MANAGING ACOUSTIC FEEDBACK: MICRO ELECTRO MECHANICAL SYSTEMS (MEMS) CONTACT MICROPHONES FOR MUSICAL INSTRUMENTS

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Introduction

The integrated circuit wafer fabrication process has matured and scaled rapidly since the invention of the transistor. Semiconductor technology has the major advantage of scale and reproducibility; many thousands of identical chips can be produced on one wafer and the repeatability from wafer to wafer is very well controlled. Silicon integrated circuit technology now has the capability of creating device geometries of less than 100 nanometers.

"Suppose we use a surface transducer that measures the acceleration of an instrument's body that is so lightweight it does not affect the instrument that it is measuring."

Micro Electro Mechanical Systems (MEMS) is a technology that builds on the core silicon fabrication infrastructure that has been developed for the integrated circuit industry. Micromechanical structures are created on a silicon wafer by etching defined patterns on a silicon substrate to form core sensor elements or mechanical actuators that can move fractions of a micron. Pressure sensors were one of the first high-volume applications and hundreds of millions of MEMS pressure sensors are now in use in applications such as pressure-sensing in engine manifolds and tire pressure monitoring systems. MEMS accelerometers have been used in automotive applications for over 15 years as crash sensors for airbag deployment, for rollover detection and car alarm systems. More recently MEMS accelerometers are used for motion sensing in consumer applications such as video games and cell phones. MEMS micro-mirror optical actuators have found use in overhead projectors and projection televisions. In recent years MEMS microphones have begun to proliferate in the broad consumer market including cell phones, Bluetooth headsets, personal computers and digital cameras. In university and industry-based research departments today there is significant investment in bio-MEMS which is focusing on the use of micro- or nano-technologies to execute diverse applications from DNA testing to disposable medical diagnostic kits.

This article summarizes some of the key technologies deployed in MEMS accelerometers and then discusses how this technology may bring a new dimension to acoustic transducers for musical instruments.

MEMS accelerometer technology

The core element of a typical MEMS accelerometer is a moving beam structure. This element is typically comprised of two sets of fingers—one set fixed to a solid ground plane on a substrate and the other set attached to a known mass mounted on springs that can move in response to an applied acceleration. Under an applied acceleration there is a *change in capacitance* sensed between the fixed and moving beam fingers.[1] It is the change in capacitance (i.e., the relative change in spacing between the fingers) that is measured and converted to acceleration units, "g." (1 g, the acceleration due to gravity on Earth, is about 9.8 meters per second per second or about 32 feet per second per second). Figure 1 illustrates the MEMS accelerometer concept while Fig. 2 provides an example of an actual MEMS sensor at 1500 magnification

The dimensions of these MEMS structures are in the order of microns, requiring very high precision silicon photolithography and etching process technologies. MEMS structures are typically formed from single crystal silicon or from polysilicon that is deposited at very high temperatures on the surface of a single crystal silicon wafer. Structures with very different mechanical characteristics can be created using this flexible technology. One mechanical parameter that can be controlled and varied is spring stiffness. The mass of the sense element and the damping of the structure can also be modified by design. Sensors can be produced to measure fractions

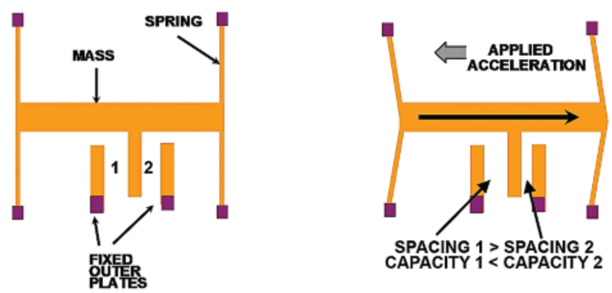


Fig. 1. MEMS accelerometer structure diagram.

