ABSTRACT

This paper describes the resonant drive technique that eliminates the need for high voltage integrated circuits (IC) in MEMS drive electronics. Resonant drive also offers a versatile solution for position sense and generates the sense signal using a single drive capacitor. Resonant drive uses the fact that the voltage across the capacitor of a series LC tank can be much higher than the input signal driving the tank. The amplification is maximum at resonance and equal to the quality factor (Q). The tank circuit consists of an external inductor and the MEMS drive capacitor. Since the input signal is amplified through the tank, low voltage electronics can fully implement the drive function. As the actuator gap closes, resonance frequency of the tank decreases. This frequency shift is used for measuring the position. Resonant drive has been successfully demonstrated using torsional MEMS mirrors that require 100V for 20 deg-optical rotation. The LC tank (Q of 15) was formed by using a 390µH inductor. All drive and sense circuits were built using only 10V CMOS parts.

1. INTRODUCTION

Interface electronics is a vital part of the MEMS design. Electronics serve three main functions for MEMS: 1) electrostatic drive, 2) position sense, 3) supply boosting. In general, electrostatic drive needs voltages much higher than regular CMOS levels. In order to deliver an arbitrary voltage within the drive range, MEMS electronics use high voltage amplifiers. Implementing high voltage capabilities requires special IC processes and limits the choice of technology. High voltage amplifiers also need careful design for avoiding excessive quiescent power dissipation and attaining adequate bandwidth. The input signal of the drive amplifier comes from a regular CMOS circuit and needs high gain amplification. High gain requires a low feedback factor and severely restricts the bandwidth of the drive stage. Commercial designs for micromirrors achieve only a few kHz BW [1,2]. In relatively fast MEMS devices (mechanical resonance > 1 kHz), however, closed-loop control needs a drive bandwidth >10kHz for assuring the stability of the feedback system [3].

Sense electronics is substantially different from the drive electronics in terms of IC specifications. Primarily, the sense circuit measures miniscule changes in the sense capacitance. Due to small signal levels, sense is vulnerable to noise and interference from other signals. Unfortunately, the main disturbance comes from the drive feed-through. Large drive signals operating close to the sense capacitor adversely affect the accuracy of the position measurement. Electromagnetic Amplitude Modulation (EAM) [3] is one of the techniques that reduce the negative effects of the drive signal. At the expense of complicated circuit design, EAM modulates the sense signal by a high frequency carrier and protects it from interference and other low frequency noise.

In addition to drive and sense, a third type of circuit is also necessary for boosting supply voltages. The need for supply boosting is especially important for portable applications that operate from a low power supply such as a battery. Charge pump circuits are effective for small factors of boosting (2-3x), but may require capacitors that are too big for integration [4]. Moreover, many MEMS devices need higher supply boosting than a charge pump can achieve. In such cases, DC-DC converters provide the necessary amplification by using resonant circuits.

The resonant drive technique presented in this paper uses an LC tank built from an external inductor and the MEMS drive capacitor. A CMOS oscillator brings the LC tank to resonance and guarantees the maximum voltage amplification. At resonance, the AC signal across the capacitor is Q times bigger than the input signal of the tank. The oscillator circuit is also capable of controlling the oscillation amplitude, which sets the MEMS position. The square-law of electrostatic actuation and the MEMS dynamics extract a DC force from the AC drive signal without any adverse effect.

The resonant drive also generates a position sense signal using a single drive capacitor. The resonance frequency of the tank is a function of the value of the drive capacitor, hence, the device position. Therefore, position change modulates the oscillation frequency and creates an electrical signal that is a measure of the device position.

In a previous work, the external inductor has also been demonstrated to be effective for increasing the travel range of parallel plate actuators [5].

Figure 1: Conventional electronics vs. resonant drive.
The resonant drive circuit simplifies MEMS interface electronics by eliminating the necessity for three separate circuits: a DC-DC converter for voltage boosting, a high voltage amplifier for drive, and a low voltage IC for position sense. All three functions are achieved by using the same low voltage IC (oscillator) and a single drive capacitor. Fig. 1 shows an abstract comparison of the conventional circuit techniques and the resonant drive method. The following sections explain the details of using electrical resonance for voltage boosting, drive, and sense operations.

