Abstract — Parallel plate accelerometers exhibit a significant meta-stable region when sufficiently over damped. Their pull-in time is highly dependent on any external acceleration disturbance. Combined with an on-off feedback control loop a pull-in time based high sensitivity accelerometer with digital output is realized. Sensor range and resolution can be adjusted through four simple operational parameters to match the intended application.

Key Words: Nonlinear dynamics, accelerometer, pull-in.

I INTRODUCTION
The nonlinear dynamic behavior of inertial micro structures offers great potential for new sensing mechanisms [1]. Traditionally the most encountered sensor read-out principles in inertial MEMS devices are displacement, force or resonance based. Either a capacitive [2] or resistive [3,4] change is measured, or force balancing [5] is applied. A careful study and characterization of the dynamic pull-in effect reveals an opportunity to use the pull-in time as a measure for external inertial forces [6].

I.1 DYNAMIC VS. STATIC BEHAVIOR
The static analysis of capacitive devices is relatively simple and only requires finding the equilibrium positions between the applied forces and to find the conditions at which the loss of stability occurs. Dynamic analysis considers the transition between the equilibrium points and pays particular attention to the trajectory of the movable electrode both before and after stability is lost. Although if the dynamic behavior is more difficult to analyze, as compared to the monotonous static behavior, the nonlinear properties of the system dynamics offer highly interesting opportunities for enhancing overall system performance. A correct understanding of the dynamic nonlinearities present in a MEMS device has been demonstrated to contribute both to enhanced device performance and to provide the insight needed for identifying new applications.

I.2 HIGH SENSITIVITY IN NONLINEARITY
Analysis of nonlinear systems is more complex as compared to linear systems. Although, some of the nonlinear characteristics are conventionally considered a nuisance, these can be applied to improve operation. This is the case for nonlinear parallel-plate electrostatic MEMS devices. When over-damped these devices exhibit a high-sensitivity meta-stable region, which has huge potential for low acceleration measurements.

II META-STABLE REGION
When applying a voltage marginally larger than the pull-in voltage to an over damped parallel-plate structure, it exhibits meta-stability during the pull-in event (figure 1).

![Figure 1 Pull-in motion characteristic of over damped and under damped MEMS devices](image-url)
Three regions can be identified. A first region where the structure moves fast until near the static pull-in displacement ($x_{pi}=d_0/3$). Here, the initial imposed electrostatic force is compensated by the elastic and damping forces. At the start of the step response the damping force dominates but with deflection the elastic force equilibrates the electrostatic one and the damping force reduces becoming almost negligible (Fig. 2a).

A second meta-stable region characterized by an almost zero velocity. At the onset of this region the structure moves very slowly and the elastic force is almost the same as the electrostatic. This results in a kind of meta-stable equilibrium. The third region takes the structure to the counter-electrode. Due to the nonlinear behavior of the electrostatic force, the elastic force cannot indefinitely compensate for the electrostatic one and the structure completes the pull-in event (Fig. 2b).

The important aspect is the high sensitivity of the transition time in the second region to an external acceleration. This is due to the intrinsic behavior of the meta-stable region. Since this region is characterized by a tight equilibrium between electrostatic and elastic force, any small change acts as a perturbation to the meta-stable equilibrium, thus providing the means to achieve a very high sensitivity on the time domain.

### III SYSTEM ARCHITECTURE

#### III.1 ON-OFF CONTROL

Recently an extended travel range technique was introduced, based on an on-off closed-loop electrostatic actuation of a capacitive structure that achieves dynamic yet stable electrode positioning over the entire gap [7]. By measuring the displacement and comparing it with the desired displacement, either a voltage higher than the pull-in voltage is applied or no voltage is applied. (Fig. 3) Due to the device dynamics and the delay introduced by the feedback loop, a small ripple remains on the displacement, while the actuation signal from the comparator is a square wave.

#### III.2 HYSTERESIS

By combining the on-off control with the sensitivity of the pull-in time to external acceleration a flexible solution to measure external accelerations is achieved. The full-system block diagram envisioned is depicted in figure 4a. The accelerometer operation is based on the comparison of the structure displacement with a reference position ($x_{ref}$). Unlike the on-off method, a hysteresis is introduced in the
The use of hysteresis in the comparator increases the transition time of the structure. If no acceleration is present, and by proper selection of the operation parameters, $\alpha$ and $\beta$ with $\alpha > 0$ and $\beta > 0$, a square wave at a well-defined frequency is seen at the output. If an external acceleration is present, both the frequency and pulse width change. These changes are proportional to the external acceleration present during device motion.

III.3 ADJUSTABLE RANGE AND RESOLUTION

This approach has several advantages as compared to conventional accelerometer operation. The main one, and the most prominent, is that by proper selection of the operation parameters ($\alpha$, $\beta$, $x_{ref}$ and $\Delta x$), the range and resolution of the accelerometer can be adaptively adjusted.

Figure 4 Concept for a digital output accelerometer. a) Block diagram and b) comparator with hysteresis.

Figure 5 Simulated output of the on-off based accelerometer for two distinct operation parameters.
Choosing $x_{\text{ref}}$ equal to the static pull-in position ($d_0/3$) results in sensitivity to both DC and AC accelerations. Choosing $x_{\text{ref}}$ different it is possible to compensate for a DC acceleration and AC acceleration sensitivity results, thus circumventing common mode problems typically associated with this kind of measurement. It enables accurate measurements of small inertial forces superimposed on for example gravity.

This implies that the same MEMS structure can be used in several different applications (automotive, vibration analysis, inertial navigation), just by changing the operation parameters. Another advantage is the digital output of the sensor. A few simulations using a large-signal model for a one-degree-of-freedom device used in previous work are presented in figure 5. Two cases with different operation parameters are presented which are illustrative of the potential of this approach.

**IV CONCLUSIONS**

There is huge potential in using the nonlinear dynamics of MEMS devices while keeping a quite simple mechanical parallel-plate structure. The envisioned accelerometer features low complexity in terms of micro structure and micro system, yet has several advantages over current inertial force sensors. Its range and resolution are adjustable on the fly, to accommodate a wide range of operating environments and applications. Its output is digital to allow easy interfacing to other systems and integration with on-chip electronic circuits.

**REFERENCES**


