2nd Biennial

Movable Bridge Symposium

November 10, 11, & 12, 1987

St. Petersburg Beach, Florida

AEROSPACE TECHNOLOGY BROUGHT DOWN TO EARTH -- TILT SENSORS MONITOR BRIDGES FOR CRITICAL MOVEMENT

by

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A situation recently arose requiring the use of a continuous motion detection and warning system to be installed on a critical bridge which had undergone excessive movement.

In October of 1986, the Ludlow Viaduct, a 70-year old hollow barrel concrete arch bridge owned by the county of Hamilton, Ohio, experienced severe pier rotation on two of its seven piers. This movement occurred during work being done as a part of the Mill Creek Valley flood control project. Cracks appeared in 90% of the concrete columns rising from the arches and supporting the deck on the old section of the structure. The viaduct was closed immediately and remained closed for nine weeks until corrective action could be taken.

The Ludlow Viaduct is a major artery connecting a busy retail district and a major residential area. The structure is 1500 feet long, 60 feet out-to-out, with four lanes of traffic, carrying approximately 20,000 vehicles per day. The foundation in the affected area of the structure is timber piling with spread footings.

Once the pier movement was initially arrested and the deck shored up, there still remained the concern of future rotation or settling of the piers which could result in further problems with the deck. Inclinometers were being used, but it took a full day to take all of these readings and the data provided was not continuous.

At this time, George C. Hartman, City of Cincinnati-Chief Structures Engineer, ordered the use of a Tilt Sensing System to monitor, record and warn of possible continued movement of the viaduct. Four sensors were installed, two each on the critical piers and two on their respective arches. This configuration allowed not only for detection of rotation in the piers, but also absolute vertical settlement of the piers, which would result in rotation of the arches.

The sensors, an adaptation of aerospace navigation technology, are high resolution, gravity-referenced instruments which measure angular rotations as slight as 0.01 arc minutes, or 1/6000th of a degree. They are relatively insensitive to temperature fluctuations, extremely repeatable, and have a calculated MTBF (mean time between failure) of 200,000 hours, or 23 years.

The sensors attach to a specially cast, anodized, heat treated mounting plate, which bolts to any section of a structure requiring monitoring. Once aligned, the sensors are hard wired to a control console, which monitors up to eight sensors continuously and simultaneously. The console also displays the angular position of the sensors, provides sensor power and signal translation, delivers data output to the recorders, and functions as the warning mechanism. The threshold warning level of each individual sensor is determined in the console by the plugging in of a simple resistor. If movement on any sensor exceeds this level, the relay is tripped and the warning system is activated, in this case a high power strobe light. The warning system on the Ludlow Viaduct is set to activate at ±6 minutes of arc rotation on arch 1, ±4 minutes on arch 2 and ±2 minutes of arc rotation on each of the piers.

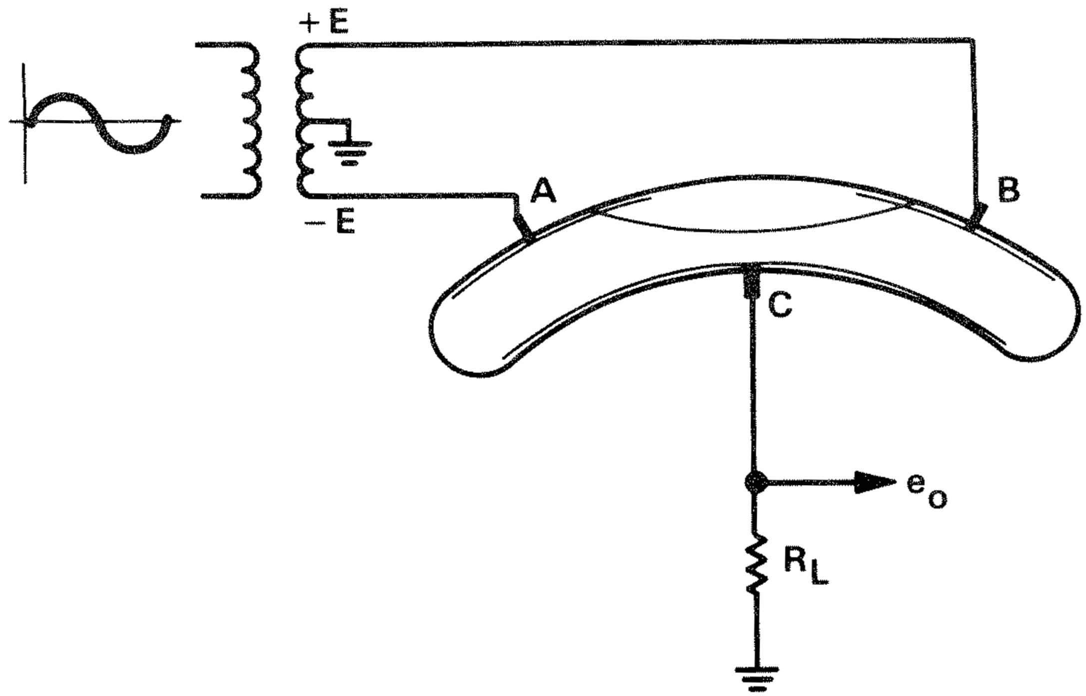
The console and recorder are situated several hundred feet from the sensors in a local health department building where the equipment can be readily accessed and the warning light is easily visible. Because of the low power requirement and signal output of the sensors, they may be cabled miles from the console if need be, or the data transmitted via phone lines or alternate means of telemetry.

