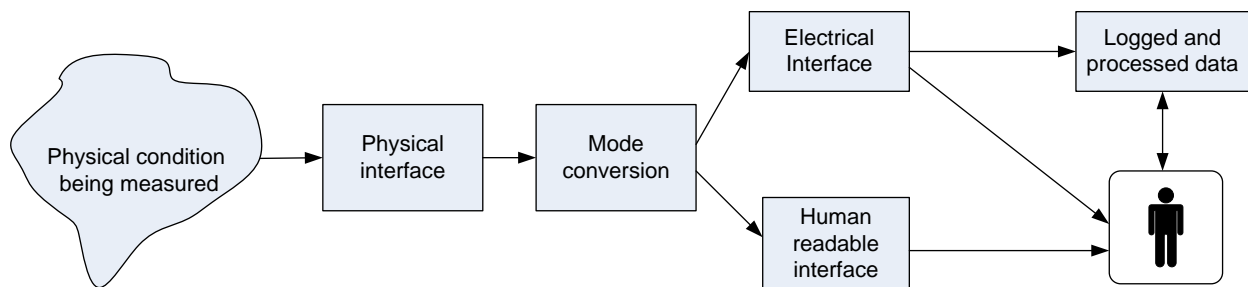


## 1.0 Mechanical Measurement Systems

Measurement of mechanical systems has long been an issue for engineers. Having been trained to deal with mechanical systems, the use of electrical or electronic system to make measurements on these mechanical systems are far from obvious. For a mechanical engineer to properly select and utilize electronic measurement devices requires both an understanding of the mechanical system and an understanding of the characteristics of the transducers. This is not to say that all measurement systems are electronic, because there are a number of purely mechanical measurement devices that far predate the high tech electronic systems that are used in many of today's systems. To fully understand how a measurement system works, we have to first understand exactly what a measurement system is and what it is capable of.

### 1.1 Definition of a Measurement system

The measurement system can be defined as the all the components included from the interface to the physical property being measured, pressure, vibration etc, to the recorded data storage. This not only includes the physical devices, but the user as well.



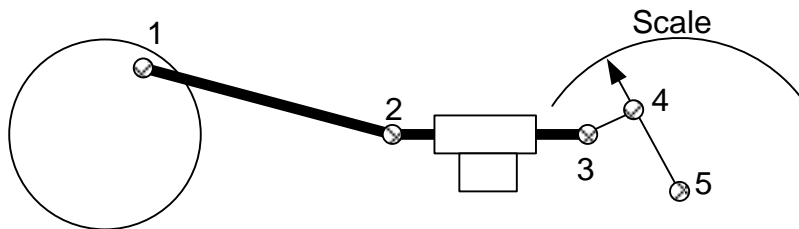
**Figure 1.1: Complete measurement system**

The measurement system in its simplest form generates a human readable interface that can be used for simple monitoring. In this simple system any data must be recorded by the operator. The measurement system may include an electrical interface, allowing the data to be converted to some other format, or in some other location before it is presented to the operator. Data in this configuration is still recorded by the operator, but the additional level of complexity allows for a certain amount of pre-processing to be completed. As we work through the various transducer technologies the range of pre-processing that may be useful should become evident. As stated this configuration also allows the measurement to be transmitted to some remote location. A simple example might be reading a temperature. It should be obvious that there is simply no good way to read a glass thermometer from a

control room several hundred feet away, let alone several states or countries away. However if we convert this measurement to an electrical measurement, we have techniques that will allow this information to be transmitted to this remote control room, and under some conditions anywhere in the world.

The third configuration is quickly growing to the most common method of measurement. With the quick growth of computing power in the last ten years, it had become a relatively simple and common matter to make these readings using a computer system and then relaying converted, scaled and corrected data to the user, not only for the current moment, but also for a significant amount of the measurement history, allowing for graphical trending as well as the raw single values of the past.

