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Acoustics ● Shock ● Vibration ● Signal Processing   **March 2002 Newsletter**

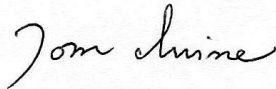## Hola

This month's issue presents two articles.

The first article describes Moonquakes. Apollo astronauts set up an array of seismometers to measure lunar seismic activity. Meteorites impacting the lunar surface generated some of these events. In addition, deep Moonquakes are caused by gravitational tides.

The topic of the second article is suspension footbridge resonance induced by marching. A bridge may oscillate violently if a group of pedestrians march across in cadence with the bridge's natural frequency. Thus soldiers will often break formation and walk at a random pace across a bridge.

As a reminder, I invite readers to submit their own articles to this newsletter. Please become an active participant!

Thank you.

Sincerely,

Tom Irvine
Email: tomirvine@aol.com

Feature Articles

Moonquakes   page 4

Suspension Footbridge Resonance Induced by Marching   page 14

Welcome to Vibrationdata.com
Shock and Vibration Response Spectra and Software Training
Correspondence Course (Distance Learning via Email and Online Resources)

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B.S. degree 1985. M.S. degree 1987.
Experience: Fourteen years consulting in the aerospace, automotive, and semiconductor industries.

TOPICS

1	Natural frequency and damping from flight data	13	Synthesizing time history to satisfy power spectral density using random vibration
2	Sine vibration characteristics, GRMS, histogram, kurtosis	14	Integration of acceleration time history to determine displacement and velocity
3	Sine sweep frequency, octave calculation	15	Integration of power spectral density
4	Random vibration characteristics, GRMS, histogram, kurtosis	16	Sample rate criteria/Nyquist rule
5	Nonstationary random vibration, GRMS versus time.	17	Aliasing
6	Fourier transforms	18	Filtering
7	Power spectral density, GRMS	19	Force shock, classical pulse, develop SRS
8	Transmissibility function for acceleration	20	Force shock, arbitrary pulse, develop SRS, arbit program
9	Transmissibility function for force	21	Base excitation, classical pulse, develop SRS, sdofi program
10	Vibration response spectrum – Miles rule	22	Base excitation, arbitrary pulse, develop SRS
11	Vibration response spectrum - general method	23	Integration to velocity and displacement
12	Synthesizing time history to satisfy power spectral density using sinusoids	24	Simple trend removal

(Continued on next page)

COURSE DESCRIPTION

The course includes reading material as well as hands-on software training.

1. Each student must have access to a PC with Windows 95, 98, ME, NT or 2000 operating system.

2. Each student will receive software programs that perform the following calculations: power spectral density (PSD), Fast Fourier Transforms (FFT), shock response spectrum (SRS), and digital filtering.

3. Students will receive time history data samples so that they can practice using the software programs.

4. Students must have a graphics program such as Axum, EasyPlot, Mathcad, Matlab, Origin, SigmaPlot, etc.

5. Each student may complete the course at his or her own pace. There is no time limit.

GRADUATES

Students from the following organizations have successfully taken this course:

Boshart Automotive Testing   Hitachi Medical Systems
British Petroleum   Racal Defense
Flir Systems

PREREQUISITES

Engineers, Technicians, and Managers who must analyze or interpret shock and vibration data or specifications will benefit from this course.

A degree in engineering or technology is helpful but is not required.

TUITION

The Tuition Fee is $800. Payable by check, money order, or PayPal.

