Tablet Press Instrumentation

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INTRODUCTION

This article is designed to facilitate the understanding of the general principles of tablet press instrumentation and the benefits thereof by the formulators, process engineers, validation specialists, and quality assurance personnel, as well as production floor supervisors who would like to understand the basic standards and techniques of getting information about their tableting process.

HISTORY OF TABLET PRESS INSTRUMENTATION

In 1952 1954 Higuchi and his group[1] have instrumented upper and lower compression, ejection, and punch displacement on an eccentric tablet press, and pioneered the modern study of compaction process. This work was followed by Nelson[2,3] who was the member of the original group.

In 1966, a U.S. patent was granted to Knoechel and co workers[4] for force measurement on a tablet press. This patent was followed by two seminal articles in Journal of Pharmaceutical Sciences on the practical applications of instrumented rotary tablet machines.[5,6] A number of other patents related to press instrumentation and control followed from 1973 on ward.[7 15]

Despite the availability of published designs for instrumenting rotary presses, much of the early work on compaction properties of materials was done on instru mented single punch eccentric presses primarily, due to the relative ease of sensor installation, as well as availability of punch displacement measurement.[16 18]

In mid 1980s, custom made press monitoring systems were described,[19,20] and the first commercial instrumen tation packages became available, including both the systems for product development and press control. The first personal computer based tablet press monitor was sold in 1987, and the first Microsoft Windows based press instrumentation package in 1995.

A new era of compaction research has begun with the introduction of an instrumented compaction simulator[21] in 1976, while a compaction simulator patent was issued as recently as 1996.[22]

A new generation of "compaction simulators" was born when a mechanical press replicator was patented in the year 2000.[23]

A good exposé of the early stages of press instrumentation and resulting research is presented in review articles by Schwartz,[24] Marshall,[25] and Jones.[26] A comprehensive review can be found in a relatively recent paper by Çelik and Ruegger.[27]

For other historical information on the press instru mentation, the reader is encouraged to peruse Ridgeway Watt's[28] volume. There have been a number of papers published on various disparate instrumentation topics, and in a recent volume by Muños Ruiz and Vromans,[29] there are two good articles on the subject but, unfortunately, they deal with marginal issues of single station press and instrumented punch only.

DATA ACQUISITION PRINCIPLES: FROM TRANSDUCERS TO COMPUTERS

To monitor and control a tablet press, certain sensors must be installed at specific locations on the machine. These sensors are called transducers. In general, a transducer is a device that converts energy from one form to another (e.g., force to voltage). Tablet press transducers typically measure applied force, turret speed, or punch position. Because the signals coming from such transducers are normally in millivolts, they need to be amplified and then converted to digital form in order to be processed by a data acquisition system.

Piezoelectric Gages

Historically, high impedance piezoelectric transducers that employ quartz crystals were used in early stages of press instrumentation. When subject to stress, the crystal accumulates electrostatic charge that is directly propor tional to the applied force. Both low and (more modern) high impedance piezoelectric gages have high frequency response, but may exhibit signal drifting due to charge

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leakage (approximately 0.04% decay per second can be seen in modern piezoelectric transducers). Nowadays, the preferred way of instrumenting tablet presses is with strain gages.

Strain Gages

Strain gages are foil, wire, or semiconductor devices that convert pressure or force into electrical voltage. When a stress is applied to a thin wire, it becomes longer and thinner. Both factors contribute to increased electrical resistance. If an electrical current is sent through this wire, it will be affected by the changes in the resistance of the conduit. This principle is used in strain gage-based transducers. Foil gages, known for robust application range, useful nominal resistance, and reliable sensitivity control, are most commonly used for instrumentation of compression, precompression, and ejection forces. Semiconductor-based strain gages are inherently more sensitive but suffer from high electrical noise and temperature sensitivity. Such gages are not commonly used in tablet press instrumentation except for measurement of die-wall pressure and take-off forces.