2. ELECTRICAL RESONANCE FOR HIGH VOLTAGE

Electrical resonance is commonly used in circuit applications such as oscillators, tuned circuits or certain types of DC-DC converters. A resonant circuit is either a parallel or a series combination of an inductor and a capacitor. Resonant drive uses series resonance because of its significant advantages as a MEMS drive circuit. The series resonant circuit is formed by connecting an inductor directly in series with the MEMS drive capacitor. The resulting circuit is also known as the series LC tank. Fig. 2 depicts the LC tank with typical component values. The MEMS drive capacitor \( C_{MEMS} \) is the parallel combination of the actuator capacitance and associated parasitics. The resistor \( R \) represents the total electrical losses in the inductor and the MEMS capacitor. In this particular example, series parasitic resistance of the MEMS capacitor dominates (~ 65% of R).

![Figure 2: The series LC tank formed by an external inductor and MEMS drive capacitor.](image)

At the electrical resonance frequency \( f_{\text{res, el}} \), inductive and capacitive reactances are equal in magnitude but have 180° phase difference. The resonance frequency can be expressed in terms of the inductance and the capacitance as given in Eqn. 1:

\[
    f_{\text{res, el}} = \frac{1}{2\pi} \sqrt{1/LC_{\text{MEMS}}} \quad (1)
\]

Since the two components are subject to the same current flow, voltages across them are also equal in magnitude but opposite in phase. As a result, the inductor voltage \( V_L \) cancels the capacitor voltage \( V_C \). In other words, the signal driving the tank \( V_{in} \) is equal only to the resistor voltage \( V_R \), Fig. 2. Using this property, the LC tank can build an oscillation with tens of volts across the capacitor from a small input signal at \( f_{\text{res, el}} \). The amplitude of the capacitor voltage \( V_C \) relates to the tank input \( V_{in} \) by the ratio of the capacitor’s impedance (at \( f_{\text{res, el}} \)) to the parasitic resistance. This ratio is also known as the quality factor \( Q \) and can be expressed in terms of component values \( L \), \( C_{MEMS} \), and \( R \):

\[
    Q = \frac{1}{R} \cdot \sqrt{\frac{L}{C_{\text{MEMS}}}} \quad (2)
\]

The capacitor voltage \( V_C \) is simply \( Q \) times bigger than the tank input \( V_{in} \). The \( Q \) value for typical values shown in Fig. 2 is \( \sim 15 \). Using a high conductivity MEMS device layer can significantly reduce \( R \) to a point that the inductor becomes the dominant cause of parasitic losses. In such a case, the inductor’s \( Q \) value limits the passive amplification. Thus, we can expect the practical limit of \( Q \) to be as high as 50.

The LC tank must operate at the resonance frequency \( f_{\text{res, el}} \) to maintain the maximum voltage amplification \( (Q) \). The general way of ensuring operation at \( f_{\text{res, el}} \) is to build an oscillator around the LC tank, Fig. 3. In this circuit, the transR amplifier brings the tank to resonance and ensures maximum voltage amplification. Besides generating the high voltage, the drive circuit must also control the MEMS position by adjusting the drive signal. For this purpose, the Automatic Gain Control circuit (AGC) compares the RMS value of the oscillation to \( V_{\text{ctrl}} \) and adjusts the oscillator’s loop gain by a variable gain amplifier. So, increasing \( V_{\text{ctrl}} \) increases \( V_{in} \) and results in an increase in the amplitude of \( V_C \).

![Figure 3: The resonant drive circuit.](image)

In summary, the key idea behind the resonant drive is the use of passive components for voltage amplification. Unlike a DC-DC converter, resonant drive applies a high voltage signal directly across the MEMS capacitor and eliminates the need for high voltage amplifiers. The oscillator controls the drive signal amplitude in order to set the MEMS position. In terms of setting the MEMS position, the main difference between the conventional electrostatic drive and the resonant drive is the use of an amplified AC signal instead of a DC voltage. The next section explains how the MEMS device creates a DC force.
from the AC drive signal and also eliminates any possible mechanical vibration.

3. **Electrostatic Drive with AC Signals**

The AC drive signal $V_C$ has zero average value although its peak amplitude can reach very high values. In order to generate a net DC displacement from the AC drive signal, force must be created through a process that has rectification and vibration attenuation. Rectification naturally comes from the fact that the electrostatic force depends on the square of the drive voltage. The MEMS device mechanically filters the vibration coming from the resulting force. So, in the resonant drive, electromechanical properties of the MEMS device generate a DC force from the AC drive signal without extra electronics.

