RESONANT DRIVE FOR STABILIZING PARALLEL-PLATE ACTUATORS
BEYOND THE PULL-IN POINT

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ABSTRACT

In this paper, we present a circuit technique (resonant drive) that offers solutions for the three major challenges in electrostatic actuation and sense: 1) pull-in instability in parallel-plate actuators, 2) high voltage circuits for creating large electrostatic forces, 3) the need for extra circuitry and capacitor (in most cases) for position sensing. The key idea is a series LC tank formed by placing an inductor in series with the actuator capacitor and operating the circuit at its electrical resonance frequency by the help of an oscillator loop. Electronics operate at voltages significantly smaller (by the Q factor, 10-15, of the electrical tank) than the voltage needed for the electrostatic actuation of the MEMS device.

Keywords: Electrostatic actuation, position sense, parallel-plate actuator, pull-in.

INTRODUCTION

Electrostatic actuation and capacitive sense are the most common means of building MEMS interface electronics. Such an interface becomes a complicated design problem in cases where simultaneous drive and position sense are needed for a high voltage demanding MEMS device. In modern CMOS technologies, developing the high voltage drive circuit and avoiding interference between the large drive signal and the precision sense signal are some of the challenges in the circuit implementation. Depending on the type of the actuator, pull-in instability can also be an additional issue that should be addressed by the MEMS designer.

Previous works have proposed various circuit techniques alleviating some of these abovementioned challenges but not all at once. Feedback control can stabilize parallel-plate actuators but needs simultaneous position sensing for its implementation [1]. An additional series capacitor provides a simpler solution for the parallel-plate pull-in [2]. A recent work has presented a practical circuit implementation for the charge control that stabilizes parallel-plate actuators over the entire gap [3]. The circuit in [3] also provides position sense without an extra sense capacitor. In all these solutions [1,2,3] electronic circuits must still operate at voltages that are, at least, as high as the levels that MEMS actuator needs ([2] operates at even higher, 3-5x, voltages).

An alternative to conventional drive circuits uses AC signals for the electrostatic drive. In this technique a series RLC tank is formed by connecting an inductor in series to the MEMS drive capacitor, Fig. 1. A recent work [4] has demonstrated that this tank can successfully stabilize parallel-plate actuators. A similar idea has also been used for stabilizing an electrostatically levitated disk [5]. The circuit in [4] does not provide position sensing but has the potential for reducing the voltage requirements on the electronics when it is driven at the electrical resonance frequency of the tank.

Figure 1: The series LC tank formed by an external inductor and MEMS drive capacitor.

The resonant drive method, presented in this work, shows that a proper circuit implementation using a series inductor can address all of the three issues mentioned earlier. Since the series tank provides maximum passive amplification at its electrical resonance frequency $f_{res,el}$, the resonant drive circuit uses an oscillator loop for resonating the RLC tank, Fig. 2. Using only a simple AC signal generator, Fig. 1, makes the operation at resonance a complicated problem due to stability issues, some of which are explained in [4]. By operating at the electrical resonance frequency of the tank, resonant drive reduces the voltage requirements on drive electronics by the quality factor of the tank $Q_{el}$. The oscillator loop is also capable of tracking the MEMS position by following the shift in the electrical resonance frequency, which is now a function of the MEMS position. The quality factor $Q_{el}$ is also position dependent, which extends the stable operating range by countering the strong position dependence of the parallel-plate capacitor. The following section presents a summary of the resonant drive operation that was first reported in [6].

THE RESONANT DRIVE CIRCUIT

Electrical resonance for electrostatic drive

At its electrical resonance frequency $f_{res,el}$, the series RLC tank has some features that are especially beneficial to a MEMS drive circuit.
Figure 2: The resonant drive circuit: an oscillator with amplitude control driving the RLC tank with the MEMS drive capacitor.

