs when $S_2$ is closed instead. The result generates a square wave bias voltage across two piezoelectric actuators. For more details on the operation refer to [6].

Generation of the bias voltage is assumed to be achieved by a boost converter circuit, which could be integrated in a similar fashion to the boost converter in the Texas Instruments DRV8662 but would require an external inductor. They typically achieve around 50% efficiency [8], therefore power consumption measurements should be doubled to for an estimation of total power consumption required to drive actuators from a battery.
2.3. Experimental comparison

Both driver techniques were tested with stripe actuators from APC International (350/025/0.70SA stripe actuator) [9]. The actuator’s measured capacitance was 96 nF and a maximum bias deflection voltage of 200 V\textsubscript{DC}. It was clamped at one end and the mechanical resonant frequency was measured at 200 Hz.

The haptic driver was connected to a single actuator and supplied with 5 V. The gain was set to maximum and a 140 mV\textsuperscript{−}p\textsuperscript{−}p square wave at 200 Hz from a signal generator was applied at the input, generating 80 V\textsubscript{pk−pk} across the actuator. The power consumption was measured using a Yokogawa WT310 power meter as 1.604 W.

The switching driver circuit was connected to two actuators and a 120 V bias voltage was supplied by a laboratory power supply. The power consumption for one actuator was 87 mW, thus with 50% inefficiency for the boost circuit, the power is likely to be nearer 173 mW [8]. In comparison with the haptic driver this is still much better however the boost circuit would require an inductor, and for every pair of actuators required, another inductor would be necessary.

3. Shared inductor hybrid topology

The experimentation and analysis of drive circuits for piezoelectric actuators highlights the need to reduce the number of inductors required in order to keep the weight of a UAV to a minimum. A new circuit topology is therefore proposed which shares the inductor between multiple piezoelectric actuators by reconfiguring the connections between the inductor and the actuators in real time. The proposed scheme is called Shared Inductor Hybrid Topology (SIHT).

3.1. SIHT operation

Figure 3 shows the circuit for the SIHT. It is comprised of a bidirectional H-bridge [10] with an inductor at the centre. One side of the inductor is then connected to one side of an actuator...
which itself is connected to a bidirectional half-bridge. Multiple actuators can be connected by joining them at the same inductor-piezoelectric actuator node. The SIHT operation is as follows. To bias actuator, \( P_A \), switches \( S_{BRh1n}, S_{BRh1p}, S_{Alp} \) and \( S_{Aln} \) are closed, providing a current path from the biasing voltage through the inductor to \( P_A \). The final voltage on \( P_A \) is then determined by the proportion of half the current path’s resonant period, the gates are held on for [10]. If the switches are opened before half the resonant period, the energy stored in the inductor will be freewheel to the supply by closing switches \( S_{BRl1p}, S_{BRh2p} \) and \( S_{BRh2n} \) and opening switches \( S_{BRh1n}, S_{BRh1p}, S_{Alp} \) and \( S_{Aln} \). Once all the energy has been removed all the switches can be opened ready for the next biasing event.

Actuator \( P_B \), could also have been biased by closing switches on the low side of \( P_B \)’s half bridge, so that the \( P_A \) and \( P_B \) are operated in parallel. Alternatively \( P_B \) could be biased after \( P_A \) enabling different biasing phases to be applied. To generate a negative voltage across \( P_A \), switches \( S_{BRl1n}, S_{BRl1p}, S_{Alp} \) and \( S_{Aln} \) are closed first, then any freewheel current is routed through switches \( S_{BRl2p}, S_{BRh1p} \) and \( S_{BRh1n} \). Therefore a single inductor can be used to bias multiple actuators with different biases and phases.

The number of piezoelectric actuators that can be driven in this way is limited by the electrical current path resonant frequency as this must be short enough that all switching events have been completed before the half the mechanical resonance period of the actuators. However through careful selection of the inductor, switches and piezoelectric actuators, the electrical resonance frequency can easily be in excess of 10 kHz.

Further utilisation of the inductor is also possible as the inductor can be reconfigured to form a boost converter circuit from a low voltage battery to generate the high voltage bias (Figure 3). In between biasing the piezoelectric actuators, switches \( S_{Battp} \) and \( S_{Battn} \) can be closed, then the inductor with switches \( S_{BRh2n}, S_{BRh2p}, S_{BRl2p} \) and \( S_{BRl2n} \) can be used to form a synchronous boost converter thus eliminating the need for another inductor.

3.2. SIHT verification
The functionality of the SIHT was verified fully in PSpice. The simulation used 400 nF for the piezoelectric actuator capacitance, 100 \( \mu \)H inductor, 1.5 \( \Omega \) on-state resistance for the switches and 7.2 V battery. Two piezoelectric actuators were biased with different gate conduction times to show different final bias voltages. The biasing of each actuator was also performed out of phase. Figure 4 shows the results of the simulation which verify the functionality of SIHT. The voltage across the two actuators are shown in red and green and the bias capacitor voltage is blue. Note that the biasing capacitor was assumed to have been pre-charged and that both actuators initially started with zero bias, hence a few cycles are taken to reach steady state.

Figure 4. PSPICE simulation showing SIHT driving two actuators with different bias voltages and phases (green and red), whilst also operating a boost circuit (blue).
Figure 5. Measured piezoelectric voltage (green), inductor current (purple) and switch timing (blue) when driven by the SIHT.

A low voltage implementation of the piezoelectric actuator biasing was implemented using high voltage p-type and n-type MOSFETs for the switches (BSP317P and BSP126), a 100 µH inductor (VLP8040T-101M), a MSP430FR1433 microprocessor, a 350/025/0.70SA stripe actuator and lower power gate drive circuits based on [11]. Figure 5 shows the measured results where the green line is the voltage across the actuator, the purple line is the current through the inductor, and the blue lines show various gates signals used to trigger the switches.

4. Conclusion
A new circuit topology capable of both driving multiple piezoelectric actuators and stepping up a voltage through a single inductor has been presented. This new topology will enable a large weight saving in small flapping UAVs over previous piezoelectric actuator driving techniques. The topology has been fully simulated in PSpice and a low voltage bench demonstration of the actuators being driven has been presented. Further work is required to experimentally demonstrate the technique for multiple piezoelectric actuators with a high bias voltage being generated, before a custom integrated chip should be developed to reduce the size and weight of the complete power electronics.

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