Actuator Power Reduction Using L-C Oscillator Circuits*

JAYANT SIROHI† AND INDERJIT CHOPRA

Alfred Gessow Rotorcraft Center, Department of Aerospace Engineering, University of Maryland, College Park, MD 20742

ABSTRACT: Piezoelectric actuators are widely used in smart structural systems to actively control vibration and noise, and to enhance performance. Because of the highly capacitive nature of these actuators, special power amplifiers, capable of delivering large currents, are required to drive these systems. The large currents result in excessive heat generation, and are a cause of concern in designing rotating actuation systems with sliprings for power transmission. In this paper, a means of reducing the current drawn from the power amplifier is investigated. This is accomplished by incorporating the actuator in a tuned L-C oscillator circuit. Non-ideal circuit performance is addressed, along with theoretical limits to possible power savings and practical difficulties in achieving them. The practical limitation of the size of a physical inductor needed for this purpose is recognized and the use of an active pseudo-inductor is investigated. This pseudo-inductor is connected in parallel with a commercially available power amplifier and reduction in current drawn from the amplifier is demonstrated.

INTRODUCTION

A piezoelectric actuator can be treated as a lossy capacitor. Though the actual energy dissipated in the capacitor is small, a large current is drawn from the power amplifier driving it. This makes the driving circuitry bulky and inefficient, and poses a challenge to compact smart systems with embedded electronics. This problem becomes even more critical for a rotary wing smart system where the transfer of power from fixed frame to rotating frame poses serious restrictions on the slip ring unit (Lee and Chopra, 1998). Several approaches to address this issue can be found in the literature, and can be broadly grouped under two methods: those that involve the design of efficient driving electronics to supply power to the actuator, and those that modify the effective impedance of the actuator by adding components to the actuator circuitry. For example, in the first approach, special Pulse Width Modulated (PWM) amplifiers can be designed to decrease the power dissipated in the amplifier and make it more compact than conventional amplifiers. High power PWM amplifier designs have been proposed in the past to drive piezoelectric actuators and electrostrictive actuators (Zvonar et al., 1996; Clingman and Gamble, 1998). However, these amplifiers do not recover the energy necessary in charging the actuator capacitance, that is wasted on the negative half cycle of excitation. Hybrid techniques have also been suggested (Newton et al., 1996), wherein the charge used to displace the actuator is recirculated within the amplifier. This research is still in an early stage of development. In the second approach, the effective impedance of the actuator is changed by adding passive or semi-active components to the actuator driving circuitry. Niezrecki and Cudney (1993, 1994) addressed this problem through the modification of the driving circuit using an additional inductor in a series or parallel arrangement. Though the concept is theoretically feasible, the size of the correcting inductor required for practical applications can become prohibitive.

This paper explores the feasibility of connecting a pseudo-inductor in the actuator driving circuit as a means of reducing the current drawn from the power amplifier. Apart from power savings, the change in effective actuator impedance as a result of the pseudo-inductor has applications in other areas, such as semi-active damping augmentation. Though analyses of the behavior of L-C circuits can be found in the literature, they are often limited to ideal components. This paper first presents a detailed analysis of L-C circuits, emphasizing the effects of non-ideality in the components, which places an upper bound on the theoretically achievable performance. It then examines a parallel L-C circuit with the use of a gyrator circuit set up to simulate an inductor, as a means to circumvent problems inherent in purely passive physical inductors. Park and Inman (1999) have discussed series and parallel R-L shunt circuits with a pseudo-inductor, but were limited to low power measurements of the system impedance. In the present work, the gyrator circuit, or

*Presented as AIAA Paper #2000-1791 at the 41st AIAA/ASME/AHS/ASC Structures, Structural Dynamics and Materials Conference.
†Author to whom correspondence should be addressed.
E-mail: sirohij@eng.umd.edu

1045-389X/02/12 0867–11 $10.00/0 DOI: 10.1106/91U8-PB1G-D1RK-LCV9

pseudo-inductor is connected in parallel with an unloaded piezoceramic stack actuator, and is driven by the output of a commercially available power amplifier. As this configuration can effectively increase the driving capability of an off-the-shelf power amplifier, peak current drawn from the power amplifier is considered as the primary metric of the performance of the circuit. The power consumed by the pseudo-inductor itself is also measured and included in the overall system performance.

THEORY OF L-C OSCILLATOR CIRCUITS

A capacitor is an energy storage element and under a harmonic voltage excitation, it charges up during the positive half cycle of excitation and discharges during the negative half cycle. The current drawn by an ideal capacitor leads the applied voltage by a phase angle ϕ, of 90°. Therefore, for an ideal capacitor, the net energy consumed in one cycle is zero. In the case of a non-ideal capacitor, that is modeled as a pure capacitor with a resistance in series, there is some energy dissipated by the resistance in the form of ohmic heating. This energy loss has to be supplied by the power supply, whereas the energy used in charging the capacitor in the first half cycle is returned to the power supply during the second half cycle. For a load drawing a current $\bar{I}$ at a voltage $\bar{V}$, the power consumption is given by (Toro, 1972):

$$\bar{P} = \bar{V} \times \bar{I} \tag{1}$$

where the bars represent complex quantities. The real part of this power is called the active power and represents the actual physical energy dissipated in the system. For the case of the nonideal capacitor, this is the ohmic heating loss. The active power is given by:

$$P_{\text{active}} = Re(\bar{P}) = V \times I \times \cos\phi \tag{2}$$

where the quantities without bars represent the absolute values and $\cos\phi$ is known as the power factor of the circuit. In the case of an ideal capacitor, $\cos\phi = 0$ and so, the real power consumed (P_{active}) becomes zero. Even though the real power consumed is zero or close to zero in the case of an nonideal capacitance, the power supply has to be designed to handle the current I, and the heat dissipation associated with it. Therefore, the power supply has to be rated for a much higher power output than the actual dissipation in the load, resulting in a much larger and heavier power supply than necessary. In order to increase the efficiency of the power circuitry, it is desirable to increase the power factor and make it as close to unity as possible. This is equivalent to making the impedance of the circuit purely resistive.

It is possible to correct the power factor by adding an inductor in the circuit. An inductor is also an energy storage element, however, an ideal inductor causes the current to lag behind the applied voltage. Thus, a combination of an inductor and a capacitor can cause the net phase difference between voltage and current in the circuit to be zero. This effectively causes the circuit to be purely resistive and the power factor becomes unity.

An inductor can be incorporated into the circuit in two fundamentally different ways. The inductor can be either connected in series with the capacitance (Figure 1a), or in parallel with the capacitance (Figure 1b). These two configurations are the ideal cases, where the inductor is a pure inductor and the actuator is a pure capacitance.

