Piezoelectric Shaker Development for High Frequency Calibration of Accelerometers

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Abstract. Calibration of vibration transducers requires sinusoidal motion over a wide frequency range with low distortion and low cross-axial motion. Piezoelectric shakers are well suited to generate such motion and are suitable for use with laser interferometric methods at frequencies of 3 kHz and above. An advantage of piezoelectric shakers is the higher achievable accelerations and displacement amplitudes as compared to electro-dynamic (ED) shakers. Typical commercial ED calibration shakers produce maximum accelerations from 100 m/s^2 to 500 m/s^2. Very large ED shakers may produce somewhat higher accelerations but require large amplifiers and expensive cooling systems to dissipate heat. Due to the limitations in maximum accelerations by ED shakers at frequencies above 5 kHz, the amplitudes of the generated sinusoidal displacement are frequently below the resolution of laser interferometers used in primary calibration methods. This limits the usefulness of ED shakers in interferometric based calibrations at higher frequencies.

Small piezoelectric shakers provide much higher acceleration and displacement amplitudes for frequencies above 5 kHz, making these shakers very useful for accelerometer calibrations employing laser interferometric measurements, as will be shown in this paper. These piezoelectric shakers have been developed and used at NIST for many years for high frequency calibration of accelerometers. This paper documents the construction and performance of a new version of these shakers developed at NIST for the calibration of accelerometers over the range of 3 kHz to 30 kHz and possibly higher. Examples of typical calibration results are also given.

Keywords: accelerometers; calibration; interferometric; laser; shakers; vibration
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INTRODUCTION

The calibration of vibration transducers requires sinusoidal motion over a wide frequency range with low distortion and low cross-axial motion. Piezoelectric ceramic shakers are well suited to generate such motion and are suitable for use with laser interferometric methods, especially at frequencies above 3 kHz. Electrodynamic (ED) shakers sometimes allow the shaker mounting table to be agitated by low-frequency mechanical noise due to their soft suspension, whereas piezoelectric shakers, having a very stiff construction, minimize this effect.

Another advantage of piezoelectric shakers is the higher acceleration possible as compared to the ED shakers. A typical commercial ED shaker may produce 100 m/s^2 to 200 m/s^2. Very large ED shakers may produce higher accelerations but require large amplifiers and cooling systems to dissipate heat. Relatively small piezoelectric shakers provide much higher accelerations, 2000 m/s^2 to 3000 m/s^2 at higher frequencies, which are very useful for laser interferometric measurements, as will be shown in this paper. Piezoelectric shakers have been developed and used at NIST for many decades for calibration of vibration transducers.

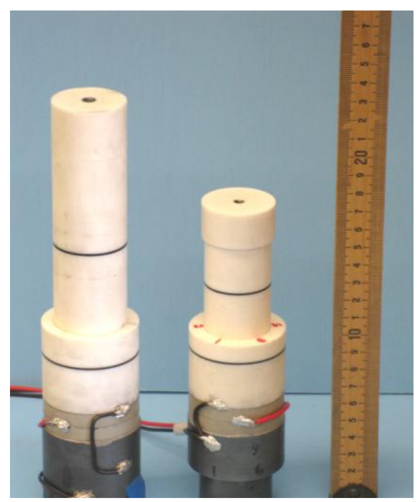

FIGURE 1. Shaker P102 and Shaker P103.

This paper documents the construction and performance of a new piezoelectric shaker (P102) that has been in use at the NIST vibration calibration lab over the past year for accelerometer calibrations over the range of 3 kHz to 20 kHz. This paper also documents another piezoelectric shaker (P103) designed to extend the frequency range beyond 20 kHz, which is currently being evaluated to obtain performance data.

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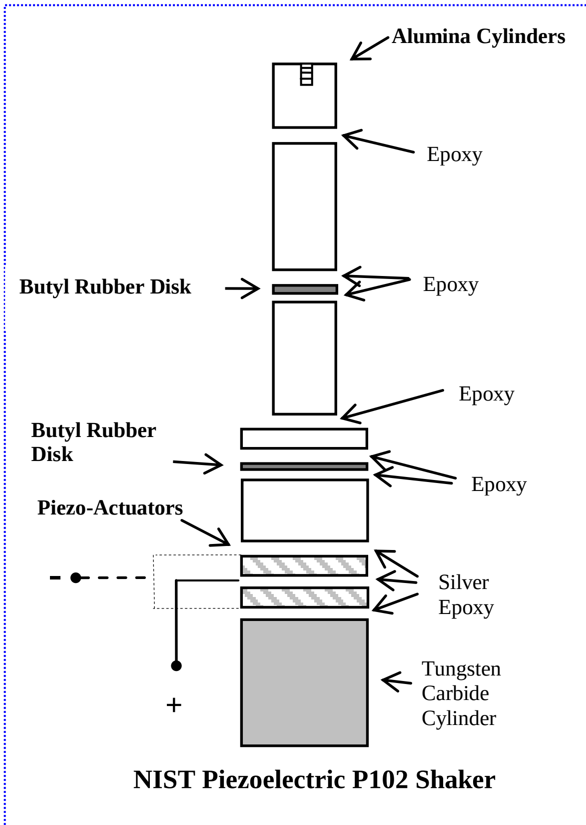
DESIGN THEORY AND HISTORY OF THE NIST PIEZOELECTRIC SHAKERS



