Vibration Spectrum Analysis by Steve Goldman

Appendix A: Pulse Theory

This author has spent many years lecturing to different groups of people who were interested in spectrum analysis for problems ranging from detailed physical tests of cavitation phenomena to philosophical questions about why the walls of Jericho fell. Often, a very simple explanation involving pulse theory has sufficed to explain some of the observed phenomena. This section is designed to give the reader food for thought rather than quantitative answers.

The Basic Characteristics Of The Pulse
The most commonly discussed pulse is probably the impulse. The unit impulse is a mathematical fiction and is shown in the time domain representation of Figure B.1a as having an amplitude of 1 unit and a width of 0 sec.

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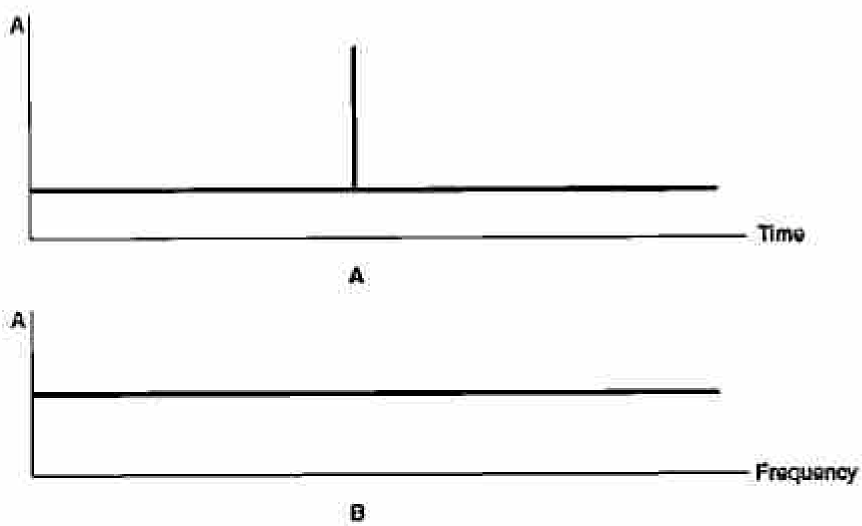

Figure B.1. The impulse.

The Fourier transform of a single impulse is pure white noise in the frequency domain. Since white noise has equal amplitude at all frequencies, the energy of the impulse is spread rather thin, yielding a low amplitude of white noise at all frequencies (see Figure B.1b).

Since we know that nothing in nature happens over a zero time duration, it makes sense to talk about a pulse of finite width. Figure B.2a shows a pulse of time width T sec. Note that the frequency domain of the pulse looks very different from the pure white noise spectrum caused by an impulse. Examination of Figure B.2b shows a series of lobes in the frequency domain. The first lobe contains most of the total energy of the pulse and rolls off toward the zero amplitude line at a frequency of 1/T. Each successive lobe has considerably less energy than the previous one and approaches zero amplitude at harmonics of I/T.