The net impedance of the circuit is:

$$\bar{Z}_{\text{tot}} = R + \bar{Z}_p \tag{3}$$

where $\bar{Z}_p$ represents the impedance due to the combination of capacitance and inductance, or in the ideal case, the net reactance of the circuit. For the series configuration, $\bar{Z}_p$ can be derived as:

$$\bar{Z}_{ps} = \frac{j(\omega^2 LC - 1)}{\omega C} \tag{4}$$

and for the parallel configuration, $\bar{Z}_p$ is given by:

$$\bar{Z}_{pp} = \frac{j\omega L}{1 - \omega^2 LC} \tag{5}$$

where ω is the circular frequency (radians/s). From Equation (4), it can be seen that at a particular frequency ω_o, the series impedance $\bar{Z}_p$ goes to zero. This frequency is called the resonant frequency and is given by:

$$\omega_o = \frac{1}{\sqrt{LC}} \tag{6}$$

At this point, since $\bar{Z}_p$ is zero, the net impedance of the circuit is R, which is purely resistive. At resonance,

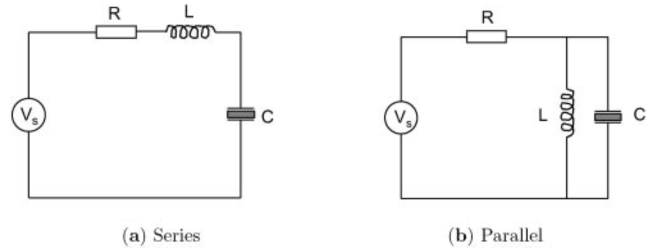


Figure 1. *Ideal series and parallel configurations.*

energy is continuously being transferred between the inductor, which stores the energy in a magnetic field, and the capacitor, which stores the energy in an electric field. Ideally, at this point, no external forcing is needed to sustain the oscillatory flow of current through the capacitor. In practice, however, resistive losses add damping to the system, and some energy needs to be input to the system to maintain the oscillations.

In the case of the parallel circuit, at the resonance frequency ω_o, from Equation (5), the value of $\bar{Z}_p$ goes to infinity. This means that there is no voltage drop across the resistance R and so no current flows from the power supply. Ideally, at this point, the voltage across the actuator is the same as the power supply voltage, and the current drawn by the actuator is supplied by the parallel inductive arm of the circuit. This current is maintained by the transfer of energy between the two arms at resonance. The net current drawn from the power supply is therefore zero. The parallel L-C oscillator concept is therefore pursued further in an attempt to minimize the absolute value of current drawn from the supply.

DEVELOPMENT OF NONIDEAL CIRCUIT BEHAVIOR

In reality, an ideal inductor and an ideal capacitor are not possible. A piezoelectric actuator itself acts like a non-ideal capacitor, and can be modeled as an ideal capacitor with a resistor in series. The total non-ideal impedance is given by:

$$\bar{Z}_c = R_c + \frac{1}{j\omega C} \tag{7}$$

The series resistance can be mathematically modeled in terms of a complex permittivity factor (Matsch, 1964). The capacitance $\bar{C}$ of a parallel plate capacitor of area A with a dielectric of permittivity $\bar{\varepsilon}$ and thickness t is given by:

$$\bar{C} = \frac{\bar{\varepsilon} A}{t} \tag{8}$$

and the complex permittivity is expressed as

$$\bar{\varepsilon} = \varepsilon(1 - j\tan\delta) \tag{9}$$

where tan δ is the dielectric dissipation factor. From Equations (8) and (9), the impedance of such a nonideal capacitance can be derived as:

$$\bar{Z}_c = \frac{1}{j\omega\bar{C}} = \frac{\tan\delta - j}{\omega C(1+\tan^2\delta)} \approx \frac{\tan\delta - j}{\omega C} \tag{10}$$

since $\tan\delta \ll 1$. From Equations (7) and (10), the value of R_c is found to be

$$R_c = \frac{\tan\delta}{\omega C} \tag{11}$$

The resistive part of the impedance is related to the dissipation factor. This is because the constant reorientation of dipoles in the dielectric medium in the presence of an alternating electric field results in energy dissipation similar to ohmic heating. The value of this resistance drops as the frequency of excitation increases, which means that it is actually a pseudo-resistance since a real resistance is independent of frequency. A plot of the theoretical variation of R_c with actuator capacitance at different actuation frequencies is shown in Figure 2. This plot is obtained for a PZT-5H actuator material, with tan $\delta = 0.035$ and a relative permittivity of 3400. For comparison, a plot of Z_c with capacitance is shown in Figure 3. It can be seen that R_c is negligible compared to Z_c, but as will be shown, still has a significant effect on system performance.

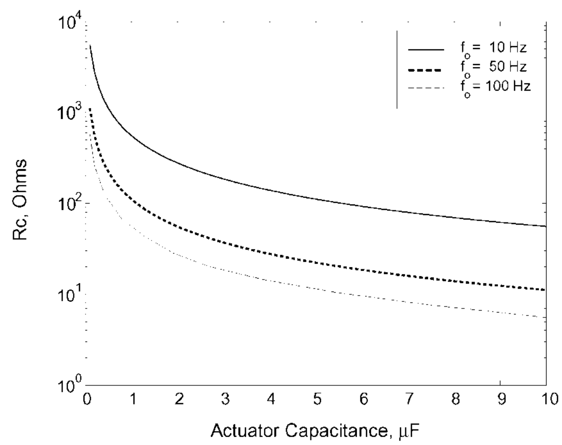


***Figure 2.** Variation of R_c for tan $\delta = 0.035$, relative permittivity of 3400.*

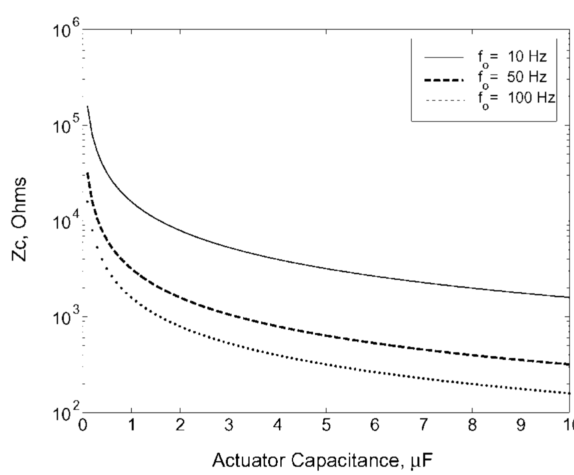


***Figure 3.** Variation of Z_c for tan $\delta = 0.035$, relative permittivity of 3400.*

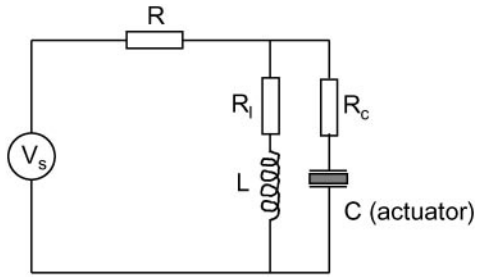


Figure 4. *NonIdeal L-C circuit.*

Any physical inductor has some finite resistance due to the coil windings. The nonideal parallel L-C circuit is shown in Figure 4. A real inductor can therefore be represented by a pure inductance with a resistance in series as

