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Advanced bode plot techniques for ultrasonic transducers

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Abstract

The Bode plot, displayed as either impedance or admittance versus frequency, is the most basic test used by ultrasonic transducer designers. With simplicity and ease-of-use, Bode plots are ideal for baseline comparisons such as spacing of parasitic modes or impedance, but quite often the subtleties that manifest as poor process control are hard to interpret or are nonexistence. In-process testing of transducers is time consuming for quantifying statistical aberrations, and assessments made indirectly via the workpiece are difficult. This research investigates the use of advanced Bode plot techniques to compare ultrasonic transducers with known "good" and known "bad" process performance, with the goal of a-priori process assessment. These advanced techniques expand from the basic constant voltage versus frequency sweep to include constant current and constant velocity interrogated locally on transducer or tool; they also include up and down directional frequency sweeps to quantify hysteresis effects like jumping and dropping phenomena. The investigation focuses solely on the common PZT8 piezoelectric material used with welding transducers for semiconductor wire bonding. Several metrics are investigated such as impedance, displacement/current gain, velocity/current gain, displacement/voltage gain and velocity/voltage gain. The experimental and theoretical research methods include Bode plots, admittance loops, laser vibrometry and coupled-field finite element analysis.

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Keywords: Ultrasonic transducer; Wire bonding; Bode plots; Piezoelectric; PZT8; Vibrometer; Coupled-field FEA; ANSYS

1. Introduction

The Bode plot, displayed as impedance or admittance versus frequency, is the most basic test used by ultrasonic transducer designers. With simplicity and ease-of-use, Bode plots are ideal for baseline comparisons such as spacing of parasitic modes and impedance. But, quite often the subtleties that manifest as poor process control are hard to interpret or are nonexistent from standard Bode plots. In-process testing of transducers is time consuming for quantifying statistical aberrations, and assessments made indirectly via the workpiece are difficult for identifying

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cause and effect relationships. Transducer modal surveys require an expensive scanning laser vibrometer and interpretation is esoteric. Advanced bode plot techniques are needed for a-priori process assessment of ultrasonic transducers.

2. Specific transducer application

Kulicke & Soffa Industries is the leading manufacturer of semiconductor wire bonding equipment. This "back-end" type of equipment provides ultrasonically welded interconnect wires between the wafer level semiconductor circuitry (die) and the mounting package (frame) as shown in Fig. 1. The ultrasonic transducer delivers energy to a capillary tool for welding tiny gold or copper wires, typically on the order of .001 inches in diameter. Fig. 2 shows the primary steps of the wire bond cycle used to produce the interconnect wires, and how the ultrasonic energy from the transducer is delivered in a "scrubbing motion" to make the welded bonds. Fig. 1(d) shows the on-machine configuration. The single-piece construction "Unibody" transducer uses four diced, rectangular PZT8 piezoceramics, and is ideal for research studies (DeAngelis et al., 2006, 2009, 2010). Portability across 100's of machines is required for the same customer device in production operations.

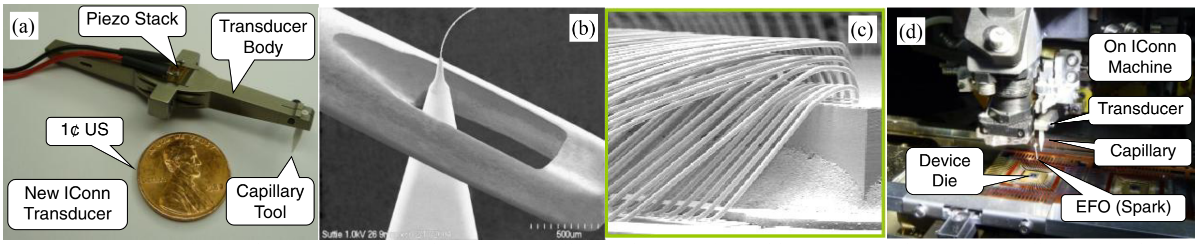

Fig. 1. (a) K&S "Unibody" ultrasonic transducer, (b) Ceramic capillary tool tip with fine gold wire compared to sewing needle, (c) Actual wire bonds from multi-tier package, (d) On-machine configuration of "Unibody" transducer during device wire bonding.