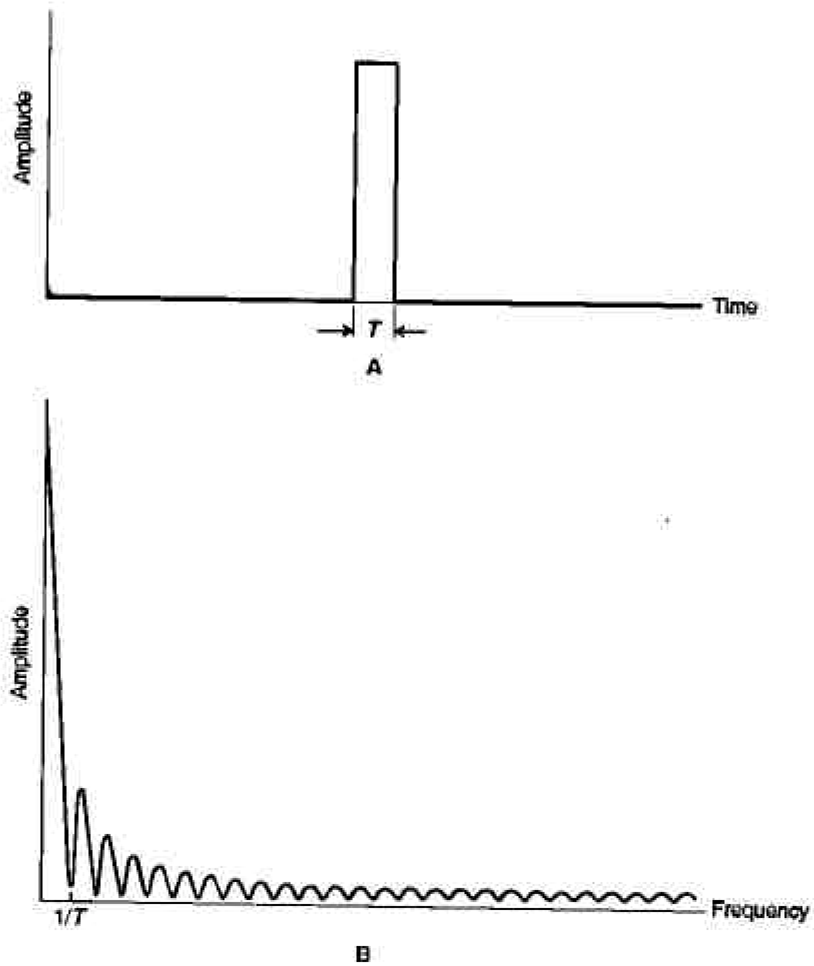

Figure B.2. A wide pulse.

Notice what happens when the FFT of a still wider pulse is taken, as in Figure B.3. Almost all of the energy of the pulse is located in the first lobe, going from 0 to I/T in frequency (note that 1/T is a lower frequency than for the narrower pulse discussed above because T is larger). Succeeding lobes have relatively little energy.

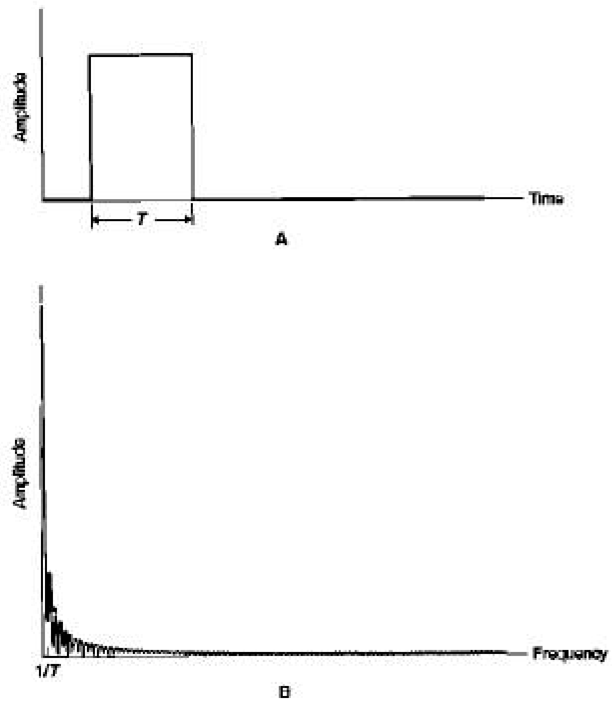

Figure B.3. A still wider pulse.

Ramifications of Pulse Duration

The key to all that follows lies in comparing the plots for the three pulse widths of Figures B.1, B.2, and B.3. Note that, as the width of the pulse increases, the distribution of the energy caused by the pulse shifts to lower frequencies. The effect that this energy shift has in some areas of everyday life will now be discussed.

Impulsive Testing for Natural-Frequency Determination

As discussed in Chapter 5, one very convenient way to determine the natural frequencies of a structure is to do a dual-channel impulsive (or, more properly, pulsive) test. An accelerometer is mounted on a judiciously selected location of the structure in question and connected to channel B of a dual-channel spectrum analyzer.

A special hammer, with a built-in force transducer, is connected to channel A of the analyzer. The structure is hammered at certain locations a number of times. A set of averages is taken for statistical accuracy.

The transfer function is calculated by the analyzer as the cross spectra of A and B divided by the power spectra of A and coherence is checked to determine the accuracy of the test. If the coherence is low, the natural frequencies of the structure cannot be determined with adequate certainty. One possible cause of this poor coherence has to do with pulse theory.

Hammer Hardness versus Coherence

It does not take much intuition to realize that a hard hammer tip will cause a short duration pulse. This is because the deflection of the hammer tip during the time of the blow is minimal. Since the hammer tip stops rather abruptly, the value of T describing the pulse shape is small.

Thus, a hard-tipped hammer will, because of its short time duration, have its energy spread out over a wide frequency range. The energy at any one particular frequency will be low.

Conversely, a soft-tipped hammer causes a long duration pulse. Most of the energy of such a blow will be in the low-frequency range of the first I/T lobe.

