Abstract— Electrostatically-actuated MEMS mirrors are used in a variety of applications ranging from mass sensing, gyroscopes, resonators, and displays to, more recently, endoscopic imaging, as for premalignant cancer detection. The aim of this work is to analytically and experimentally characterize the dynamics and stability of a 1D torsional micro-mirror undergoing parametric resonance for use in biomedical imaging. Analysis focuses on the effects of duty cycle variations on the stability and amplitude of micro-mirror motion. Additionally, the paper explores how proportional control can be implemented with duty cycle as the input to ensure that the desired scanning angles for imaging can be obtained. The paper outlines fundamental and simplifying assumptions made for each analysis, discusses the validity of associated models, and compares analytical outcomes to respective experimental results. Analytical models agree reasonably with experimental models in stability predictions at modest voltages and can provide more limited predictions of amplitudes given sufficient prior experimentation to estimate damping coefficients.

I. INTRODUCTION

The phenomenon of parametric excitation is used widely in MicroElectroMechanical Systems (MEMS) for mass sensing [1], high resolution laser scanning display systems [2], amplifying motion of resonators [3] and tuning filters [4]. A recent application of parametric excitation is in biomedical imaging, whereby micro-mirrors can be installed in miniaturized endoscopes for in-vivo tissue imaging via confocal microscopy [5]. Advantages of parametrically resonant mirrors in dual axes confocal imaging include a large field of view [6], better optical performance and simpler manufacturing processes compared to existing angular vertical comb-drive scanners [7]. Parametrically-excited MEMS micro-mirrors have also demonstrated large angles for other scanning applications [2], [8]. This paper will study the duty-cycle effects on new parametrically-excited scanning mirror that makes use of novel geometry and fabrication procedures to support dual-axes confocal microscopy.

Fig. 1 illustrates key components of the 1D mirror, the electrostatic actuation principle between arrays of comb fingers which enables the mirror to rotate about its torsional axis, and a sample frequency response of the micro-mirror at input square wave of 32V at 50% duty cycle. Frequency point ‘A’ on the frequency response plot indicates the frequency at which the mirror begins oscillating during

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equations with rapidly varying, typically periodic coefficients [10]. In many applications, the equations of motion governing a parametrically excited system can be simplified to take the form of a Hill’s equation. This is a class of homogeneous, linear, second-order differential equations with real periodic coefficients [11], [12]. Floquet theory [12], [13] is typically used to discuss the stability of periodic solutions for such periodic systems; however, this method requires a large number of numerical integrations that can limit its use, especially if the coefficients of the equations depend on certain parameters [14]. There is a large body of literature that examines the stability and dynamics of Hill’s type equations in parametric resonance [15–17].

Instability of the trivial solutions for special cases of Hill’s equation called the Mathieu equation has been studied extensively as especially relevant to parametric resonance in MEMS. Rand identified stability regions for quasi periodic Mathieu equations [11]. Turner described the dynamics of noninterdigitated comb-finger driven micro-oscillators using nonlinear Mathieu equations with a square rooted AC signal [18]. Linear tuning scheme was also employed to rotate the wedge-shaped instability region and a nonlinear tuning scheme was also used to achieve desired hardening or softening behavior in the oscillator system’s response [19]. Ataman also modeled transitions in stability regions for comb actuated resonant micro-scanners by expressing the equation of motion in a form of the Mathieu equation [20].

It is known from experience of various researchers that in applying square wave excitations to a system to cause parametric resonance, the duty cycle can regulate behavior and affect stability regions. However, this has not yet been studied analytically in literature and aforementioned work. The aim of the work presented in this paper is to examine the role of duty cycle in affecting the frequency and corresponding amplitudes achieved by the 1D scanning mirror and to demonstrate the effectiveness of a proportional closed loop controller in identifying duty cycles associated with target scan amplitudes.