REGISTRATION

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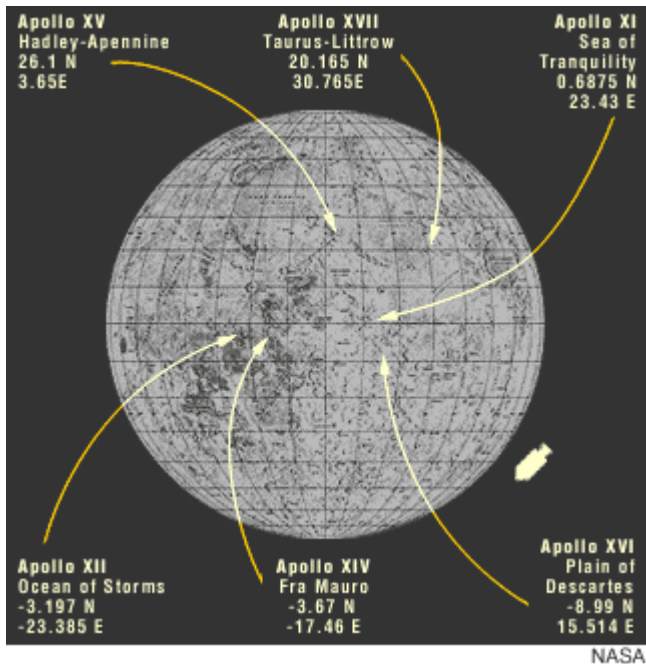FAX: 240-218-4810
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Figure 1-1.

Moonquakes

By Tom Irvine

Introduction

Twelve astronauts walked on the Moon during the years 1969-1972, as part of the Apollo program. This took place over six missions as shown in Figure 1-1 and in Table 1-1. Two astronauts from each mission ventured to the lunar surface, while a third astronaut remained in the command module.

The scientific experiments of the Apollo missions are documented in References 1-1 through 1-6.

The purpose of this article is to summarize the lunar seismic experiments.

Goals

The primary goal was to "x-ray" the interior of the Moon using seismic waves. This method had successfully been used to map the interior of the Earth, beginning with research by British geologist R.D. Oldham in 1906.

The respective velocities of the seismic primary waves (P-waves) and secondary waves (S-waves) were required in order to map the Moon's interior. Note that a P-wave is a longitudinal wave, or compression wave. In contrast, an S-wave is a shear wave. Both of these waves are body waves.

The wave velocities were obtained by measuring the travel times of the waveforms to the sensors set up at each of the landing locations, given in Table 1-1.

A second goal was to determine whether the Moon had any tectonic plate activity.

A third goal was to measure the meteorite impact rate, referred to as the "meteoroid flux."

Table 1-1. Apollo Lunar Mission Summary				
Mission	Date	Landing Site	Lunar Astronauts	Command Module Astronaut
11	July 16 - 24, 1969	Southern portion of the Sea of Tranquility	Armstrong and Aldrin	Collins
12	Nov 14 - 24, 1969	Ocean of Storms	Bean and Conrad	Gordon
14	Jan 31 to Feb 9, 1971	Fra Mauro Region	Shepard and Mitchell	Roosa
15	July 26 to Aug 7, 1971	Hadley Rille at the foot of the Apennine Mountains	Scott and Irwin	Worden
16	Apr 16 – 27, 1972	Descartes Highlands	Young and Duke	Mattingly
17	Dec 7 - 19, 1972	Taurus-Littrow Highlands	Cernan and Schmitt	Evans

Sensors

The astronauts collected rock samples on the Moon. They also set up seismic sensors to measure Moonquakes.

Scientists at ground stations on the Earth maintained two-way radio links with the seismic sensors. The scientists had the ability to send various command signals to the sensors, such as calibration commands. The sensors sent telemetry data back to these stations.

A diagram of the sensor housing is shown in Figure 1-2. The Long Period (LP) seismometers mounted inside the housing were based on a pendulum design as shown in Figure 1-3.

A seismometer consists simply of a mass that is free to move in one direction and that is suspended by a spring and hinge from a framework. The suspended mass is provided with damping to suppress vibrations at the natural frequency of the system. The framework rests on the lunar surface and moves with the surface. The suspended mass tends to remain fixed in space because of its own inertia, while the framework moves in relation to the mass. The resulting relative motion between the mass and the framework can be recorded and used to calculate the original ground motion, if the instrument constants are known.