**Rectification**

Electrostatic force is proportional to the square of the voltage difference between the terminals of the drive capacitor. As a result of this square-law relation, electrostatic force always attracts plates of the drive capacitor together. When an AC drive signal is applied, the force vector has varying amplitude but always points in the same direction. We can easily derive the magnitude of the RMS force for a sinusoidal drive voltage:

$$ F = \frac{1}{2} \frac{dC}{dx} \left( V_C \sin (\omega_{res \_el} t) \right)^2 $$
$$ F = \frac{1}{2} \frac{dC}{dx} V_C^2 + \frac{1}{2} \frac{dC}{dx} \frac{V_C^2}{2} \cos (2\omega_{res \_el} t) \tag{3} $$

The AC ripple is at twice the electrical resonance frequency and has the same magnitude as the RMS component of the force. Fig. 4 shows the rectification process and the resulting force signal in the time domain.

![Figure 4: Inherent rectification in electrostatic actuation.](image)

The RMS component of the force, Eqn. 3, suggests that an equivalent DC drive voltage would be equal to $|V_C|/\sqrt{2}$, where $|V_C|$ is the peak amplitude of the amplified AC drive signal. Consequently, the gain from the peak input signal $|V_{in}|$ to the equivalent DC drive voltage is $Q/\sqrt{2}$.

**Vibration Attenuation**

The previous section shows that the AC drive signal creates a DC RMS force and an AC component with equal magnitudes. The RMS component sets the MEMS position while the AC component causes mechanical vibration. For resonant drive to be practical, the mechanical vibration must be considerably smaller than the minimum position resolution of the drive.

Assuming a mass-spring-damper system, MEMS devices have second order transfer function with low-pass characteristics. Beyond the mechanical resonance frequency ($f_{res\_mech}$), MEMS devices become very reluctant to move and their response to AC excitation rolls off by -40dB/decade. Resonant drive rejects the mechanical vibration by taking advantage of the MEMS dynamics. For typical values shown in Fig. 2, the electrical resonance frequency $f_{res\_el}$ is equal to 2.5Mhz. This sets the AC component of the force to 5MHz, which is more than three orders of magnitude higher than the mechanical resonance frequency of the experimental devices ($f_{res\_mech} \sim 1kHz$). The large difference in the two frequencies rejects the AC component of the force by -150dB. In other words, for a 1µm displacement generated by the RMS force, the corresponding mechanical vibration experienced by the 1kHz device would be only 0.1picometer. 0.1picometer is ten thousand times smaller than the diameter of a silicon atom, which is insignificant for most MEMS applications. Fig. 5 shows vibration attenuation by using the frequency domain representations of the force and MEMS dynamics. In real applications, the MEMS device may not be simply a 2nd order system. In such a case, $f_{res\_el}$ must not be close to any higher order modes of the MEMS device.

![Figure 5: Force generated by the AC drive signal, MEMS transfer function, and the resulting displacement.](image)
4. **Sense Using Electrical Resonance**

Conventional position sense techniques use a separate capacitor and a special circuit for position sense. Resonant drive, however, provides position sense using a single drive capacitor and the same oscillator circuit used for the drive. Drive and sense functions operate in different domains: amplitude and frequency. Therefore, they do not hinder each other nor require special techniques for separation.

Similar to a sense capacitor, the drive capacitor is position dependent. This position dependency is the main cause generating the sense signal. As shown in Fig. 6, MEMS capacitor consists of two parallel capacitors: 1) the actuator capacitor \( C_{\text{drive}} \), 2) the anchor parasitics \( C_{\text{par}} \). As the drive amplitude builds up on \( C_{\text{drive}} \), the actuator gap closes causing \( C_{\text{drive}} \) to increase. The change in \( C_{\text{drive}} \) increases the overall value of the MEMS capacitor \( C_{\text{MEMS}} \). From Eqn. 1, the electrical resonance frequency is directly related to the MEMS capacitance in the LC tank. Thus, \( f_{\text{res, el}} \) decreases as a result of the increase in the MEMS position. The electrical resonance frequency of the tank shifts \( \sim 200\text{kHz} \) for 20deg-optical rotation of the torsional mirror used in experiments, Fig. 6.