$$\bar{Z}_l = R_l + j\omega L \tag{12}$$

The net nonideal impedance of the parallel configuration can be derived to be:

$$\Re(\bar{Z}_p) = \frac{\omega^2 C(R_l + R_c)(L + R_l R_c C)}{\omega^2 C^2 (R_l + R_c)^2 + (\omega^2 LC - 1)^2} - \frac{(\omega^2 LC - 1)(R_l - \omega^2 LCR_c)}{\omega^2 C^2 (R_l + R_c)^2 + (\omega^2 LC - 1)^2} \tag{13}$$

$$\Im(\bar{Z}_p) = \frac{-(\omega^2 LC - 1)(L + R_l R_c C)\omega}{\omega^2 C^2 (R_l + R_c)^2 + (\omega^2 LC - 1)^2} - \frac{\omega C(R_l + R_c) + (R_l - \omega^2 LCR_c)}{\omega^2 C^2 (R_l + R_c)^2 + (\omega^2 LC - 1)^2} \tag{14}$$

Because R_l and R_c, are always positive, the denominators of Equations (13) and (14) can never be equal to zero, and therefore, $\bar{Z}_p$ can never be infinity. To make the impedance wholly resistive, the imaginary part of $\bar{Z}_p$ should be set to zero. Setting $\Im(\bar{Z}_p) = 0$ in Equation (14): frequency ω_{o1} at which this occurs is derived to be:

$$\omega_{o1}^2 = \frac{L - R_l^2 C}{(L - R_c^2 C)LC} \tag{15}$$

It can be seen that $\omega_{o1} = \omega_o$ if either R_l and R_c are zero or $R_l = R_c$. To see how the nonideality affects the performance of the circuit, let us examine three cases:

Case (I): $R_l = R_c$

In this case, $\omega_{o1} = \omega_o$ and the reactance from Equation (13) reduces to:

$$Z_p = \frac{L}{2R_l C} + \frac{R_l}{2} \tag{16}$$

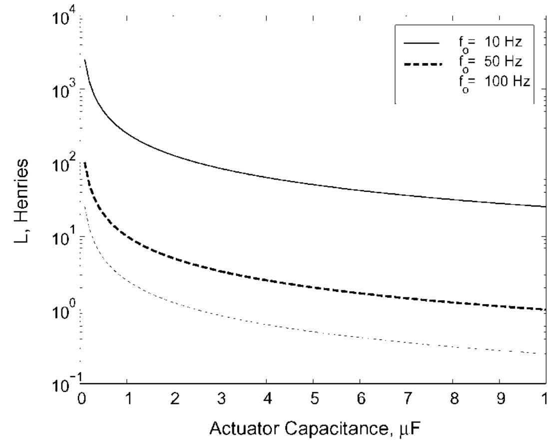


Figure 5. *Inductance requirement, $R_c = R_l$.*

The values of inductance required in an ideal system to achieve resonance at 10, 50 and 100 Hz are plotted versus actuator capacitance in Figure 5. The lower end of the capacitance scale ($\approx 0.1\,\mu$F) is a typical value for piezoceramic sheet actuators, while the higher end value ($\approx 7\,\mu$F) represents a typical piezoceramic stack actuator. It can be seen that the required value of the inductance increases rapidly as the excitation frequency and actuator capacitance decrease. To get the best performance, as close to the ideal case as possible, Z_p should be as high as possible. From Equation (16), Z_p depends directly on the L/C ratio. It can be concluded that a high value of Z_p can be achieved if either L/C is very high, or R_l is as small as possible, or both.

Since the current drawn in the parallel case is $I_p = V_p/Z_p$, and the current drawn by the actuator in the absence of the inductor is $I_c = V_p/Z_c$, the relative current saving by adding the inductor is given by $(1 - Z_c/Z_p)$. Hence, the value of Z_p/Z_c is a direct indicator of the performance of the circuit. As long as $Z_p/Z_c > 1$, the addition of the inductance in parallel with the actuator decreases the current drawn from the supply. In order to achieve best performance, the dependence of Z_p/Z_c on system parameters must be investigated and the parameters should be set so as to give as high as Z_p/Z_c value as possible at the operating point. Rewriting Equation (16) at resonance,

$$Z_p = \frac{1}{2\omega_o C}\left[\frac{1}{\tan\delta} + \tan\delta\right] \tag{17}$$

and from Equation (10)

$$Z_c = \sqrt{1 + \tan^2\delta}\,\frac{1}{\omega_o C} \tag{18}$$

From the above two equations,

$$\frac{Z_p}{Z_c} = \frac{1}{2}\frac{\sqrt{1 + \tan^2\delta}}{\tan\delta} \tag{19}$$

An interesting feature of this is that the maximum Z_p/Z_c is independent of the operating point (for $R_c = R_l$). The maximum gain achievable from the circuit, which is set by the maximum value of Z_p/Z_c, depends purely on the dissipation factor of the actuator. This gives a direct idea of the effect of nonideality on performance. For a $\tan\delta = 0$, $Z_p/Z_c \to \infty$, which is the ideal case. For a $\tan\delta = 0.035$, $Z_p/Z_c \approx 14.3$, which translates to a theoretical maximum achievable current saving of 93%. Therefore, even in the presence of nonideality, the achievable saving is significant.

Case (II): $R_l = 0$, $R_c \neq 0$

In order to study the effect of nonideality in the actuator alone, let us consider a nonideal capacitor with an ideal inductance in parallel, that is, set $R_l = 0$. Then, ω_{o1} from Equation (15) becomes:

$$\omega_{o1}^2 = \frac{1}{C(L - CR_c^2)} \tag{20}$$

which is very close to the ideal ω_o. Substituting $R_l = 0$ in Equation (13) and simplifying leads to:

$$Z_p = \frac{\omega^3 L^2 C \tan\delta}{(1 - \omega^2 LC)^2 + \tan^2\delta} \tag{21}$$

This results in

$$\frac{Z_p}{Z_c} = \frac{\omega^4 L^2 C^2 \tan\delta}{((1 - \omega^2 LC)^2 + \tan^2\delta)\sqrt{(1 + \tan^2\delta)}} \tag{22}$$

Since in this case, $\omega_{o1} \approx \omega_o$, $\omega_o^2 LC \approx 1$ and also since $\tan\delta \ll 1$, Equation (22) at the resonance point reduces to

$$\frac{Z_p}{Z_c} \approx \frac{1}{\tan\delta} \tag{23}$$

From this it can be seen that if the nonideality is limited to the capacitor alone, the maximum theoretical Z_p/Z_c depends on the dissipation factor of the capacitor. As before, if $\tan\delta = 0$, $Z_p/Z_c \to \infty$. The dissipation factor of the capacitor is therefore a very important quantity and places a physical limit on the maximum achievable current saving.