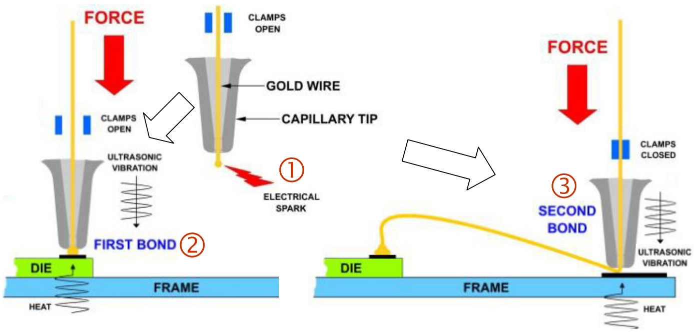

Fig 2. Primary steps 1, 2 and 3 of the wire bond cycle

3. Assessment methodology

What aspects of transducer performance are important for ideal process control (Stansfield, 1991, Wilson, 1991, Sherman et al., 2007, Uchino et al., 2003)? The mechanical interfaces must behave linearly in vicinity of the operating mode, such that there is no separation or "gapping" with drive level or frequency change (DeAngelis et al., 2009, 2010); the critical interfaces are tool-to-clamp and the piezoceramic stack. The displacement gain of all surfaces must behave linearly in vicinity of the operating mode and proportional to drive level: the displacement/current gain should be linear in vicinity of resonance, and the displacement/voltage gain should be linear in vicinity of antiresonance (DeAngelis et al., 2006). The tool motions must be consistent in all directions above and below the operating mode: in-plane motions remain in-plane, and linear motions remain linear and in same direction. No local parasitic resonances should be competing with the operating mode; parasitic coupling has a 180° phase change when driven through the operating mode. The usual suspects are shim electrodes, tool clamps, screws and tools. Shim electrode resonances are hard to detect since their manifestation can vary wildly with slight change of operating frequency. There should be no hysteresis in frequency or displacement gain with sweep direction; the phase lock loop (PLL) can approach arbitrarily from either side, and thus hysteresis can cause phase/amplitude oscillation or failure of PLL to lock at resonance. Interface gapping can change with phase of parasitic coupling above and below operating mode, causing hysteresis in gain and frequency. Internal self-heating effects from impedance are different above and below operating mode due to antiresonance and sweep start direction.

4. Research summary

Advanced Bode plot techniques were developed from the basic constant voltage versus frequency sweep; this included constant current and constant velocity interrogated locally on transducer (Uchino et al., 2003, Ural et al., 2009), with added up and down directional frequency sweeps to quantify hysteresis effects (Umeda et al., 2000). Selected transducers with known "good" and known "bad" process control were studied, and a linear coupled-field FEA model was correlated to the "good" transducer. The advanced Bode plot methodology for a-priori process assessment was established based on these comparisons.

5. Experimental methods and metrics

Fig. 3 shows the hardware setup for the advanced Bode plot technique. Fig. 4 shows the methodology for velocity interrogation. The tool is the "business end" of the transducer and should be a starting point. The tool clamp is a close second for interrogation, since it may exhibit more non-linearities than tool with free-air assessment (i.e., off work). As shown in Fig. 5, the piezoceramic stack should also be another target area, and especially for Langevin or sandwich transducers which are prone to uneven preload stress. High power piezo stacks can rely on adhesives in tension which can fail, and shims and preload bolts are dynamic components that are prone to resonate.

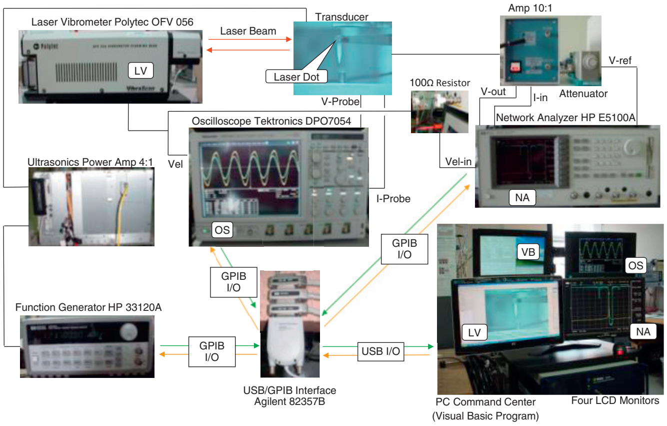

Fig. 3. Advanced Bode plot technique hardware setup.