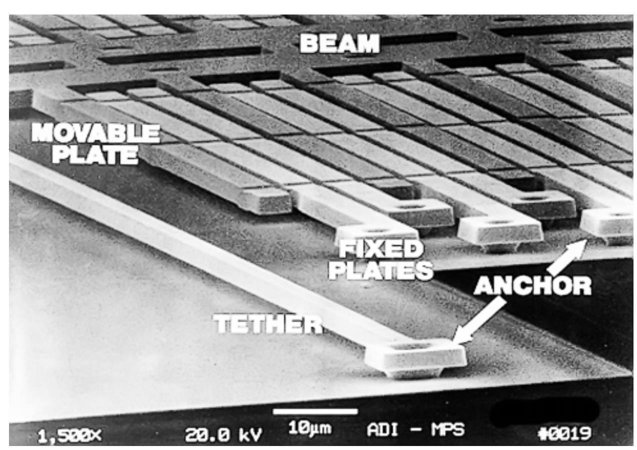
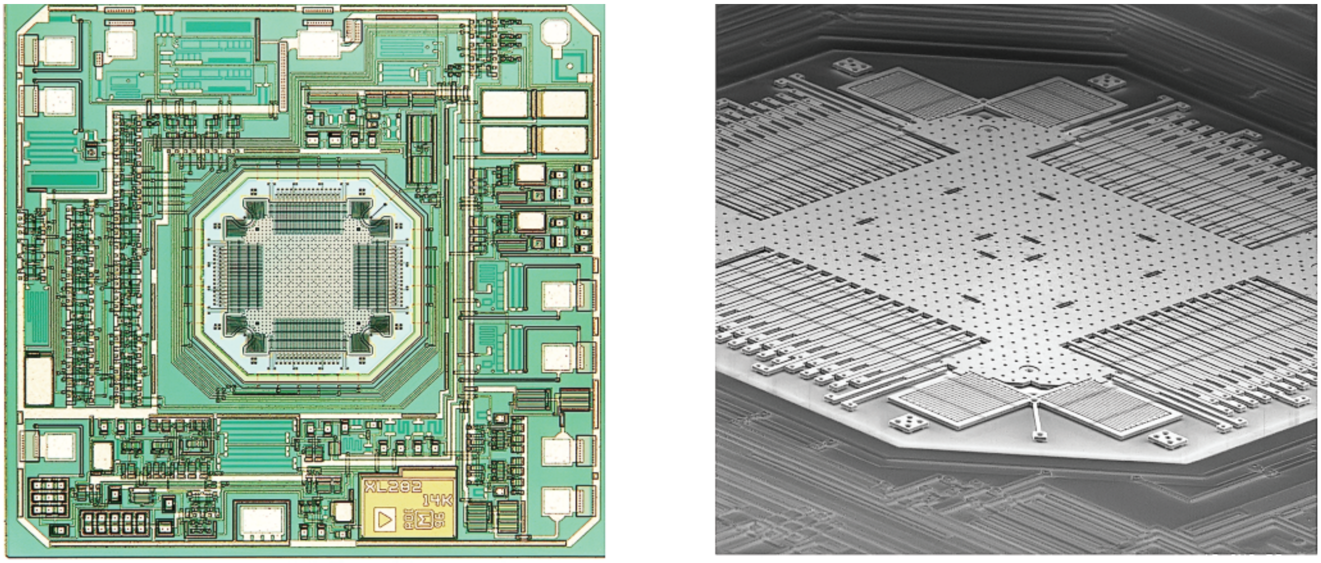


Fig. 2. ±50g MEMS accelerometer physical structure (1500x).



(A) (B)

Fig. 3. Dual-axis 2g accelerometer at two magnifications showing accompanying electronics (A) and sensors (B.)

of one g or hundreds of g's with bandwidth as high as 20 kHz. Figure 3 shows a dual axis MEMS accelerometer mounted on a substrate with its accompanying electronics (A). Further magnification (B) reveals the MEMS structures themselves.

