THE LOAD CELL PRIMER

The "Elastic Force Transducer"

People have known for centuries that heavy objects deflect a spring support more than light ones. Take, for example, a fly fisherman as he casts his line and catches a fish. The fishing pole is a flexible tapered beam, supported at one end by the fisherman's grip and deflected at the far end by the force of the line leading down to the fish. If the fish is fighting vigorously, the pole is pulled down quite a bit. If the fish stops fighting, the pole's deflection is less. As the man pulls the fish out of the water, a heavy fish deflects the pole more than a light one.

Figure 1. Bending Beam Deflection

This knowledge about the deflection of a springy rod is not confined to the human race. As we watch movies of monkeys in the trees, we realize that they have some understanding of this principle also.

The phenomenon that is demonstrated in Figure 1 relates to the deflection of a *bending beam* under load. We could also determine the relationship between the deflection of a *coil spring* and the force which causes it. For example, when the fisherman hangs his catch on a fish scale, a heavy fish pulls the scale's hook down farther than a light one. Inside that fish scale is nothing more complicated than a coil spring, a pointer to mark the position of the end of the spring, and a ruler-like scale to indicate the deflection, and thus the weight of the fish.

We can demonstrate a more exact quantitative relationship by running an experiment. We can calibrate a coil spring of our own choice by clamping the top end of it to a cross bar, connecting a pointer at the lower end of the spring, and mounting a ruler to indicate the deflection as we place weights in a pan hanging from the lower end of the spring.

WEIGHT	MARK
0	0.5
1	1.5
2	2.5
3	3.5
4	4.5

On our particular scale, we note that the *resolution* of the ruler is 1/20 of an inch, because the marks are 1/10 of an inch apart. This is because we can tell the difference between two readings of about ½ the distance between the marks.

With no weight in the pan, take a reading of the pointer on the ruler. Next, apply a one pound weight and note that this particular spring is deflected one mark on the ruler from the original reading. Add another weight, and the deflection is one mark more. As we add more weights, we record all the readings. The table is a record of the weight versus deflection data which we recorded.

If we plot these data on a graph, we find that we can connect all the points with a single straight line. An algebra teacher or geometry teacher would tell us that the equation

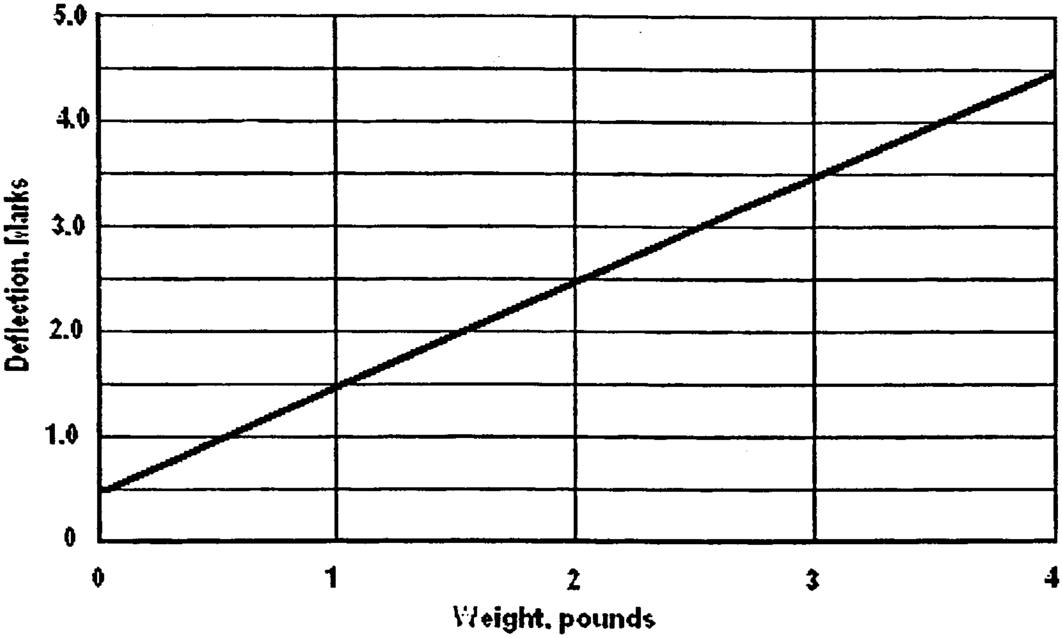

Figure 2. Deflection versus Applied Weight

of this line is:

$$D = D_0 + \frac{W}{k}$$

Where:

D	=	Deflection of the spring
D_0	=	Initial deflection of the spring
W	=	Weight on pan
k	=	Stiffness constant of the spring

The idea that the *transfer function* of the spring scale is exactly a straight line occurs to us only because the measurements did not have enough resolution. Our straight line graph is only a rough approximation of the spring's true characteristics.