Case (III): $R_c \neq R_l \neq 0$

This represents the most general case. The frequency at which $\bar{Z}_p$ becomes wholly resistive is given by Equation (15). From this, the value of the correcting inductance required can be derived to be:

$$L = \frac{(C^2\omega_o^2 R_c^2 + 1) + \sqrt{(C^2\omega_o^2 R_c^2 + 1)^2 - 4C^2\omega_o^2 R_l^2}}{2C\omega_o^2} \tag{24}$$

For a solution to exist.

$$(C^2\omega_o^2 R_c^2 + 1)^2 - 4C^2\omega_o^2 R_l^2 \geq 0 \tag{25}$$

which gives:

$$R_l \leq \frac{1}{2C\omega_o} \tag{26}$$

This gives the maximum allowable value of R_l, the nonideality in the inductor, for the circuit to function. However, substituting this value of R_l in Equation (13) leads to $Z_p/Z_c \approx 1$, at which point the addition of the inductor is ineffective.

For an operating frequency of 100 Hz, and an actuator capacitance of 10 μF, the maximum R_l is 79.6 Ω. For values of $R_l = 10$, 50 and 75 Ω, Figures 6 and 7 show the variation of required correcting inductance and Z_p/Z_c with actuator capacitance respectively, at an operating frequency of 10 and 100 Hz.

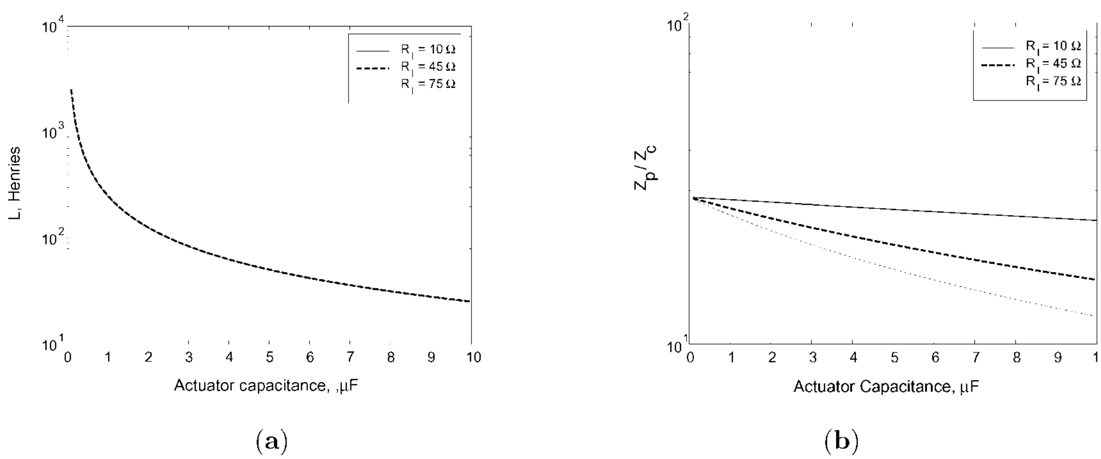
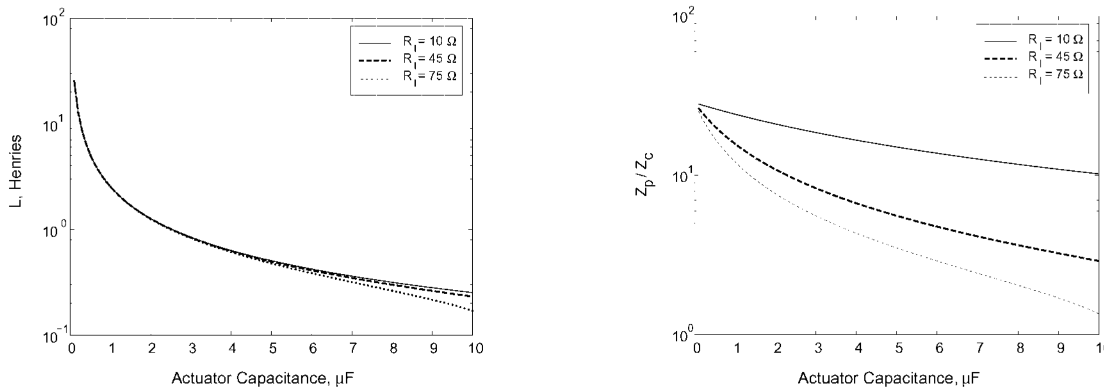


Figure 6. *Required inductance and Z_p/Z_c for $f = 10$ Hz.*



(a) (b)

Figure 7. *Required inductance and Z_p/Z_c for $f = 100$ Hz.*

It can be seen that the value of R_l has a small effect on the inductance required, but has a large effect on the achievable value of Z_p/Z_c. As the nonideality R_l and the actuator capacitance increase, the maximum possible Z_p/Z_c decreases. For this reason, the remainder of this paper addresses the behavior of a high capacitance piezoelectric stack actuator as opposed to a low capacitance piezoelectric bimorph actuator.

IMPLEMENTATION OF THE POWER REDUCTION CIRCUIT

The power saving circuit should be able to operate over a range of frequencies for a given actuator. As an example, consider a typical stack actuator, with a capacitance of 7 μF. The range of operating frequencies is 0–100 Hz, which corresponds to the frequency requirement for the application of the stack actuator in the smart trailing edge flap of a helicopter rotor system (Lee and Chopra, 1998). In such a system, the piezostack provides the actuation force to actively control vibration. However, for the purposes of this study, only a free actuator is considered, performing no mechanical work output. Figure 8 shows the theoretical variation of Z_p/Z_c with excitation frequency for the actuator in parallel with a 1 H inductor. Both the ideal case ($R_c = R_l = 0$) and the nonideal case (with nonzero dissipation and $R_l = 50\,\Omega$) are plotted for comparison. The circuit performs well only in a small range of excitation frequencies about the resonance frequency and the addition of the inductance actually degrades the performance of the actuator at excitation frequencies away from the resonance frequency of the circuit. Thus, the operation of the system is limited to only a small range of frequencies.