Tilt Sensing System Description

Now, for details on the technical operation of the Tilt Sensing System. What does it measure? The sensor measures angular rotation around a center point. How does it measure? It uses what we call a gravity referenced sensor. This is very important because now our reference point is a constant; the center of gravity. Other motion detection methods, such as surveying, rely on man-made references such as benchmarks, which can also move. Hopefully, the center of gravity will not move. Let's examine an illustration of how the sensor works. (See Illustration 1.)

Visualize, if you will, that this curved glass vial is filled with a proprietary conductive solution. It is similar to the glass vial that you would find in a carpenter's level, however, that's where the similarity ends. You'll notice that it does have a radius of curvature and inside the vial at points A, B and C there are platinum electrodes. You will notice that there is a bubble in the top of the vial. The sensor vial operates on a basic law of physics that a line bisecting a bubble suspended in a fluid points directly to the gravitational center of the earth. Hence the name gravity based sensor.

Sensor Operation



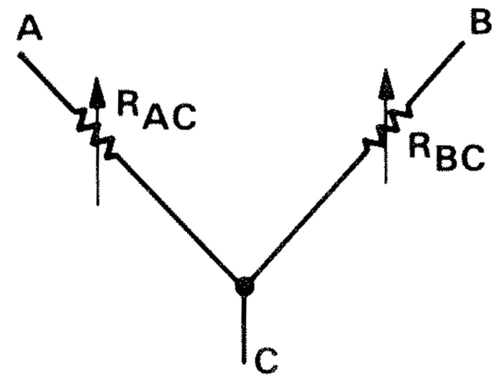


Illustration 1

The way it works is quite simple. We introduce a three milliamp AC current 180° out of phase at points A and B to point C. We then measure the differential in current resistance between points A to C and B to C and translate them into an angle. You'll notice the illustration at the bottom is half of a Wheatstone bridge where we are measuring differential between points A and C and points B and C. When the vial is perfectly level (and therefore vertical), the resistances are equal, and the console display reads "0.00". When the vial is rotated, say in a clockwise direction, the air bubble shifts, causing more of electrode A to be exposed to air and more of electrode B to be covered with liquid, thereby changing the relative resistances of both currents. This change is detected, translated, and displayed on the console LCD as a rotation, either plus or minus, of the structure. We sign the polarity, the rotation in a clockwise direction is signed as a positive angle and a rotation in a counter clockwise direction is a negative angle.

How much does the sensor measure? The resolution of the system is 1/100th of an arc minute and its full range is plus or minus 30 arc minutes. And while we are talking about arc minutes, let's put what an arc minute is into perspective.

We are all aware that a circle has 360 degrees and a degree is a relatively small unit of angular measure. (See Illustration 2.)

