Acoustics • Shock • Vibration • Signal Processing **April 2002 Newsletter**

Päivää

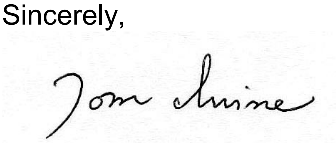
Vibration is usually an undesired environment in aerospace vehicles. Nevertheless, there are certain instances where vibration can serve a useful purpose in these vehicles. The first article gives an example of device called a Quartz Crystal Microbalance that uses vibration to measure either erosion or contamination in space environments.

The second article deals with sonic booms. During the 1960s, I lived in Tempe, Arizona, which is located between Luke and Williams Air Force Bases. I remember sonic booms rattling our windows as fighter aircraft flew at supersonic speeds above our community. Such events were more of a curiosity than a nuisance.

Years later, I was sitting in an apartment in Uwajima, Japan, when I again heard windows rattling. The rattling seemed to last longer than a normal sonic boom, however. Finally, I realized that a mild earthquake was occurring.

Nostalgic musings.

Sincerely,



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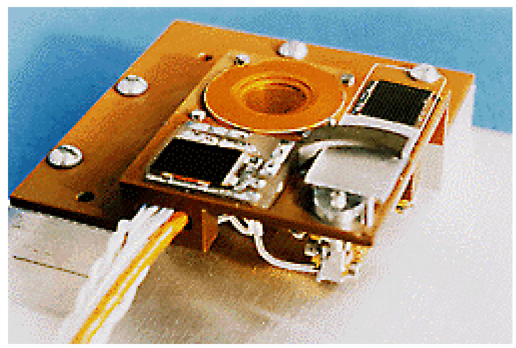
Feature Articles



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2. Data analysis and report writing
3. Custom software development and training
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Quartz Crystal Microbalances
By Tom Irvine

Introduction

A Quartz Crystal Microbalance (QCM) is a device that can be used to measure the mass of dust and contamination particles on a surface. The QCM measures this mass indirectly through its oscillating piezoelectric crystal.

As an alternative, the QCM can measure erosion in an environment where fast moving ions or particles collide with a surface.

This articles focuses on the use of QCMs in spacecraft and space probes, although these devices are also used in clean rooms and in industrial settings.

Contamination Sources

Contamination may come from natural sources, such as the dust surrounding a planet.

A spacecraft can also create its own contamination. This contamination may degrade the performance of any optical or infrared sensors mounted in the spacecraft.

Various portions of the spacecraft may "outgas" when exposed to the near vacuum condition of space.

Some space vehicles also have ablative material that provides insulation by change from a solid to a gas when exposed to high temperatures. Outgassing of ablative insulation may thus be a contamination concern.

Furthermore, the spacecraft may have attitude control thrusters. The thrusters discharge bursts of gas to control the orientation of the spacecraft or to change its orbit.

Hydrazine is a typical gas used for this purpose. The thrusters operate by the catalytic decomposition of hydrazine (N_2H_4) into ammonia (NH_3), nitrogen (N_2), and hydrogen (H_2). These exhaust particles create another potential contamination source.

Dust and Contamination Condensation

The QCM is exposed to a given environment. Dust and contamination particles from the environment condense on the crystal. The crystal may be cooled to facilitate this condensation. Another technique for collecting particles is to coat the crystal with a "sticky polymer" substance.

The collected particles change the mass of the crystal. The mass, in turn, changes the crystal's natural frequency. The relationship between the frequency f and the mass m is

$$f \propto 1 \big/ \sqrt{m}$$

The change in mass can thus be calculated from the change in frequency. The change in mass represents the mass of the collected particles. The "mass flux" is then calculated by dividing the collected mass by the surface area of the crystal.

Reference QCM

Note that typically two QCMs are used for the mass flux measurement. One QCM is exposed to the environment as explained previously. The other QCM is a reference QCM that is shielded from the contamination particles. The reference QCM is used to account for any frequency shift due to temperature, pressure, or radiation.

Oscillation Frequency and Sensitivity

A typically oscillation frequency is 15 MHz, with a corresponding sensitivity of

$$5.09 \times 10^{8} \ \frac{\text{Hz}}{\text{gram cm}^{2}}$$

Note that QCMs with higher frequencies have greater sensitivities.