The MEMS accelerometer structure can be connected to the conditioning electronics either on the same chip as the sensor or on a separate chip. In the case of a single chip solution the capacitance of the sense element can be as low as 1 to 2 femtofarads per g (1 femtofarad = 10^{-15} farads which equates to measurement resolutions in the attofarad range (1 attofarad = 10^{-18} farads). In a two chip structure, the capacitance of the MEMS element is typically higher to overcome the parasitic capacitance effects of the bond wires between the MEMS and the conditioning ASIC (Application Specific Integrated Circuit).[2] Figure 4 shows a cross-section of a typical two-chip accelerometer.

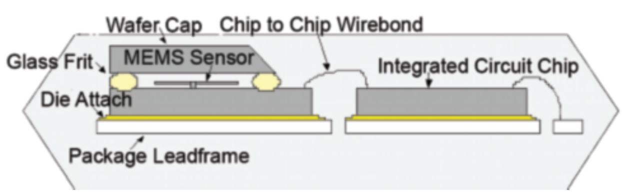


Fig. 4. Cross-section of a typical two-chip accelerometer.

Accelerometers as vibration measurement sensors

The concept of using vibration sensing transducers for measurement of acoustic vibration in musical instruments is not new.[3] Piezo and electromagnetic transducers are the basis for many acoustic pickup applications today and a discussion on the performance of these sensors would fill far more pages than this article would allow. It might be attractive to be able to add tiny MEMS accelerometers to the list of available transducers for such applications—transducers so small and low in mass that they have no mechanical or mass loading effect on the instrument. To date there has been limited success in using MEMS accelerometer technology for this application due primarily to the narrow bandwidth of commercially available small acceleration sensors. Some recent breakthroughs in accelerometer technology have enabled the production of very small accelerometers with very wide bandwidth. The Analog Devices ADXL001 is a high g (±70 g to ±500 g) single axis accelerometer that has a bandwidth of 22 kHz that comes in a 5 mm x 5 mm x 2 mm package (See Fig. 5). This is ideal for vibration monitoring in industrial applications. It is particularly suited to high g applications such as

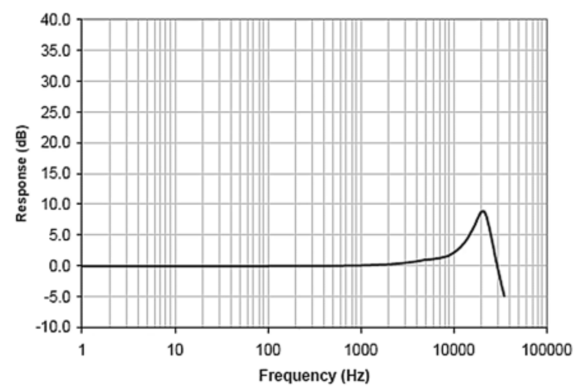


Fig. 5. ADXL001 frequency response curve.

condition monitoring of motor life and general machine condition by detecting changes in bearing acoustic characteristics. In the early stages of bearing wear a clear vibration signature develops in the audio band that can be detected with a high g vibration sensor attached to the system housing. This particular sensor is not suitable as an acoustical vibration sensor for musical instruments because it measures acceleration in the order of tens of g's and is therefore not sensitive enough. Also, it only senses along one axis of motion while an ideal acoustic sensor will have a desired response in all three axes. However, it does demonstrate that full audio bandwidth acceleration transducers can be produced using MEMS technology.

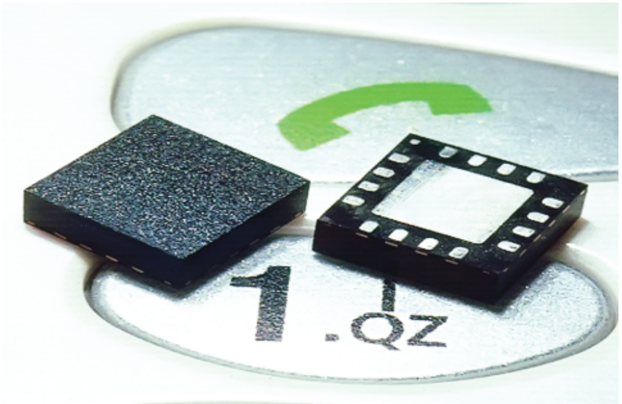


Fig. 6. MEMS accelerometer 4 mm x 4 mm x 1.45 mm.