Figure B.4 shows the actual power spectra of a 1-lb PCB force hammer with a medium hardness tip.

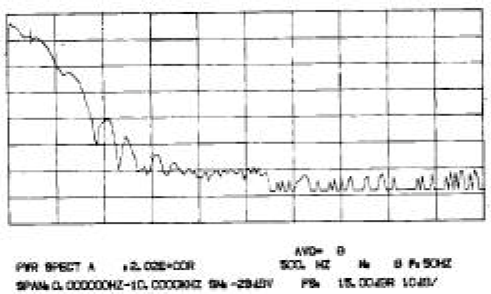

Figure B.4. The power spectrum of a 1-lb PCB force hammer with a medium hardness tip.

Because the energy distribution of the forcing spectra (hammer blow) changes with hammer tip hardness, careful consideration should be given to using the proper tip for the job at hand to insure good test coherence.

Large, Flexible Machine

Suppose that one is testing a large, flexible machine to determine its natural frequencies. The use of a hard-tipped hammer, which approximates an impulse in the time domain, would have a larger proportion of its energy at the high end of the frequency spectra. There will not be much energy available to excite the large mass of the machine with sufficient force to cause it to resonate at the low natural frequencies one would expect to find in a large, flexible machine. The accelerometer motion fed into channel B of the spectrum analyzer, therefore, would be too small to cause a high level of coherence. The test would be inclusive.

The solution to this problem is to use a soft-tip hammer. The resulting wide pulse will cause a large percentage of the energy of the hammer blow to be located in the low frequency region of interest. Thus, barring other test errors, a high level of coherence can be expected, yielding reliable results. This is why a 1-lb force hammer is often adequate to test objects as large as a locomotive.

Light, Stiff Machine
In testing a light, stiff structure, the expectation is that the natural frequencies will be high. Although a soft-tip hammer will certainly give the impression of moving the structure, the fact is that there may not be adequate energy at a high enough frequency to resonate the structure at the frequencies of interest.

The coherence of this kind of test can be improved by using a hard-tipped hammer. Although the energy of the hammer blow is distributed over a larger frequency range, there will be at least some energy in the high-frequency range of interest.

Cavitation and the Pulse
Cavitation occurs in the flow of a fluid when the pressure in a flow stream drops below the vapor pressure of the liquid, causing vapor bubbles to form. When local pressure further downstream increases above the liquid's vapor pressure, the bubbles implode. Considerable damage results to the metal surfaces in the vicinity of the millions of imploding bubbles. This is shown schematically in Figure B.5.

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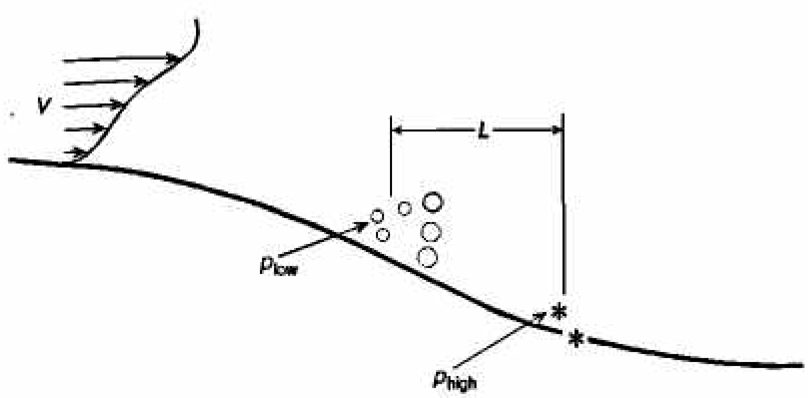

Figure B.5. Cavitation.

There are three common causes of vapor formation in a liquid:

1. Flow separation of a viscous fluid from its guiding surface due to a surface discontinuity

2. The addition of heat to the fluid, raising its vapor pressure (boiling point)

3. Reducing the pressure of the fluid to below its vapor pressure (as in the case of too high a vacuum in a liquid-ring vacuum pump)

If a flow is such that small vapor bubbles form and almost immediately implode, the bubbles that collapse will have been small because of inadequate time to grow. The resulting pulses will be quite short in the time domain, approximating white noise in the frequency domain. Thus, cavitation in a small, high-speed pump will sound like a hiss at most and may well be undetectable. The addition to a normal pump spectra of white noise will "fill in the valleys" between the usual peaks of running speed, blade frequency, and so on.