Discoverer 26 Satellite

The first QCMs were flown in space on the Discoverer 26 Satellite, launched on July 26, 1961 in support of the Atlas Missile program.

After the Discoverer 26 flight, three additional Discoverer flights were made.

The purpose of the flights was to measure the sputtering erosion rates of surfaces by molecular impacts in the upper atmosphere. The goal was to determine what effect erosion would have on the re-entry of the Atlas Missile nose cone.

Note that Discoverer 26 was in a low orbit, with a perigee of 230 km and an apogee of 810 km.

Mars Rover

The Mars Pathfinder spacecraft was launched from Kennedy Space Center on December 4, 1996. The Pathfinder landed successfully on Mars on July 4, 1997.

The Pathfinder then released a robotic surface rover known as Sojourner, shown in Figure 1-1.

"Sojourner" means traveler. In addition, Sojourner Truth was the name of an African-American woman who was a reformist during the Civil War era.

The Sojourner was powered by solar cells and batteries.

The Sojourner had six wheels. It traveled to a number of rocks located nearby the Pathfinder. The Sojourner had instruments to analyze the chemical composition of the Martian rocks.

The Sojourner transmitted its data to the Pathfinder via radio signals. The Pathfinder then relayed the signals to the Earth.

In addition, the Sojourner had a QCM to monitor Martian dust. The QCM was part of the Materials Adherence Experiment (MAE).

The QCM had a “sticky polymer” substance to collect the dust particles. In addition, the Rover had a reference QCM that was shielded from the ambient environment.

The exposed QCM is shown in Figure 1-2. The QCM is the orange disk in this figure. The QCM is also shown in Figure 1-3.

A particular contamination concern was that the Martian dust would settle on the solar cells, thereby degrading their performance. The MAE thus had a small solar cell, in addition to the QCM. The decrease in the small solar cells performance was considered to result from the accumulation of dust on its surface.

The author is still searching for definitive results from the Mars Rover QCM. In the mean time, some results for the MAE solar cell experiment are discussed in Reference 1-1.

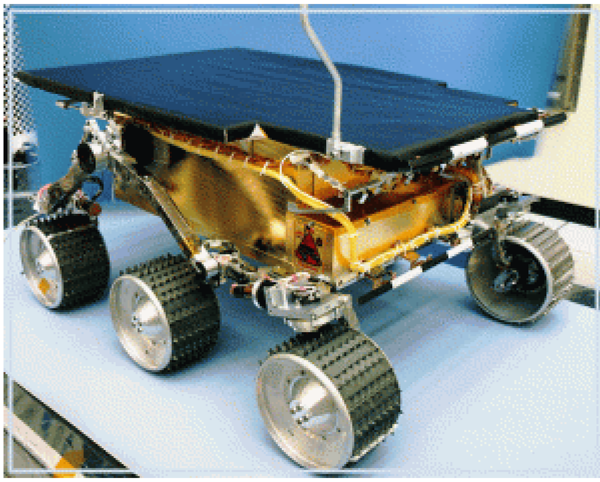

Figure 1-1. Sojourner Rover

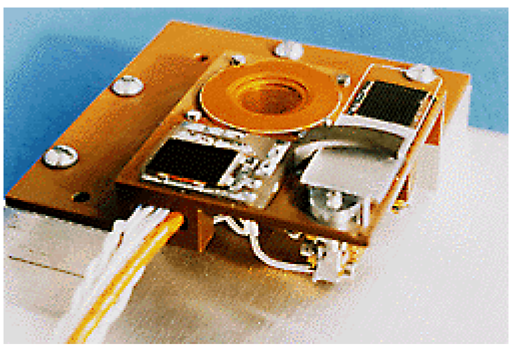

Figure 1-2. Sojourner QCM

Figure 1-3. Sojourner on Mars

The QCM is the bright disk above the wheel at the right side of the image.

MSX

The Midcourse Space Experiment (MSX) was launched on April 24, 1996, on a Delta II rocket from Vandenberg Air Force Base in California. Its purpose was to gather vital data for the future design of space-based and ground-based missile defense systems.

Figure 1-3. MSX Satellite

The MSX had numerous instruments, including the SPIRIT III (Spatial Infrared Imaging Telescope).