However, within each degree there are 60 subdivisions known as arc minutes. (See Illustration 3.) An arc minute is a very small unit of angular rotation, but remember we have a resolution of 0.01 arc minutes, or 1/6000th of a degree. This is an extremely small unit of measure and may pose a question: Why are we

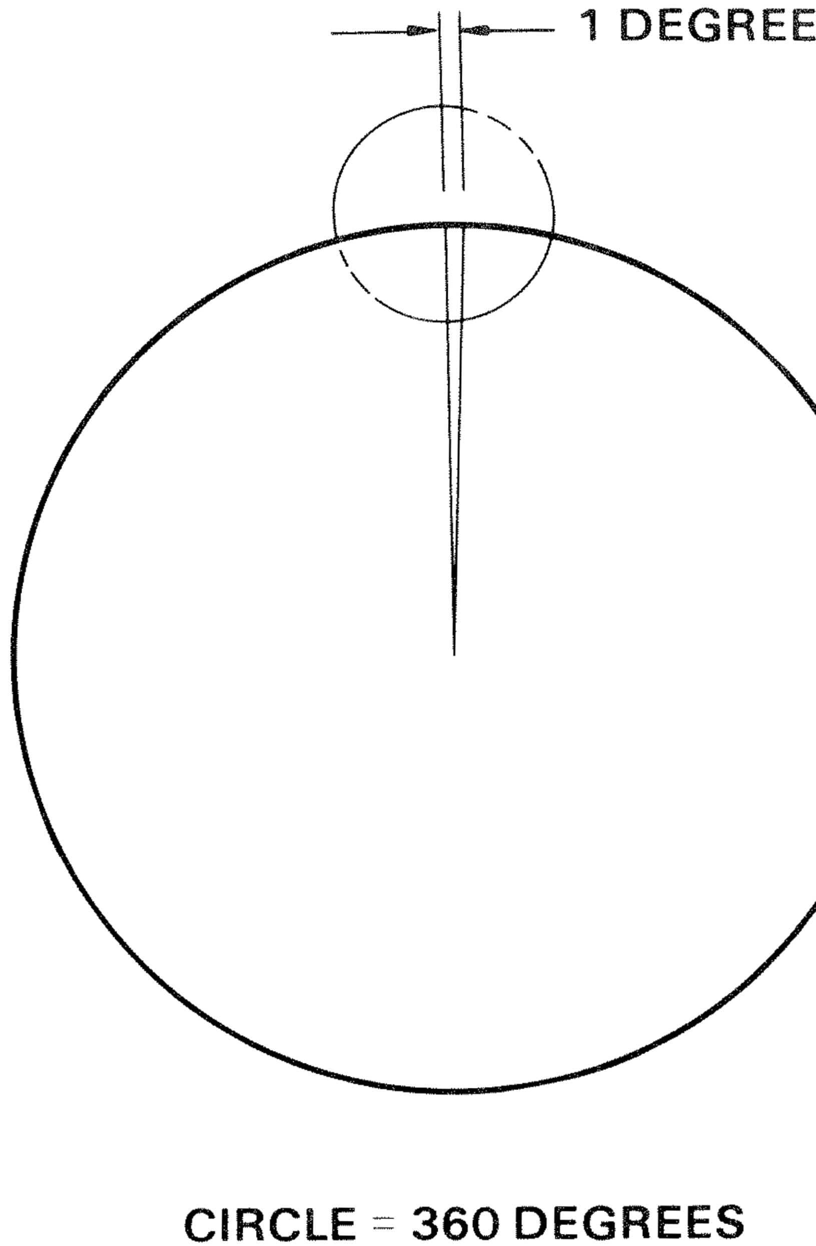
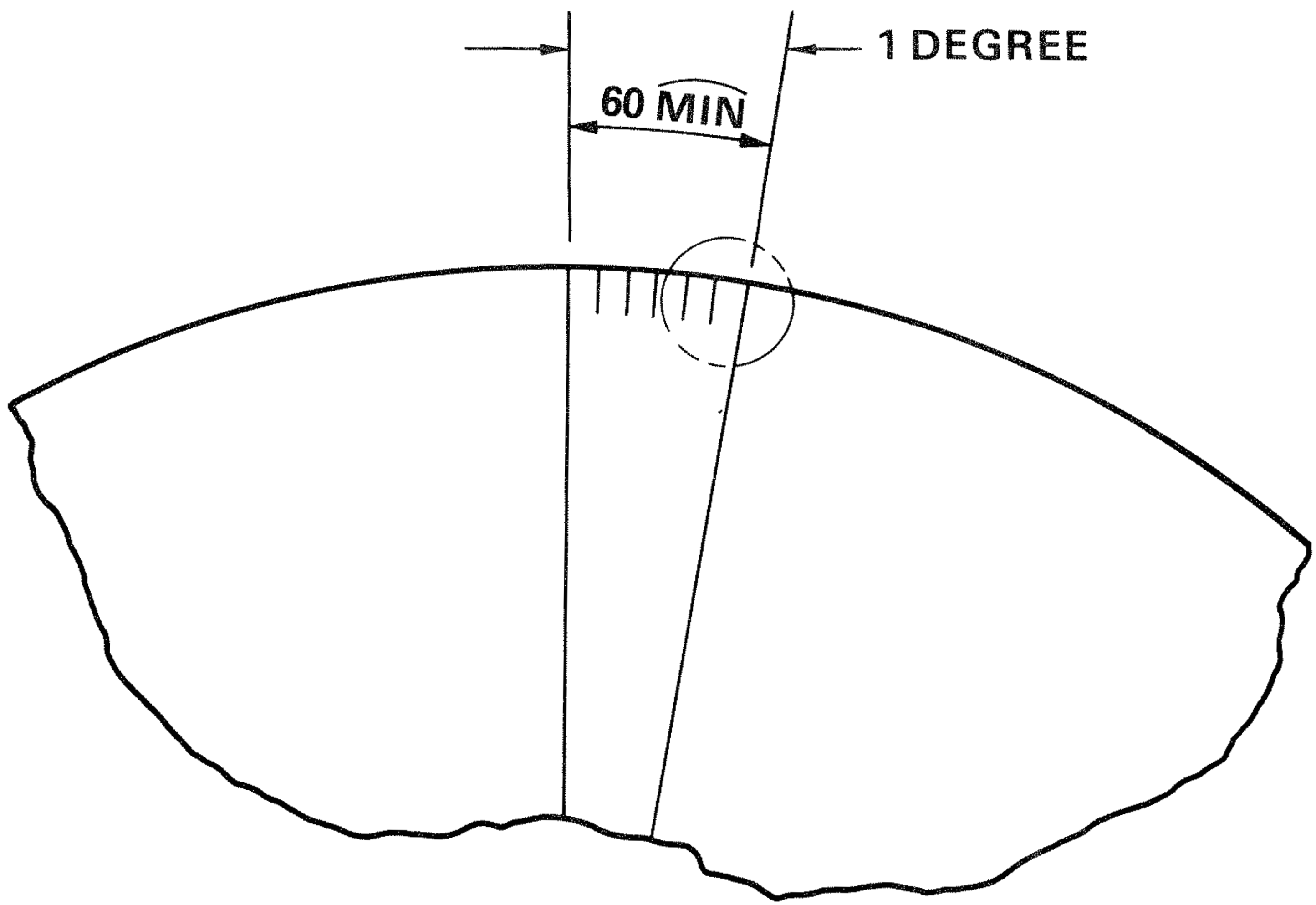