In addition, a short period (high frequency) sensor was mounted in the housing, although it is omitted from Figure 1-2. The short period sensor measured the seismic vibration in the vertical axis only. It was designated SPZ.
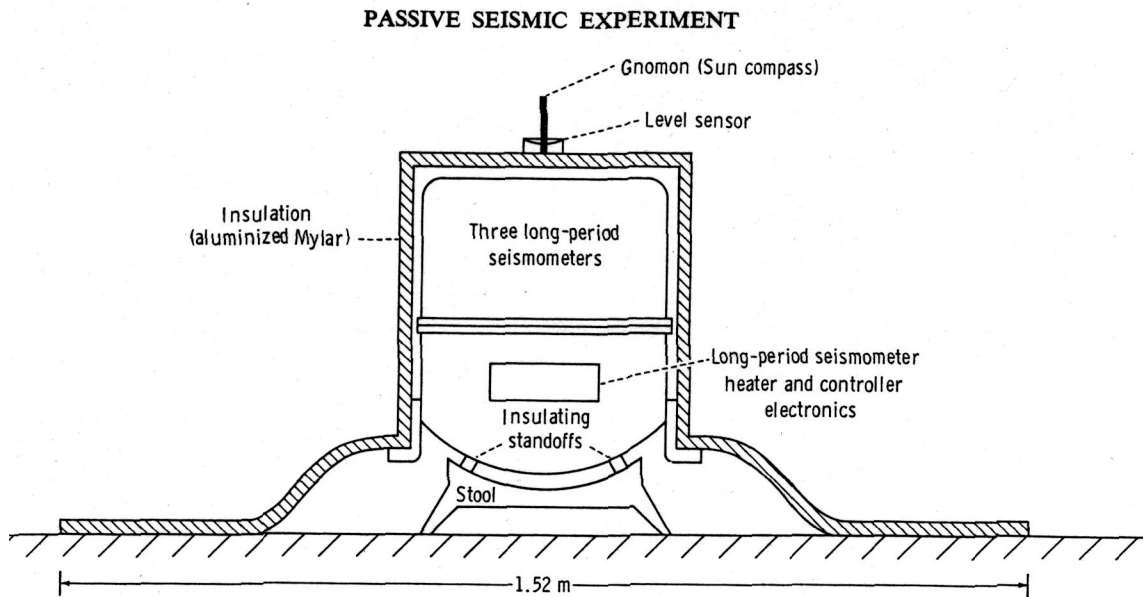
PASSIVE SEISMIC EXPERIMENT

Figure 1-2. Schematic Diagram of the Passive Experiment (PSE)

Solar Panel Vibration

The PSE was powered by rectangular solar panels that were attached by brackets to the PSE. These panels are omitted in Figure 1-2.

The PSE solar panels had a vertical oscillation mode of 2.6 Hz, according to Reference 1.

The panels were excited by micrometeorite impacts and by the sudden release of thermoelastic stresses.