The MSX also had a Contamination Experiment (CE) to monitor and measure contamination around the orbiting spacecraft. The contamination sensors included a mass spectrometer and QCMs.

QCMs were used to measure contamination both before and after launch.

A particular concern was the thickness of the contamination layer on the SPIRIT III telescope mirror.

The QCM data showed that the mirror accumulated a contamination layer at the rate of about 1 Angstrom/day during the early phase of the orbital mission.

Further results are given in Reference 1-2.

References

1.1 Geoffrey A. Landis and Phillip P. Jenkins, Dust on Mars: Materials Adherence Experiment Published in: *Proceedings of the 26th IEEE Photovoltaic Specialists Conference - 1997*, IEEE, NJ, 1997, pp. 865-869.

1.2 B.E. Wood, et al; Quartz Crystal Microbalance (QCM) Flight Measurements of Contamination on the MSX Satellite. Published at: http://www.jhuapl.edu/cedac/papers/SPIEqcm/qcm.html

Sonic Booms by Tom Irvine

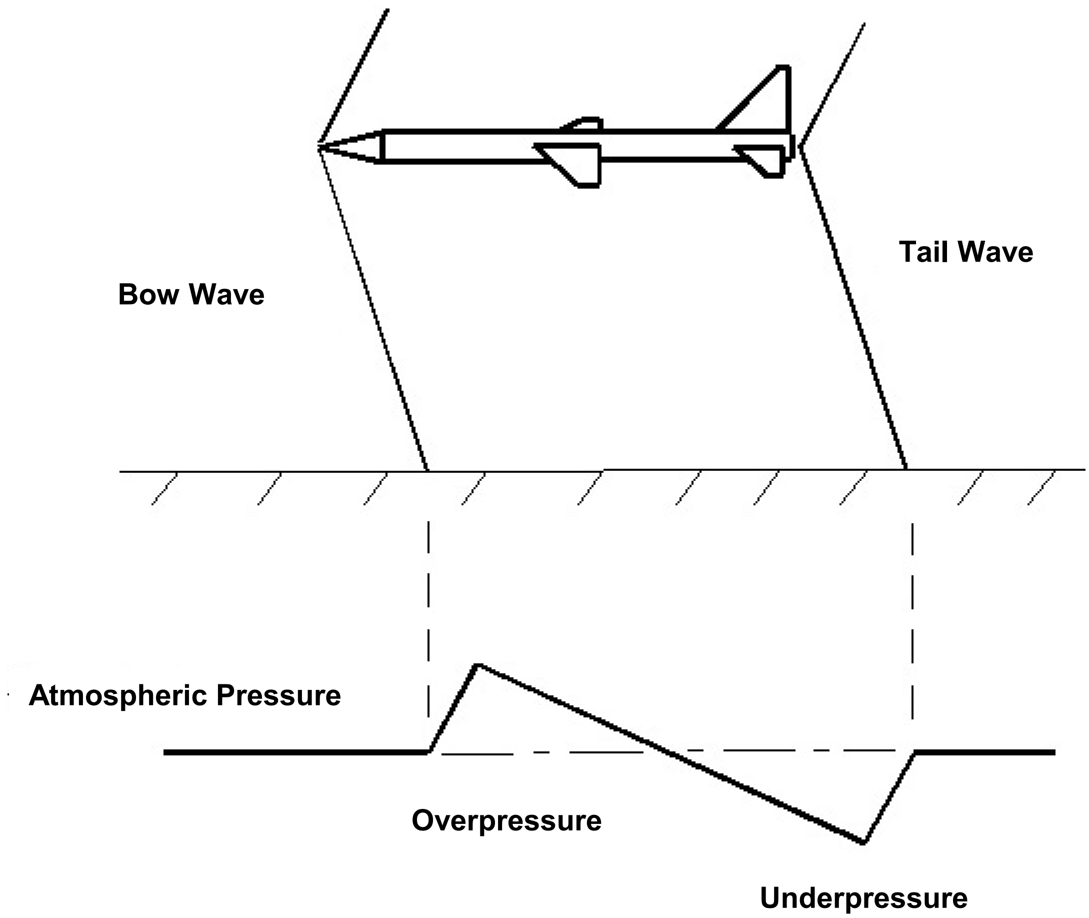

Figure 2-1. N-wave

Introduction

This article is inspired, in part, by a number of young students who asked "Why does the Space Shuttle Orbiter make a double sonic boom when it lands?"