However, if the circuit could be continuously tuned at each operating frequency, the variation of Z_p/Z_c for the same actuator could be extended over a range of

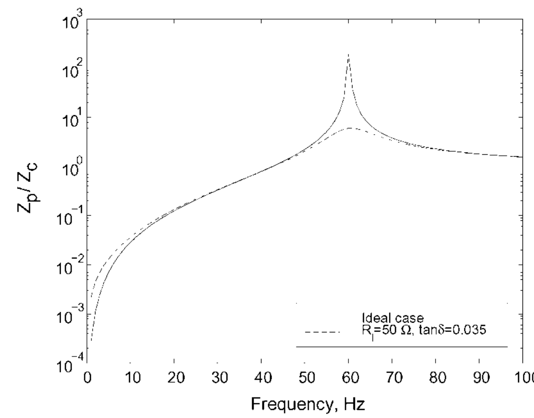


Figure 8. *Variation of Z_p/Z_c with frequency for a 7 μF actuator.*

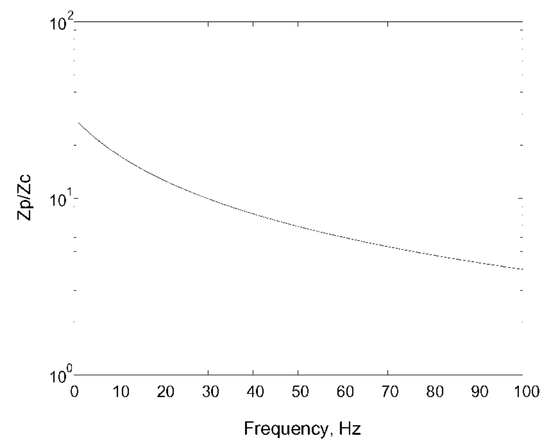


Figure 9. *Z_p/Z_c achievable by continuous tuning, 7 μF actuator, $R_l = 50\,\Omega$.*

frequencies, as shown in Figure 9. Apart from the difficulty in tuning the circuit to operate over the entire frequency range, from Figures 5–7, it can be seen that the required inductance increases rapidly for low values of actuator capacitance and excitation frequency. It is in practice, difficult to obtain physical inductors in the range of tens of Henries. Physical inductors of such magnitude also tend to be very bulky and heavy, which make them inconvenient to integrate in a smart system such as a smart rotor blade. Such inductors also tend to have a high value of R_l. To overcome these disadvantages, the concept of a pseudo-inductor, or active inductor is used. Depending on the frequency of interest, a pseudo-inductor can be easily tuned to generate a large range of inductance values, and the size of the circuit is independent of the value of inductance. Inductance values as high as 10^6 H have been reported in the literature, and are obtainable with just one operational amplifier.

IMPLEMENTATION OF A PSEUDO-INDUCTOR

A pseudo-inductor is a gyrator circuit using an operational amplifier, which effectively inverts the impedance of a capacitor. Energy is no longer stored in a magnetic field, but as a charge on a capacitor in the pseudo-inductor circuit. The amplifier changes the phase of the current flowing in the circuit so that the input impedance is inductive. Two circuits were investigated for this purpose. The first circuit, suggested by Berndt and DuttaRoy (1969); DuttaRoy and Nagarajan (1970) was chosen for its simplicity since it uses only one operational amplifier and three other components. The second circuit, suggested by DuttaRoy and Nagarajan (1970); Prescott (1966) was discarded because of certain difficulties, which will be discussed below.

Pseudo-inductors have been widely used in Integrated Circuits and other small signal, high frequency circuits. Use of these circuits in power management applications has not been attempted before. Using a pseudo-inductor as compared to a physical inductor has many advantages. Firstly, the inductor is very compact, not exceeding the size of a single operational amplifier, and inductance values of the order of 100 H can be easily achieved with no increase in size. The value of the inductance can be changed by changing the values of the capacitance or the resistance in the pseudo-inductor circuit. This is easily realized in practice by making use of a potentiometer by varying its resistance. Also, the effective value of the series resistance, R_l can be made smaller than the corresponding value for a physical inductor.

The main disadvantage of the pseudo-inductor is that by using an active element in the circuit, namely the operational amplifier, it now becomes necessary to supply power to the operational amplifier for its functioning. This must be supplied at a voltage equal to or above the peak voltage of the input signal, depending on the type of op-amp chosen for the purpose. However, the power supply for the amplifier will only be a simple DC power supply that is much more compact than the power amplifiers which supply power to the actuator. Thus, by reducing the actuator current consumption, and thereby reducing the size of the power amplifier, the addition of a DC power supply will still result in an overall weight saving. Normally, sufficient DC power is available on any aircraft, justifying the use of the psuedo-inductor, and resulting in an overall weight reduction of the system.

Circuit-1 is shown in Figure 10 and is discussed in detail by DuttaRoy and Nagarajan (1970). Assuming an ideal unity gain amplifier, the impedance of this circuit can be derived to be:

$$\bar{Z}_{in} = R_{in} + jwL_{in} \tag{27}$$

where R_{in}, which is the same as R_l and L_{in} are

$$R_{in} = \frac{R_2(1+\omega^2C^2R_1R_2)}{1+\omega^2C^2R_2^2} \tag{28}$$

$$L_{in} = \frac{CR_2(R_1-R_2)}{1+\omega^2C^2R_2^2} \tag{29}$$

For the input impedance to be inductive, it can be seen that $R_1 > R_2$. The Q factor of the inductor is

$$Q = \frac{\omega C(R_1-R_2)}{1+\omega^2C^2R_1R_2} \tag{30}$$

where the Q factor is defined as $\omega L/R$, and can be shown to be equivalent to Z_p/Z_c. The Q of an inductor gives an indication of the amount of nonideality present. To get a high value of Q, or as close to ideal performance as possible, $R_2 \ll R_1$, and so, $L_{in} \approx CR_1R_2$.