The seismic sensors recorded the vibration of the solar panel events. The scientists thus had to carefully interpret the seismic records in order to determine whether a signal was due to an actual moonquake or to a solar panel response.
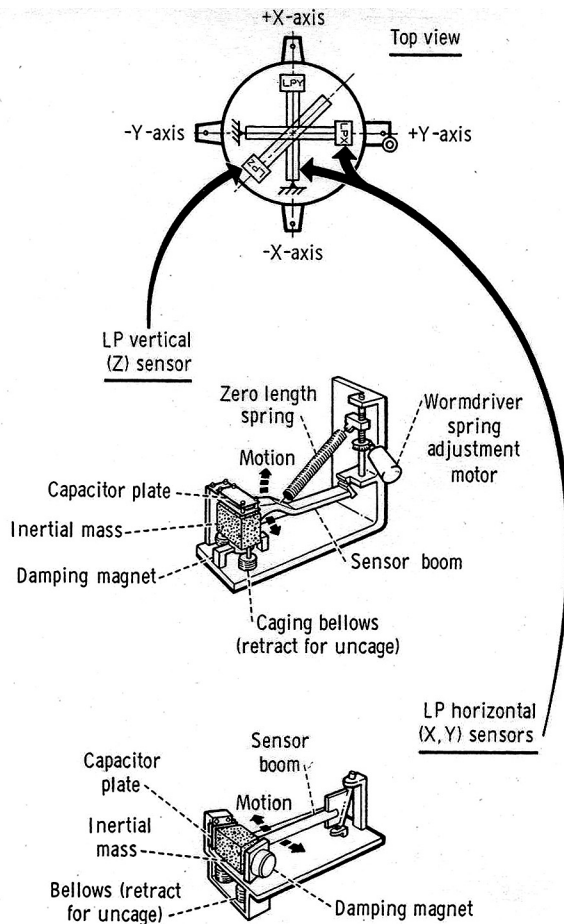
Figure 1-3. Long Period Sensor Details

Moon's Layers

The measured seismic data revealed that the Moon has a crust, mantle and core, as shown in Figure 1-4.

The crustal shell is about 65 km thick, although the thickness may vary greatly. The surface is composed of fractured rocks. These rocks have been smashed by impacts with meteorites. Some of the fractures may extend downward to a depth of 20 km below the surface.

The surface contains Breccias, which are composite rocks formed from all other rock types through crushing, mixing, and sintering during meteorite impacts.

The fine dust resulting from the meteorite impacts is called regolith. The regolith is the top, sub-layer of the crust. The regolith thickness is commonly estimated from the total crater population with a higher density implying a greater regolith thickness.

The mantle below the crust is a dense solid about 1000 km thick. The mantle is divided into two layers. The lithosphere extends from a depth of 65 km to 1000 km. The underlying asthenosphere extends from 1000 km

down to 1200 km. Furthermore, the lithosphere is rigid. The asthenosphere is relatively weak and perhaps partially molten.

A "moonquake zone" straddles the boundary between the lithosphere and the asthenosphere. This zone is discussed in the Deep Moonquake section.

The central core is softer than the mantle but is probably a solid rather than a liquid. The core radius is between 500 km and 800 km, as reported in Reference 1-6.

Shear waves do not readily propagate through the Moon's core. This core likely has a high temperature that approaches, but does not exceed, the melting point of the material. The attenuation of seismic shear waves is strongly dependent on temperature, with greater attenuation occurring at higher temperatures.
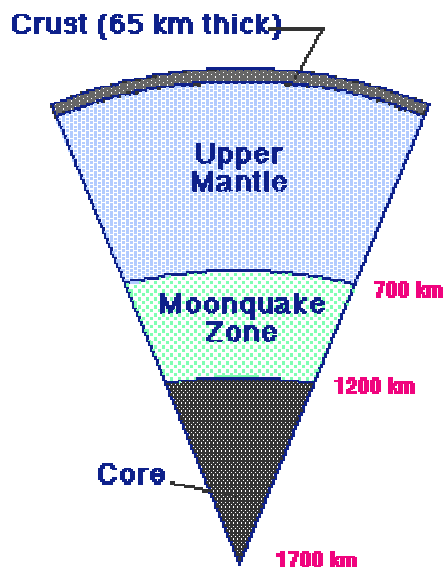

Figure 1-4. Moon's Layers

Wave Propagation

The velocity of P-waves in mantle is approximately 8 km/sec, according to Reference 1-5, page 9-8. The velocity in the crust is significantly slower due to the presence of broken rocks. Data from the Apollo 16 mission gave a P-wave velocity of 0.1 km/sec for the surface crust. This velocity is also called the "regolith velocity."

The S-wave velocity is slower than the P-wave velocity for all depths. This is true on both the Earth and the Moon.

The S-wave velocity in the lunar mantle is between 2 and 4 km/sec, depending on the depth, per Reference 1-5, Page 9-16.

