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Shock Motions and Their Measurement

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Introduction

A review in expanded outline form is presented, wherein shock motions and means of their measurement are described. Because of their present popularity, more detailed considerations are given to piezoelectric accelerometers. References to recent literature are included which contain detailed considerations of these subjects. The first three references are regularly issued publications. References 4 through 13 are handbooks and texts. The remaining refer to individual papers.

Shock Motions, Shock Spectra, Simple Shock Pulses

A *shock motion* is defined[14] as a transient disturbance that involves a significant change in position in a relatively short time. Shock motions normally encountered in field work involve translations and rotations in all directions. In addition there are distortions and relative motions which may cause damage to items having several attachment points. Consideration is given here, as usual, to only the translational component of motion in a uniaxial direction.

Recordings of shock motions as normally obtained from field measurements are too complex to be of direct use to the engineer. They must be expressed in some simplified manner which includes their most significant components of *damage potential.* What constitutes damage potential is complicated and controversial, but, roughly, the probability of damage to an item can be taken as proportional to the magnitude of response of the item to a shock motion. Fatigue is important if the shocks involve many cycles of stress.

Shock Spectra[15] constitute one such way of expressing the damage potentials of shock motions. Consider a series of mass-spring systems (single-degree-of-freedom systems) having a range of natural frequencies and attached to a common rigid base. The base is then subjected to a shock motion. The *shock spectrum* of that motion is a curve representing the maximum responses of each of these systems plotted as a function of their natural frequencies. Shock spectra can be expressed in terms of (absolute) accelerations, velocities or (relative) displacements.

If the duration of the shock transient is very short, such as may be caused by an impact when an item is dropped, then it may be permissible to approximate the shock motion by merely expressing it as a sudden velocity change. This is called *velocity shock* (see Ref. 3, page 89) and its magnitude is equal to the step-change in velocity. If the duration of the impact time is appreciable, then the shock may be approximated by a simple pulse. A *half-period sine pulse* (of acceleration) is frequently used because it is easy to generate; a rigid mass dropped against a linear spring experiences a half-period sine pulse. However, a *sawtooth pulse*[16] is generally considered to be better for test purposes as its shock spectra has equal positive and negative values with no periodically varying small values. The *maximum value* of acceleration is significant only if its duration (time spent near the maximum value) is long compared with periods of fundamental modes of vibration of an item subjected to the acceleration. This statement is generally true relative to structural damage;

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however, exceptions occur for conditions such as relay chatter and microphonics. When the waveform of the shock motion is complex in a significant manner, then it may be analyzed in terms of a continuous Fourier spectrum (Fourier integral techniques), or its damage potential can be expressed in terms of a shock spectrum.

Although shock motions are not usually analyzed in terms of their frequency components, it is useful, from the viewpoint of their measurement, to think of the frequency-amplitude range associated with their Fourier spectra. The shock motions can be measured in terms of acceleration, velocity or displacement. As the ranges of amplitudes involved in the three cases are greatly different, there are advantages in selecting a unit which provides the most convenient range for measurement. If the shocks are caused by an impact, it can be taken as a rule-of-thumb that the range of maximum probable velocity amplitudes will be small and independent of frequency. The maximum probable amplitude values of accelerations will increase directly with frequency, and the maximum probable amplitude values of displacements will decrease inversely with frequency. (The rule is, of course, applicable only within a limited frequency range.) This makes the measurement of shock motions in terms of velocity much easier than in terms of displacement or acceleration because of the smaller range of values encountered for an extended frequency coverage. However, if high frequencies are of most importance, then acceleration measurements are indicated, and if low frequencies are of most importance, then displacement records may be obtained. These can, of course, be obtained by integrating the output of an accelerometer.

Transducers or Pickups

A *transducer*, or *pickup*, is a device that converts a quantity to be measured into a signal that is more easily recorded. Pickups that provide output signals proportional respectively to displacement, velocity, or acceleration, are called displacement, velocity, or acceleration pickups, although the latter is usually misnamed by calling it an accelerometer.

All pickups are limited as to the *amplitude and frequency range* over which they will perform with acceptable accuracy. These ranges must be specified.[17,18] The pickup specification should state (Ref. 6, chapter 15) upper and lower frequency limits and upper and lower amplitude limits within which it will perform within specified accuracy. Calibrations[18] are required to establish the specifications and to check the sensitivity of the pickup. The *sensitivity* is defined as the ratio between the output and input of the pickup. As phase and amplitude are both involved, this ratio is a complex number.