N-wave

As a simple example, consider an aircraft flying at supersonic speeds. The aircraft typically creates two shock waves: a bow wave and a tail wave. The waves together form an N-wave, as shown in Figure 2-1.

The N-wave continues with the aircraft the entire time it flies at supersonic speeds.

Each of the two waves actually generates a cone. The two cones intersect the ground. Regions of overpressure and underpressure exist between the cones.

Imagine that you are standing on the ground. The air pressure is the normal atmospheric value. Suddenly, the bow wave from a supersonic aircraft comes past you. The air pressure level rises instantaneously because the air is highly compressed at the bow wave. You hear a sonic boom as a result.

You are now between the bow wave and the tail wave. The pressure gradually decreases and even dips below the normal atmospheric value. Suddenly, the tail wave comes past you. The air pressure jumps to the normal atmospheric value. You hear a second sonic boom as a result.

Of course, all of this may happen in a fraction of a second depending on the aircraft size, aircraft speed, wind conditions, and other variables.

Not all sonic booms reach the ground, but those that do arrive less than one minute after flyover and generally last less than one second.

Pressure Amplitude

For today's supersonic aircraft in normal operating conditions, the peak overpressure varies from less than one pound to about 10 pounds per square foot for a N-wave boom, according to Reference 2-1. Examples are shown in Table 2-1.

Note that the normal air pressure is 2,116 psf or 14.7 psi. The overpressure is measured with respect to this reference pressure. The absolute pressure is the overpressure plus the reference air pressure.

Effects

The effects of overpressure on people and structures are shown in Table 2-2, as taken from Reference 2-2.

Table 2-1.
Overpressure Measured at the Ground

Overpressure (psf)	Aircraft
0.8	F-104 at Mach 1.93 and 48,000 feet
0.9	SR-71 at Mach 3 and 80,000 feet
1.25	Space Shuttle at Mach 1.5 and 60,000 feet during landing approach
1.94	Concorde SST at Mach 2 and 52,000 feet
2.0	SR-71 at Mach 1.3 and 31,000 feet

Table 2-2. Overpressure Effects

Overpressure (psf)	Predicted Effects
0 to 1.0	No damage to ground structures. No significant public reaction day or night.
1.0 to 1.5	No damage to ground structures. Probable public reaction.
1.5 to 1.75	No damage to ground structures. Significant public reaction particularly at night
1.75 to 2.0	No damage to ground structures. Significant public reaction.
2.0 to 3.0	Incipient damage. Widespread public reaction.
11	Threshold of significant structural damage.
720	Damage to eardrums

The most likely structural damage is cracked plaster and broken windows.

Frequency

The energy of sonic booms is concentrated in the 0.1 to 100 Hz frequency domain. The audible frequency range for the average human varies from about 20 Hz to about 16,000 Hz. In general, people are less sensitive to low-frequency noise, below 100 Hz, than they are to high-frequency noise, above 2000 Hz.

Frequencies below 16 Hz are referred to as infrasonic frequencies and are not audible.

Duration

The duration of the sonic boom is about 100 milliseconds for most fighter-sized aircraft and 500 milliseconds for the space shuttle or Concorde jet.

A sample measured pressure time history is shown in Figure 2-2. The data is from a SR-71, as taken from Reference 2-3. The N-wave occurs from 1.0 to 1.2 seconds.

Space Shuttle

The aerodynamics of a landing shuttle are more complicated, but the basic principle is the same.

The space shuttle orbits the Earth at about 17,500 miles per hour, which is about Mach 25. It is traveling at this speed as it re-enters the atmosphere. It is moving at about 224 miles per hour as it touches down. The duration from touchdown to complete stop is about 70 seconds.

Note that the speed of sound is about 750 miles per hour at sea level. The shuttle thus decelerates through this speed during its descent.

F/A-18 Hornet

A classic photograph of an F/A-18 Hornet with two shock wave cones is shown in Figure 2-3.