II. ANALYTICAL MODEL CONSTRUCTION

A. System Model

The equation of motion of the single DOF parametrically resonant MEMS micro-mirror is governed by [9]:

$$J \ddot{\theta} + c \dot{\theta} + k \theta = F(t, \theta)$$  \hspace{1cm} (1)

where \( \theta \) is the rotation angle of the mirror, \( J \) is the mass moment of inertia of the mirror, \( k \) is the torsional spring stiffness constant, \( c \) is the average damping constant and \( F \) is the applied torque. The out of plane torsional mode was the dominant vibration mode of the mirror and modal analysis in ANSYS confirmed that the resonant frequencies of other modes were well separated from the torsional mode frequency. The damping constant and spring stiffness constant were assumed constant for the purpose of this analysis. The applied torque, \( F \), is defined as

$$F(t, \theta) = N \frac{dc}{d\theta} V^2(t)$$  \hspace{1cm} (2)

where \( N \) is the number of comb fingers on one mirror side and \( dc/d\theta \) is the rate of change of capacitance with respect to angular displacement. \( V(t) \) is the periodic square wave driving signal and it assumes the following form as a Fourier series:

$$V(t) = A \left[ \sigma + \sum_{\substack{n=1, \text{odd} \\text{or} \text{even}}} \left( \frac{1}{2} \cos(2n\pi\sigma \theta) + \frac{1}{2} \sin(2n\pi\sigma \theta) \right) \right]$$  \hspace{1cm} (3)

where \( \sigma \) is the duty cycle fraction, \( A \) is the magnitude of the input excitation signal, \( w \) is the frequency, \( t \) represents time and \( n \) is an integer. Equation (3) was obtained by expressing the following periodic function in Fourier series in terms of the duty cycle,

$$g(t) = \begin{cases} A, & 0 < t < \sigma T \\ 0, & \sigma T < t < T \end{cases}$$  \hspace{1cm} (4)

where \( T \) is the time period for one cycle. Using a square root voltage representation in (3) isolates parametric effects from the harmonic effects [21]. This form has been used extensively in literature for studying nonlinear Mathieu equations and Duffing equations [22], [23].

The capacitance was modeled using a fixed comb-drive and a pair of movable comb-drive in COMSOL [24] to capture the fringe capacitance effects. The movable comb drive was rotated about the torsional axis of the mirror to obtain the capacitance corresponding to each angle and the following sixth order polynomial was used as the best fit for the capacitance-angle relationship:

$$C = b_6 \theta^6 + b_5 \theta^5 + b_4 \theta^4 + b_3 \theta^3 + b_2 \theta^2 + b_1 \theta + b_0$$  \hspace{1cm} (5)

For stability analysis, the forcing function as defined by (2) and (5) is linearized to define a constant, \( a \), such that \( dC/d\theta \approx a \) at \( \theta = 0 \).

Using aforementioned approximations and introducing a dimensionless constant, \( \tau = wt/2 \), (1) becomes:

$$\frac{d^2\theta}{d\tau^2} + \frac{2c}{J\tau} \frac{d\theta}{d\tau} + \left( \frac{4k}{J\tau^2} + \frac{4}{J\tau} \frac{aV^2(\tau)}{\theta} \right) \theta = 0$$  \hspace{1cm} (6)

Isolating amplitude term, \( A^2 \)

$$\frac{d^2\theta}{d\tau^2} + \frac{2c}{J\tau} \frac{d\theta}{d\tau} + \left[ \frac{4k}{J\tau^2} + \frac{4aV^2(\tau)}{\theta} + \sum_{n=1}^{\infty} \frac{1}{n\pi} \sin(2n\pi\sigma \theta) \cos(2n\pi\sigma \theta) \right] \theta = 0$$  \hspace{1cm} (7)

and defining

$$\mu = \frac{c}{J\tau} \quad \delta = \frac{4[k + \sigma A^2 a]}{J\tau^2} \quad \varepsilon = \frac{4aV^2}{J\tau^2}$$  \hspace{1cm} (8)

results in a form of the damped Hill’s equation for parametrically excited systems [10] such that,

$$\frac{d^2\theta}{d\tau^2} + 2\mu \frac{d\theta}{d\tau} + [\delta + \varepsilon f(\tau)] \theta = 0$$  \hspace{1cm} (9)

where

$$f(\tau) = \sum_{n=1}^{\infty} \alpha_n \cos(2n\pi \tau) + \beta_n \sin(2n\pi \tau)$$  \hspace{1cm} (10)

$$\alpha_n = \frac{1}{\pi} \sin(2n\pi\sigma) \quad \beta_n = \frac{1}{\pi} (1 - \cos(2n\pi\sigma))$$  \hspace{1cm} (11)