As you can see in the figure 1.1, there are a number of levels of interface that must occur between the physical condition being measured, and the operator. Each of these blocks represents some form of conversion of the data, either mechanical, physical or electronic. Each of these also represents an opportunity for error to occur in the measurement.



**Figure 1.2 Mechanical display system**

As you can see in the above figure, this entirely mechanical system would show the position of the slider portion of the slider crank on the indicating scale. Each one of the numbered interfaces, in this case coupling flexible joints, introduces some amount of error. A tight joint introducing less error than a loose joint. In addition the slider bearing fit could contribute some amount of error in the output scale reading. Let us not forget the operator. Since the needle is always moving, the operator must make some kind of decision as to when to read the scale, and can introduce unintended errors himself, by anticipating the reading and not actually recognizing the true reading at the instant it is being read. We will take a much closer look at all these potential error points in a later section, as well as how to determine the amount of anticipated error, or uncertainty, in the reading.

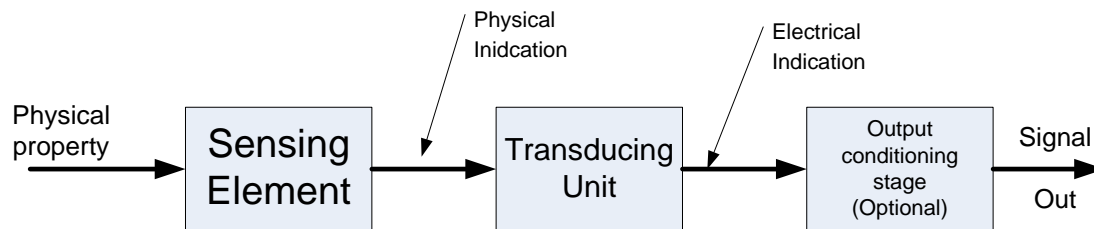
Another concern of any measurement system is the resolution of the system. Again looking at the system in figure 1.2, it should be easy to see that the more accurately we can number the scale for the pointer, the more accurately we can read the position. It should also be fairly obvious that there will be some physical limit where adding more little tick marks really won't help, because they will have gotten too small to determine. We might then increase the diameter of the scale, effectively spreading the marks out, again allowing us to add more marks. Is there a realistic limit to how many times we can increase the size of the scale and add more marks? The answer should be obviously yes. While each step of increase in diameter allows more marks, the system reaches a point where the slop in the

system equals or exceeds a single increment on the scale. This is the effective readable limit of the system.

### 1.3 Electrical transducer systems

While there are still many applications that require only an indicator, the vast majority of the devices we are going to study are electrical transducers. These electrical devices are highly useful and flexible, but this flexibility comes with a cost. Unlike mechanical indicators, electrical transducers must be calibrated and, for most, have some form of external recording or display device to be useful. There are a number of newer transducers that include a readout with the transducer, allowing them to be used as a transducer, a local indicator, or both at the same time.

Electrical based transducers can be modeled as a series of three functional blocks. Each of these three blocks manage one portion of the conversion from the physical world to the electrical world. Figure 1.3 illustrates these three blocks.



**Figure 1.3 Electrical Transducer model**

The sensing element stage of the transducer converts the physical property to some measurable physical indication. A diaphragm would be an example of such a sensing element, converting a pressure into a physical motion. The transducing unit's job is to convert this physical indication into some form of electrical indication. There are a wide variety of methods of making this conversion, which will be looked at in detail as we discuss the transducers that utilize these methods. The final stage is an optional signal conditioning stage. Some electrical indications are not particularly well suited to transmission over long distances, or are particularly difficult to deal with. In these cases some additional signal conditioning may be helpful. The most common of these signal conditioning systems is a conversion to 4-20 ma current loop.

There are some special case transducers and exceptions to this model, as there are with any model. One such exception is a device that senses temperature and directly converts this temperature into an electrical signal, effectively merging the first two blocks of the model into a single block.

The totally mechanical system we discussed previously had some slop in the system at each joint. This tolerance is unavoidable and will always exist, no matter how closely the machining tolerances are held.