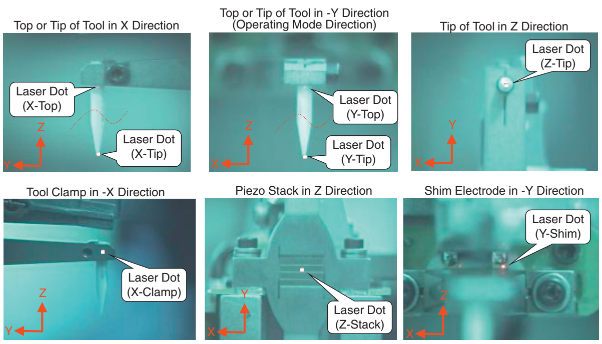

Fig. 4. Methodology for velocity interrogation.

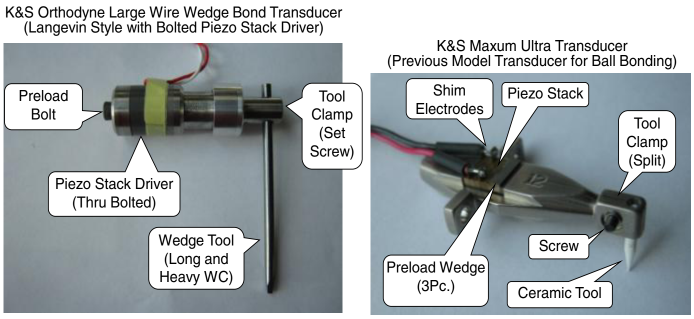

Fig 5. Velocity interrogation target areas for typical transducers.

6. Finite element modeling

Fig. 6 shows the piezoelectric coupled-field finite element model from the ANSYS software with coupling via “stiffness” matrix which includes the piezoelectric properties for PZT8 material. The nodes have structural (X, Y, Z displacements) and electric (volt) degrees of freedom. The linear model was created without interface gapping (i.e., no gap elements) to correlate to the “good” transducer, and a constant damping ratio of 0.2% was used for all materials. The forced response was generated using a sine-sweep voltage input to the piezoceramic stack. Fig. 7 shows the FEA derived Bode results for clamp and top of capillary tool in the X-Clamp, X-Top and Y-Top directions as shown in Fig. 4; there is no hysteresis with the linear model, so results are independent of sweep direction. Fig. 8 shows the FEA derived gain ratio results for these same directions. The current and velocity gains are the same with a FEA linear model.

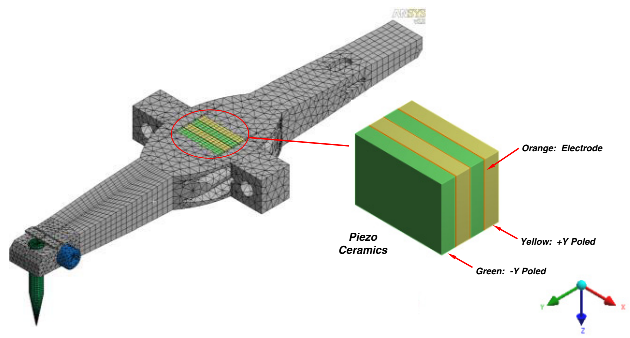

Fig. 6. Piezoelectric coupled-field finite element model in ANSYS software.

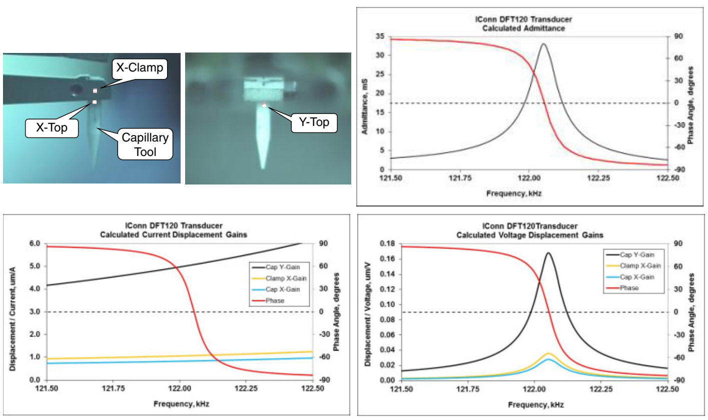

Fig. 7. FEA derived Bode results for clamp and top of capillary.