Wheatstone Bridge

Wheatstone bridge (Fig. 1) is a special arrangement of strain gages that is used to ensure signal balancing. The "full" bridge is composed of two pairs of resistors in a circle, with two parallel branches used for input and two for signal output. By applying the so-called excitation voltage (typically, 10 V DC) to the bridge input and changing the resistance of different "legs" of the bridge by adding special resistors, we can make sure that there is a zero output voltage when no load is applied to the transducer. This is called zero balance. Once the bridge is

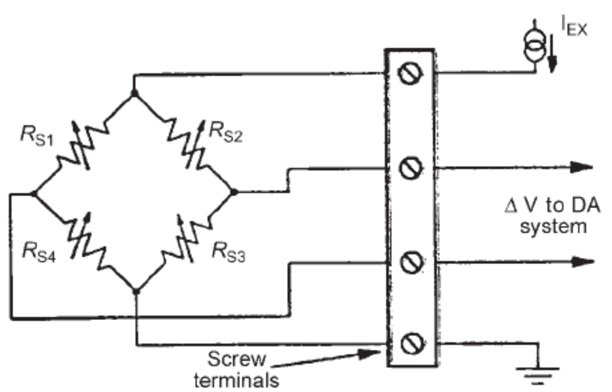

Fig. 1 A typical Wheatstone bridge arrangement of strain gages.

balanced, a small perturbation in the resistance of any "leg" of the bridge results in a nonzero signal output.

The output of the Wheatstone bridge is normally expressed in millivolts per volt of excitation per unit of applied force. For example, sensitivity of 0.2 mV/V/kN means that applying, say, 10 kN force and 10 V excitation will produce 20 mV output. To utilize such output, it usually needs to be amplified several hundred times to reach units of volts.

Another important function of the bridge is balancing of temperature effects. Although individual strain gages are sensitive to temperature fluctuations, Wheatstone bridge arrangement provides for temperature sensitivity compensation, so that the resulting transducer is no longer changing its output to any significant degree when it heats up.

Because the output of these bridges is in the range of millivolts, the cables utilized to carry the signal are normally shielded with a braided or foil-lined sheath around individual wires. The shield, as a rule, is connected to the amplifier, but never touches the actual instrumented equipment (i.e., tablet press). If this rule is violated, a ground loop may generate electrical noise and present a dangerous electrical shock hazard.

Gage Factor

The gage factor is a specific characteristic of a strain gage. It is calculated as the change in resistance relative to unit strain that has caused this change. Strain gages that are commonly used for tablet press instrumentation are made from copper nickel alloy and have a gage factor of about 2. In a typical bending beam application (such as compression roll transducer), one side of the beam experiences tension while the other side undergoes compression. By mounting two gages on each side, the sensitivity of the transducer can be doubled.

Strain gages have to be bonded to areas of machine parts that are most sensitive to applied force. Such areas can be identified with the use of polarized light technique that "points out" the stress distribution.

Manufacturing a Force Transducer

Usually, instrumentation designs are proprietary and specific detail drawings are held in fiducial capacity. Each force transducer is custom designed for a particular machine part. Overall specifications are taken from the actual party and/or manufacturer approved drawings.

Duplicate steel members, such as pins and cams, are normally made from A2 tool steel in a fully annealed (softened) state. Original machine parts are first annealed, if required. The member is then machined, hardened to Rockwell 60 64, tested, and finally, ground to specified dimensions.

It is highly advantageous to determine stress distribution using polarized light beams identifying the areas of maximum strain yet avoiding areas of uneven strain.

A typical procedure of transducer manufacturing in a professional gaging lab might be as follows. Foil type strain gages are bonded to the steel member utilizing a high-performance 100% solid epoxy system adhesive under controlled heating rate conditions. After intrabridge wiring is completed using solid conductor wiring (to prevent electrical noise), multistrand wire cabling with a combination of foil and braided insulation is connected to the bridge. Wire anchoring is achieved utilizing epoxy adhesive and protected with a combination of latex-based adhesives and/or epoxy resins. Lead wire cabling is protected by Teflon outer shield, as well as inner braided wire shield. The Teflon to steel joint is sealed with epoxy but should not be subject to stresses that would cause the cable to kink or yield in such a way as to expose the inner braided wire shield. Protective coatings are then applied and final postcure heating is performed for at least 2 hr at a temperature approximately 50°C above the transducer normal operating temperature (approximately 175 or 105 °C). A silicon-based adhesive, such as RTV, is used to fill large cavities while maintaining a low modulus of elasticity, preventing undue influence upon the actual strain measurement. The coating is resilient to moderate mechanical abrasion, as well as most solvents, oils, cleaners, etc. It is not intended for protection against penetrating sharp objects.

A high-quality connector is then attached to the cable. The next step is to perform offset zeroing with fixed, 1% precision, low-temperature coefficient resistors, followed by NIST (National Institute for Standards and Technology) traceable calibration.

