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SENSORS

Enhancing Crane Safety:

Digitally Compensated Tilt Sensors

Crane safety systems using high-performance tilt sensors help avert serious accidents, enhance production, and control costs for a highly competitive industry.

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A Liebherr LR 1400/1 crawler crane lifts a 38 metric ton propeller 70 m for installation at a wind power plant in Dorntal, Germany. Normally two cranes lift and manipulate the propeller from horizontal to vertical, but in this case the task was accomplished with a single specially rigged crane. (Photo courtesy of Liebherr-Werks Ehingen GmbH.)

Every day, all over the world, cranes of all types and sizes are lifting every conceivable size and type of load at construction sites, seaports, and industrial locales. It is hard to imagine how the industrialized world would survive without these workhorses. Unhappily, though, crane accidents have claimed lives, injured bystanders and operators, and damaged property. These accidents usually have involved cranes that fall or tip over under load as a result of a change in their center of gravity (see Figure 1). Investigations into the events have identified operator and other human errors, training deficiencies, improper use of equipment, or negligence. Whatever the actual cause, the general agreement is that if the operator had received some warning of the impending problem, most accidents could and would have been avoided.

Figure 1. This accident occurred in North Carolina when the crane exceeded its safe working load as the result of an out-of-level condition. (Photo courtesy of Barth Crane Inspections.)

First Steps Toward Safety

Fifty years ago, crane accidents were occurring at an alarming rate. Workers were at risk and companies suffered losses in terms of equipment damage and delayed schedules. The need for safety systems was evident, and they accordingly began to appear in the marketplace. The first were relatively crude mechanical devices that in time gave way to electromechanical equipment and ultimately developed into fully electronic, microprocessor-based systems. Known in the industry as safe load indicators, or load moment indicators, these sophisticated systems rely on sensors to monitor numerous crane variables such as boom angle, load, telescoping length, two-block conditions, and wind speed (see Figure 2).

During operation, signals from the individual sensors are fed into a central controller, where calculations primarily geometric) are continuously made, updated, compared with the crane manufacturer's load charts, and displayed. When the crane reaches a preset percentage of its safe working load, alarms (visual, audible, or both) alert the operator. Some systems can also interface directly with the crane's operating system and lock out particular control functions to automatically prevent an unsafe condition from occurring. The overall quality and effectiveness of these safety systems are directly related to the accuracy of the sensors used to measure crane variables. For example, fractional changes in boom angle can cause a dramatic difference in the actual working load, depending on the particular crane configuration. If the sensor measuring the boom angle has a stated accuracy of ±2°, the system must compensate for this error to prevent misleading indications of a safe working condition. Systems usually do this by means of a safety factor, in essence artificially exaggerating the measured working load (or specific measured crane variable) to compensate for sensor inaccuracy. While this technique does prevent an unsafe condition, it also keeps the operator from using the crane to its full capacity, thus diminishing job site productivity.

Most tilt sensors (also known as inclinometers or clinometers) commonly used to measure boom angle can handle certain parameters better than others. Some have good linearity but have relatively large temperature coefficient errors. Others perform well in both linearity and temperature, but have poor repeatability or hysteresis, or vice versa. Finally, some do well in all these performance areas but are prohibitively expensive for most players in this highly competitive industry.

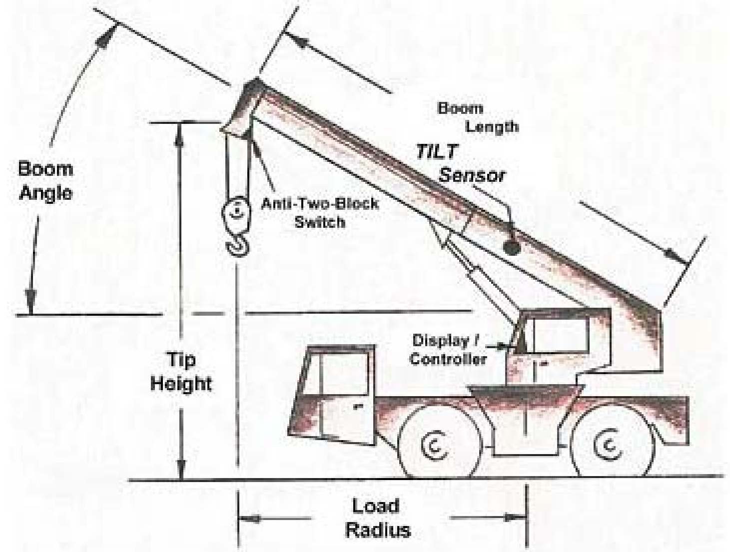

Figure 2. Typical crane safety systems can measure variables including boom angle, load, telescoping length, and two-block conditions. Minor changes in the boom angle can lead to large variations in the working load of the crane and bring about an unsafe condition.