Natural Moonquakes

The Earth is an elastic body. It has numerous active volcanoes. In addition, magma is continually upwelling at the midoceanic ridges, driving tectonic plates across a partially molten layer called the asthenosphere. Strain energy builds at the boundaries of these plates due to friction. The sudden release of this energy generates earthquakes.

In contrast, the Moon is a relatively rigid body. It lacks oceans, volcanoes, and tectonic plates. Nevertheless, the Apollo seismic sensors were able to record a number of natural events. These events are categorized as either shallow or deep Moonquakes.

Shallow Moonquakes

Shallow moonquakes are generated by thermal stresses along fracture planes in the lunar surface.

Note that the mean lunar surface temperature varies from 107° C at day

down to -153° C at night. The temperature difference is thus 260° C.

Differential expansion and contraction can thus occur between the opposing sides of a large fracture or bedding plane. This relative motion is impeded by friction along the boundary. Strain energy thus builds up until a rupture occurs. The sudden release of strain energy causes a moonquake.

Deep Moonquakes

Deep moonquakes originate at a depth of 700 km to 1200 km, in a zone that straddles the boundary between the lithosphere and the asthenosphere.

This moonquake zone may be a consequence of the differing yield strengths of the material within these two zones. Slow changes in the shape of the Moon, in response to time-varying tidal stresses produces stress concentrations at the lithosphere-asthenosphere boundary. Rupture occurs when the stress exceeds the shear strength of the material.

The deep moonquake activity is somewhat cyclical. Clusters of moonquakes occur when the Moon is at its apogee, or furthest point from the Earth. Fourteen days later, another cluster occurs when the Moon is at is perigee, or lowest point from the Earth.

Other orbital perturbations also affect the moonquake cycle.

Meteorite Impacts

Several criteria have been devised to distinguish moonquake signals from meteorite impact signals. The most useful are the characters of the shear waves and the time interval from the beginning of a signal to its maximum amplitude (signal rise time).

Moonquakes signals have impulsive shear wave arrivals and short rise times relative to those of impact signals. Furthermore, the shear wave is a much more prominent signal in the wave trains from moonquakes than in those from meteorite impacts.

In addition, many of the moonquake signals can be grouped into sets of matching events; signals of each set have nearly identical waves forms. Signals from meteorite impacts cannot be matched with one another, however.

Manmade Moonquakes

The seismic sensors measured both natural and manmade Moonquakes.

Some of the events were generated as spent third stage engines impacted the lunar surface, as shown in Figure 1-5.

In addition, the Apollo 12 astronauts crashed their lunar module ascent stage into the Moon's surface after the three astronauts had reunited in the command module.

Apollo 14 Active Seismic Experiment

Furthermore, the Apollo 14 astronauts, Shepard and Mitchell, performed an active seismic experiment (ASE) in which they detonated 13 small charges on the lunar surface. They used geophones to measure the resulting reverberation. The geophone had a moving magnetic coil to measure the ground vibration. The purpose of the ASE was to characterize the properties of the local crustal layer.

Apollo 16 Active Seismic Experiment

The Apollo 16 astronauts also performed an ASE. They used two methods to excite the lunar surface. The first method was a "thumper" device that detonated small charges.

The second method was a mortar assembly that fired grenades. The grenades detonated upon impacting the lunar surface. The resulting ground vibration was measured via geophones.

The Apollo 16 mortar experiment was actually a robotic device that was controlled from an Earth station. The grenades were fired after the astronauts had returned the Earth.

In addition, the Apollo 16 geophones were able to record the affects of the lunar module ascent stage thrust event. This was the event whereby the astronauts entered the lunar module ascent stage to rendezvous with the command module.

Reverberation

The data from the seismometers revealed that the Moon is very reverberant, with oscillations continuing for one hour or longer. Examples are shown in Figures 1-5 and 1-6.

