A NOVEL METHOD FOR MEASURING RING-DOWN IN A HIGH NOISE AND HIGH FREQUENCY SYSTEM USING LASER DOPPLER VIBROMETRY

B. Gibson^{1*}, K. Qalandar¹, G. Piazza², and K.L. Turner¹

¹University of California Santa Barbara, Santa Barbara, California, USA

²Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

ABSTRACT

This paper reports on a novel method for measuring the ring-down of high-frequency MEMS devices in a high-noise environment using laser Doppler vibrometry (LDV). This method was validated using a 220 MHz aluminum nitride (AlN) piezoelectric contour-mode resonator, but could be applied to many other high frequency devices where low displacement magnitudes and excessive measurement noise makes traditional ring-down methods impossible. Even when noise dominated the desired signal and with out-of-plane displacements decaying from 120 pm down to only 4 pm, a ring-down time constant was extracted which was within 5.25% of the electrical measurements allowing for precise measurements of quality factor.

INTRODUCTION

A key figure of merit for resonator performance is the quality factor, Q . This is an inverse measure of the energy dissipation per cycle of the resonator. High quality factors are necessary in resonators to minimize power consumption and oscillator phase noise. Standard LDV ring-down measurements used in determining the quality factor of a resonator are performed by applying a step function input to the device and measuring the exponential decay in the time domain [1,2]. This is suitable for large displacements (>500 pm) but below this, thermal noise as well as the inherent noise in the LDV results in an unacceptably low signal to noise ratio. Figure 1 shows a ring-down measurement of a 220 MHz resonator in the time domain with no signal averaging applied. The exponential decay characteristic of a ring-down is indiscernible due to the noise level.

Figure 1: A ring-down measurement captured in the time-domain. The drive signal was cut off at 5 μ s, but because of inherent LDV system noise, the exponential decay is not visible.

To extract a usable signal from this level of measurement noise, repeated measurements must be taken and averaged together. This is not possible at high frequencies due to a 40ns triggering error between the LDV and the function generator. At lower frequencies

this small error is negligible, but at 220MHz it is an order of magnitude larger than the period of a single wavelength (4.5ns). Figure 2 shows a simulation of a 220MHz ring-down that has been averaged ten times in the presence of a 40ns trigger error. The result is a severe degradation in the desired signal making ring-down measurements impossible. For time domain measurements it may be necessary to apply as many as 10,000 averages to obtain a clean, low noise signal.

By taking multiple, short time sample measurements and averaging in the frequency domain, substantial averaging can be employed and measurements can be made all the way to the noise floor of the vibrometer (4pm) even when the time signal is dominated by noise.

Figure 2: A simulation of a ring down (in blue) that has been averaged ten times in the presence of a trigger error of 40ns (in red). Averaging causes the magnitude of the transient, exponential decay to decrease by more than an order of magnitude as a result of the variation in its position within each time sample.

THEORY

The LDV takes a short, discrete time sample of a small portion of the ring-down event and performs a fast Fourier transform (FFT) to extract the magnitude and phase of the resonant frequency of the resonator. This is repeated over and over and the results are averaged in order to suppress the noise. There are two methods for averaging that are most commonly used in vibrometry measurements. Magnitude averaging simply averages the displacement and phase values independently, whereas complex averaging combines the two into a phasor and averages the real and imaginary portions of that phasor independently,

$$S = \frac{1}{N} \left(\sum_{n=1}^N \text{Re}(S_n) + i \cdot \sum_{n=1}^N \text{Im}(S_n) \right)$$

Where N is the number of averages and S_n represents the phasor. Complex averaging is the preferred method because it is much more

effective at suppressing Brownian motion and other incoherent noise. In the frequency domain the 40 ns trigger error becomes negligible since it is two orders of magnitude smaller than the 8μs sample time used in the FFT.

To measure the decaying amplitude of a ring-down profile the timing between when the measurement starts and when the drive signal is cut off is delayed. Figure 3 shows an example of three such delay points. The start of the time sample is progressively delayed with respect to drive signal cutoff. The magnitude of the resonant frequency for each sample is then used to reconstruct the ring-down. For the example shown in Figure 3 a sample time of 8μs was used and the time step between each sample was 10μs. In practice, the step between each time sample can be considerably smaller than the sample time so that each measurement overlaps the previous one. This maximizes the resolution of the decaying signal. At each of these delay points as much complex averaging can be applied as necessary to suppress unwanted noise.