The value of Q however, depends on the frequency of operation. It can be shown that Q reaches a maximum when

$$\omega_o = \frac{1}{C\sqrt{R_1R_2}} \tag{31}$$

The corresponding maximum value of Q is

$$Q_{\max} = \frac{1}{2}\sqrt{\frac{R_1}{R_2}} \tag{32}$$

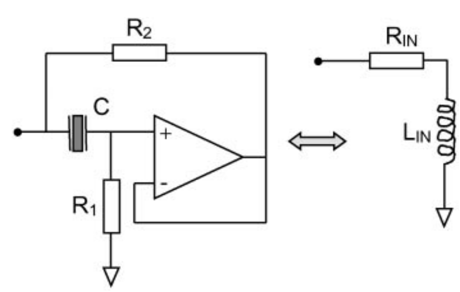


Figure 10. *Pseudo-inductor circuit-1.*

If the capacitance C is chosen so that it is equal to the external tuning capacitance, which in this case is the actuator capacitance,

$$\omega = \frac{1}{\sqrt{LC}} = \frac{1}{C\sqrt{R_1 R_2}} \tag{33}$$

and

$$Q = \frac{1}{2}\sqrt{\frac{R_1}{R_2}} \tag{34}$$

This means that Q is independent of frequency and reaches the maximum possible value at each tuned resonant frequency of the circuit. This therefore represents the best possible design of the circuit. However, in practice, it was observed that the best performance was achieved if the capacitance C was less than the actuator capacitance, though of the same order of magnitude.

Circuit-2 was suggested by Prescott (1966) and is shown in Figure 11. The L and Q of this circuit are

$$L = CR_1R_2 \tag{35}$$

$$Q = \frac{\omega C R_1 R_2}{R_1 + R_2} \tag{36}$$

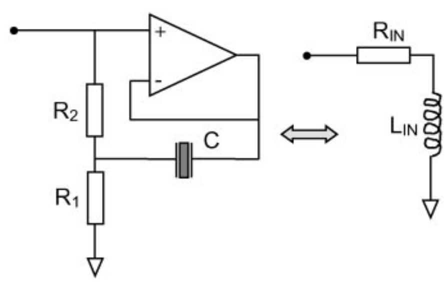


Figure 11. *Pseudo-inductor circuit-2.*

It is recommended to keep $R_1 = R_2$ for stability reasons. If the actuator capacitance is C_a, Equations (35) and (36) become

$$\omega = \frac{1}{\sqrt{C_a C R_1 R_2}} \tag{37}$$

and

$$Q = \frac{\omega C R_1}{2} = \frac{1}{2}\sqrt{\frac{C}{C_a}} \tag{38}$$

For the circuit to be effective, $Q \geq 1$ and so the minimum value of C is

$$C_{\min} \geq 4C_a \tag{39}$$

This means that a large capacitance has to be used for the circuit to work effectively. The large size of this capacitor makes the construction and use of the circuit inconvenient and so it was decided to implement circuit-1 for the pseudo-inductor.

RESULTS AND DISCUSSION

The pseudo-inductor test circuit-1 was implemented using a PA88 high voltage operational amplifier. The resistance R_{in} (Equation (28)) varies almost quadratically with frequency, as the terms multiplying ω^2 in the numerator are typically several orders of magnitude larger than the terms multiplying ω^2 in the denominator. This is shown in Figure 12, where a pseudo-inductor is compared to a physical inductor, a 0.1 H choke coil. The pseudo-inductor was constructed with component values $R_1 = 10\,\text{k}\Omega$, $R_2 = 100\,\Omega$, and $C = 0.1\,\mu\text{F}$. The actual value of the pseudo-inductance is just under 0.1 H because 10% components were used throughout the circuit.

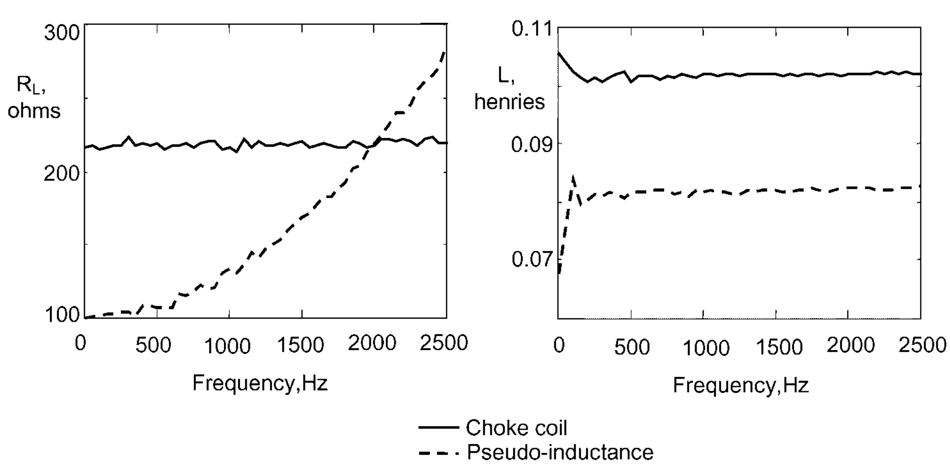


Figure 12. *Comparison of choke coil and pseudo-inductor performance.*

It was decided to choose component values that gave the worst performance, in order to demonstrate the feasibility of the concept at an adverse operating point. Therefore, from the nonideal analysis described above, and from Figures 6 and 7, the actuator chosen was a commercially available piezoelectric stack actuator (P-804.10) (Physik Instrumente, 1997) with a capacitance of 7 μF. The value of R_{in} ($\approx R_2$) of the pseudo-inductor was chosen to be 100 Ω, which, for the chosen actuator, is close to the maximum allowable R_l for circuit operation. The power saving circuit was implemented by connecting the pseudo-inductor in parallel with the stack actuator. A commercially available power amplifier (PI E-501.00 LVPZT-amplifier) (Physik Instrumente, 1997) was used to drive the stack and the pseudo-inductor circuitry was driven off a DC power supply. To allow the pseudo-inductor to operate effectively independent of any DC bias present in the actuator excitation voltage, it was AC coupled to the actuator. The values of C and R_2 were held fixed at 1 μF, and 100 Ω respectively, while R_1 was a 2 M Ω potentiometer to enable tuning of the pseudo-inductor at each operating frequency. This gave a maximum achievable inductance of 200 H. It should be noted that such a high value of inductance is very difficult to achieve with a physical inductor.

Figure 13 shows the power savings obtained by connecting a 100 H pseudo-inductor in parallel with a stack actuator of capacitance 7 μF, which gives a resonant frequency of ≈ 5 Hz. The stack was actuated at 0–50 V. The power supply to the inductor was at 75 V_{DC}. The reduction in power consumption shown is the quantity $V \times I$, which is the actual volt–amperes consumed from the power supply. Power consumed to run the pseudo-inductor is also plotted, and it can be seen that even after accounting for power consumed by the pseudo-inductor, significant overall power saving can be achieved. Since the circuit is tuned to ≈ 5 Hz, the maximum savings occurs at this frequency and drops off at other frequencies.