Illustration 2



1 DEGREE = 60 MIN

CIRCLE = 21,600 MIN

Illustration 3

working in such small units; this is much too sensitive for my application. Let's illustrate why we work in arc minutes and why you need this level of sensitivity. (See Illustration 4.)

This simple matrix lists the size of a structure across the top. Down the left side we are showing inches or fractions of inches of linear movement. If we were to be concerned with a two inch linear movement at the top of a 200 foot bridge pier, we would go down to two inches, go into the column headed 200 feet and you will notice that amount of movement is described by an angle of 2.86 arc minutes, very small in terms of angle, about 1/20th of a degree, but a significant linear movement. Now conversely if we were to have one degree of movement across that same span, it would result in approximately 42 inches of movement. I do not think that we have to measure 42 inches of movement; all we have to do is get out of the way of the pier.

If you take other values you'll see that they result in even smaller units. A one inch movement, for example, across a 500 foot span would result, or be described by, an angle of .57 arc minutes. One degree across the same span would result in over 100 inches of movement.

Hopefully this illustrates why we have elected to work in arc minutes rather than in degrees, and it's quite simple to personalize this to your own particular situation. If you will define how much movement you deem to be critical in inches, divide it by the size of the structure in feet and multiply the result by 286, it will then give you the angle in arc minutes that defines that amount of linear movement across that size structure.

ARC Minute Deflection

MOVEMENT	DISTANCE					
	50′	100′	150′	200′	250′	500′
1/8″	.71	.36	.24	.18	.14	.07
1/4″	1.43	.72	.48	.36	.29	.14
1/2″	2.86	1.43	.95	.72	.57	.29
3/4″	4.29	2.14	1.43	1.07	.86	.43
1″	5.72	2.86	1.91	1.43	1.14	.57
2″	11.44	5.72	3.81	2.86	2.29	1.14
3″	17.16	8.58	5.72	4.29	3.43	1.72
THE LINE BELOW IS FOR REFERENCE ONLY USING A MEASUREMENT VALUE WE ARE FAMILIAR WITH.						
1°	10.45″	20.90″	31.35″	41.80″	52.25″	104.50″

EQUATION:

$$\frac{\text{LINEAR MOVEMENT (INCHES)}}{\text{SIZE OF STRUCTURE (FEET)}} \times 286 = \text{ANGLE IN ARC MINUTES}$$

Illustration 4

This level of sensitivity also enables us to detect and plot movement of a very small nature. You may not care that a structure moves 0.01 arc mintues, however if it continues this movement in the same direction over a period of several weeks, you can draw the conclusion that the structure is moving in a permanent, detrimental fashion. Now you have time to correct the problem.

There are several unique features associated with the Tilt Sensing System, but let's just mention a few. First of all, its extreme sensitivity allows you to detect movement that you cannot see with the naked eye. The continuous monitoring and recording does two things: it allows you to develop a base line or footprint of the structure and it also continuously monitors to give you a warning the instant the critical movement occurs. The variable threshold of warning can be preset very easily in the field by merely plugging in a resistor that sets the amount of movement that you deem to be critical. And we can power the system either through AC line power or through a battery. Each system can be designed to exactly fit a particular situation and a particular application. You can alter the number of sensors, you can alter the amount of threshold settings, and you can change the scale on the recorder.