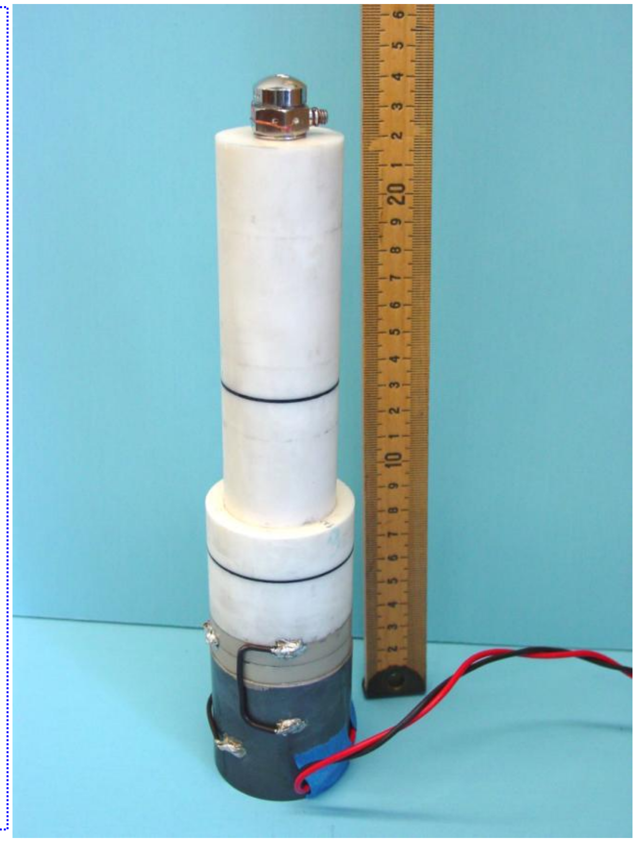
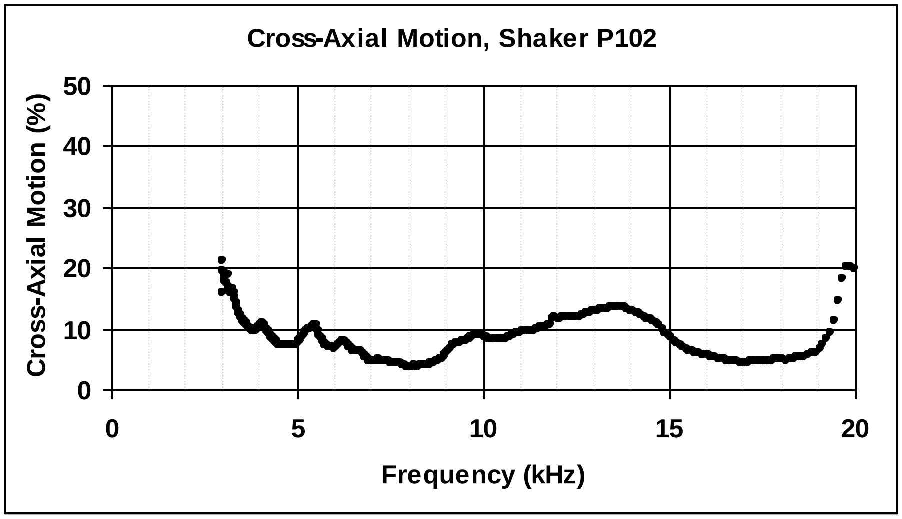


FIGURE 2. Shaker P102.

The methods for piezoelectric shaker design and construction were developed and documented by Jones in Reference [1]. Figure 2 shows a diagram of the components of a new NIST shaker based on the original shaker design developed by Jones for mid to high frequency range calibration of accelerometers. The base is made from tungsten carbide and the shaker is constructed of solid ceramic cylinders. The cylinders have larger diameters near the base and smaller diameters near the top of the shaker to maximize the motion of the top mounting surface. Butyl rubber disks are used to attach the elements together, resulting in various modes of vibration. This method of resonating cylinders is known as "staggered tuning" [1]. The top element has a threaded steel insert to attach accelerometers. The performance characteristics of the shaker can be adjusted by changing the size of the cylinders and the thickness of the butyl rubber disks to optimize the resonances, performance, and desired frequency range. As will be shown below, the design gives an acceptable response over the range of 3 kHz to 20 kHz and permits calibration by the fringe disappearance method [2,3] at 121 nm displacement with a stabilized helium-neon laser (632.8 nm wavelength).

PERFORMANCE DATA FOR PIEZOELECTRIC SHAKER P102

The cross-axial motion and harmonic distortion for the shaker were measured with a small tri-axial accelerometer that was mounted with wax on the center-top surface of the shaker. Initially, the shaker was excited by a low distortion voltage source and without a power amplifier in order to obtain the overall frequency response data. A sinusoidal drive voltage of 3 V amplitude was used for the cross-axial tests. Figure 3 shows the maximum cross-axial motion as a percent of axial motion and a photo of the tri-axial accelerometer mounted on shaker P102.



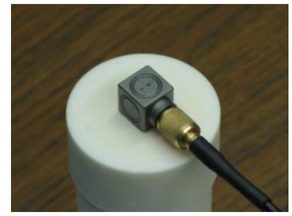


FIGURE 3. Cross-Axial Motion for Piezoelectric Shaker P102.