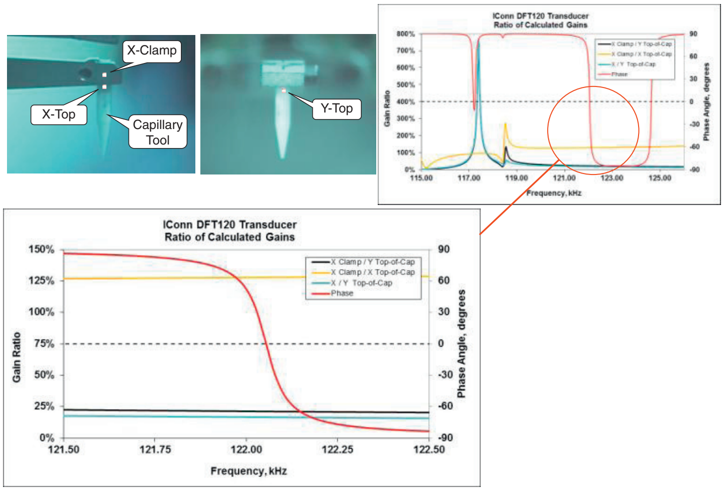

Fig. 8. FEA derived gain ratio results for clamp and top of capillary.

7. Experimental results

Figs. 9-12 show the advanced Bode technique results for the "good" transducer with the expected or "good" process response. As shown in Fig. 4, the velocity interrogation locations are X-Clamp, X-Top and Y-Top. The gain ratio results presented in Fig. 12 are for comparison to the linear FEA model, to demonstrate that a "good" process response is inherently a linear response. Figs. 13-17 show the advanced Bode technique results for the "bad" transducer with poor process response (i.e., inconsistent shears). The velocity interrogation locations are the same as the "good" transducer.

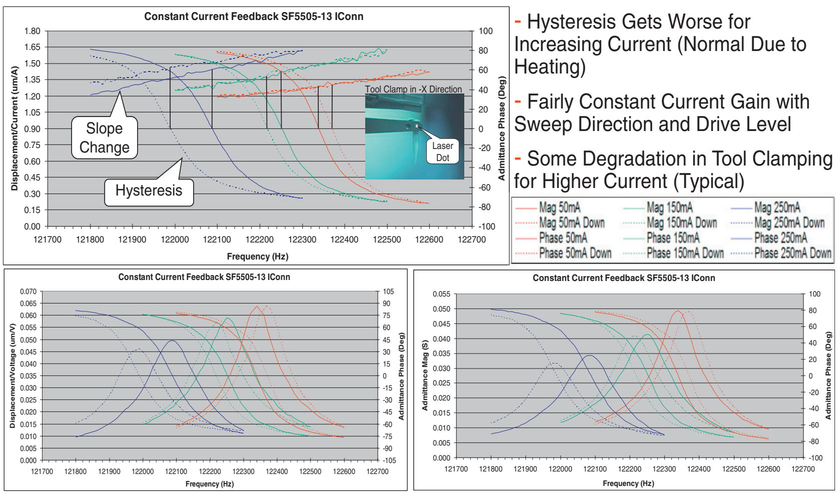

Fig. 9. Constant current Bode for "good" transducer with X-Clamp velocity.