It is worth noting that, in general, the duplicate members are not made of corrosion-resistant steel, because high tensile strength and ability to be easily machined are required. Prior to storage, the surface should be treated like any high-grade tablet press punch steel will be treated; a thin coating of oil should be used after wiping with alcohol.

Load Cells

In some cases, where appropriate, a load cell can be used in place of bonded strain gages.

A load cell is a strain gage bridge in an enclosure forming a complete transducer device.

Like any properly made transducer, it produces an output signal proportional to the applied load. Unlike custom-made transducers that require application of strain gages directly to press parts, load cells are self-contained and can be placed on a press in specially machined cavities to be easily replaced or serviced. As a drawback, load cells generally are less sensitive or less suited to measure the absolute force than custom-made strain gage transducers. Load cells can be used on punch holders in a single station press. Another example of load cell use is a die assembly for calibration of existing traducers on a press.

Linear Variable Differential Transformer

Linear variable differential transformer (LVDT, Fig. 2) is a device that produces voltage proportional to the position of a core rod inside a cylinder body. It measures displacement or a position of an object relative to some predefined zero location. On tablet presses, LVDTs are used to measure punch displacement and in-die thickness. They generally have very high precision and accuracy, but there are numerous practical concerns regarding improper mounting or maintenance of such transducers on tablet presses.

Proximity Switch

Proximity switch (Fig. 3) is a noncontact electromagnetic pickup device that senses the presence of metal. On tablet presses, it is widely used to detect the beginning of a turret

Fig. 2 Linear variable differential transformer (LVDT).

Fig. 3 Proximity switch.

revolution, to identify stations and to facilitate peak detection in tablet force control applications.

Instrumentation Amplifier and Signal Conditioning

Signal conditioning involves primarily an amplifier that provides the excitation voltage, as well as gain (a factor used in converting millivolt output of the strain gage bridge to the volt-based range of the input of the data acquisition device).

Instrumentation amplifier is different from other types of amplifiers in that the signal from each side of the transducer bridge is amplified separately and then the difference between the two amplified signals is, in turn, amplified. As a result, noise from both sides of the sensors is reduced.

Some instrumentation amplifiers also offer filter functionality. A filter circuit combines resistors and capacitors that act to block the undesirable frequencies. It is a fact, however, that a good transducer should provide a clean signal. Use of analog or digital filters may cause the loss of some important portions of the signal that one is attempting to measure. Frequency filters may cause the measured compression force peak, for example, to be skewed toward the trailing edge of the peak and can yield a lower than actual peak force. Because filters distort the signal, they must be avoided unless absolutely necessary. In many cases, better electronics may make filter use obsolete. For example, the so-called antialiasing filter that is used to condition a high-frequency signal for a slow sampling rate is generally not required for tablet press applications if modern fast speed data acquisition devices are used for signal processing.

In addition to amplification, excitation, and filtering, signal-conditioning devices may provide isolation, voltage division, surge protection, and current-to-voltage conversion.

Instrumentation Terms: Definitions

Several important terms may be now defined with respect to transducers and signal conditioning:

- *Full Scale (FS)*: The total interval over which a transducer is intended to operate. Also, it can define the output from transducer when the maximum load is applied.
- *Excitation*: The voltage applied to the input terminals of a strain gage bridge.
- *Accuracy*: The closeness with which a measurement approaches the true value of a variable being measured. It defines the error of reading. Good tablet press transducers have at least 1% accuracy (with this level of accuracy, for example, a compression force transducer with 50 kN FS will produce at most an error of 500 N).
- *Precision*: Reproducibility of a measurement, i.e., how much successive readings of the same fixed value of a variable differ from one another. If a person is shooting darts, for example, the accuracy is determined by how close to the bull's eye the darts have landed, while the precision will be indicated by how close the darts are to each other.
- *Resolution*: The smallest change in measured value that the instrument can detect.
- *Dynamic range of a transducer*: The difference between the maximal FS level and the lowest detectable signal. Measured in decibels (dB), it indicates the ratio of signal maximum to minimum levels:

$$\mathrm{dB} \quad 10\log_{10}(S_{\max}/S_{\min})$$

  Some press sensors may have a rather narrow dynamic range not necessarily correlated with accuracy. For example, a very accurate compression roll pin designed to measure 50 kN force may not detect 5 kN signal.
- *Calibration*: Comparison of transducer outputs at standard test loads to output of a known standard at the same load levels. A line representing the best fit to data is called a calibration graph.
- *Calibration factor*: A load value in engineering units that a transducer will indicate for each volt of output, after amplifier gain and balance. Calibration factor is usually expressed in relation to FS.
- *Shunt calibration*: A procedure of transducer testing when a resistor with a known value is connected to one leg of the bridge. The output should correspond to the voltage specified in the calibration certificate. If it does not, something is wrong and the transducer needs to be inspected for possible damage or recalibrated.