B. Stability Analysis

To build an analytical model to determine the stability boundaries of the system at various duty cycles, the Lindstedt Poincare technique was applied to (9) to construct a relationship between \( \delta \) and \( \varepsilon \) [25]. Assuming small \( \varepsilon \), expansions of the following form were assumed:
\[ \theta(t, \varepsilon) = \theta_0(t) + \varepsilon \theta_1(t) + \varepsilon^2 \theta_2(t) + \cdots \]  
\[ \delta(\varepsilon) = \delta_0(t) + \varepsilon \delta_1(t) + \varepsilon^2 \delta_2(t) + \cdots \]  

Substituting (12) and (13) into (9) results in

\[ [\ddot{\theta}_n(t) + 2\mu \dot{\theta}_n(t) + \theta_n(t) + \theta_{0n}(t) + \varepsilon \theta_{1n}(t) + \varepsilon^2 \theta_{2n}(t) + \cdots] + [\delta_0(t) + \varepsilon \delta_1(t) + \varepsilon^2 \delta_2(t) + \cdots + \varepsilon^2 \delta_2(t = \varepsilon + \varepsilon^2 + \cdots)] = 0 \]  

The damping term in (9) was then scaled to facilitate the analysis by letting \( \mu = \varepsilon \bar{\mu} \) [10], [26] and this was substituted in (14). Next, coefficients of \( \varepsilon^0, \varepsilon^1 \) (higher order terms were ignored) were equated to zero to obtain the following second order differential equations:

\[ \ddot{\theta}_0(t) + \theta_0(t) = 0 \]  
\[ \ddot{\theta}_1(t) + \delta_0 \theta_1(t) = -\delta_1 \theta_0(t) - 2\mu \dot{\theta}_0(t) - \theta_{0f}(t) \]  

In order to let \( \theta_0(t) \) be periodic with period \( \pi \) or \( 2\pi \), the solution for (15) was assumed to be,

\[ \theta_0(t) = a_0 \cos(n\pi t) + b_0 \sin(n\pi t) \]  
\[ \delta_0 = n^2 \]  

where \( a_0 \) and \( b_0 \) are arbitrary constants and \( n \) is non-zero [10], [16], [25].

Substituting (17) into (16) yields

\[ \ddot{\theta}_1(t) + \delta_0 \theta_1(t) = -\delta_1(a_0 \cos(n\pi t) + b_0 \sin(n\pi t)) - 2\mu (a_0 \cos(n\pi t) - a_0 \sin(n\pi t)) - \delta_1 \]  

For \( \delta_1 \) to be periodic, the secular terms (\( \cos(n\pi t), \sin(n\pi t) \)) on the right hand side of (18) are eliminated [10], [16] and this results in,

\[ [\delta_1 + \frac{1}{2}a_n]a_0 + \frac{1}{2}b_n + 2\mu n]b_0 = 0 \]  
\[ \frac{1}{2}b_n - 2\mu n]a_0 + [\delta_1 - \frac{1}{2}a_n]b_0] = 0 \]  

For a non-trivial solution to exist,

\[ \delta_1^2 = \frac{1}{4}(b_n^2 + a_n^2) - 4\mu^2n^2 \]  
\[ \delta_1 = \pm \sqrt{\frac{(b_n^2 + a_n^2) - 4\mu^2n^2}{2}} \]  

Substituting \( \delta_1 \) and \( \delta_0 \) in (13) results in

\[ \delta = n^2 \pm \frac{1}{2}\sqrt{(b_n^2 + a_n^2)\varepsilon^2 - 16n^2\mu^2} \]  

The equations of the boundary curves in the frequency – voltage amplitude domain can be obtained for parametric resonance at \( n = 1, 2, 3 \) ... by replacing (8) back into (23).