We have now demonstrated the two basic components of a load cell ... a springy element (usually called a *flexure*) which supports the load to be measured and a deflection measuring element which indicates the deflection of the flexure resulting from the application of loads.

Adding Sophistication

We can improve the resolution of the measurements by replacing the ruler with a micrometer having a fine-thread screw, so that we can resolve one-thousandths or even one ten-thousandths of an inch. Now, as we re-run the experiment, we can easily see, by simple visual inspection of the data, that it will not exactly fit on a straight line.

WEIGHT	DEFLECTION, INCHES
0	0.500
1	1.509
2	2.516
3	3.511
4	4.495

When we look closely at the deviation of the data from our hoped-for straight line, we can see that the differences are so small that they are less than the thickness of the graph line. Such a graph would not be useful, since it would not portray any useful information except a gross representation of the zero intercept and slope of the spring's characteristics. Therefore, in order to present the data in a meaningful form, it is necessary to modify our classical idea about the graphing of data. We will need to magnify the scaling of the graph in such a way that the deviations from a straight line are easier to see.

Rather than graphing "Weight" versus "Deflection", we can plot "Weight" versus "Deviation from a Straight Line". Then, it becomes necessary to choose which straight line to use as a reference. One common choice is the "End Points Straight Line", which is the line passing through the point at zero load and the point at maximum load.

As you can see in Figure 3, the horizontal axis represents the straight line we have chosen to use as a reference. But, notice, we have given up the scaling information about the spring ... we can't calculate the "pounds per inch" constant of the spring from the graphed information. Therefore, for the graph to be most useful, we should print the scaling constant somewhere on the graph.

Also, if we choose "Deviation" for the vertical axis, it is not too useful, since we can't relate the numbers to the performance of the spring without dividing all the numbers by the full scale output range of the test. We can help the user of the graph by performing that division ahead of time ... this will change the units on the vertical axis to "Percent of Full Scale". In our example, we would divide all the deviation numbers by 4.495 (that is: 4.995 - 0.500), the range of the test outputs from no load to full load.

By using "Percent of Full Scale", we can easily compare the performance of many springs in a way which lets us select the ones which have the characteristics we want. Later on, we will see that springs have many more parameters than just the simple spring constant which was presented earlier in the deflection equation for springs.

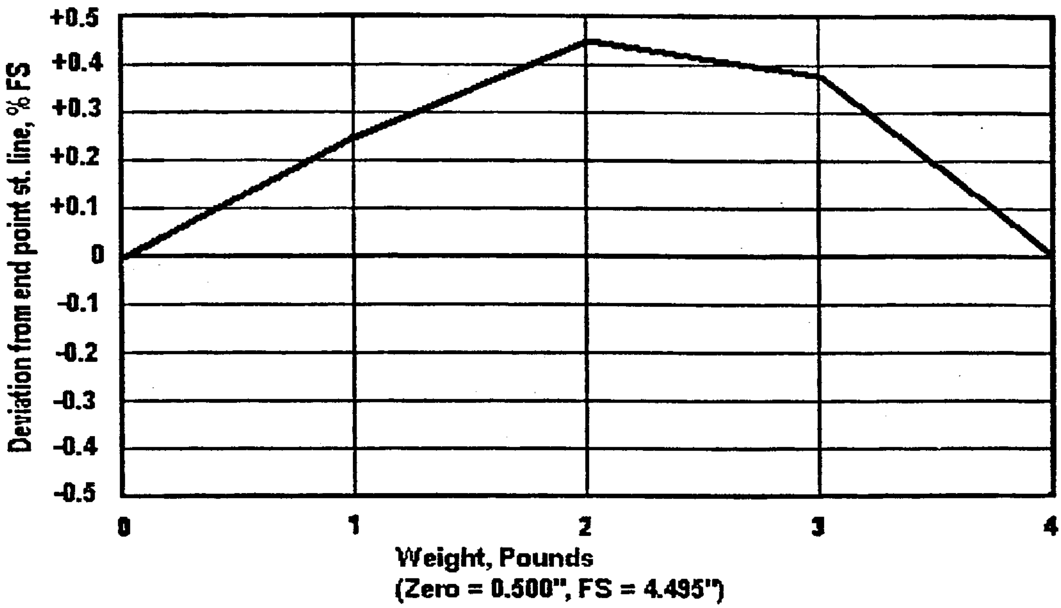

Figure 3. Deviation from Straight Line versus Applied Weight

You will notice that our new graph in Figure 3 gives us a much clearer picture of the true characteristics of the spring over the range of interest.