![Figure 6: MEMS capacitor, and \( f_{\text{res, el}} \) vs. MEMS position.](image)

Since the oscillator circuit always operates at \( f_{\text{res, el}} \), its output frequency is proportional to the device position. Fig. 7 illustrates the simultaneous operation of drive and sense during a positive transition in the MEMS position. As mentioned earlier, \( V_{\text{ctrl}} \) sets the oscillation amplitude through the automatic gain control circuit. A positive step is applied to \( V_{\text{ctrl}} \) in order to increase the MEMS position, Fig. 7a. The AGC dynamics are fast enough that the signal \( V_{\text{in}} \) immediately follows the step in the \( V_{\text{ctrl}} \), Fig. 7b. For the capacitor voltage \( V_{\text{C}} \), however, the amplitude change is slower, Fig. 7c. The time constant of this exponential transient is proportional to the ratio of the inductance to the resistance, Eqn. 4.

\[
\tau_{\text{TANK}} = \frac{2L}{R} = 2Q/\omega_{\text{res, el}}
\]  

(4)

One implication of the time constant \( \tau_{\text{TANK}} \) is the decrease of drive bandwidth \( (BW = (2\pi\tau_{\text{TANK}})^{-1}) \) as the \( Q \) is improved by reducing the parasitic resistance. The drive bandwidth in the current implementation is \( \sim 100\text{kHz} \), which is two orders of magnitude higher than the mechanical resonance frequency.

Finally, higher drive amplitude results in larger electrostatic force and moves the MEMS device to a further position, Fig. 7d. The effects of position change can be seen as an increase in the period of the oscillation, Fig. 7b-c. So, in addition to voltage amplification and drive, the oscillator also creates a sense signal in the form of frequency change. This frequency change can easily be converted into a voltage signal by a proper frequency detection technique such as a Phase Locked Loop (PLL).

5. **Experimental Results**

The oscillator circuit and the PLL were implemented using off-the-shelf 10V CMOS parts. The MEMS device used for testing is a 1DOF torsional mirror made using a multilayer SOI process [6]. Mirrors need \( \sim 100\text{V} \) for 20 degree-optical rotation. Actuators use vertical comb drives with initial finger overlap. \( C_{\text{drive}} \) and \( C_{\text{par}} \) of the mirror are 1pF and \( \sim 9\text{pF} \) respectively. For achieving a reasonable tank \( Q \) and an electrical resonance frequency, a 390\muH inductor was used. A packaged mirror chip, a 390 \muH inductor, and an SEM picture of the device are shown in Fig. 8. The inductor has a maximum \( Q \) value of 50 at \( \sim 1.5\text{MHz} \). The
choice of inductance results in a $f_{\text{res,el}}$ value of 2.5MHz. At 2.5MHz, the inductor’s equivalent resistance is $\sim$150Ω while the MEMS capacitor has an equivalent parasitic resistance of $\sim$300Ω. So, the voltage amplification in the LC tank is $\sim$15. For testing the Q value, mirror was actuated up to 4 degrees-optical, and the DC drive voltage corresponding to that position was compared to the peak $V_{\text{in}}$ driving the LC tank. Results are shown in Fig. 9.

![Figure 8: Packaged mirror die, inductor, and the device.](image)

Frequency shift for the same amount of rotation as in Fig. 9b is shown in Fig 10. As expected, for further rotation resonance frequency of the circuit decreases, Fig 10a. In order to demonstrate that PLL can dynamically demodulate the sense signal from the frequency shift, mirror transfer function was measured using the PLL output, Fig 10b. As expected mirror has a second order transfer function with 1.3kHz mechanical resonance frequency.

6. CONCLUSIONS

We have successfully demonstrated resonant drive to be a viable technique for implementing MEMS drive and position sense. The external inductor allows low voltage CMOS circuits to effectively drive high voltage MEMS devices. The experimental implementation achieved a Q of 15. Q can be improved 2-3x by lowering the parasitic losses in the MEMS device. Every time the device moves, drive capacitance changes, causing a shift in the electrical resonance frequency ($f_{\text{res,el}}$) of the LC tank. The oscillator circuit tracks changes in the $f_{\text{res,el}}$ and generates the position sense signal without the need for an extra sense capacitor. Avoiding an extra sense capacitor simplifies the MEMS design. Sense signal strength can be improved by reducing the parasitic capacitance in the MEMS drive.

7. REFERENCES


![Figure 9: Mirror position vs. drive voltage: a) High voltage drive, DC drive signal; b) Resonant drive, peak tank input $V_{\text{in}}$.](image)

![Figure 10: Position sense: a) $f_{\text{res,el}}$ vs. mirror position; b) Resonant drive, input of the tank $V_{\text{in}}$.](image)