Mathematical analysis from (12) through (22) is characteristic of the Lindstedt Poincare approach when seeking periodic solutions [25]. The disadvantages of this approach are that it is only accurate for small \( \theta \) and that this technique is incapable of determining transient responses [25]. These simplifications do cause the analytical results to deviate from results obtained using the unabridged capacitance model in (1). Thus far, the linearization of (5) has the strongest impact on analytical outcomes and simulations are being used to seek an accurate ‘a’ value.

C. Predicting Scanning Amplitudes in the Stable Region

An alternative method was also tested for predicting scanning amplitudes as a function of duty cycle at a given frequency, since the method at the conclusion of Section B includes certain small angle assumptions that can be less accurate for large motions. The simplified approach assumed that during resonance the system could be approximated by the forced, second order differential equation:

\[ j\dot{\theta} + c\dot{\theta} + k\theta = \frac{1}{2}N \frac{dc}{d\theta} \left. V^2(t) \right|_{\theta=0} \]  

with duty cycle incorporated in the expression for \( V^2(t) \) through an alternating square wave at half the applied frequency, so that over a cycle from \( t=0 \) to \( t=T_2 = 4\pi/w \),

\[ V^2(t) = \begin{cases} A^2, & 0 < t \leq \sigma T_2/2 \\ 0, & \sigma T_2/2 < t \leq T_2/2 \\ -A^2, & T_2/2 < t \leq T_2/2 + \sigma T_2/2 \\ 0, & T_2/2 + \sigma T_2/2 < t \leq T_2 \end{cases} \]  

The response to input (25) is solved numerically for duty cycles indicated to be resonating at a given frequency by preceding stability analysis.

Since the model in Section II.A. could not be used to obtain accurate scan amplitudes, numerical simulations were first used to model the forcing function in (2). The details of these simulations will be discussed in a forthcoming article. Equation (25) was then developed to simplify and replicate a form of the forcing function from the simulations.

The models in Section II.A. and Section II.B. are similar because they both linearize the change in capacitance about the origin and assume that this linearization remains constant over the range of all scan amplitudes achieved by the micro-mirror. This assumption best approximates small scan angles (\( \pm 3^\circ \)), however, this assumption will cause deviations from the experimental outcomes at larger scan amplitudes where the nonlinear change in capacitance terms are dominant.

III. SIMULATING EXPERIMENTAL AND ANALYTICAL RESULTS

A. Experimental Setup and Mirror Parameters

The experimental setup comprised a data acquisition system (LabVIEW) with a connectivity enclosure (NI-CA-1000) connected to a PCI data acquisition card. This was connected to a position sensing amplifier (OT-301) and the analog output from LabView was connected to a high voltage amplifier (TEGAM 2350), which was then linked to the 1D micro-mirror. The position sensing amplifier was connected to a position sensing detector (On-Trak). The lights in the room were switched off for each experiment since the position sensing detector was sensitive to light. The position sensing detector was also calibrated to obtain the conversion between output voltage readings and scanning angle.

Table 1 (page 4) highlights the key design parameters of the micro-mirror. Assuming small rotations about the stable equilibrium, the slope of the capacitance curve, \( dC/d\theta = \alpha = -1.1 \times 10^{-10} \text{ Nm/radV}^2 \) was approximated at \( \theta=0 \), given the number of combs in the device. The value for the damping constant was determined empirically using simulations to predict the frequency response of the micro-mirror at given reference operating point (50% duty cycle at 6765 Hz and 32 V), since damping coefficient for the system could not be predicted theoretically.
Spring stiffness and inertia were calculated from finite element analysis of the mirror using ANSYS, which further predicted that the spring constant should remain in the linear regime for the range of displacements expected.

B. Voltage-Frequency Stability

Fig. 2 (above) illustrates that the analytical model predicts voltage – frequency stability curves accurately under a portion of driving scenarios. Traits characteristic to the stability curve are visible in analytical results in Fig. 2, for example, the voltage necessary for starting mirror oscillations, the unstable region between the wedge and the stable regions on either side of the wedge, and the effect of damping to cause the wedge to round off at the bottom. This rounding is most prominent at a duty cycle of 50%.