A Rudimentary Load Cell: The Proving Ring

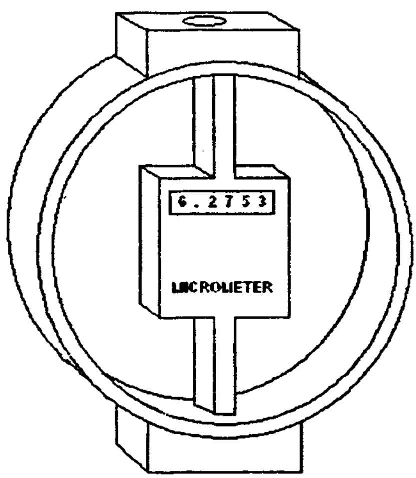

Figure 4. The Proving Ring

Decades ago, the Proving Ring was conceived, as a device to be used for the calibration of force measuring dial gages. It consisted of a steel ring with a micrometer mounted so as to measure the vertical deflection when loads were applied through the threaded blocks at the top and bottom.

For many years proving rings were considered the standard of excellence for force calibration. However, they suffer from the following adverse characteristics:

Creep: All solid materials exhibit a very small instantaneous elongation if a force is applied in tension. For compressive forces, the material will become slightly shorter. However, if we maintain the same force and continue to measure the length, we will see that the length continues to change slightly. If we plot the change in length versus time, we will arrive at the graph of Figure 5 which shows *creep,* and also shows *creep recovery* when the force is removed.

A tool steel ring, such as the proving ring, has creep of about 0.25% of the applied force in the first 20 minute interval after application of the force. Referring to Figure 5, the force is applied from zero time to time "a".The initial deflection is "j", and then we see a rapid initial increase in length, followed by length "k" at time "b" and length "m" at time "c". Note that, although the time "a to b" is equal to the time "b to c", the increase in length "j to k" is much greater than the increase "k to m". (The creep scaling is exaggerated in Figure 5, to demonstrate the principle.)

If we were to run a test for a much longer time, even weeks, we would continue to see a continuing but decreasing rate of creep, provided our measuring system had enough resolution to be able to detect extremely small deflections. Creep recovery follows a curve similar to the creep curve, but in a reverse sense.

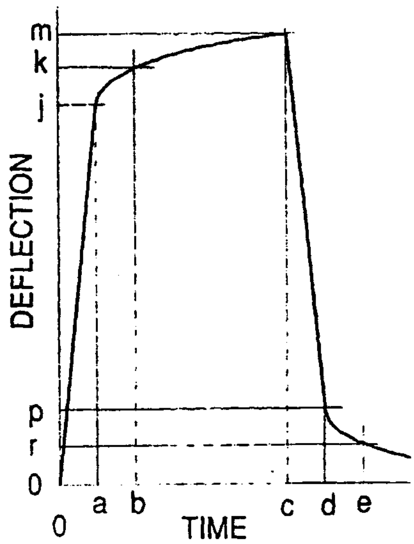

Figure 5. Creep versus Time

Deflection Measurement: When forces are applied to the proving ring, it departs from its circular shape and becomes slightly egg-shaped. The determination of the deflection of a proving ring depends on the subtraction of two large numbers, namely, the inside diameter of the proving ring and the length of the micrometer measurement assembly. Since the difference is so small, any slight error in measuring either dimension leads to a large percentage error in the number at interest, the deflection.

Any mechanical deflection measurement system introduces errors which are difficult to control or overcome. The most obvious problem is *resolution,* which is limited by the fineness of the micrometer threads and the spacing of the indicator marks. *Non-repeatability* of duplicate measurements taken in the same direction depends mainly on how much force is applied to the micrometer's screw threads, while *hysteresis* of measurements taken at the same point from opposite directions is dependent on the preload, friction, and looseness in the threads.

Temperature Effects: Variation in the temperature of either the steel ring or the micrometer assembly will cause expansion or contraction, which will result in a change in the deflection reading. A first order correction would be to make all the parts out of the same material, so that their relative temperature effects are equal, causing them to cancel each other out. Unfortunately, this presumes that all the parts track each other in temperature, and this is not true in practice. A light shining on one side of the ring, or a warm breeze from a furnace vent will cause differential warming, and a proving ring is very susceptible to temperature gradients in the proving ring mechanism. Also, the spring constant changes with temperature, thus changing the calibration.