Pickups of all types have been extensively discussed in recent literature.[7,9,11] Because of this, consideration will be limited to piezoelectric type accelerometers (acceleration pickups) which have undergone considerable improvements in the last few years.

Mechanical Considerations

An accelerometer consists essentially of a mass supported by a sensing element which, in the case considered, is a piezoelectric material. In order for the mass to experience the same acceleration as the accelerometer case, and consequently exert an inertial force on the sensor which is proportional to the acceleration, the support must be relatively rigid. This condition exists for all frequencies less than about 1/4 the natural frequency of the system. The accelerometer should therefore have a natural frequency as high as possible, and at least 4 times as high as any measured frequency component. The pickup should be as small and light as possible so that its weight will not influence the shock motions. However, as the pickup is made smaller, and of higher natural frequency, its sensitivity decreases, and suitable compromises must be made to obtain optimum values.

Sensing Elements

A general consideration of sensing elements is given in Ref. 9, chapter 15. Discussion will be limited here to ceramic piezoelectric materials[12,13] of the barium titanate class. The electrical properties of these materials are analogous to the magnetic properties of iron, so they are sometimes called "ferroelectric" materials. The ceramics can have their sensitive piezoelectric axis established in any direction by applying a suitable polarizing voltage under proper temperature conditions. The piezoelectric properties can be improved by adding suitable "impurities." Nonlinearities and relaxation effects become important if pressures or voltages of excessive values are applied; or if lesser values are applied for long times. These effects would be functions of temperature. At a certain upper temperature limit, called the *Curie Point*, the thermal energy is sufficient to destroy the polarization, and the material ceases to be piezoelectric. Low-temperature Curie Points (transition temperatures) may also exist below which the piezoelectric effect becomes small. Devices employing these materials should operate within these temperature limits.

Zero Shifts and Spurious Outputs

Fortunately, zero shifts and output distortions of an accelerometer and associated equipment can usually be recognized from the appearance of the record. In addition, the integration of the record should give values that check with final values of velocity and displacement involved. The latter are usually known. Causes of distorted outputs will now be considered.

If an accelerometer is operated within limits established by the manufacturer, most causes of zero shifts are faults of the associated electrical equipment. These faults are:

1. Inadequate Time Constant. The piezoelectric sensor generates a given charge (quanitity of electricity) in response to a given acceleration (force). This charge will gradually leak through any resistance across the sensor. This will make it appear as though the acceleration were decreasing. If the acceleration should become zero, the sensor will absorb the charge it had previously developed. If this charge has leaked away, a signal will be generated which appears like an acceleration of opposite sign. To eliminate this effect, the "RC" time constant must be made large compared to periods of acceleration pulses. R is the leakage resistance and C is the capacitance of, and in parallel with, the sensor.
2. Nonlinear Amplification. If a low-pass filter is used to eliminate an upper frequency range of accelerations, and if an amplifier provides less amplification for, say, negative signals than for positive signals in this upper frequency range, then a "rectified" signal will result which will be passed by the filter and appears as a zero shift. To reduce this effect, place more capacity across the accelerometer so as to reduce its voltage output, or use preamplifiers capable of handling greater swings of input voltage.
3. Cable Signals. The cable connecting the accelerometer to the preamplifier is subjected to severe shock motions that may cause it to develop electrical signals. Tests for this effect can be made by subjecting the cable to the shock motion while it is disconnected from the accelerometer. To reduce this effect, use specially prepared low-noise cable and higher output accelerometers.
4. Ringing Frequencies. Characteristic frequencies, in particular, cut-off frequencies of filters, may be shock-excited and appear in the record. These can be eliminated by introducing resistance in the electrical circuits in which the ringing occurs.

Occasionally spurious signals are the fault of the accelerometer. Frequency-dependent amplitude and phase distortions are functions of the natural frequencies and damping of the pickup. The frequency range where these are important is above that which should be specified for their proper operation.[17] Spurious signals may occasionally be introduced by the sensor. It is not surprising that this is so. The piezoelectric material consists of electric domains whose change-of-alignment cause changes of the dimensions of the material. A load applied to the material will cause some domains to change direction. This is accomplished by internal stresses and mechanical relaxations. Removal of the load will permit internal stresses and electrical forces to eventually bring about the original condition. For relatively small loads applied for relatively short times, the magnitudes of these effects are negligible. However when the loads become excessive and when they are applied for an appreciable time, a significant amount of internal inelastic motion may take place. When the load is removed, an appreciable time is required for the internal elastic stresses to re-establish the original condition. During this time the signal will slowly drift back to zero. To eliminate this effect requires either that a better sensor material be used or that the sensor be subjected to less load.

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