Experiments confirmed that the mirror was stationary outside the wedge and that it transitioned sharply to high amplitudes inside the unstable region of the wedge [27]. When the source of excitation was halted within this unstable region, the mirror stopped oscillating and did not resume its oscillations once the excitation source was resumed. In the unstable region, the amplitude is achieved by the nonlinearity in the system; therefore such parametric resonances can attain significant amplitudes in the unstable region [27].

As seen in Fig. 2 (above) the analytical model predicts corresponding voltages best for experimental frequencies relatively accurately for the duty cycles near 50%. As duty cycles increase through 60% and 70%, the analytical model shows, on average, increasing initiating voltages, as seen in the experimental results, but with increasing divergence between upper and lower transition frequencies, to experimental results, and also from experimental results. Meanwhile, for 30% duty cycle, a drop in frequency and voltage is successfully predicted, but the analytical model is only able to predict stability bounds at these low frequencies and on the upper stability bound.

Fig. 2 illustrates how the analytical outcomes agree with experimental results at low voltages (~20V to ~40V). One limitation of the analytical model is that it does not consider several nonlinearities in the operation of the micro-mirror. For example, the torsional spring constant was assumed to be constant throughout the mirror operation. Given observed trends at high voltages, it is likely that in truth the experimental system undergoes spring hardening, despite preliminary finite-element modeling indications. The change in capacitance with respect to scanning angle was also considered constant based on ‘a’ derived in Section II. However, preliminary results in modeling the frequency response of the micro-mirror in time simulations indicated that behavior is often predicted better with a very small introduced bias moment, not included in the baseline analysis (in practice, possible due to fabrication imperfections which create asymmetric structures [28] or inherent variation in material properties [29]); a lump sum in the change of capacitance term significantly affected the amplitudes achieved by sweeping the mirror from low to high frequencies as mirror oscillation was initiated.

Table 1: Design parameters of the micro-mirror.

<table>
<thead>
<tr>
<th>$J$ (kg.m²)</th>
<th>$k$ (N.m/rad)</th>
<th>$c$ (N.s.m/рад)</th>
<th>$N$</th>
<th>$b_1$ ($F/\text{rad}^3$)</th>
<th>$b_2$ ($F/\text{rad}^3$)</th>
<th>$b_3$ ($F/\text{rad}^3$)</th>
<th>$b_4$ ($F/\text{rad}^3$)</th>
<th>$b_5$ ($F/\text{rad}^3$)</th>
<th>$b_6$ ($F/\text{rad}^3$)</th>
<th>$a$ (F/рад)</th>
</tr>
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<tr>
<td>6.2E-15</td>
<td>2.76E-06</td>
<td>3.33E-13</td>
<td>400</td>
<td>2E-09</td>
<td>-8E-10</td>
<td>6E-11</td>
<td>2E-11</td>
<td>-3E-12</td>
<td>-1E-14</td>
<td>2E-14</td>
</tr>
</tbody>
</table>

Figure 2: (Top left through bottom right) Voltage – frequency stability regions for duty cycles 30%, 50%, 60%, 70% respectively. The analytical model is in good agreement with the experimental results at low voltages (~20V to ~40V). At 30% duty cycle only one stability branch could be predicted based on the limitations of the analytical model. At 60% and 70% duty cycles the analytical results predict a spring softened system relative to the experimental results.

Figure 3: (Left through Right) Voltage – amplitude stability regions for duty cycles 30%, 50%, 60%, and 70% respectively. The analytical model trend is in good agreement with the experimental results at low voltages (~20V to ~40V) for most duty cycles. However the analytical model fails to predict accurate scan angles from ~40V to ~60V, though at 50% better overall trend matching is observed.
These effects are considered as topics for future work. Ongoing analytical analysis indicates that ‘a’ should be adjusted over amplitude ranges to model nonlinearities in the capacitance model.

C. Voltage-Amplitude Stability

Next, the amplitude of vibration at critical frequencies was measured experimentally for comparison to analytical predictions. Fig. 3 on page 4 demonstrates that the analytical model outlined in Section II.B. predicts trends for amplitudes at critical frequencies and most duty cycles when voltages and angles are relatively low (~20V to ~40V) relative to experimentally obtained data. At higher voltages, ~40 to ~60V, even though under parametric resonance the system is capable of achieving high amplitudes, the amplitudes appear to be smaller, possibly saturated by other nonlinearities in the system [10], [30]. Experimental and analytical amplitudes differ likely for similar reasons as noted regarding voltage-frequency stability testing.