Equipment Design

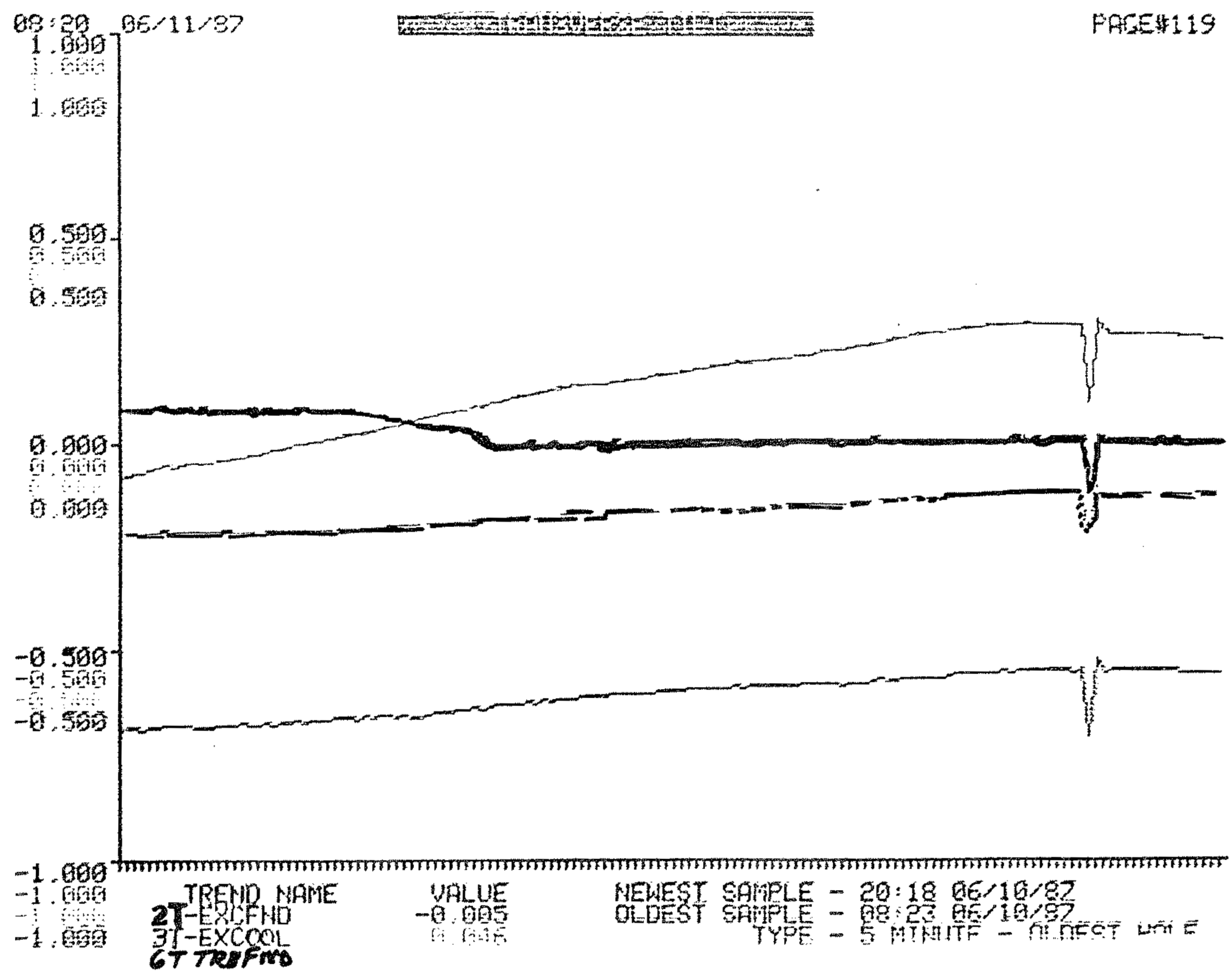
Let's talk briefly now about the various components of the system, and note what each component contributes to the total system. The Tilt Sensor itself, of course, is the heart of the system. It contains the sensor mechanism, the translation electronics and the packaging material. It is weatherproof and to some degree waterproof. It comes with either a twist-lock connector or with a pigtail cable if you are using it under more than 20 feet of water.

The mounting plates are anodized, machined aluminum jig plate that are stress relieved. They attach directly to the surface of the structure being monitored and the Tilt Sensor in turn is mounted to the mounting plate. The console is the human interface between you and the sensor itself via the liquid crystal display which allows you to read the angular movement of each individual sensor. A total of eight sensors can be connected. It has a warning strobe light and it also contains eight red light emitting diodes that will identify which sensor or sensors have reached or exceeded the preset threshold setting. It also supplies power to the system, either through AC line power or through batteries.

The field recorders are very basic, durable types. They record on pressure sensitive paper with a stylus. The chart speed is one inch per hour so we can record for a little over 31 days. By going with a more sophisticated data acquisition system, the data collected can be massaged and put in various forms. (See Illustrations 5 and 6.)

These graphs show the movement of 4 sensors mounted on a turbine foundation at Union Electric's Rush Island, Missouri plant on June 10, 1987. Notice the sudden jump in the plots. They happened to correspond with the Lawrenceville, Indiana earthquake, whose epicenter was over 200 miles away. The quake measured 5.1 on the Richter scale. These data points were taken every 5 minutes.

The engineers immediately ordered their computer to draw a new plot based on one minute samples. This is the result. Notice the improved resolution. From this graph we can see that this foundation, a massive structure some 200 feet