Figure 4 shows the accelerations for the 3 kHz to 50 kHz frequency range, measured on the shaker table with a small 0.5 gram accelerometer, using a 0.8 V signal drive. For use in calibrations, a power amplifier and step-up transformer are used to obtain the higher accelerations needed.

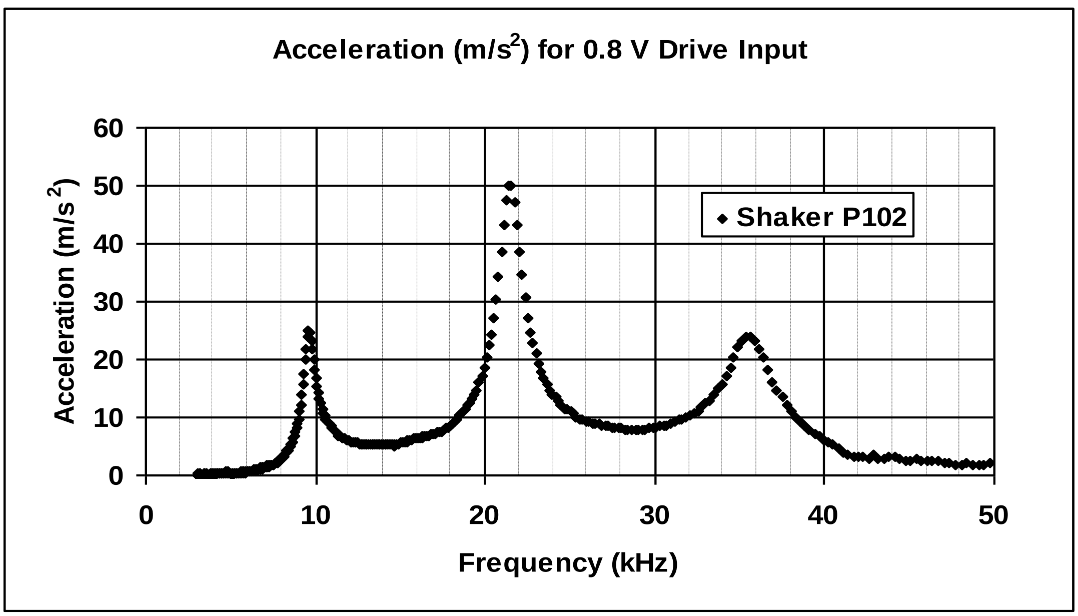


FIGURE 4. Accelerations for Shaker P102 Using 0.8 V Drive Voltage.

Figure 5 shows the frequency response of the shaker: input drive voltage per nanometer of displacement on the shaker table, measured with a 0.5 gram uniaxial accelerometer, over the frequency range of 3 kHz to 40 kHz, using 0.8 V input drive voltage.

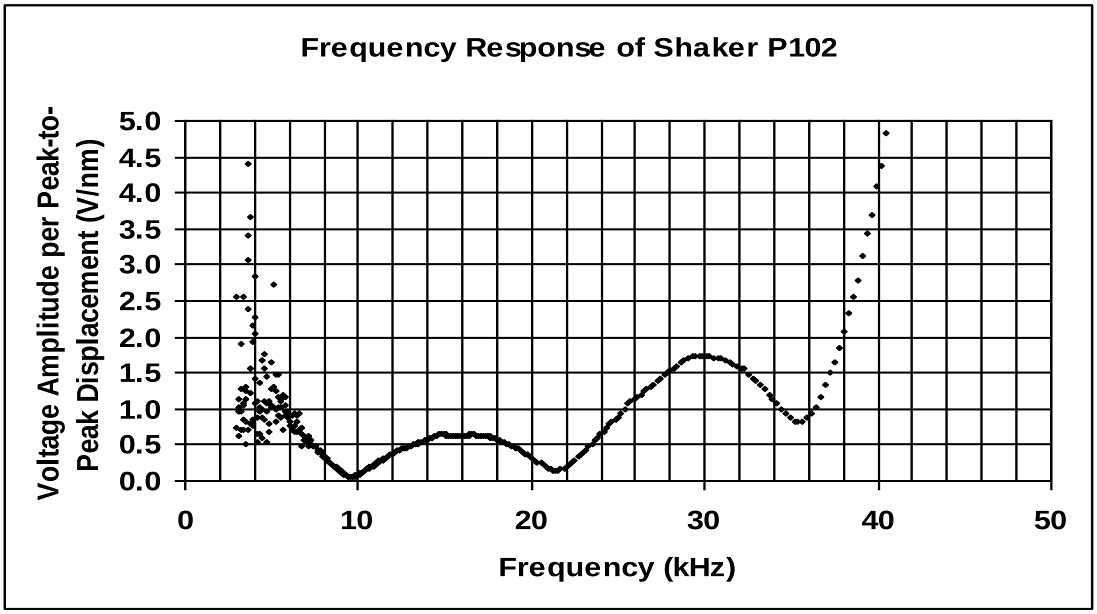


FIGURE 5. Frequency Response of Shaker P102**.**

Peak-to-peak displacement of 121 nm is required for fringe disappearance calibration. This is attainable by energizing the piezo actuators using a low distortion function generator followed by a power amplifier, and step-up voltage transformer, as well as impedance matching inductors (for impedance matching) at frequencies above 15 kHz. Figure 6 shows the total harmonic distortion at 121 nm displacement.