IV. DUTY CYCLE SWEEPS AND IMPLICATIONS FOR CONTROL

A. Duty Cycle Sweep from 1% to 99%

The case of sweeping across the duty cycle from 1% - 99% was next considered. Experimentally, this was performed at a fixed frequency of 6765Hz and voltage of 32V. The fixed 6765 Hz reference frequency was selected from the pool of data collected at 50% duty cycle for frequencies and amplitudes corresponding to Point ‘A’ and Point ‘B’ (Fig. 1, page 1) such that the fixed frequency was greater than frequency at Point ‘A’. This ensured that the reference frequency was in the stable region of the frequency response curve (Fig. 1, page 1). The span of operability for scanning amplitudes corresponding to duty cycles will vary based on the frequency and voltage combination.

Fig. 4 shows a comparison between experimentally measured amplitude and analytically approximated amplitude from Section II.C. Predicted amplitude was taken to be zero for duty cycles outside the stability regions predicted by the nonlinear stability analysis. As can be seen, the approximated amplitude shows reasonable agreement to the experimental result, but fails to capture smoother transitions from oscillating to non-oscillating responses observed in experiments. The stability bound at this frequency is also somewhat wider than the experimentally observed bound.

An important implication of the result in this sub section is that maximum scan amplitudes may not occur at the conventional duty cycle of 50% based on a specific voltage and frequency combination. Instead, operating the mirror at other duty cycles must be considered for optimum scanning performance. It also is worth re-iterating that approximate response fitting can only be performed if at least one reference test has been performed to estimate damping coefficient.

B. Control Implications Using Duty Cycle

The micro-mirror’s scan angle response to a change in duty cycle can be harnessed to implement feedback control and duty cycle can be used as a tuning variable to achieve the maximum scan angle. A classical proportional control algorithm was used to tune the duty cycle from an initial amplitude and duty cycle to achieve target amplitude using,

\[ d_2 = d_1 + \alpha (A_2 - A_1) \]  

where \( d_2 \) is the predicted duty cycle after each iteration, \( d_1 \) is the initial duty cycle and it is updated at each iteration, \( \alpha \) is the constant gain, \( A_2 \) is the measured amplitude corresponding to each duty cycle, \( d_2 \), and \( A_1 \) is the initial amplitude associated with \( d_1 \).

The aim of this experiment was to investigate how well proportional control could perform set point tracking for a provided target scan amplitude and duty cycle. Fig. 5 on page 6 confirms that duty cycle, in this case updated each second to adjust amplitude, can be an excellent candidate for controlling the amplitude of the scanning mirror as the target amplitude (4.990 degrees) is met with measured amplitude (4.993 degrees). For large angle scanning the micro-mirror would have to operate at frequencies corresponding to maximum amplitudes, however the mirror is at risk of its oscillations coming to a complete halt with any perturbation at these frequencies. In practice, implementing feedback control is required to ensure that the mirror can scan near the maximum target amplitude and its corresponding frequency.

For more general operating guidelines, Fig. 6 (page 6) illustrates the 3D view of the relationship between duty cycle, frequencies at which the mirror can achieve maximum amplitude before it stops oscillating, and the maximum scanning amplitudes from several experimental sequences. The frequencies and maximum scanning angles were obtained experimentally for voltages ranging from ~20V to ~60V. Fig. 6 also illustrates that increasing voltages result in higher scanning angles.

V. CONCLUSION

Experimental and analytical dynamics of a 1D mirror for use in high resolution imaging of the GI-tract were presented as they respond to various duty cycled square waves. The trends from the analytical results for stability and scanning amplitude predictions show reasonable agreement with experimental observations for modest voltages and intermediate duty cycles, with other nonlinearities causing deviation at higher voltages and wide duty cycle ranges. For
considered, for e.g. modeling with a nonlinear spring-accurate magnitude matching analytical models incorporating effects of duty cycle contributions from nonlinearities... driver by angular vertical comb actuators”, Microelectromechanical Systems, Journal of, 14(6), Dec. 2005