Low-g accelerometers can measure acceleration down to milli g's but are typically bandwidth-limited to around 5 kHz. This limitation may be associated with the fact that few commercial applications of these sensors require significant bandwidth (the primary applications involve the detection of human motion or gravity driven acceleration events that are lower frequency dominated) and so there has been little motivation to develop sensors suited specifically for audio band measurement. The output of an accelerometer is typically measured in millivolts per g and a three axis accelerometer has three separate output channels measuring the Cartesian x,y, and z axes separately. A typical low-g MEMS accelerometer is housed in a standard surface-mount package, taking further advantage of the mature semiconductor manufacturing infrastructure. Measuring less than 4 mm x 4 mm x 1.5 mm, the product can fit into places unimaginable with traditional accelerometer technology and because of its very small size it does not cause mass loading or other changes in the response of the system that it is measuring. Figure 6 shows an example of surface-mount housing.

Acoustic feedback

Beginning with the introduction of the omnidirectional condenser and dynamic microphone in the mid 1920s,[4] followed by Søren Larsen, the Danish scientist who first discovered the principles of audio feedback (also known as the Larsen effect), acoustic feedback has been a demon that few audio engineers are able to totally control. Acoustic feedback is an unavoidable fact of life in live sound production. The Beatles experimented with this audio artifact and decided to add it to their memorable introduction to "I Feel Fine" in 1964.[5] Rock 'n Roll then set out to tame the beast by embracing it, thereby making acoustic feedback a striking characteristic of rock music. Electric guitar players such as Pete Townshend and Jimi Hendrix deliberately induced feedback by holding their guitars close to the amplifier sensors. As the fad waned, audio engineers continued to struggle with acoustic feedback's often undesirable ear shattering effects particularly in live sound applications. In the perfect world of a well-appointed and acoustically treated recording studio, a high-end omnidirectional microphone will record an instrument with an astonishing degree of realism and fidelity. Artists who know and cherish this sound have long sought to be able to reproduce it on stage. Although recording a live show with studio sound quality is every musician's dream, it has been virtually impossible. Even if sound reinforcement rigs sounded good, and if arenas had excellent acoustics, and if sound engineers knew everything there was to know about mixing sound and had the best gear available, there still would remain one obstacle on the road to sonic nirvana—feedback.

Acoustic pickups

There are several conventional ways of dealing with acoustic feedback. A primary method is to use different microphone technologies that are primarily focused on the directionality of microphone systems. This method does work up to a certain point, but requires constant management by sound engineers to adapt to the different and changing characteristics of a stage venue.

A second method used is to employ contact pickups on the instrument itself. The technologies vary, but the basic idea is to sense the vibrations of the instrument's body directly, rather than the sound it produces in the air. The advantage is obvious—practically no acoustic feedback—as these pickups are not sensitive to airborne sound. Unfortunately, the shortcomings are many—finding a good-sounding location on an instrument body is notoriously difficult, piezo pickups' sonic characteristics are far from perfect and they have high output impedance requiring special instrument inputs or direct boxes. They also tend to be large and can actually interfere with the natural acoustic behavior of the instrument itself.

This suggests the idea of a new form of a low mass "contact microphone." Suppose we use a "surface transducer" that measures the acceleration of the instrument's body, preferably on more than one axis,[6] with good linearity and so lightweight that it does not acoustically affect the instrument that it is measuring. Suppose further, that such a transducer has an interface identical to that of a traditional microphone—similar output level, output impedance, and power requirements. In short, suppose that a musician can just plug this transducer into a microphone preamp or a mic input of the mixer like any other microphone.