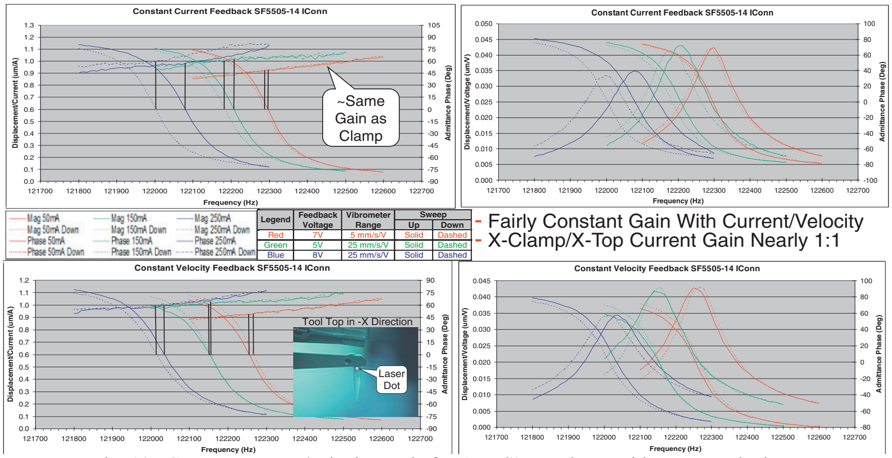

Fig. 10. Constant current/velocity Bode for "good" transducer with X-Top velocity.

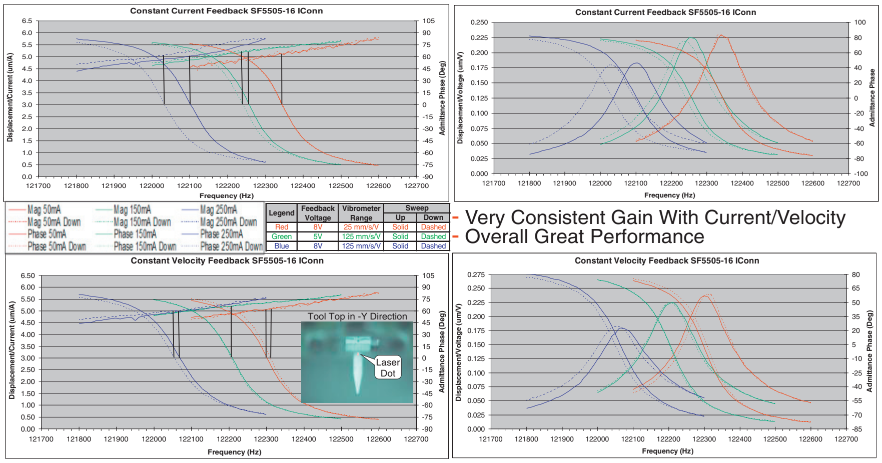

Fig. 11. Constant current/velocity Bode for "good" transducer with Y-Top velocity.

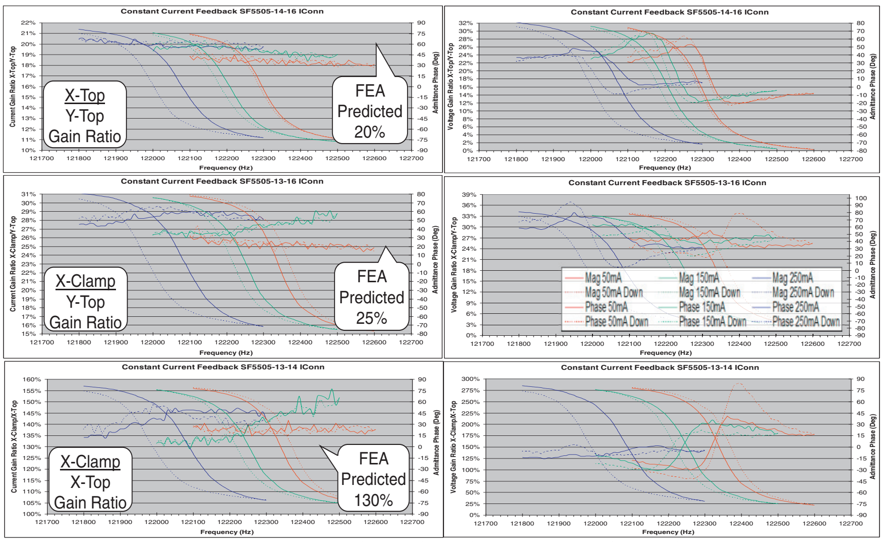

Fig. 12. Gain ratios with X and Y velocities for "good" transducer.