These slight tolerances are essentially a mechanical error. In addition to these errors, each link will change length with temperature, there may be some misalignment between the centerline of the wheel and the slider. All of these slight sources of error will combine into some total amount of error at the scale, or readout. We will discuss these errors in more detail in a later section.

Each stage of the electronic system also contain errors. Mechanical errors in the sensing element, mechanical to electrical transition errors in the transducing unit, electrical variations in the transducing element and finally electrical variations in the output stage, all these errors combine to have the same effect as the combination of the individual errors in the mechanical system. These errors may manifest themselves as non-linearity, hysteresis, and repeatability errors, all combining to effect the overall accuracy of the transducer. These errors will be discussed in greater detail in the

## 1.4 Sources of error in measurement systems

If we sought the most general definition of error, we would define it as the difference between the actual value and the measured value. This difference can occur from many sources and in a wide range of ways. We can break these down into three basic categories, systemic errors, random errors and illegitimate errors.

By far the most common systemic errors are Calibration errors, more specifically, non-linearity, hysteresis, repeatability and calibration curve errors. These are generally fairly easy to determine and are quite quantifiable. Probably the least quantifiable systemic error is the tendency for a person taking a reading to consistently “jump the gun” and take the reading before it actually gets there, anticipating the data, rather than reading the data that actually exists. This particular type of error is not only difficult to quantify, in many cases it is difficult to even determine as existing.

Spurious readings from defective equipment also count as systemic errors. This particular error is best dealt with by having a good feeling for what the reading should be, and if the reading taken is out of the “credible” range, it should be considered suspect, and the data should be checked with other probes, or the device checked for accuracy. More difficult to detect are readings that are within the “credible” range, yet are incorrect by small amount, or readings that are generally correct, but contain intermittent incorrect readings. An example of this could be a failing transducer that is subject to vibration. This transducer could occasionally give a bad reading as one wire vibrates loose, but then “fixes” itself a few seconds or minutes later. These type of intermittent errors are extremely difficult to locate and resolve.

Another type of systemic error is known as loading error. If we fully analyze any measurement system, we will realize that the very process of taking data can affect the physical system we are measuring. One simple example would be measuring sound levels emitted from a piece of equipment. The very fact that the sound meter is located in the sound field affects the sound pressure waves. Similarly, if we were to measure the temperature of water in an ice cube tray in a freezer, as it freezes, we would find

that the measurement probe we have inserted into the water will affect how fast this water freezes. These types of loading errors are seen in virtually every measurement we take. Even simple electrical measurements, such as voltage or current, will be affected slightly by the very instruments we are using to measure it. The goal of any good measurement system is to get the best possible data, while minimizing the impact to the system being measured.

The final systemic error is caused by having a measurement device, or system that does not have adequate resolution. Resolution of the measurement system is defined as the smallest increment of change the system is capable of indicating. Say for example, we are using a glass thermometer to measure the temperature of water. This thermometer might have graduations at 1 degree increments. This is the resolution of the measurement device. If the process we are trying to measure needs to be recorded in 0.1 degree increments, the tendency would be to try to interpolate the small space between the 1 degree graduations into tenths of a degree, extending the resolution. The error introduced by this attempt is known as resolution error.

If we have done the best we can to minimize the systemic errors, we still must deal with other types of errors, such as those caused by disturbances in the equipment, fluctuating conditions and insufficient measurement system sensitivity. These three fall into a class of errors known as random errors. These types of errors are simply impossible, in most cases, to determine beforehand. These errors are most easily seen in a situation where multiple readings of the same system are taken, and there is a variation in these readings. Statistically you could calculate the total amount of error and precision, after subtracting the known errors from this spread of points, you are left with the random errors.

There is one final class of errors, known as illegitimate errors. This class of errors includes all the things that can go wrong but shouldn't, such as blunders by the person doing the experiment, or incorrectly calculating results after the data has been taken. These types of errors are rarely accounted for and are by far the most embarrassing to admit to.