When deriving the accuracy specification for a particular tilt sensor, all the previously noted parameters must be measured and summed to give a true representation of performance. Out of necessity, some system manufacturers have painstakingly characterized each sensor for linearity and temperature effects as a means of reducing their aggregate system error. But this step is both time consuming and costly.

Building a Better Sensor

Spectron Systems Technology's standard product, the Spectrotilt electronic inclinometer, had already solved most of these problems. The inclinometer is compact, rugged, and impervious to the elements, and has a user-friendly electronic interface. The proprietary electrolytic sensing element, a fluid-filled, hermetically sealed glass/ceramic hybrid, together with an integral signal conditioning circuit and full ESD and EMI protection, is housed in an aluminum enclosure. For environmental protection, the entire assembly is encased with an epoxy-based potting compound (see Figure 3).

Still, several improvements suggested themselves. The existing versions of the Spectrotilt were strictly analog I/O devices. Nearly all system manufacturers were either producing or developing next-generation systems that would require digital inputs from the peripheral sensors. The inclinometer's accuracy, which was roughly equal to that of other sensors already serving the market, would have to be greatly upgraded.

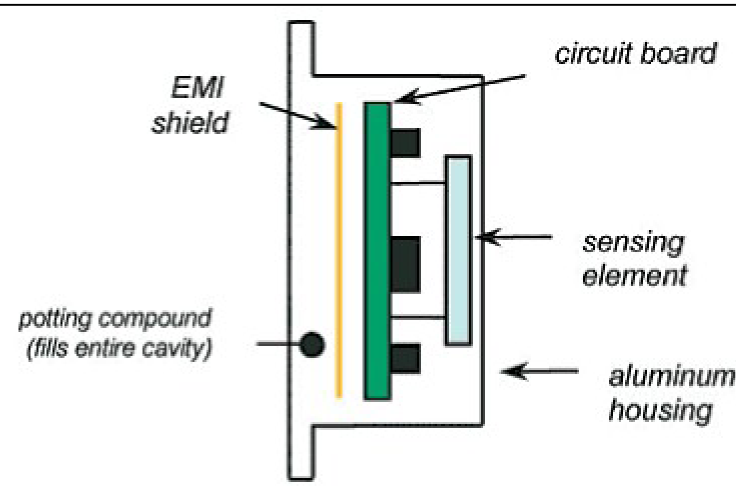

Figure 3. In this cross-sectional view of the Spectrotilt electronic inclinometer, the circuit board can be seen to contain all signal-conditioning and compensation components. The EMI shield protects the electronics from external electrical interference.

The issue of the electrical interface was relatively easy to solve. The input circuit could be designed to accept unipolar, bipolar, or unregulated DC voltages. COTS digital drivers could be simply patched into the existing circuit to provide the desired output. The more significant challenge lay in improving the accuracy from more than ±2.5° nominal to ±0.5° max., with all effects considered.

Test data revealed that the repeatability of the sensing element itself was extremely good, not only under ambient conditions but also through temperature excursions. Although good repeatability is vital to making finite error corrections possible, the data also indicated a need for corrections to the actual linearity curve, as well as the temperature coefficients of null (zero) and scale, to achieve the accuracy target.

Early on, as various error correction methodologies were being explored, it was determined that a digital compensation routine would be required. For one thing, the sensing element's base linearity could not be further improved without adding significant cost. In addition, the random nature of the temperature coefficients, in terms of polarity and magnitude, ruled out traditional compensation techniques (e.g., thermistors or tempsistors) and "blanket" corrections. This situation did, however, present oýportunities. Correcting errors by means of software would allow the use of sensing elements that otherwise would be scrap. Furthermore, all calibration and compensation routines could be accomplished in a fully automated test system, thereby significantly reducing labor**.**

Figure 4. The Spectrotilt RS-232 uses onboard linearity and temperature compensation to eliminate intrinsic measurement errors. The EMI/ESD protection, hermetically sealed sensor, aluminum housing, and fully potted electronics give it immunity to harsh environments.

High-Performance Tilt Sensing

The Spectrotilt RS-232 represents a next-generation electronic inclinometer (see Figure 4). This device, with an accuracy of better than ±0.5° over a ±60° angular sensing range, uses linearity correction, onboard temperature sensing and compensation, and custom algorithms to eliminate the intrinsic errors typically exhibited by lower-cost devices.