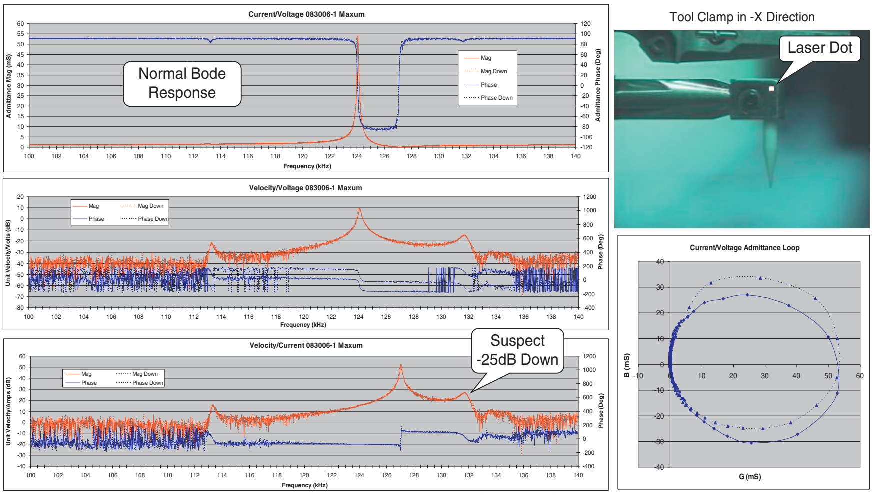

Fig. 13. Standard Bode for “bad” transducer with X-Clamp velocity.

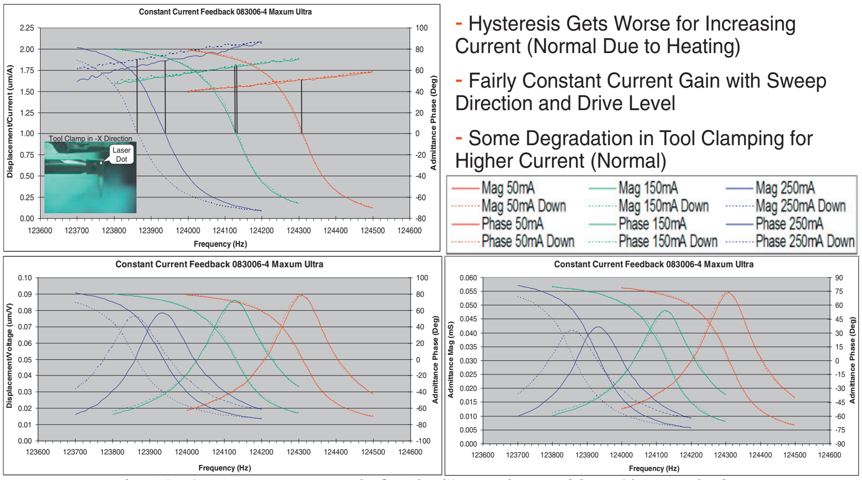

Fig. 14. Constant current Bode for “bad” transducer with X-Clamp velocity.

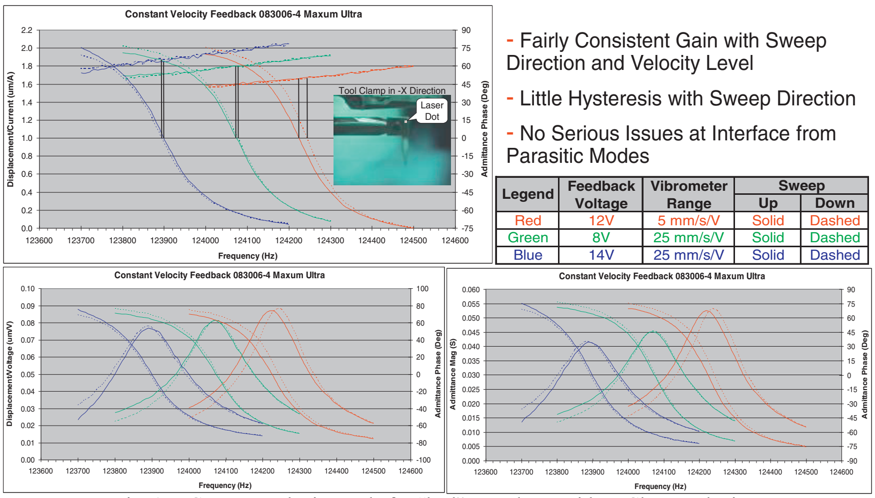

Fig. 15. Constant velocity Bode for “bad” transducer with X-Clamp velocity.