In contrast, the 1964 Alaskan earthquake lasted less than five minutes, even though it had the highest magnitude of any quake ever recorded in North America.

Moonquakes have a long duration because the surface soil is dry and rough. It is also very heterogeneous. Craters and cracks in the surface rocks scatter the seismic waves in all directions.
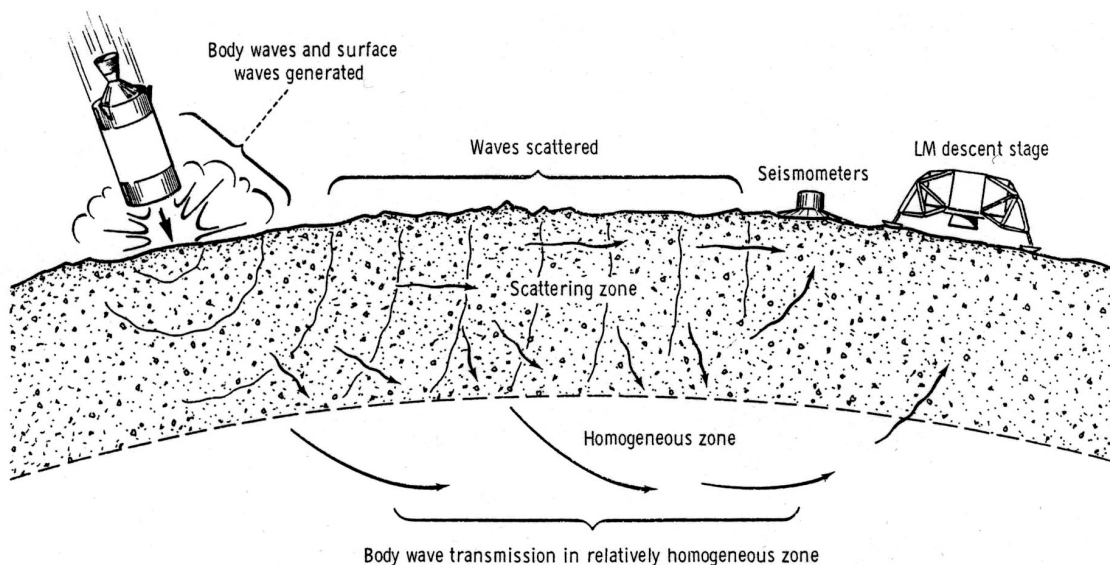

Figure 1-5. Seismic Wave Excitation and Scattering

The seismic waves generated at or near the surface are scattered intensively in a surface zone (scattering zone) with maximum thickness of 50 to 100 km. As the primary waves travel outward from the source, some of the seismic energy is scattered downward and "leaks" into the interior as compression waves and shear waves. Seismic waves travel through the interior (homogeneous zone) with little or no scattering and with very high efficiency, returning through the scattering zone.
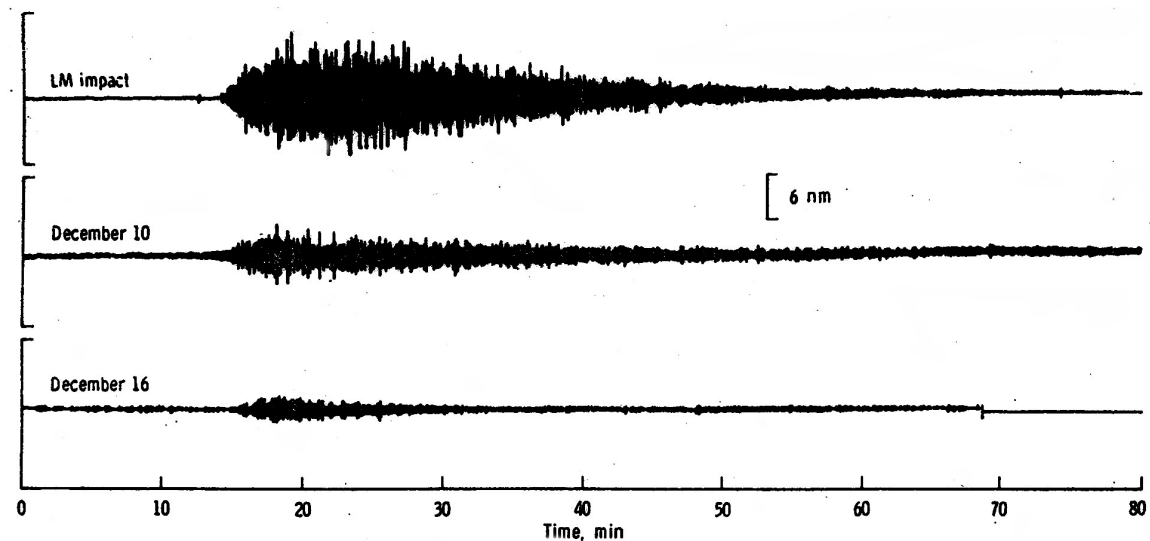
Figure 1-5. Lunar Seismic Time Histories