Contact microphones

An attentive reader will notice the mention of "acceleration" in the preceding paragraph. Because our ears respond

Fig. 7. Accelerometer mounted on Fender Strat Acoustic Guitar.

to sound pressure, microphones are designed to sense sound pressure. To simplify matters greatly, the sound pressure in the immediate vicinity of a vibrating body is proportional to acceleration.[7] What if there were an accelerometer that had enough bandwidth to be used as a contact microphone?

To explore this concept, a three axis accelerometer was mounted on an acoustic guitar to act as a pickup. While not ideal, we used an Analog Devices ADXL330, a three axis low-g accelerometer that has wider effective bandwidth than other traditional low-g accelerometers. It has a bandwidth up to 6 kHz on the x and y channels and around 1 kHz for the z axis. The expanded bandwidth allowed the MEMS accelerometer to gather useful information in the audio band. Since the output is analog it is easily instrumented and can be used with standard audio recording equipment

The vibration of the instrument was measured and compared to the built in piezo pickup and to a MEMS microphone mounted near the guitar. The guitar used was a Fender Strat acoustic with a built in Fender pickup. An analog output MEMS accelerometer was mounted on a light-weight flex circuit and attached using beeswax on the guitar body at the bridge location, as seen in Fig. 7. The x axis of the accelerometer was oriented along the axis of the strings, the y axis perpendicular to the strings and the z axis normal to the surface of the guitar. A MEMS microphone with a flat frequency response out to 15 kHz mounted 3 inches from the strings was used as a reference.

A short sound segment was recorded using the accelerometer, the built in piezo pickup and the MEMS microphone. The time domain waveforms for each transducer are shown in Fig. 8. No post processing was done on any of the audio clips.

Figure 9 shows an FFT-based spectrum of the piezo pickup measured at one of the peaks in the time domain wave

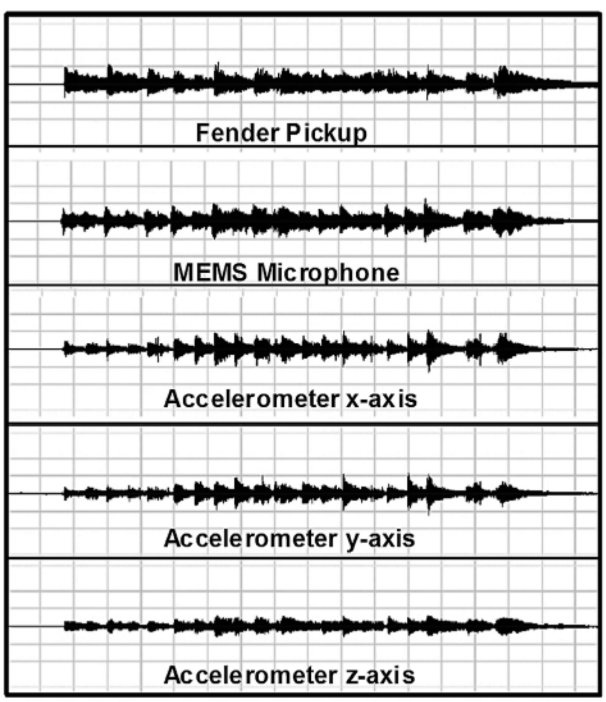


Fig. 8. Time domain waveforms using different transducers (as indicated).

