Characterization of MEMS resonators via feedthrough de-embedding of pulsed-mode response

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Abstract

In this paper, we analyze and give experimental evidence of the efficiency of pulsed-mode actuation for the characterization of capacitive MEMS resonators. In particular, we show how to process the output signal in pulsed mode to eliminate parasitic feedthrough effects and characterize the resonator. We test our approach on a pressure sensor, developed by THALES Avionics, used for avionics applications. Contrary to the existing state-of-the-art techniques, the method described in this paper can be used to characterize an electrostatic MEMS without a spectrum analyzer or high-performance ADC.

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1. Introduction

Feedthrough is a major obstacle to the characterization of capacitive MEMS resonators via electrical measurements [1-4]. Open-loop frequency responses are distorted by parasitic feedthrough, which leads to poor-quality estimations of the natural frequency and Q-factor of the resonator. Previous work has addressed direct parameter extraction from feedthrough-embedded frequency response via considerations on the Nyquist plot [1]. Another option consists in de-embedding parasitic feedthrough via subharmonic actuation [2,3]. Foregoing these spectral approaches, we present a

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new paradigm for the cancelation of feedthrough effects in the time domain. The principle of feedthrough de-embedding using pulsed-wave actuation and the experimental setup are described in section 2. In section 3, the method is illustrated and our experimental results are compared to those obtained with sine-wave actuation.

2. Feedthrough de-embedding

2.1. Experimental setup

The resonator characterized in this study was originally developed by SEXTANT Avionics (currently THALES) [5]. It is industrially assembled by the fusion-bonding of three etched silicon wafers (see Fig. 1-a) and consists of a resonant beam resting on a rectangular diaphragm. During the manufacturing process, the beam is encapsulated in vacuum to achieve a high mechanical Q-factor (∼20000). The resonance frequency $f_0$ of the device is close to 65kHz.

In our setup, a bias voltage $V_b$ is applied to the resonator. It is directly actuated in open-loop by a waveform generator delivering voltage pulses of width $T_p$ and amplitude $V_p$, repeated every $T$ seconds, where $T (=1/f)$ is close to $T_0=1/f_0$. The motion of the resonator gives rise to a motional current which is integrated in a charge amplifier (see Fig. 1-b). Hence, the output voltage $V_{out}$ is the image of the mechanical motion of the resonator (slightly distorted by the capacitive detection nonlinearity). $V_{out}$ is recorded with an oscilloscope for every pulse frequency. Due to the parasitic feedthrough characteristic of the capacitive actuation and detection scheme, voltage pulses are superposed to the motional signal (Fig. 2-a).

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2.2. Principle of feedthrough de-embedding

One can notice that feedthrough effects are concentrated within the pulses, i.e. localized in time. This is the main difference between pulsed-wave and sine-wave actuation. Thus, the pulses can be very easily detected and removed from the waveform via post-processing, as shown in Fig. 2-b, for example with Matlab. A $T$-periodic sine-wave can then be fitted (in the least-squares sense) to the remaining part of the signal, which allows us to determine the corresponding amplitude and phase of $V_{\text{out}}$. Sweeping $T$ in the neighborhood of $T_0$, one may then obtain a frequency response similar to the one which would be obtained with sine-wave excitation, as explained in sub-section 2.3, but with all feedthrough effects cancelled.

2.3. Determination of the pulsed-mode frequency response

Assuming the width $T_p$ of the pulses is very short compared to $T$, the output of the resonator over one period may be written as the response of a 2nd order linear system with static gain $G$ to a Dirac comb, i.e.

$$s(t) = G \frac{2V_p T_p}{T} \text{Re} \left( \exp((-\alpha + j2\pi f_0)t) \sum_{n=0}^{\infty} r^n \right)$$

where $r = \exp((-\alpha + j2\pi f_0)T)$ and $\alpha = \frac{\pi f_0}{Q}$ (1)

Writing the limit of the geometric series leads to a general analytical expression of $s(t)$. In the present work, we limit ourselves to the case when $Q>>1$ and $|X|<<1$, where $X=f_0/f$. This yields:

$$s(t) \approx S \sin(2\pi ft + \Phi_p)$$

with $S = 2V_p T_p f_0 \frac{GQ}{\pi \sqrt{1+4Q^2X^2}}$ and $\Phi_p = \arctan(2QX) - \frac{\pi}{2}$ (2)

Thus, under the abovementioned assumptions, the amplitude and phase response obtained with our method are the same as those obtained with sine-wave actuation, provided the sine-wave amplitude $V_{\text{sin}}$ is equal to $2V_p T_p f_0$.

3. Results

The simulated frequency responses obtained in the presence of capacitive feedthrough are plotted in Fig. 3, for the following three methods: (i) sine-wave actuation ($V_{\text{sin}}=39mV$, $V_b=10V$), (ii) pulsed-wave actuation ($V_p=2V$, $T_p=150ns$, $V_b=10V$) without signal post-processing (as performed in [4]), and (iii) with partial or total pulse-removal processing. For each method, the estimated amplitude and phase are obtained through least-squares fitting of a sine-wave with known frequency $f$ over 3 periods of the simulated signal, sampled at $f_s>>1/T_p$. Thus, in methods (i) and (ii) a total of $3T_f$ points are used for fitting. In method (iii), the signal is processed before performing the fit: the pulses are localized in time and the signal is cleaned out, leaving $3(T-KT_p)f_s$ points to perform the fit, where $K \leq 1$ is a user-chosen parameter, illustrating the effect of partially or totally cleaning out the signal (i.e. $K=1$ corresponds to total pulse removal). The Bode diagrams obtained with method (i) and (ii) perfectly coincide. Feedthrough is greatly reduced with partial pulse removal and is completely cancelled with total pulse removal.

Experimental results obtained in the same conditions as above are shown in Fig. 4. There is a good agreement between the experimental results and those predicted by the simulations, except one must choose $K>1$ (here $K=30$, as represented in Fig. 2) in method (iii) to perfectly cancel the effect of feedthrough. This is because the pulses are not only fed through $C_p$, but are also filtered and spread over time by the low-pass characteristic of the electronic architecture. There is a good correspondence between the fit and the experimental results and gives a satisfactory value of the quality factor and the natural frequency. The remaining errors can be attributed to several causes: imperfect feedthrough cancellation, poor signal-to-noise ratio far from resonance and model inaccuracy (e.g. nonlinearity).
4. Conclusion

The original analysis and results presented in this paper show that pulsed-wave actuation of MEMS resonators allows frequency response analysis. We highlighted the similarities between the theoretical sine-wave and pulsed-mode frequency response for high-Q resonators. The proposed approach is based on a simple post-processing of the measured signal, as opposed to existing methods based on semi-harmonic actuation or piezoelectric effects [2, 3, 6]. Contrary to other characterization methods based on pulse-actuation [4], our method suppresses nearly all the parasitic feedthrough effects and permits a better characterization of the resonator, as validated through experiments on a resonant MEMS sensor. Further work will aim at a wholly automated characterization procedure.

References