The inductor and the capacitor have reactances that are equal in magnitude but opposite in phase and hence cancel each other. The input drive signal $V_{in}$ effectively drives only the resistor $R_{par}$ whose impedance is $Q_{el}$ times smaller than the impedances of the inductor and the capacitor. Consequently, the resistor voltage $V_R$ is equal to $V_{in}$ while amplitudes of the capacitor and the inductor voltages are both $Q_{el} V_{in}$, Fig. 2. Thus, using resonant circuits we can drive MEMS devices that need voltages $Q_{el}$ times higher than what electronics can deliver.

The AC drive signal amplified by the tank creates an electrostatic force that has a DC RMS component and an AC component at twice the frequency of the drive signal $2f_{res \_el}$ [6]. The RMS component determines the MEMS position while the low-pass mechanical characteristics of the MEMS device filters the AC component of the force. As long as $2f_{res \_el}$ is much higher than the MEMS bandwidth, this process allows us to use AC signals for driving MEMS devices almost as accurately as DC signals.

The RLC Tank with the parallel-plate actuator

The MEMS capacitor $C_{drive}$ shown in the RLC tank is the capacitance between the plates of the parallel-plate actuator, Fig. 3.

Figure 3: The parallel-plate actuator with an initial gap of $g_0=1.6 \mu m$. Initial value ($x=0$) of the $C_{drive}$ is 1pF.

A linear spring with spring constant $k_x$ creates a mechanical restoring force $F_{mech}$ that increases linearly with the position $x$. When a drive voltage $V_C$ applied between the plates of the actuator, the moving plate increases its position until the restoring force $F_{mech}$ becomes equal to the electrostatic force $F_{el}$ at a stable equilibrium point. As the actuator moves further, the drive capacitance increases its value:

$$C_{drive} (x) = C_{drive0} \left(1 - x/g_0\right)$$

where

$$C_{drive0}$$

is the nominal value of the drive capacitance when the position $x$ is 0.

$R_{par}$ represents the parasitic electrical loses in the RLC tank. The parasitic resistance of electrical connections ($R_{MEMS}$ in Fig. 3) in the MEMS device contributes 90% of the total parasitic resistance $R_{par}$. Losses in the inductor dominate if $R_{MEMS}$ is reduced by using a high conductivity material.

We can characterize the RLC tank by its electrical resonance frequency $f_{res \_el}$ and the quality factor $Q_{el}$, which are given by equations 3 and 4.

$$f_{res \_el} = \frac{1}{2\pi} \sqrt{\frac{L}{C_{drive}(x)}}$$

$$Q_{el} = \frac{R_{par}}{L/C_{drive}(x)}$$

Figure 4: Electrical resonance frequency $f_{res \_el}$ and the quality factor $Q_{el}$ vs. the actuator position.
The position dependence of the drive capacitor causes both the electrical resonance frequency \( f_{\text{res,el}} \) and the quality factor \( Q_{\text{el}} \) to be position dependent. Figure 4 shows the change in the \( f_{\text{res,el}} \) and the \( Q_{\text{el}} \) of the tank as a function of the actuator position. As the moving plate closes the gap, \( C_{\text{drive}} \) becomes infinitely large and causes both \( f_{\text{res,el}} \) and \( Q_{\text{el}} \) to become 0.

**Position sense in the resonant drive**

The frequency of the oscillation in the oscillator circuit is always equal to the electrical resonance frequency \( f_{\text{res,el}} \) of the tank, which is now a function of the actuator position. By tracking the frequency of oscillations (e.g., using a PLL circuit), we can create a position sense signal. The resonant drive circuit accomplishes position control in the voltage domain while performing position sensing in the frequency domain. This natural separation eliminates the need for an extra sense capacitor or circuitry [6].