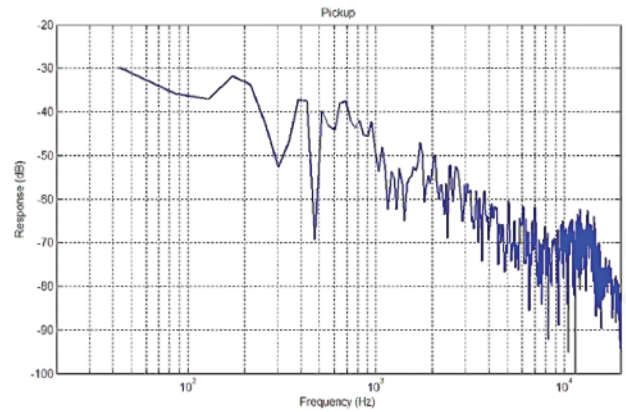


Fig. 9. Spectrum of piezo pickup.

form. This spectrum shows a response with a strong bass component. Indeed the actual audio file sounded excessively full with a lot of bass response. This sounds pleasing (depending on your taste) as the cavity resonance creates a fuller bass sound that is not the same as that heard when listening to the instrument directly.

The MEMS microphone output is very flat and reproduces the sound of the instrument very well. It sounds very natural, well balanced and true to life. The FFT-based spectrum measured at the same point in time as the piezo pickup is shown in Fig 10(a). The frequency response of the MEMS microphone is shown in Fig 10(b) for reference.

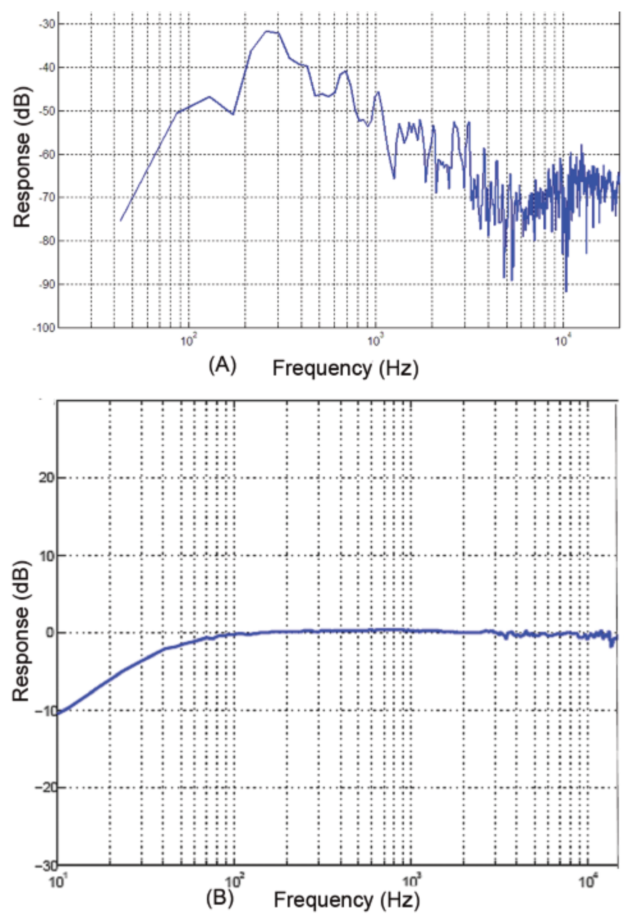


Fig. 10 (a). Spectrum of MEMS microphone; (b). Frequency response of MEMS microphone.