The time history at the top resulted from the Apollo 12 lunar module crashing into the lunar surface. The middle and bottom signals resulted from natural events. Only the vertical components are shown.

Note that the signals take several minutes to build up to their respective peaks levels. The signals oscillate for nearly an hour. The signals thus have "prolonged wave trains."

Furthermore, the phases corresponding to the various types of familiar body and surface waves are either indistinct or absent in the lunar signals.
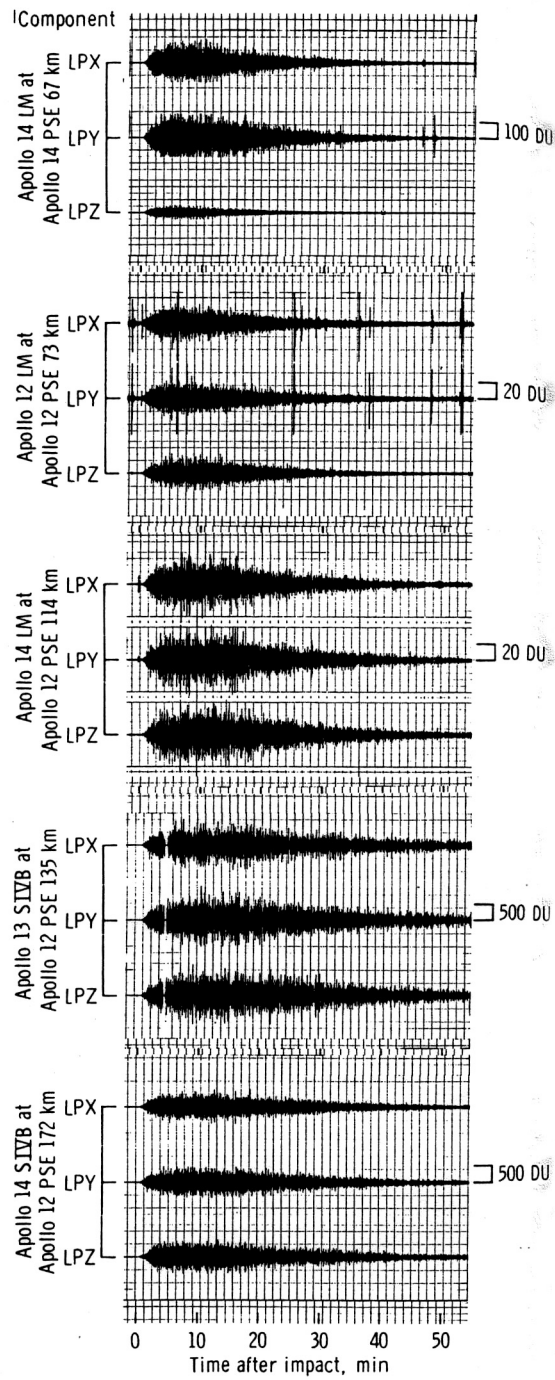
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Figure 1-6. Impact of the Apollo Third Stages and Lunar Modules

Note that the Apollo SIVB is the third stage.