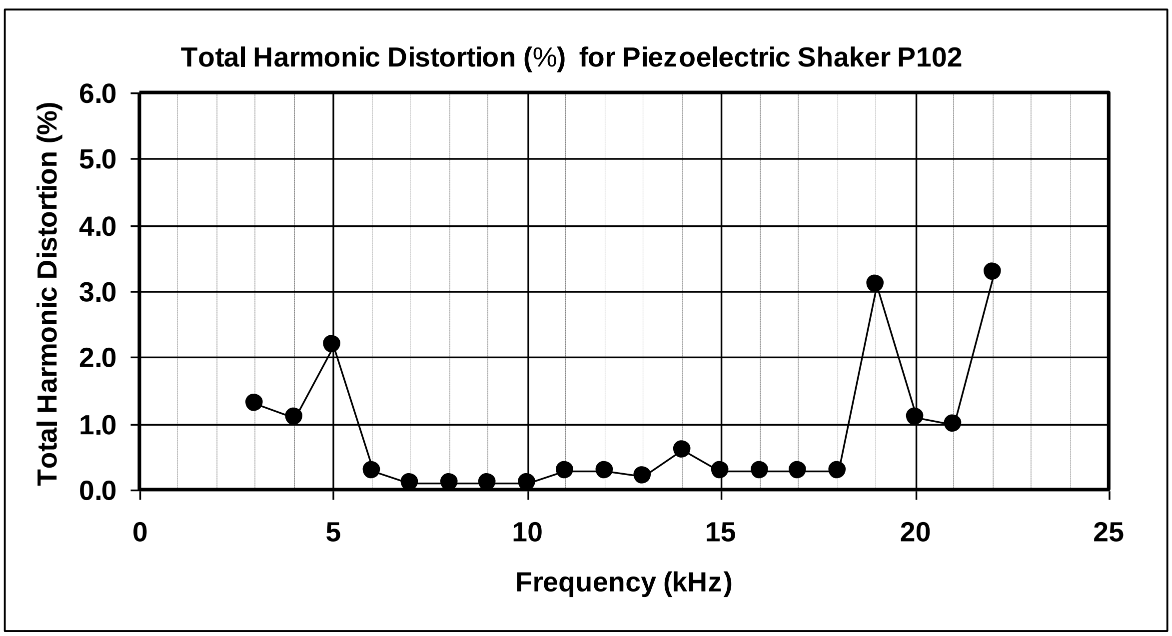


FIGURE 6. Total Harmonic Distortion at 121 nm Displacement.

Table 1 below shows total harmonic distortion (THD) for shaker P102 at accelerations corresponding to fringe disappearance displacement at 121 nm. Also listed are the accelerations (m/s^2) necessary for 121 nm at each frequency and the maximum achievable acceleration at each frequency for shaker P102.

TABLE 1. THD at Displacements Corresponding to Fringe Disappearance at 121 nm, Achievable Accelerations and Displacements, and Impedance Matching Inductor Values for Shaker P102.

Frequency (kHz	THD (%)	Fringe Disappearance Acceleration (m/s^2)	Maximum Achievable Acceleration (m/s^2)	Inductance (mH)	Maximum Available Displacement (nm)
3	1.3	44	76		213
4	1.1	78	312		494
5	2.2	123	290		294
6	0.3	177	758		533
7	0.1	245	981		507
8	0.1	314	1426		565
9	0.1	392	2585		808
10	0.1	490	2987		756
11	0.3	588	3035		635
12	0.3	706	3076		541
13	0.2	834	3031		454
14	0.6	961	3120	11	403
15	0.3	1098	3076	9	346
16	0.3	1255	2857	8	283
17	0.3	1422	2899	7	254
18	0.3	1589	2697	6	211
19	3.1	1765	2533	5	178
20	1.1	1961	2779	4	176
21	1.0	2177	2329	4	134

Note that 21 kHz appears to be the upper limit for fringe disappearance for shaker P102, but calibrations are possible at higher frequencies using the quadrature interferometric calibration procedure [4] which does not require a displacement of 121 nm. Values of necessary inductors for impedance matching for each frequency are also listed. The inductor values are approximate and may change slightly due to the mass loading properties of the accelerometer under test.

Figure 7 shows the maximum accelerations possible using no matching inductors for frequencies up to 13 kHz, as well as maximum accelerations possible using inductors for frequencies of 11 kHz and above. Also shown in Figure 7 are the required accelerations for fringe disappearance. The values of the inductors are listed in Table 1.