Small bubble cavitation may well cause high levels in a shock pulse or spike energy type of bearing fault detector, because the device cannot tell the difference between the white noise of a bad bearing and the white noise of a small bubble implosion. There is no difference. White noise is white noise. More will be said of white noise bearing fault detectors in a later section of this Appendix.

If the above mentioned small bubbles are permitted to grow in size, the pulses caused at their implosion will be wider in time duration. Since the wider pulses will have more energy in the low-frequency range, the modification to the spectra of a normally operating pump will be more dramatically changed by large bubble cavitation.

Bubbles can be allowed to grow by adding heat, dropping the pressure, using a lower vapor pressure liquid, or simply allowing the bubble to spend more time below its vapor pressure as it moves to its high pressure implosion location. Thus, while small, high-speed pumps hiss when cavitating, large, low-speed pumps sound like rocks hitting. Middle-size, medium-speed pumps sound like pebbles. These sounds can be changed by adding heat or pulling a localized vacuum on the liquid. Also, gasoline pumps are likely to have a deeper cavitation sound than a cold-water pump because of the difference in the vapor pressure of these two liquids.

As a result of the way in which the pulse shape of the cavitation of a particular sized bubble affects the vibration spectrum of the pump in question, it is not obvious that cavitation will always show up in as a clear pattern when performing condition monitoring on that pump. If large bubbles are expected, one would look for an increase in broad-band noise in the low-frequency range of the vibration spectra. If small bubbles are expected, condition monitoring will require an examination of the amplitude of the valleys between the peaks.

Rolling-Element Bearing Checkers

There are two basic methods of checking rolling-element bearing condition that have had some success. The classical method is to calculate the frequencies expected in a spectra for each possible component fault of a given bearing (based on the specific geometry of the bearing). We then look for these frequencies in the machine's vibration spectra. If there are no other signals obscuring these low-energy bearing frequencies, a failing bearing can be identified.

The shock pulse and spike energy methods of checking bearing condition are quite similar to each other in their basic operation. Both methods rely on the assumption that a small fault in one of the components of a rolling-element bearing will cause a short duration pulse when it comes in contact with another part of the bearing (for example, an outer race fault contacting a ball).

Since the components of a rolling-element bearing are quite hard, the pulse mentioned above will approximate an impulse. Thus, the signal one may expect from a bearing fault will be white noise in the frequency domain. Remembering that white noise contains all frequencies at equal amplitude, the manufacturers of bearing-checking devices need only follow a routine to observe bearing condition in a frequency region above that normally contaminated by such signals as blade frequency, gear mesh, sidebands, and so on.

A rolling-element bearing checker is basically a meter that reads the output of a band pass filter selected to remove everything except the response of the natural frequency of an accelerometer to a pulse. The operation of such a device can be simulated as follows:

1. Mount an accelerometer with a known natural frequency, usually between 30 and 50 kHz, as close to the bearing as possible. There should be no electronic dampening of the natural frequency.

2. Since the accelerometer has a natural frequency of, say, 36 kHz, it will amplify, by a factor of several orders of magnitude, the level of the signal at 36 kHz. It will not amplify other signals, such as a 400-Hz gear mesh

3. Put the output signal of the accelerometer through a bandpass filter with a center frequency equal to the accelerometer's natural frequency, in our example, 36 kHz.

4. Measure the amplitude of the output of the bandpass filter.

5. As more faults occur in the bearing, the level of the white noise increases. This increases the amplitude of the output of the bandpass filter, showing incipient failure of the bearing assembly.

6. Older bearing-checking devices simply measured the output of the bandpass filter. One was expected to trend this value in order to trend bearing condition. Newer devices follow the time variation of the output of the filter, crunch some numbers in various algorithms, and display a calculated value that represents the time variation of the white-noise signal caused by a bearing fault.

There are two possible problems in using the shock-pulse method of monitoring bearing condition. One is the inability to differentiate between various sources of white noise. The other is the phenomena of the “healing bearing."

White-Noise Differentiation

As stated above, the shock-pulse method cannot differentiate between one source of white noise and another. A bearing checker designed to measure the amplitude of white noise amplified by the natural frequency of its accelerometer may well yield high values due to a bearing fault. The problem, however, is that it will also yield high values due to small bubble cavitation, steam leaks near the accelerometer, turbulence, and so on. The presence of steam leaks near a bearing to be monitored is a common problem in the dryer section of paper mills, where this method, if blindly followed, will lead to the replacement of a great many perfectly good bearings.