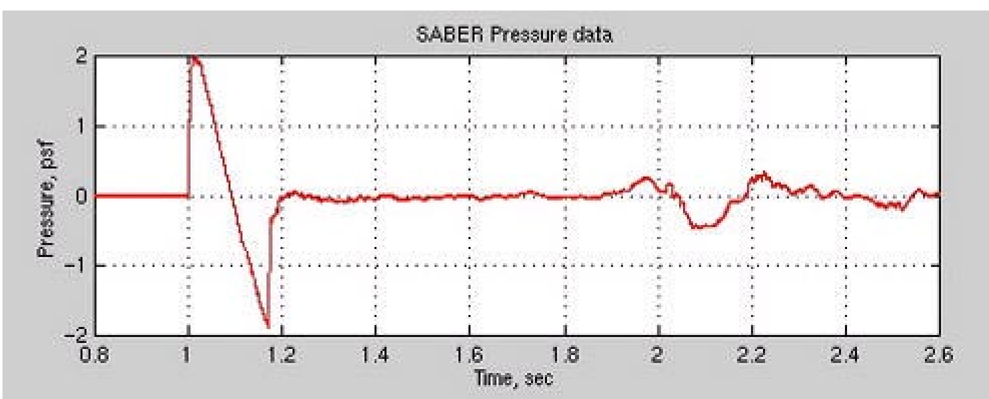

Figure 2-2. SR-71 Sonic Boom

The SR-71 was flying with a speed of Mach 1.27 and at an altitude of 30,500 feet.

Figure 2-3. F/A-18 Hornet

An F/A-18 Hornet assigned to Strike Fighter Squadron One Five One (VFA-151) breaks the sound barrier in the skies over the Pacific Ocean, July 7, 1999. VFA-151 is currently deployed with USS Constellation (CV 64). U.S. Navy photo by Ensign John Gay. [990707-N-6483G-001] July 7, 1999.

References

2-1. USAF Fact Sheet 96-03.

2-2. Aviation Noise Effects, ADA-154319, Federal Aviation Administration, Washington D.C.

2-3. http://www.dfrc.nasa.gov/Projects/SRbooms/srbooms.html

Triangle Sound and Vibration

by Tom Irvine

Figure 3-1.

Introduction

A triangle is a percussion instrument that consists of a piece of metal in the shape of a triangle open at one corner, as shown in Figure 3-1.

It is suspended by a loop of nylon and is struck by a beater, usually of the same material and thickness as the instrument itself.

Sound

The triangle gives a bright, shimmering sound. A single stroke on the instrument is clearly audible through the full force of the modern symphony orchestra. The triangle is thus typically used sparingly.

A triangle has numerous overtones in the human hearing frequency domain. The overtones are inharmonic. This means that the overtones are non-integer multiples of the fundamental frequency. Thus, the sound produced is of no definite pitch, theoretically.

The triangle is an ensemble instrument. Its purpose is to enhance the sound produced by other instruments. This goal is accomplished as the triangle's overtones harmonize with the overtones of other instruments.

Examples

Ludwig Van Beethoven

Beethoven made use of the triangle in his Ninth Symphony, fourth movement, "Turkish March." A sample can be heard at Turkish March

The media player required to play the sample can be downloaded at http://www.real.com/

Bedrich Smetana

The Czech composer Bedrich Smetana used the triangle to enhance his Ma Vlast (The Fatherland), particularly during the Moldau movement. This movement depicts the great river of the country from its source in small springs gradually flowing with increasing breadth and force through fields and woods, past village celebrations, a nocturnal dance of water nymphs, and finally through Prague and onward into the Elbe.

Franz Liszt

As mentioned earlier, the triangle is an ensemble instrument. Franz Liszt, however, took a certain pride in creating his own adventurous creativity. He thus placed a triangle solo in the middle of his Piano Concerto No. 1. The triangle solo is actually interspersed with the piano music such that the triangle's tingling fills the space between the piano notes.

One critic was so outraged that he called the work a "Triangle concerto." This nickname is still used to describe the piece.

Finite Element Analysis

A finite element model of a sample triangle was constructed. The model is shown in Figure 3-2. The properties are shown in Table 3-1 and 3-2.