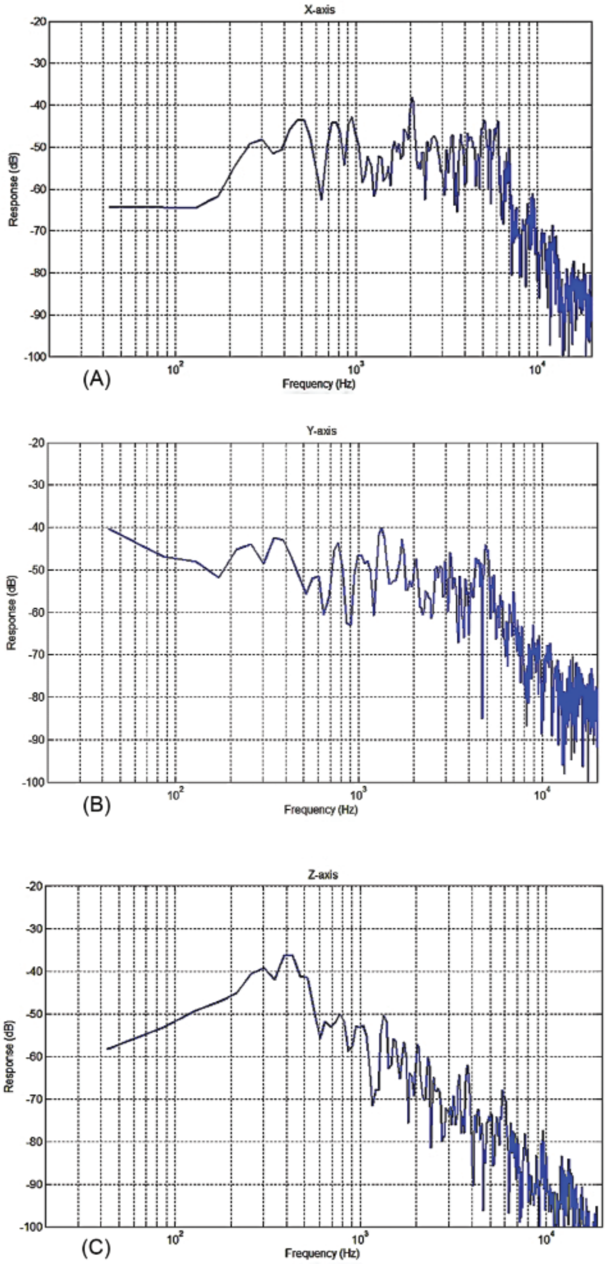


Fig. 11 (a). Spectrum of x-axis; (b). Spectrum of y-axis; (c). Spectrum of z-axis.

The output from the MEMS accelerometer is very interesting. The immediate weak points are that the noise floor was too high and audible at the beginning and end of the track and the bandwidth of the z-axis was clearly limited to lower frequencies. The sound reproduction from each axis was noticeably different.

The x and y-axis sounded bright and articulate and had clearly discernable differences in tonality. As expected the z-axis obviously sounded bass dominated. Figure 11(a) shows the x-axis spectrum, Fig. 11(b) the y-axis and Fig. 11(c) the z-axis.

The x, y and z axes mixed together produced a fair representation of the instrument with some brightness. By adjusting the mix, a variation in tonal balance can be achieved with natural sound reproduction. The extended upper harmonics are still missing due to the bandwidth limitation of the current accelerometers but the sound reproduction was still surprisingly true.

Conclusion

We are essentially reporting on a work-in-progress. Low-g MEMS accelerometers demonstrate clear potential as high quality acoustic pickups for musical instruments and they do not suffer from traditional feedback problems. A three-axis accelerometer mounted on a Fender Strat acoustic guitar achieved promising sound reproduction. The three axes clearly have different tonal characteristics related to the vibration modes of the instrument in the different directions of the body. The three output channels can be mixed to generate realistic sound reproduction. In addition, these channels can be mixed in different ways resulting in creative tonal effects.

While the performance of the accelerometer in this experiment is very promising, there are a few drawbacks. The noise floor of the sensor is audible, a problem that can be minimized using noise gating or other techniques, but the ideal sensor must have a noise floor comparable to conventional microphones. The high frequency response of the sensor must be extended, ideally up to 20 kHz, to capture the full tonal range of the instrument.

MEMS accelerometer technology has clear potential for acoustic pickup applications in musical instruments especially in live performances where acoustic feedback is often a problem. A very small, low power MEMS device can be mounted unobtrusively anywhere on the instrument without affecting the instrument's natural vibration characteristics. In fact, multiple sensors can be mounted at different points around the instrument providing additional flexibility to the sound engineer to reproduce the natural character of the instrument without fear of acoustic feedback in live sound application— one step closer to "Sonic Nirvana."**AT**

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