The test results of power savings achieved by continuously tuning the circuit is shown in Figure 14. Two different excitation voltages are shown, 0–50 V and 0–100 V, for which the supply voltages to the pseudo-inductor are 75 and 125 V_{DC} respectively. The actuator power saving and the overall system power saving are shown. The power savings decreases with frequency, which is in agreement with the trends shown in Figure 9. Figure 15 shows the power required for operation of the pseudo-inductor. It can be seen that the actuator power savings is relatively constant with excitation voltage, but power consumed by the pseudo-inductor increases with excitation voltage. Hence, at low frequencies, where the Z_p/Z_c value is inherently high, and at low excitation voltages, when the pseudo-inductor itself draws less power from its power supply, there is an overall saving in power. But at higher frequencies and higher excitation voltages, though the actuator power saving is still significant, the overall power saving is negative. This means that some extra power has to be supplied to the system to run the operational amplifier which forms the pseudo-inductor. However, as mentioned before, the power to run the pseudo-inductor can be supplied by a

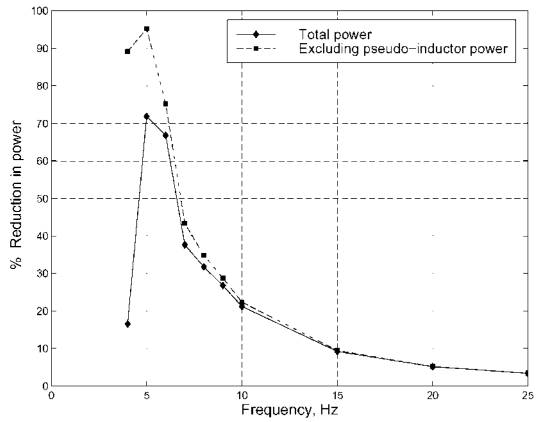


Figure 13. *Pseudo-inductor circuit performance.*

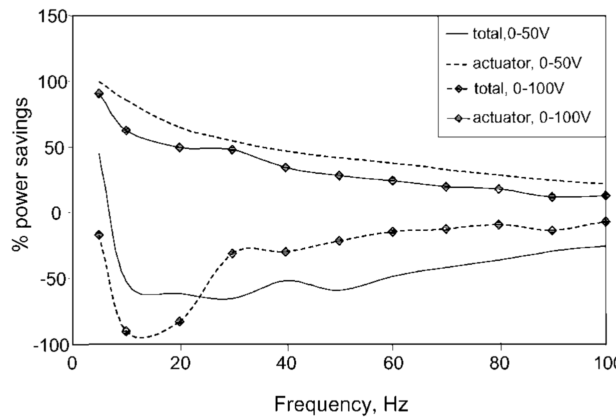


Figure 14. *Pseudo-inductor circuit performance with adaptive tuning.*

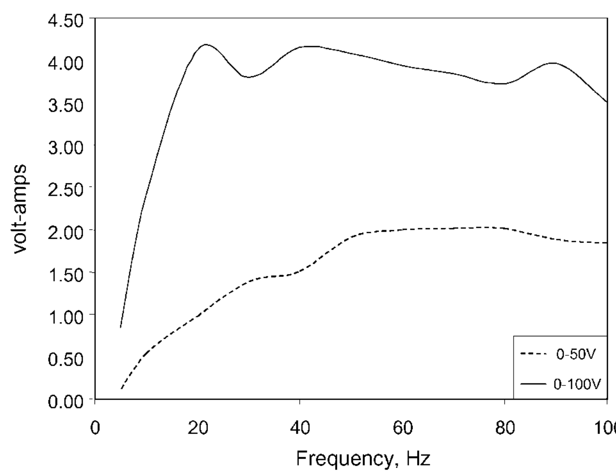
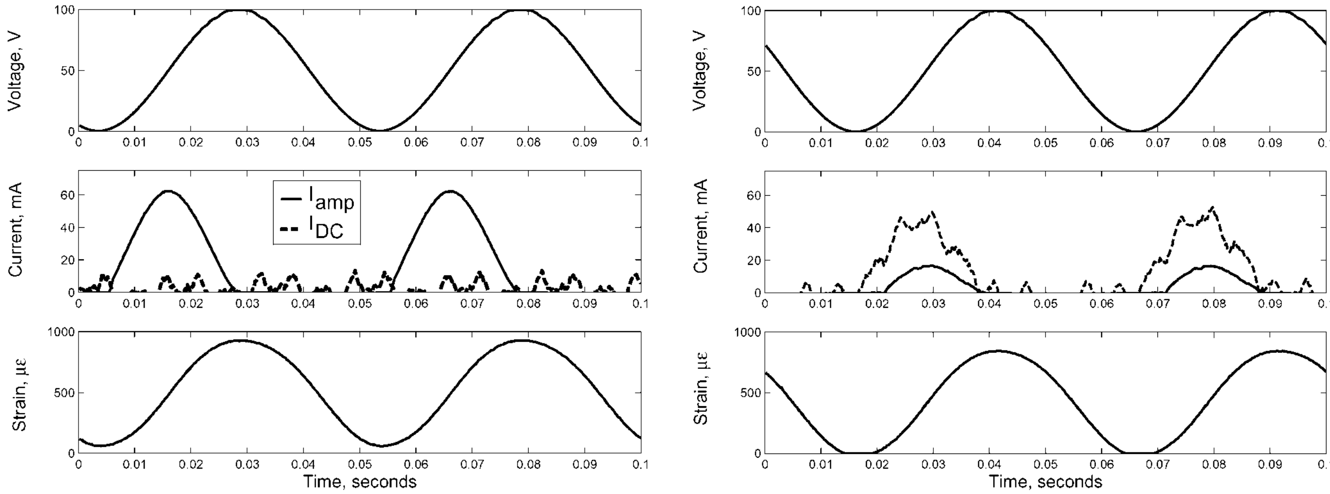


Figure 15. *Pseudo-inductor power consumption.*



(a) Without pseudo-inductor (b) With pseudo-inductor

Figure 16. *Time variation of voltage, current and strain at 30 Hz.*

compact DC power supply, thus resulting in a net saving in weight of the system.