Figure 3: Short sample times are captured (red area) and an FFT is taken to determine the average magnitude of the sample. The delay between the start of measurement and the cut off of the drive signal is increased so that the entire ring-down event is captured in multiple discrete steps.

EXPERIMENTAL RESULTS

The UHF-120 Ultra High Frequency Vibrometer from Polytec Inc. was used in conjunction with a Rhode&Schwarz SMBV-100A function generator [5,6]. Data from the vibrometer is collected via a LeCroy WavePro 725Zi where it is digitized and then transferred to a PC for post processing. To simultaneously trigger the vibrometer measurement and cut off the drive frequency, an HP33120A function generator produced a square wave at 1kHz. Electrical measurements were taken using a Rhode&Schwarz ZVL network analyzer which were used to determine the devices quality factor and resonant frequency (figure 4).

Six devices were used for validation of our measurement approach. They were 220MHz AlN piezoelectric contour-mode resonators (CMR) similar to the one shown in Figure [3,4]. They are composed of a 1μm aluminum nitride device layer sandwiched between a lower 100nm aluminum electrode layer and a 100nm platinum upper electrode layer. The electrode layout and the size of the body of these devices was identical but their designs varied by the length and width of the supporting anchors.

Figure 4: The schematic of the LDV measurement system. A second function generator is used to trigger the vibrometer measurement and the cut off of the drive signal simultaneously. Data is collected on the LeCroy WavePro 725Zi oscilloscope where it is fast-digitized and transferred to a PC for processing.

Figure 5: One of the 220MHz AlN contour-mode resonators used for testing. The body of the resonator is 137μm x 57μm. Depending on drive level, the out-of-plane displacement has a steady-state peak magnitude between 120 and 255pm. At these displacements the drive signal is masked in thermal noise. Measurements were taken at the center of the resonator (marked with an X).

The operating frequency of the resonator is set by the electrode spacing and is governed by,

$$f_0 = \frac{1}{2W} \sqrt{\frac{E_{eq}}{\rho_{eq}}}$$

Where W is the electrode spacing, and E_{eq} and ρ_{eq} are the effective Young's modulus and density respectively of all three layers of the device. The devices were driven at -6dBm and at resonance. The quality factors were extracted through electrical measurements from the VNA and varied between 1161 and 3155. At low power levels the maximum out-of-plane motion of some of the devices was as low as ~120pm at resonance. Figure 4 shows the experimental measurements from a single point at the center of the body of device #1 with a sample time of 8μs and a time step between each sample of 1μs. The sampling rate was 2GHz.

Device Number	f_0 [MHz]	Anchor Length [μm]	Anchor Length [μm]	Initial Displacement [μm]	Electrical Q	τ [μs]	LDV Measured Q	% Error
1	220.38	7.5	8	125.20	1610	2.40	1664	3.35
2	220.58	22	15	155.60	1161	1.59	1100	5.25
3	220.53	21	15	125.40	1575	2.38	1650	4.76
4	220.75	11	15	219.40	2207	3.32	2300	4.21
5	220.78	40	15	255.30	3155	4.50	3121	1.08
6	220.81	21	17	225.60	2944	4.18	2900	1.49

Table 1: Six devices were tested using this ring-down method. They had identical electrode configurations but varied in terms of the width and length of their anchors. The resonant frequency and the electrically and LDV measured Quality factors are shown in addition to the error in the LDV measurement as compared with that from the vector network analyzer. There is a maximum of 5.25% error in the LDV measurement.

Figure 5: The resulting experimental profile is due to the fact that each point is a convolution of a portion of the ring-down event. To extract the time constant of the exponential decay, a ring-down profile is simulated using known parameters such as the resonant frequency, steady-state magnitude, drive signal cutoff time and sample time. A measurement process identical to the experimental method is then applied to the simulated data and the time constant is then varied until a good fit is obtained.