Healing Bearings

It has occasionally been found by people who regularly take white-noise-type bearing readings that a given bearing will show signs of deteriorating but, shortly before total failure, exhibit lower amplitude values. Machinery monitoring personnel have been fooled into believing that the bearing was getting better by lower readings when it was actually on the verge of failure. A possible explanation of this phenomenon can be found in pulse theory.

Suppose the bearing was failing not simply by adding more tiny faults (which would increase the white noise content), but because the existing fault was growing. As the fault grew, the time duration of the pulse generated when the fault came in contact with other components of the bearing would grow. The pulse would lose more and more of its white noise characteristics until there was no more energy in the frequency range necessary to excite the natural frequency of the accelerometer. The amplitude reading of the bearing-checking box would drop, implying that the bearing had healed (see Figure B.6).

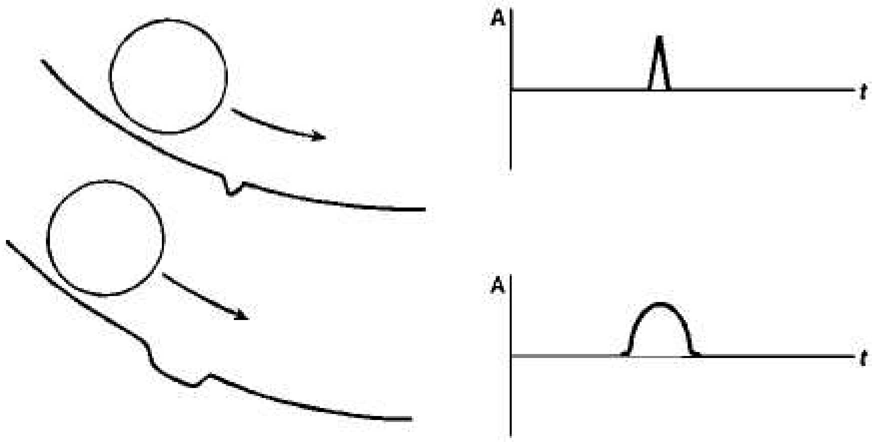

Figure B.6. A healing bearing.

The above described possibility for a bearing to appear to heal puts an additional requirement on the work of machinery-monitoring personnel. When the reading of a bearing-checking device begins to drop for a particular bearing, careful consideration must be given to the possibility that the bearing is very near to failure. It is wise, at this point, to look at the amplitudes of the classical discrete frequencies of that bearing in order to make a decision as to when it must be changed.

The Walls of Jericho

To demonstrate that pulse theory may be applied to a great many varied phenomena, one last case will be covered: the falling of the walls of Jericho. Jericho is one of the oldest known cities on earth.

The people of Jericho were not very good wall builders. In fact, the walls of Jericho had fallen many times before the time of Joshua.

Figure B.7. The walls of Jericho.

As can be seen by the background of the photo of some of the remains of the walls of Jericho in Figure B.7, Jericho is located on a fertile plain, not on sand and gravel, as many people think. The area was probably the same in Joshua's time; it was not called “The Land of Milk and Honey” because it was an arid desert. Note that wet, fertile ground transmits low-frequency signals rather well.

Stone walls, especially of the primitive kind shown in the photo, tend to have a large mass and a very little stiffness. Therefore, the natural frequency of the structure would be quite low. Joshua commanded his people to march around the city seven times, blowing ram's horns and shouting and the walls came tumbling down.

Pulse theory yields, an interesting insight into this historical event. The blowing ram's horns and shouting would cause pressure waves of rather high frequency, several hundred to several thousand Hertz. It is extremely unlikely that these pressure waves, while certainly capable of scaring the wits out of the citizens of Jericho, would have been capable of causing the low natural frequency walls to collapse.

On the other hand, the stomping of a large number of feet on fertile ground would have caused long-time-duration pulses of rather high amplitude. Pulse theory tells us that long-time-duration pulses have most of their energy concentrated in the low-frequency range, near the natural frequency of the wall.

We can surmise, therefore, that the walls of Jericho fell due to the marching of the Jews, not their shouting or blowing or ram's horns. The miracle was not that the walls fell, but that pulse theory was successfully employed by an ancient general at an ancient city to change history.

Something to Think About

The effect of the shape of a pulse is something that is so well known and so widely taken for granted by many of us that its ramifications in vibration analysis are seldom considered. This is unfortunate because, as shown above, the due consideration of the relationship of pulse shape to frequency response can lead to a great many insights and hypotheses that may well provide a better understanding of the phenomena being studied.