The op-amp circuit that acts as a pseudo-inductor can be run off any DC voltage greater than or equal to the peak excitation voltage, and so the power consumed by the pseudo-inductor and the actuator is not a direct indication of the effectiveness of the L-C circuit. Comparison of the actual current consumed by both the actuator and the pseudo-inductor will yield more insight into the behavior of the circuit. Figure 16 shows the voltage across the stack, currents drawn from the power amplifier and DC supply of the pseudo-inductor, and the strain output of the stack, while operating at 30 Hz. The current drawn from the amplifier in the absence of the pseudo-inductor is I_{stack}, current drawn from the amplifier when the pseudo-inductor is connected in parallel is I_{amp} and current drawn by the pseudo-inductor from its DC supply is I_{DC}. For comparison, Figure 16(a) shows the voltages, currents and strains when the pseudo-inductor is disconnected and Figure 16(b) shows the same parameters when the pseudo-inductor is connected in parallel. The pseudo-inductor in this case was set for an inductance value of 10 H, which results in a resonant frequency of approximately 20 Hz. It can be seen that the peak-to-peak magnitude of the strain output of the stack remains unaffected, and the only effect of the pseudo-inductor is to reduce the peak current being drawn from the power amplifier, while at the same time drawing some current from its DC supply. Figure 17 shows the performance of the same configuration with operating frequencies from 10 to 50 Hz. It can be seen that though the minimum current drawn from the power amplifier is around the resonant frequency of 20 Hz, the minimum overall current drawn from the power amplifier and the DC supply of the psuedo-inductor ($I_{\mathrm{amp}} + I_{\mathrm{DC}}$) is at a slightly higher frequency.

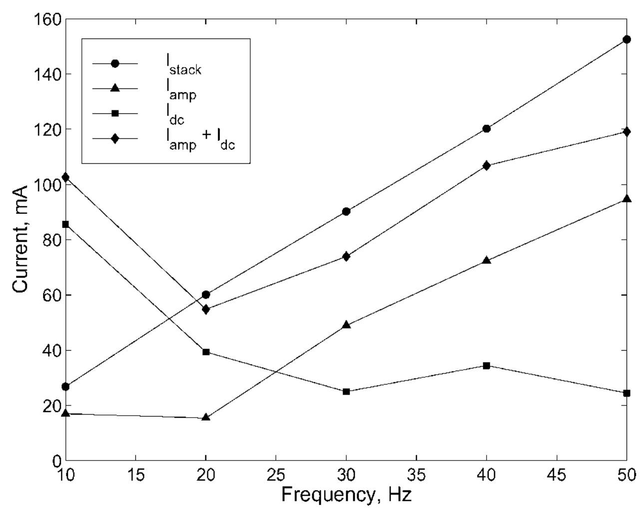


Figure 17. *Variation of current drawn with frequency.*

CONCLUSIONS

The effect of nonideality of the components on the performance of a parallel L-C oscillator circuit was derived, and the limits of nonideality for proper functioning of the circuit were identified. It was shown that assuming an ideal inductor, the maximum possible power saving depends only on $\tan\delta$, the dissipation factor of the actuator material. For a piezostack actuator of capacitance 7 μF, operating at a frequency of 20 Hz, which is representative of a typical vibration control application on a smart helicopter rotor, the value of inductance required for tuning is on the order of 10 H. This value is very dependent on the amount of series resistance associated with the inductor. A physical inductor of this inductance value would be very large and would also have a large series resistance. In order to eliminate such problems inherent with physical inductors, the concept of using a pseudo-inductor is proposed. The performance of a simple pseudo-inductor, built out of a single operational amplifier, was measured. By demonstrating functioning of the circuit at an adverse operating condition, the concept of using pseudo-inductors to reduce current drawn from the power amplifier was experimentally validated. As this circuit was connected in parallel with the piezostack actuator, to the output of a conventional power amplifier, it was possible to increase the driving capability of existing amplifiers. A peak current saving of approximately 90% has been obtained for the piezostack described above, at a frequency of 5 Hz, without affecting the piezostack output displacement. The pseudo-inductor circuit was tuned to operating frequencies in the range of 5–100 Hz and as expected from theory, the maximum achievable performance was observed to decrease with frequency. Because the pseudo-inductor is an active circuit, the power consumed by it was measured. When this power was included with the overall performance, the maximum power saving at the above operating condition was approximately 70%. The overall power savings, including the power consumed by the pseudo-inductor, decreases with an increase in operating frequency and is dependent on the selection of optimum values of circuit component. Future work in this area would involve investigation of the dependance of the circuit performance on various parameters, and optimization of the pseudo-inductor circuit to provide maximum savings in current and overall system weight over a wide range of operating conditions.

ACKNOWLEDGMENTS

This work was sponsored by the Army Research Office under grant DAAH-04-96-10334 with Dr. Gary Anderson and Dr. Tom Doligalski serving as technical monitors.

REFERENCES

1997. *Physik Instrumente* (PI) *Catalog*, *US-edition*, Physik Instrumente (PI).

Berndt, D.F. and DuttaRoy, S.C. 1969. "Inductor Simulation Using a Single Unity Gain Amplifier," *IEEE Journal of Solid State Circuits*, SC-4:161–162.

Clingman, D.J. and Gamble, M. 1998. "High-Voltage Switching Piezo Drive Amplifier," *Proceedings of the SPIE Smart Structures and Materials Symposium*, 3326:472–478.

DuttaRoy, S.C. and Nagarajan, V. 1970. "On Inductor Simulation Using a Unity Gain Amplifier," *IEEE Journal of Solid State Circuits*, SC-5:95–98.

Lee, T. and Chopra, I. 1998. "Design and Static Testing of a Trailing Edge Flap Actuator with Piezostacks for a Rotor Blade," *Proceedings of the SPIE Smart Structures and Materials Symposium*, 3329:321–332.

Matsch, L.W. 1964. *Capacitors, Magnetic Circuits and Transformers*, Prentice-Hall, Inc.

Newton, D., Main, J., Garcia, E. and Massengill, L. 1996. "Piezoelectric Actuation Systems: Optimization of Driving Electronics," *Proceedings of the SPIE Smart Structures and Materials Symposium*, 2717:259–266.

Niezrecki, C. and Cudney, H.H. 1993. "Power Factor Correction Methods Applied to Piezoelectric Actuators." In: *Proceedings of the 34th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, (AIAA-93-1688-CP): 3261–3268.

Niezrecki, C. and Cudney, H.H. 1994. "Improving the Power Consumption Characteristics of Piezoelectric Actuators," *Journal of Intelligent Material Systems and Structures*, 5(4):522–529.

Park, C.H. and Inman, D.J. 1999. "A Uniform Model for Series R-L and Parallel R-L Shunt Circuits and Power Consumption," *Proceedings of the SPIE Smart Structures and Materials Symposium*, 3668:797–804.

Prescott, A.J. 1966. "Loss Compensated Active Gyrator Using Differential-Input Operational Amplifiers," *Electronic Letters*, 2:283–284.

Toro, D. 1972. *Principles of Electrical Engineering*, Prentice-Hall, Inc.

Zvonar, G.A., Luan, A., Lee, F.C., Lindner, D.K., Kelly, S., Sable, D. and Schelling, T. 1996. "High-Frequency Switching Amplifiers for Electrostrictive Actuators," *Proceedings of the SPIE Smart Structures and Materials Symposium*, 2721:465–475.