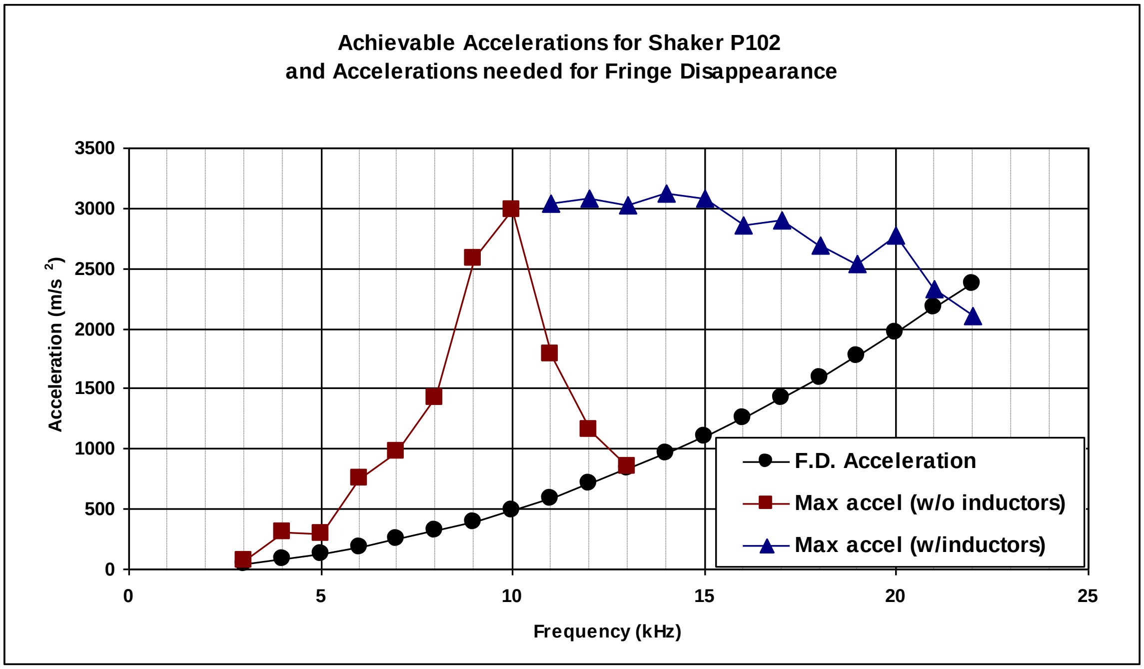


FIGURE 7. Accelerations Needed for Fringe Disappearance (F.D.) and Attainable Accelerations for Shaker P102 Using Impedance Matching Inductors for Frequencies of 14 kHz and Higher.

Likewise for displacement, Figure 8 gives the maximum attainable displacements and the required displacements for fringe disappearance for shaker P102.

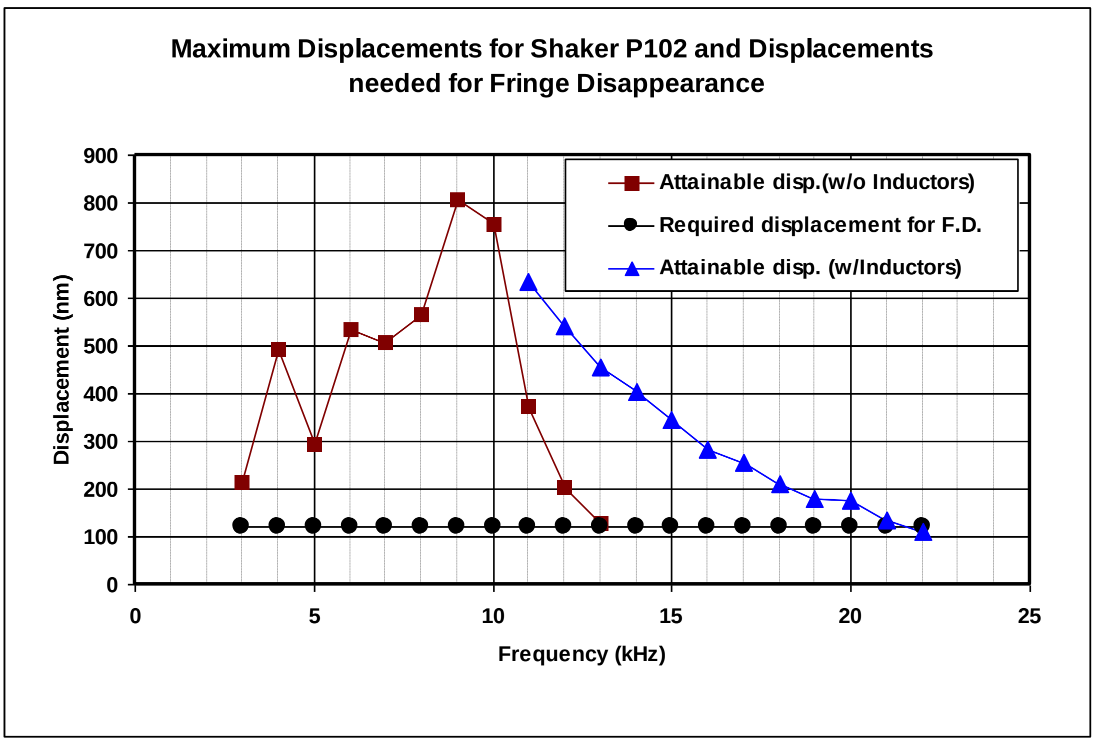


FIGURE 8. Maximum Displacements for Shaker P102 Using Impedance Matching Inductors for Frequencies of 14 kHz and Higher, and No Impedance Matching Inductors for Frequencies of 13 kHz and Less.