The model produced six rigid body modes, one for each degree-of-freedom. These modes are omitted in this article. The elastic modes are shown up to a frequency of 16,648 Hz in Table 3-3. There are 17 out-of-plane modes and 14 in-plane modes in this domain. The first and second modes are shown in Figures 3-3 and 3-4, respectively.

The extent to which each mode is excited depends on where the beater strikes the triangle, as well as from which direction the beater strikes the triangle.

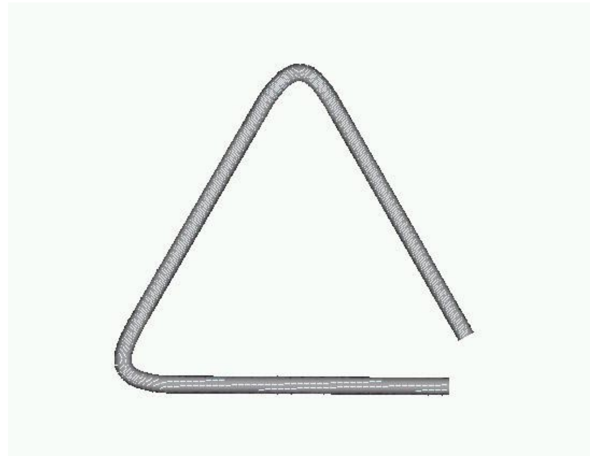

Figure 3-2.

Table 3-1. Properties

Parameter	Value
Length of Each Side	Approx. 6 inch
Diameter	0.25 Inch
Mass	0.21 lbm

Table 3-2. Model

Element Type	Bar
Grid Points	153
Elements	152
Boundary conditions	Completely free
Software	Femap & NE/Nastran

Table 3-3. Triangle FEA Results

Mode	Frequency (Hz)	Plane Orientation	
1	165	1 st	in-plane
2	172	1 st	out-of-plane
3	283	2 nd	in-plane
4	787	2 nd	out-of-plane
5	972	3 rd	in-plane
6	1516	3 rd	out-of-plane
7	1562	4 th	in-plane
8	1753	4 th	out-of-plane
9	1753	5 th	in-plane
10	2865	5 th	out-of-plane
11	3117	6 th	in-plane
12	3826	6 th	out-of-plane
13	3998	7 th	in-plane
14	4841	7 th	out-of-plane
15	4903	8 th	in-plane
16	5514	8 th	out-of-plane
17	6067	9 th	out-of-plane
18	6423	9 th	in-plane
19	7089	10 th	out-of-plane
20	8122	10 th	in-plane
21	8218	11 th	out-of-plane
22	8979	12 th	out-of-plane
23	9202	11 th	in-plane
24	10,878	13 th	out-of-plane
25	11,103	12 th	in-plane
26	11,280	14 th	out-of-plane
27	12,688	13 th	in-plane
28	13,801	15 th	out-of-plane
29	14,844	16 th	out-of-plane
30	14,924	14 th	in-plane
31	16,648	17 th	out-of-plane