Operation

The core of the inclinometer consists of a microcontroller (programmable IC) running at 10 MHz and a 10-bit A/D converter. These, in combination with a digital temperature sensor and an EEPROM, provide the necessary processing and data storage capacity (see Figure 5).

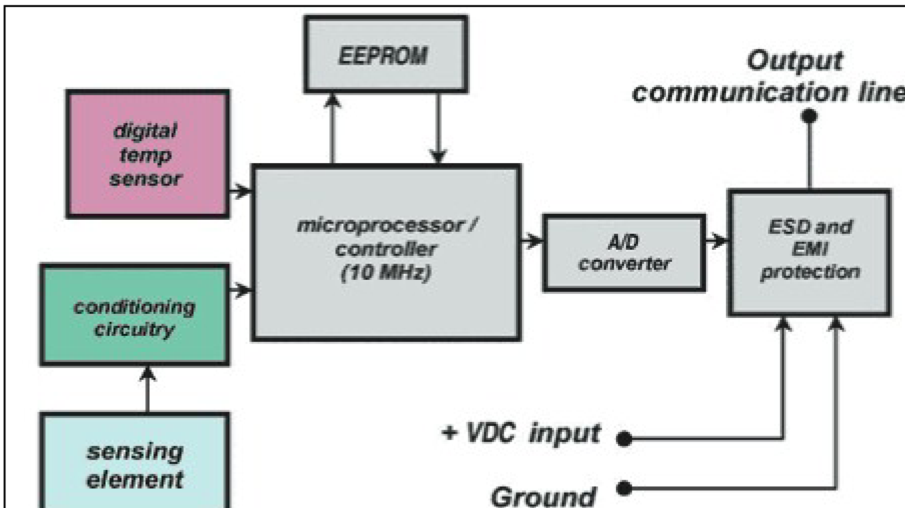

Figure 5. In operation, the microcontroller receives signals from the sensing element and digital temperature sensor, compares them to the lookup table stored in the EEPROM, and makes any necessary corrections. The resulting inclinometer output is therefore devoid of linearity and temperature-related errors.

During the test and calibration routine, the inclinometers are tilted in incremental angular steps through their ±60° sensitivity range. The raw sensing element output is measured at each step, converted to digital data, and stored in memory. Data from the onboard digital temperature sensor are simultaneously sampled and stored, first at ambient (room) temperature and then at the operating temperature extremes. Knowing the true angle of tilt and the actual temperature during sensor data collection enables the system to establish and store a lookup table. During normal operation, the software algorithms make corrections to the real-time sensor data by comparing the information with the current temperature and the lookup table. The resulting inclinometer output is therefore free of temperature-associated or linearity errors.

Figure 6.
Spectrotilt General Specifications

Input voltage: 10–14 VDC (unregulated)
Input current: 20 mA max.
Range (linear): ±60°
Accuracy: ±0.5° max.
Scale factor/resolution: 0.137°/count
Output at null (0°): 512 counts
Temperature range:
  Operating: –40°C to 70°C
  Storage: –55°C to 80°C
Startup time: <1 s

Note that accuracy includes all effects and is defined as the maximum output deviation from the absolute input angle.

The output is transmitted in RS-232 form at 9600 baud and CMOS logic levels (0 and +5 VDC). The most and least significant bytes are transmitted at 15 ms intervals. For enhanced stability, the output is further optimized by internally averaging four readings (moving average) from the A/D converters. The general specifications for the Spectrotilt are given in Figure 6.

Who Needs High-Performance Tilt Sensors?

This new sensing technology is already improving performance while reducing cost for many manufacturers of safety systems and heavy equipment. In the construction industry, road graders and pavers use tilt sensors for controlling blade angle. Telescopic material handlers, manlifts, aerial work platforms, and boom lifts use them to measure machine variables or enhance their safety systems. The mining industry's crawler drills use them to closely monitor and control the drill mast angle. Other applications are as diverse as wheel alignment systems (caster and camber measurement) and satellite antenna positioning (elevation angle).

As new needs arise, the flexibility afforded by the digital circuit design allows modification of many performance parameters by means of software. The angular range, scale factor and resolution, and number of readings internally averaged (i.e., filtering) can all be custom tailored. Another advantage is that the digital output signal eliminates concerns over signal loss and noise, making the technology a good choice for long cable runs. Finally, the viscosity of the fluid inside the sensing element can be altered to decrease susceptibility in high-vibration environments.

The adaptability, high accuracy, and cost effectiveness of these high-performance tilt sensors should help ensure that cranes remain a significant—and much safer—feature of our industrial landscape.

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