Calibrations were performed using shaker P102 on accelerometers. Calibrations are normally performed by laser interferometry with the fringe disappearance method, using three mirrors attached to the shaker table 120 degrees apart. The average of the three results is used as the reported calibration value. These methods and procedures are documented in NIST publications [2, 3] and in ISO 16063 - Part 11 [4]. The degree of agreement among the three mirrors reflects the degree of purity of motion of the mounting table of the shaker. The results of one such test are shown in Figure 9 below.

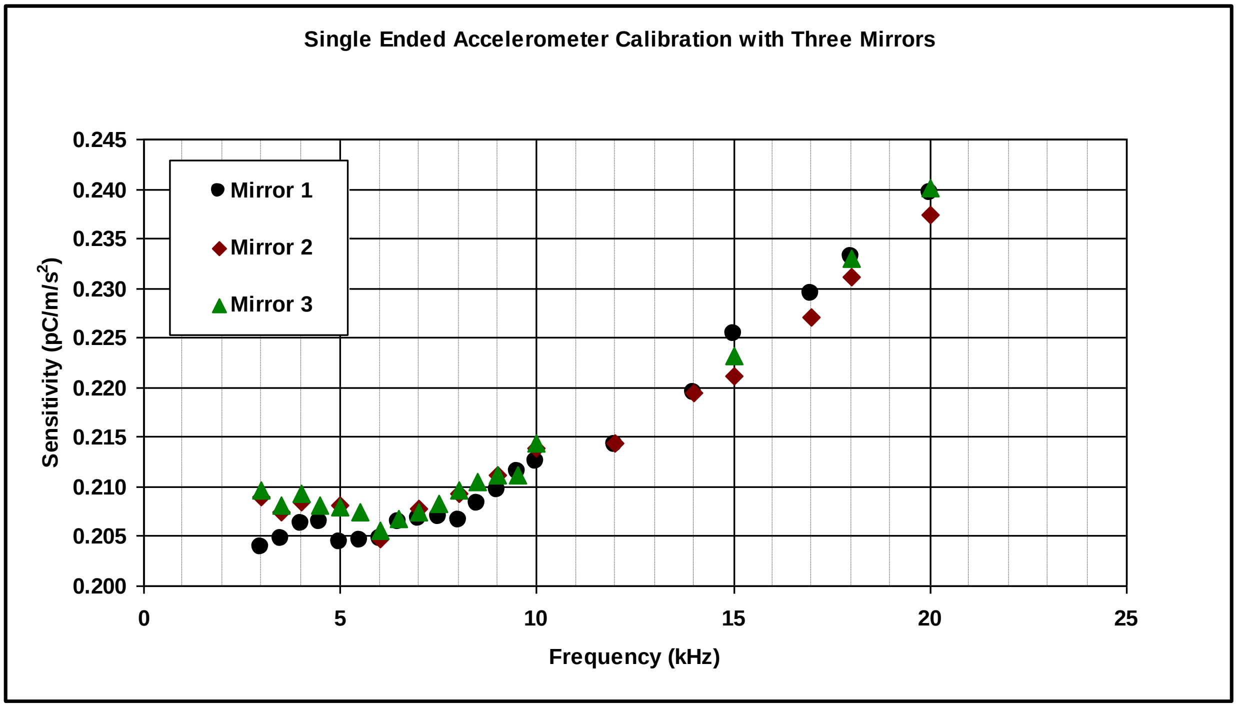


FIGURE 9. Calibration Results of Single Ended Accelerometer Using Three Mirrors.

One of the design goals of a good shaker is to perform calibrations where the results at the three mirror positions agree very closely, typically to within one to two percent. The frequency range where this is possible will thereby define the useable frequency range of the shaker.

For the test shown in Figure 9, the combined relative uncertainty for the fringe disappearance method was calculated in accordance with methodologies described in the Guide to the Expression of Uncertainty in Measurement [5] using Type A and Type B evaluations of uncertainty components, including those contained in ISO documents on the calibration of vibration and shock transducers [4]. Using a coverage factor of 2, the estimated expanded relative uncertainty, *U*, at 10 kHz is 1 %.

PERFORMANCE DATA FOR PIEZOELECTRIC SHAKER P103

Figure 10 shows a diagram of the components of a second NIST shaker based on a design developed by Jones [1] for calibration of accelerometers at frequencies higher than 20 kHz. The ceramic cylinders are somewhat smaller to provide resonances above 20 kHz in order to extend the frequency range of this shaker for calibrations.