At each time delay point, the signal was averaged one hundred times. The experimental data does not follow the expected exponential decay of a traditional ring-down. This is due to the fact that each data point is the average magnitude of the specific frequency over the entire $8\mu\text{s}$ sample time. If the sample window includes steady-state oscillation as well as a portion of the ring-down event (e.g. the center FFT in Figure 3) the magnitude is a convolution of the steady-state and the ring-down profile. The most efficient way to determine the ring-down time constant is to produce a simulated waveform that includes a steady state and ring-down event and perform a simulated measurement with identical parameters to the experimental measurement. The frequency, steady-state magnitude, drive signal cutoff time and sample time are all known a priori. The time-constant for the exponential decay can be varied until there is a good fit between the experimental and simulated data. **Error! Reference source not found.** shows the match between the experimental and simulated data from the single spatial point at the center of the

device. For this measurement the extracted time constant τ is $2.4\mu\text{s}$. To find the quality factor we use:

$$Q = f_0 \pi \tau$$

This gave a quality factor of 1664 which matches the electrically measured Q of 1610 to within 3.35%. Note that the simulated data accurately matches the experimental data down to $4\mu\text{m}$ which is the noise floor of the UHF-120. Furthermore, the ring-down curve is unaffected but the noise floor until it decays to $4\mu\text{m}$ so the time constant is unaffected by this characteristic of the vibrometer. This measurement method is capable of extracting ring-down measurements from these contour-mode resonators even when there is very little out-of-plane motion. Table 1 above shows the results from the measurements of the six resonators tested. The Q varies by a maximum of 5.25% from the electrically measured Q . Device number two has a ring down time constant of only $1.59\mu\text{s}$.

CONCLUSION

The ring-down time constant and therefore the quality factor were measured using laser Doppler vibrometry in an environment of high noise and very low displacement values with an accuracy of less than 6%. While contour-mode piezoelectric resonators were used for this paper, this method could be applied to any bulk-acoustic or flexural device that has a measurable out-of-plane motion component. Frequencies up to the 1.2 GHz limit of the UHF-120 could be measured as well, by using smaller time samples and smaller delay steps. In addition to quality factor, this measurement method could be used to determine the presence of non-linearities in the device and it could potentially be used to measure the onset of parametric resonance at previously unachievable frequencies [7].

ACKNOWLEDGMENTS

This work was supported by DARPA under contract #8-442550-59085-FGKT11-2. The content of the information does not necessarily reflect the position or the policy of the Government and no official endorsement should be inferred. Travel support has been generously provided by the Transducer Research Foundation.

REFERENCES

- [1] Klempner, A. R., et al. "Experimental Determination of the Q-factors of Microcantilevers Coated With Thin Metal Films." *Strain* 45.3 (2009): 295-300.
- [2] S. Heinrich, W. Michael, S. Georg, and R. Christian, *Measuring MEMS in Motion by Laser Doppler Vibrometry*, pp. 45-292. Optical Science and Engineering. CRC Press, 2006.
- [3] G. Piazza, P. J. Stephanou, and A. P. Pisano, "One and two port piezoelectric higher order contour-mode MEMS resonators for mechanical signal processing," *Solid-State Electronics*, vol. 51, no. 1112, pp. 1596 – 1608, 2007.
- [4] Segovia-Fernandez, Jeronimo, et al. "Anchor losses in AlN contour mode resonators." *Microelectromechanical Systems, Journal of* 24.2 (2015): 265-275.
- [5] C. Rembe, S. Boedecker, A. Drbenstedt, F. Pudewills, and G. Siegmund, "Heterodyne laser-doppler vibrometer with a slow-shear-mode bragg cell for vibration measurements up to 1.2 Ghz, in *Proc. SPIE*, vol. 7098, p. 70980A.
- [6] Eric M. Lawrence ; Christian Rembe ; Sebastian Boedecker ; Huantong Zhang; "The ultra fine dynamics of MEMS as revealed by the Polytec micro system analyzer. *Proc. SPIE* 6111, Reliability, Packaging, Testing, and Characterization of MEMS/MOEMS V, 61110L (January 05, 2006); doi:10.1117/12.646556.
- [7] T. Hiller, L. L. Li, E. L. Holthoff, B. Bamieh and K. L. Turner, "System Identification, Design, and Implementation of Amplitude Feedback Control on a Nonlinear Parametric MEM Resonator for Trace Nerve Agent Sensing," in *Journal of Microelectromechanical Systems*, vol. 24, no. 5, pp. 1275-1284, Oct. 2015. doi: 10.1109/JMEMS.2015.2400398

CONTACT

*B Gibson, tel: +1-310-418-4471; briangibson@engr.ucsb.edu