**POSITION CONTROL in the RESONANT DRIVE**

Resonant drive controls the MEMS position by setting \( V_{\text{in}} \) amplitude to the desired value. Since the circuit operates at resonance, the capacitor voltage \( V_C \) is simply \( Q_{\text{el}} \) times the input signal \( V_{\text{in}} \). The oscillator sets the amplitude of \( V_{\text{in}} \) by using an automatic gain control loop. Since the RMS value of the electrostatic force sets the MEMS position, we can calculate the electrostatic force by using the RMS value of the capacitor voltage \( V_{\text{RMS}} = Q_{\text{el}} V_{\text{in}} \sqrt{2} \).

\[
F_{\text{el}} = \frac{1}{2} \frac{dC_{\text{drive}}}{dx} \left( \frac{V_{\text{in}} Q_{\text{el}}(x)}{\sqrt{2}} \right)^2
\]

\[(5)\]

**Figure 5:** \( F_{\text{el}} \) and \( F_{\text{mech}} \) in resonant drive for \( V_{\text{in}} = 0.6V_{\text{peak}} \). From left to right, the bell shaped \( F_{\text{el}} \) curves are for input frequencies of \( f_{\text{el}} = 7.8\text{MHz}, 7\text{MHz}, \text{and } 6\text{MHz.} \)

Fig. 5 shows the electrical force as a function of the actuator position for \( V_{\text{in}} = 0.6V_{\text{peak}} \) and other parameters given in Fig. 2 and Fig. 3. This result can also be achieved by tracing the peak points of the electrostatic force curves (dashed bell shaped curves) of the circuit in Fig. 1 for a family of input signal frequencies \( f_{\text{el}} \) corresponding to electrical resonance frequencies \( f_{\text{res,el}} \) of the tank at various actuator positions. The simpler position dependence of \( F_{\text{el}} \) in the resonant drive is more convenient for using the input amplitude \( V_{\text{in}} \) for controlling the position.

As in the voltage control, the resonant drive also features two equilibrium points, of which A is the stable one. The actuator reaches A (35% of the gap) with only 0.6\( V_{\text{peak}} \) drive signal. Using traditional voltage control, the actuator reaches the pull-in point (33% of the gap) at a much higher drive voltage: \( V_{\text{pull-in}} = 3.4V \).

At pull-in, there is only one equilibrium point where \( F_{\text{el}} = F_{\text{mech}} \) and \( |dF_{\text{el}}/dx| = k_x \) (\( F_{\text{mech}} \) becomes the tangent line of \( F_{\text{el}} \)). For simplicity, we propose a new function \( f(x) \), which satisfies the following relation: \( dF_{\text{el}}/dx = F_{\text{el}} f(x) \). Using relations given above, we can show that the solution of \( f(x) x = 1 \) is the pull-in point. This result helps in calculating the new position of the pull-in point for a more complicated \( F_{\text{el}}(x) \) of the resonant drive. The solution of \( f(x) x = 1 \) for the resonant drive circuit in Fig. 2 shows that the negative position dependence of \( Q_{\text{el}} \) extends the pull-in point to 50% of the gap, Fig. 5.

**PULL-IN STABILIZATION USING THE RESONANT DRIVE**

In the resonant drive, position dependence of \( Q_{\text{el}} \) automatically reduces the amplitude of the capacitor voltage \( V_C \) as the parallel-plate actuator moves further. Fig. 6 shows the effect of \( Q_{\text{el}} \) on the \( F_{\text{el}} \) by comparing the electrostatic force generated by simple voltage control and the resonant drive. Normalization using the null position value of \( F_{\text{el}} \) clearly shows that the resonant drive has smaller position dependence due to dropping \( Q_{\text{el}} \).

In practical circuits, the position dependence of \( Q_{\text{el}} \) can show various characteristics. The parasitic capacitor in parallel with the MEMS actuator can dramatically change the position of the resonant-drive pull-in. The
following sections explain this dependence using different cases.

**Case 1: Inductor resistance only**

![Figure 7: RLC tank for Case 1.](image)

For this case we ignore the parasitic resistance in series with the MEMS capacitor. Considering the parasitic capacitor $C_{par}$ in parallel with the MEMS actuator, the RLC tank is as shown in Fig. 7. For $C_{par}=0$ this case is the same as the simple RLC tank and the pull-in point is at 50% of the gap. For $C_{par} >> C_{drive}$, $Q_{el}$ becomes less position dependent and pull-in point goes closer to 33% regardless of the value of $R_L$, Fig. 9.