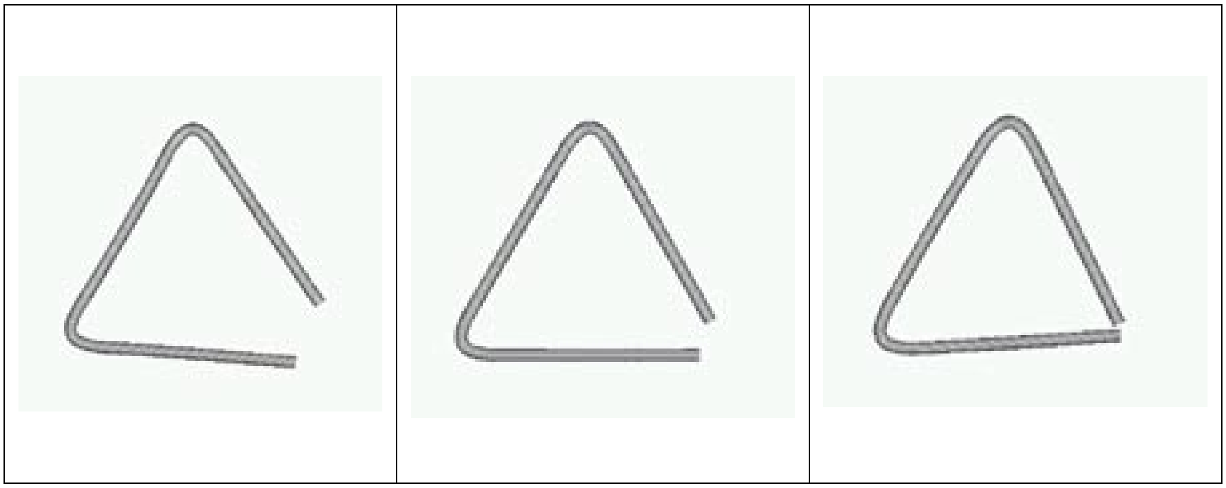

Figure 3-3. First Elastic Mode, 165 Hz, First In-plane Bending Mode

The two free ends move 180 degrees out-of-phase with one another, with the movement in the plane of the triangle.

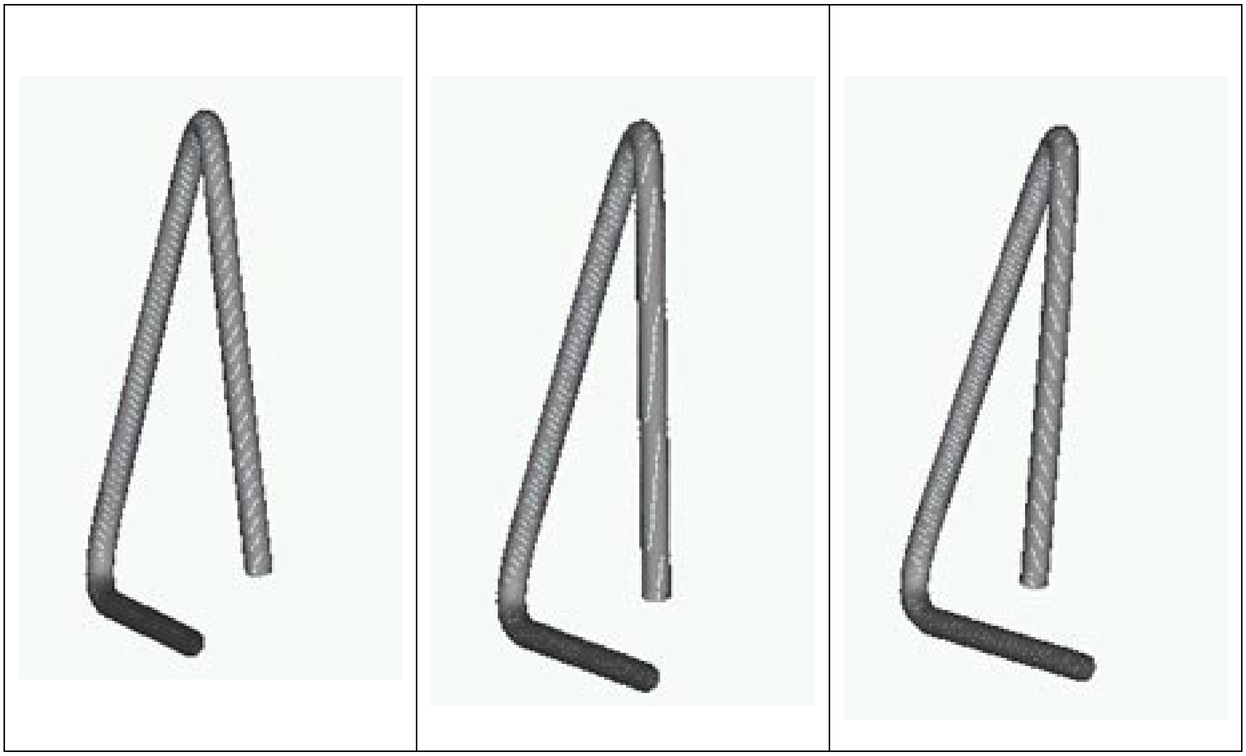

Figure 3-4. Second Elastic Mode, 172 Hz, First Out-of-plane Bending Mode

The two free ends move 180 degrees out-of-phase with one another, with the movement perpendicular to the plane of the triangle.