- *Sensitivity*: The ratio of a change in measurement value to a change in measured variable. For example, if a person ate a 1 lb steak and the bathroom scale shows 2 lb increase in the body weight, then the scale can be called as insensitive (ratio is far from unity).
- *Traceability*: The step-by-step transfer process by which the transducer calibration can be related to primary standards. During any calibration process, transducer is compared to a known standard. National or international institutions usually prescribe the standards. In the United States, such governing body is the NIST.
- *Measurement errors*: Any discrepancies between the measured values and the reported results over the entire FS. Such errors include, but are not limited to:
    - *Nonlinearity*: The maximum deviation of the calibration points from a regression line (best fit to the data), expressed as a percentage of the rated FS output and measured on increasing load only.
    - *Repeatability*: The maximum difference between transducer output readings for repeated applied loads under identical loading and environmental conditions. It indicates the ability of an instrument to give identical results in successive readings.
    - *Hysteresis*: The maximum difference between transducer output readings for the same applied load. One reading is obtained by increasing the load from zero and the other reading is obtained by decreasing the load from the rated FS load. Measurements should be taken as rapidly as possible to minimize creep.
    - *Return to zero*: The difference in two readings: one, at no load, and the second one, after the FS load was applied and removed.

A good transducer is one with the combined (or maximum) error of less than 1% of the FS.

Analog-to-Digital Converters

In order to convey analog output (in volts) from a transducer to a computer, it has to be converted into a sequence of binary digital numbers. Modern analog-to-digital converter (ADC) boards are sophisticated high-speed electronic devices that are classified by the input resolution, as well as the range of input voltages and sampling rates.

Resolution of an ADC board is measured in bits. Bit (abbreviation for binary unit) is a unit of information equal to one binary decision (such as "yes or no," "on or off"). A 12-bit system provides a resolution of one part in 2^{12} 4096, or approximately 0.025% of FS. Likewise, 16 bits correspond to one part in 2^{16} 65,536, or approximately 0.0015% of FS (for tablet press applications, such resolution is usually excessive).

Thus, resolution of ADC board limits not only the dynamic range but also the overall system accuracy. Alternatively, a higher resolution may be required to retain a certain level of accuracy within a given dynamic range. For example, a 0.5% accurate transducer with 80 dB dynamic range requires at least 12-bit ADC resolution.

Amplifying a low-level signal by 10 or 100 times increases the effective resolution by more than 3 and 6 bits, respectively. On the other hand, increasing an ADC resolution cannot benefit the overall system accuracy if other components, such as amplifier or transducer, have a lower resolution.

When an input signal change is smaller than the system's minimum resolution, then that event will go undetected. For example, for an FS of 10 V (corresponding to, say, a compression transducer output of 50 kN), using a 12-bit ADC, any signal that does not exceed 2.44 mV (12.2 N) will not be seen by the system.

The ADC boards also differ by the effective sampling rate range. Sampling rate speed is measured in Hertz (times per second). The signals coming from a tablet press have a frequency of not more that 100 Hz (compression events per second). To avoid aliasing (losing resolution of the incoming signal due to slow sampling rate), the sampling rate should be at least twice the highest frequency of the signal. Most ADC boards used for data collection in tableting applications have a sampling rate of 5 20 times larger than signal frequency. That is why antialiasing filters are not required.

Computers and Data Acquisition Software

Overall accuracy of a data acquisition system is determined by the worst-case error of all its components. One should be aware of the fact that most system errors come neither from transducers (0.5% 1% accuracy) nor from A/D converters (0.025% accuracy) but from the software analyzing the data (round-off errors, improper sampling rate, or algorithms).

The speed and capacity of a data acquisition system depend on the computer's processor and hard drive specifications. The real-time data from transducers is streamlined to both the screen (for monitoring) and the disk (for replay and analysis). Generally speaking, "real-time" processing means reporting any change in the phenomena under study as it happens. Interestingly, but

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