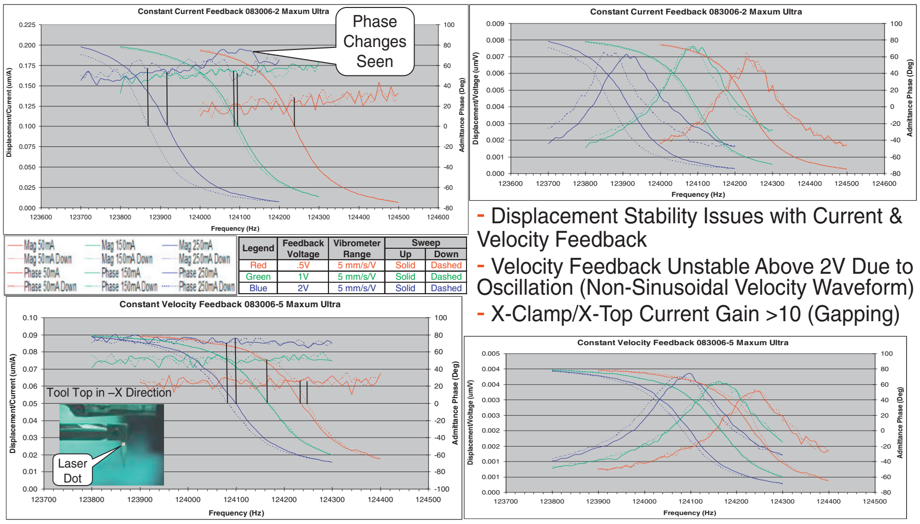

Fig. 16. Constant current/velocity Bode for “bad” transducer with X-Top velocity.

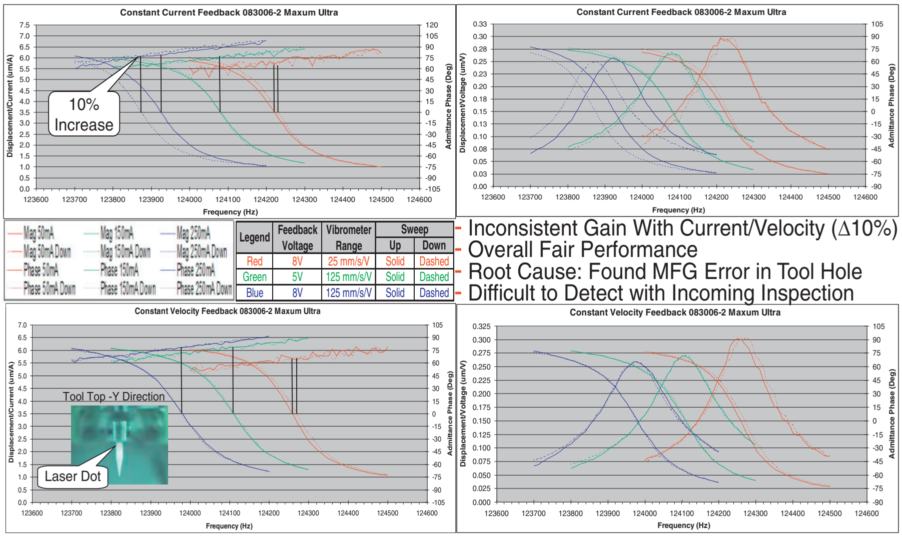

Fig. 17. Constant current/velocity Bodes for “bad” transducer with Y-Top velocity.

8. Conclusions

The transducer with “good” process performance conforms to behavior as predicted by the ideal linear FEA model with glued interfaces (i.e., no gap elements). Non-linear behavior in the tool was shown to be the root cause of poor process (i.e., low shear force): manufacturing error exacerbated inherent design problem in the tool clamp. Phase changes from closely spaced parasitic modes can lead to hysteresis effects due to interface gapping as seen from the non-sinusoidal velocity profile; heating effects can also cause hysteresis. Velocity based Bode plots can pick-up subtleties typically overlooked without a full laser vibrometer modal survey. A unique set of interrogation locations and assessment criteria is required for each specific transducer design and process application; wire bonding is inordinately sensitive to tool motions due to delicate balance of forces exerted on tiny ball and micro bond pad structure; inconsistent energy delivery to the tool is a root cause of poor process.

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