5 min AVERAGES
FOR 12HRS

Illustration 5

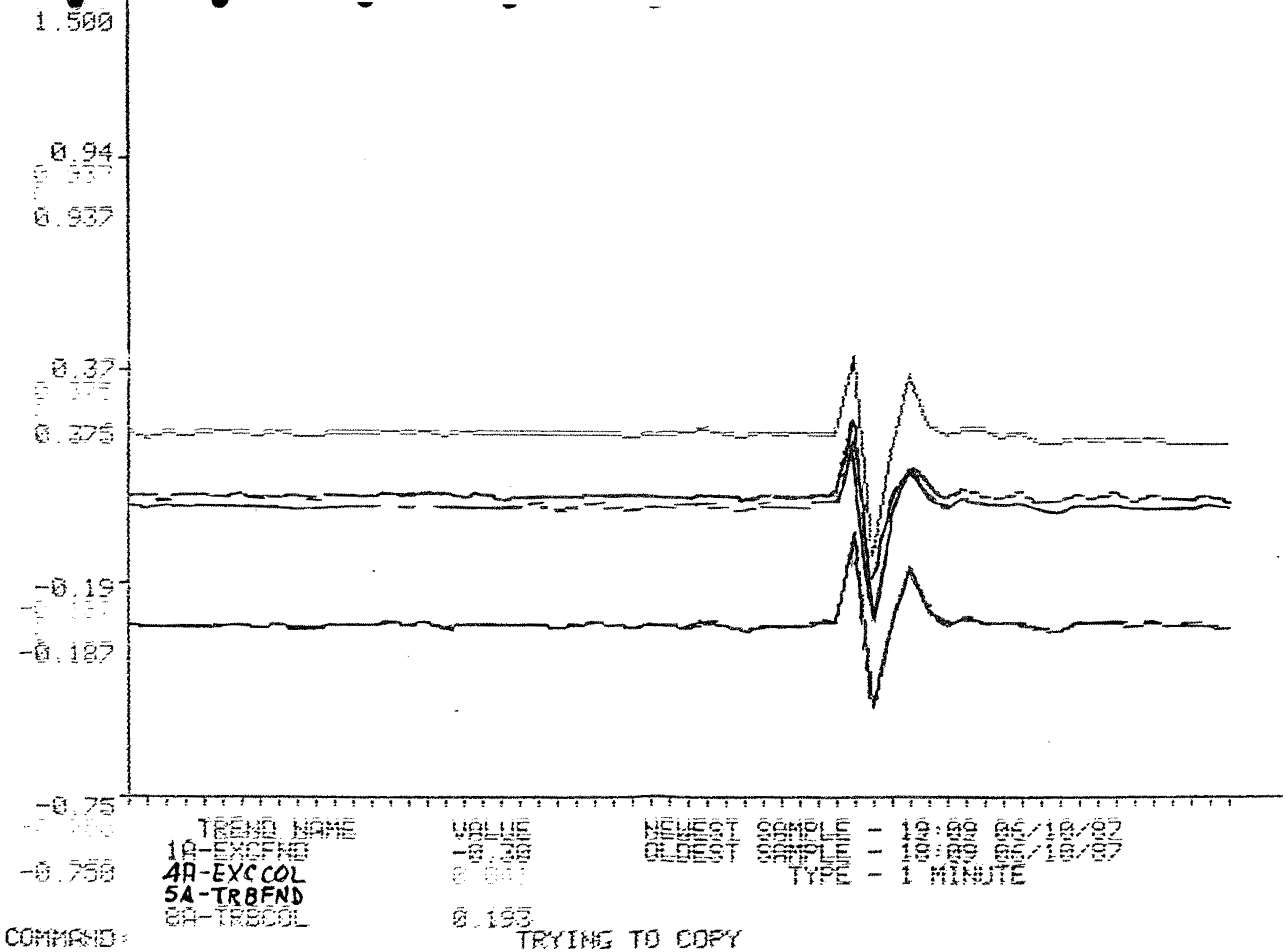


Illustration 6

long, 40 feet wide and 12 feet thick, rotated about its axis about 5 times over an 8 mintue period before returning to its original position.

Tilt sensors may be used to monitor all types of structural movement, and are especially useful when continuous monitoring/recording and warning of motion is desired. In seismic areas, they can show relative position of a structure before and after an event. In other words, did the structure move in a permanent fashion? On moveable bridges, they can help pinpoint movement which may be causing the components to bind. In new construction applications, such as the new Quincy bridge over the Mississippi River at Quincy, Illinois, they may be used to measure tower rotation during tensioning of the cables.

The applications are virtually endless, and in this day when bridge safety is of such a national concern, the benefits are very timely.