Magnitude

Moonquakes have a benign magnitude relative to earthquakes. The strongest recorded moonquakes have a Richter Magnitude from 1 to 2.

In contrast, the 1964 Alaskan earthquake had a magnitude of 8.6. Note that the magnitude scale is logarithmic.

The lack of large Moonquakes implies the absence of plate tectonic activity like that which occurs on the Earth.

References

1-1.   NASA SP-214 Apollo 11 Preliminary Science Report, 1969.

1-2.   NASA SP-235, Apollo 12 Preliminary Science Report, 1970.

1-3.   NASA SP-272 Apollo 14 Preliminary Science Report, 1971.

1-4.   NASA SP-289 Apollo 15 Preliminary Science Report, 1971.

1-5.   NASA SP-315 Apollo 16 Preliminary Science Report, 1972.

1-6.   NASA SP-330, Apollo 17 Preliminary Science Report, 1973.

Suspension Footbridge Resonance Induced by Marching

By Tom Irvine

Introduction

Suspension bridges typically have very light damping.   Steel bridges, for example, have a damping ratio as low as 0.2%, according to Reference 2-1.

Thus even a small oscillating force can excite a resonant vibration.

Note that most people have a walking frequency from 1.6 to 2.4 Hz, according to Reference 2-1.

A particular concern is a procession of soldiers marching in unison across a bridge.   The bridge may oscillate violently if the cadence of their marching coincides with the bridge's natural frequency.   Thus soldiers will often break formation and walk at a random pace across a bridge.

There is some debate as to whether any bridge has actually failed due to resonant excitation from marching soldiers.

Nevertheless, marching may have contributed to the collapse of two bridges in the nineteenth century.

Broughton Suspension Bridge

The Broughton Suspension Bridge was built to span the River Irwell in Manchester, England.   The bridge failed on April 14, 1831.

On that day, men from the Sixtieth Rifle Corps were marching over the bridge in step. As a result, a pin in one of the suspension chains broke; and the bridge collapsed at one end.

Some authors claim that the rhythmic tread of the troops marching over the bridge provoked a violent harmonic motion, thus causing the collapse. Bishop gives this explanation in Reference 2-2, for example.

Other authors claim that the bridge was simply overloaded by the static weight of the soldiers.

Perhaps the bridge failed due to a combination of the static and dynamic loads.

Angers Suspension Bridge

The Angers Suspension Bridge was built across the Maine at Angers, France. It failed in 1850, twelve years after its opening.

During a thunderstorm, 478 French soldiers marched across the bridge. One of the bridge's anchoring cables embedded in concrete tore loose. The bridge roadway collapsed into the river. As a result, 226 soldiers were killed.

The French government appointed a commission to investigate this catastrophe.   The commission noted abnormal oxidization of the wires in the anchoring blocks and questioned the technique of embedding them in mortar blocks as a means of protection. However, this oxidization alone would not have been enough to cause the cables to break.

The failure was most likely caused by several related factors. The bridge was initially swaying in response to the wind gusts from the storm.   The soldiers generated additional oscillation as they marched in step across the bridge. Both the wind gusts and the marching action

may have had frequencies that coincided with the suspension bridge's natural frequency. Resonant excitation would have thus occurred. The resulting oscillations stressed the cables until they broke away from the mounting block.

The order to send the troops across the suspension bridge was disastrous given the storm conditions. It was also tragic considering that the soldiers could have crossed the river via a stone bridge at the center of town.

References

2-1.   H. Bachmann, et al., Vibration Problems in Structures, Birkhauser Verlag, Berlin, 1995.

2-2.   R.E.D. Bishop, Vibration, Second Edition, Cambridge University Press, London, 1979.