**Case 2: MEMS resistance only**

![Figure 8: RLC tank for Case 1.](image)

This case yields some interesting results in terms of the influence of the parasitic capacitance $C_{par}$. Ignoring the parasitic resistance of the inductor, Fig 8 shows the RLC tank. As long as the $R_{par}C_{drive}$ time constant is reasonably smaller than $1/\omega_{res_{el}}$, we can replace the MEMS network with a simpler equivalent circuit where the effective capacitance $C_{eff}$ is the total capacitance. The ratio of the $C_{drive}$ to $C_{eff}$ determines the effective resistance $R_{eff}$. Since $R_{eff}$ also becomes position dependent, the stabilizing effect of $Q_{el}$ is further enhanced.

$$C_{eff}(x) = C_{drive}(x) + C_{par} \tag{6}$$

$$R_{eff} = R_{par} \left( \frac{C_{drive}(x)}{C_{eff}(x)} \right)^2 \tag{7}$$

For $C_{par}=0$, Case 2 is also the same as the simple RLC tank: the pull-in occurs at 50% of the gap. As $C_{par}$ increases, $R_{par}$ becomes smaller and makes $Q_{el}$ more sensitive to position and pull-in point approaches 100% of the gap, Fig. 8. This important result shows that a capacitance (parasitic or intentional) parallel to $C_{MEMS}$ can extend the range of stable operation range instead of degrading the performance.

**Case 3: Considering both parasitics**

In practical cases, both inductor and MEMS parasitics exist, Fig. 10. Intuitively we expect this case to lie between the Cases 1 and 2. In the Case 3, the analysis is too complicated for a closed-form solution so we used numerical calculations for finding the pull-in point. For $C_{par}=0$, this circuit also operates like the simple RLC tank and pull-in occurs at 50% of $g_0$. Using eqn. 7, we can show that bigger $C_{par}$ decreases $R_{eff}$ and makes the $Q_{el}$ more sensitive to position change. Due to the presence of the inductor resistance $R_L$, however, decrease in the total parasitic resistance is less than that for Case 2. Eventually, for large values of $C_{par}$, $R_{eff}$ becomes negligible compared to $R_L$ and the pull-in point starts following the characteristic for Case 1. Thus, in Case 3, pull-in stabilization by $C_{par}$ is less for relatively larger values of the inductor parasitic resistance $R_L$, Fig. 9. Generally, $R_{MEMS}$ is 10x or more larger than $R_L$.

![Figure 9: RLC tank for Case 3. The effective parasitic resistance in the tank $R_{par}$ is $R_L + R_{eff}$.](image)

**Practical Considerations**

In practice, inductors have a frequency dependent quality factor $Q_i$, which also affects the position dependency of the $Q_{el}$. In order to find the influence of $Q_i$, we repeated the same numerical analysis including a $Q_i$ model generated from data sheets of a 390µH inductor LQH32MN391K23 from Murata. This inductor has a...
maximum \( Q_i \) of 50 at 1MHz. The self resonance frequency of the inductor is > 5MHz, which is high enough to cover the operation range when used with the MEMS actuator and a ~1pF or higher parasitics. The maximum travel range in this case is 0.6g0, Fig. 10. One simple solution to this problem is decreasing the influence of the inductor with a bigger MEMS resistor \( R_{\text{MEMS}} \). The stable operating range can be as high as 90% by adding only a 200Ω in series with the \( R_{\text{MEMS}} \).

Figure 10: Resonant drive pull-in for non-ideal inductor with frequency dependent quality factor.

**PRELIMINARY EXPERIMENTAL RESULTS**

We have demonstrated the stabilization of the parallel-plate actuation by using a vertically actuated proof-mass, which was originally designed for testing squeeze film damping [7], Fig 11. The parallel-plate actuator and its electrical model including the off-chip parasitics and components.

![Parallel-Plate Actuator Model](image)

**CONCLUSIONS**

We have successfully demonstrated resonant drive for stabilizing parallel-plate actuators, position sensing without extra circuitry and capacitor, and eliminating the need for high voltage drive electronics. The technique could stabilize a gap closing actuator up to 50% of the gap even with significantly large parasitic capacitances due to non-optimal circuit and device implementations.

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**REFERENCES**