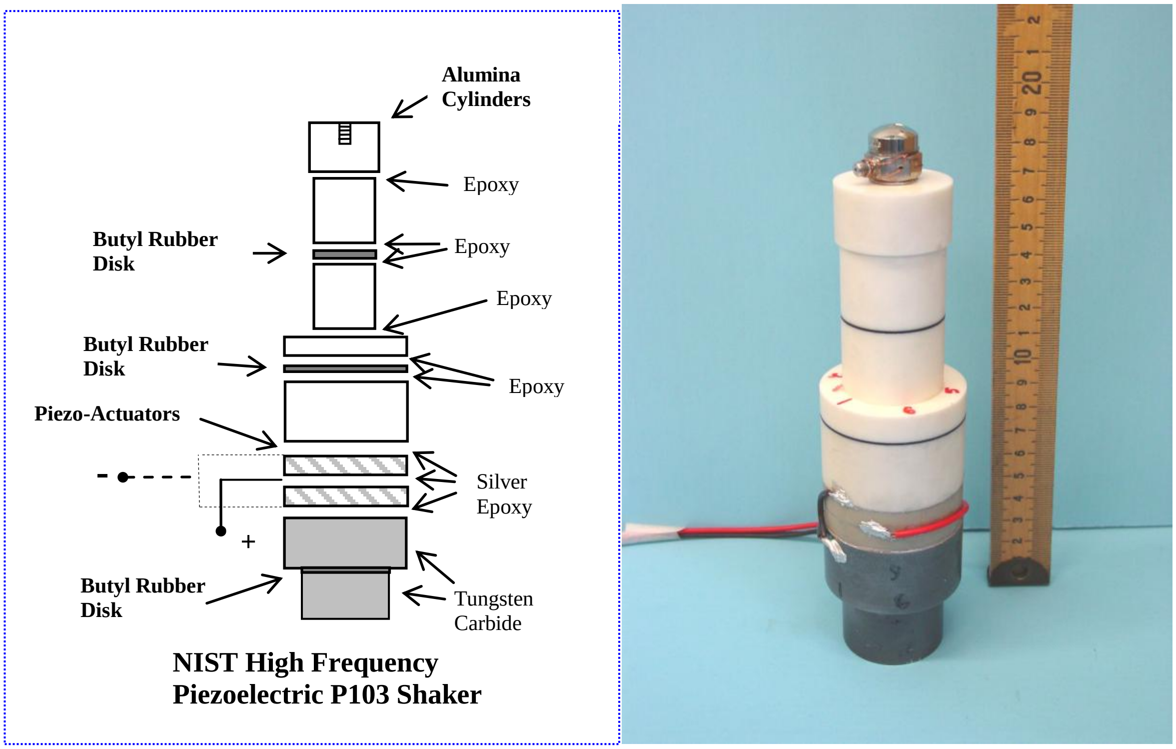


FIGURE 10. Shaker P103 Designed for Higher Frequency Calibrations.

Measurement of cross-axial motion at high frequencies always presents difficulties due to a number of factors. Figure 11 shows the cross-axial motion for shaker P103 up to 20 kHz measured with a triaxial accelerometer. But triaxial accelerometers often have high frequency limitations due to its resonances and those due to mounting. To estimate cross-axial motion at very high frequencies, three small uniaxial accelerometers with higher internal and mounted resonances and mass of about 0.5 gram each, were mounted on the shaker table as shown in Figure 12. By measuring the phase difference of signals from any two accelerometers, one can get a good indication of the degree of piston-like motion of the shaker. For frequencies above 15 kHz, calibration should be performed only at frequencies where this phase shift is minimal.

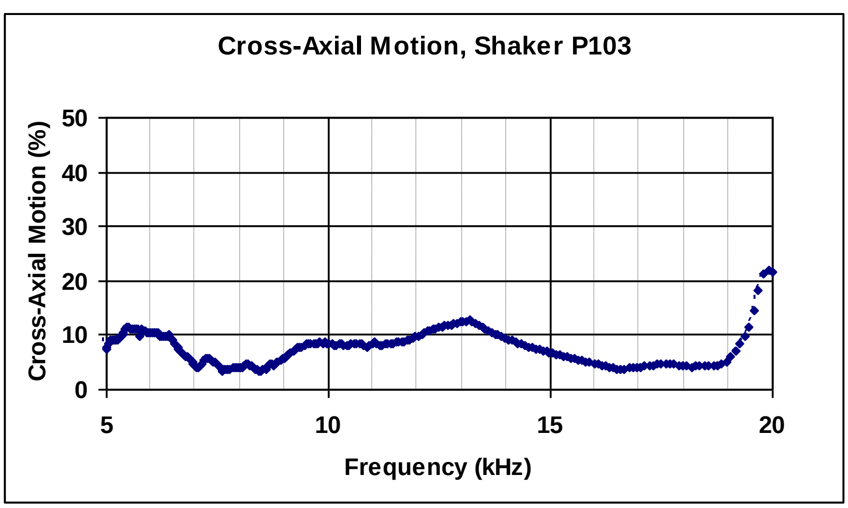


FIGURE 11. Cross-Axial Motion for Shaker P103 with 0.8 V Drive Signal.

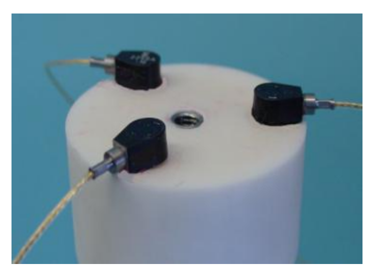


FIGURE 12. Checking shaker performance at high frequencies with three 0.5 gram accelerometers.

Initially the shaker P103 was excited by only a low distortion function generator and without a power amplifier in order to obtain the overall frequency response data as described for the P102 shaker. A drive voltage of 0.8 V was used for the tests.

Figure 13 gives the results of the approximate obtainable accelerations for the 3 kHz to 50 kHz frequency range measured at the top center of the shakers using the 0.8 V drive signal for both shakers P102 and P103. For use in calibrations, a power amplifier and step-up transformer will be used to obtain the higher accelerations needed. The data were obtained by using a small (0.5 gram) accelerometer of the type shown in Figure 12.

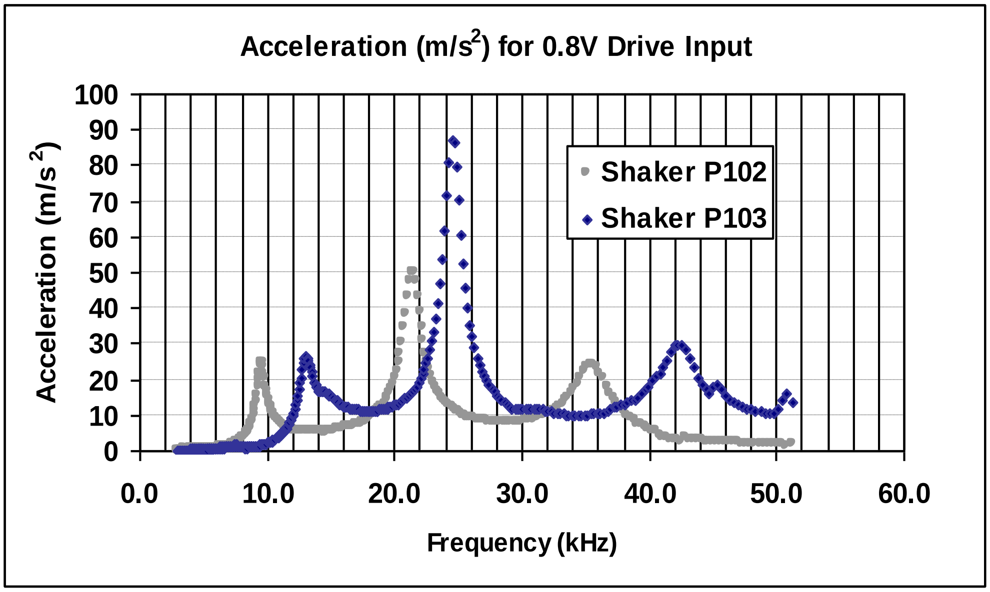


FIGURE 13. Obtainable Accelerations for the P103 Shaker Using a 0.8 V Drive Voltage.

As shown in Figure 13, as compared to the shaker P102, the P103 shaker has a larger acceleration near 25 kHz which will provide greater amplitudes to enable fringe disappearance calibrations at higher frequencies. Further testing will determine the useful range of this shaker.

Figure 14 shows the frequency response, over the range of 3 kHz to 50 kHz for shakers P102 and P103: input drive voltage per nanometer of displacement, using the 0.8 V input drive voltage. A sharp decrease in the drive voltage corresponds to a resonance of the shaker, as shown in Figures 5 and 14. Note the three sharp decreases at approximately 12 kHz, 25 kHz, and 42 kHz in shaker P103, all of which are higher frequencies than the corresponding one for shaker P102. The three resonances provide for large amplitudes over a broad frequency range. The broad frequency range is possible because the effect of the higher frequency resonance comes in to play as the lower frequency resonance falls off. This should provide for higher frequency calibrations at amplitudes necessary for fringe disappearance.

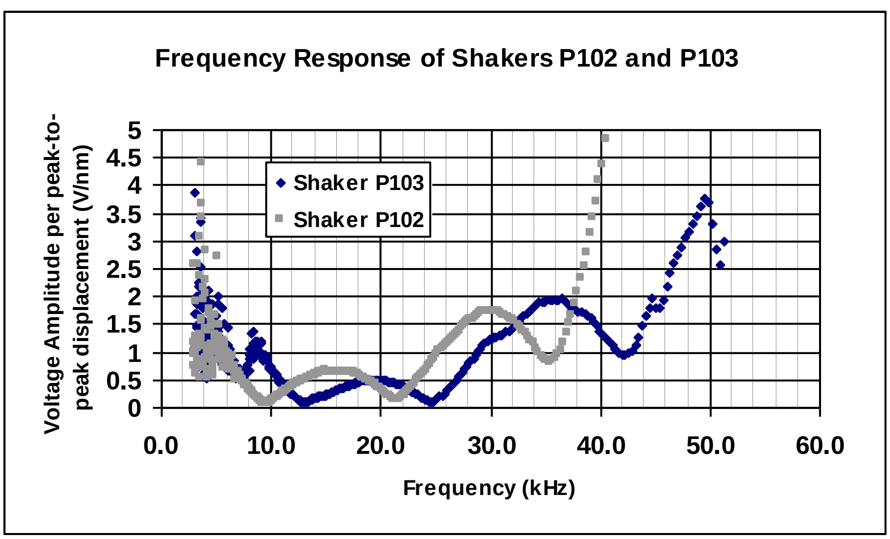


FIGURE 14. Frequency Response of Shaker P103.

FUTURE DEVELOPMENT FOR HIGHER FREQUENCY SHAKERS

The frequency range of the ceramic shaker can be modified by changing the size of the cylinders and the thickness of the connecting disks. Newer designs are planned to extend the range to higher frequencies [6]. Mathematical modeling will be used as a tool to predict the performance before actual construction of the shakers.

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