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Guidelines for the Application of Electro-Pneumatic Positioners and Transducers

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Guidelines for the Application of Electro-Pneumatic Positioners and Transducers

Selection of the right electro-pneumatic instrument for a particular process control application has always been a controversy among those who select, operate, maintain and troubleshoot process control equipment. Probably the biggest reason for the ongoing debate is that most application guidelines are either not completely reliable, or they fail to cover all the various applications that may arise.

A superior application guideline, therefore, should be easy to apply, very reliable, and consistent with the realities of the process control system, mathematically and practically. One should be able to select equipment with confidence and know that it will result in the best possible over-all control system performance.

Reliable guidelines for the application of electro-pneumatic transducers and positioners come from a fundamental knowledge of the parameters that affect over-all performance.

Open Loop Control Systems

Process control systems can be categorized as either open loop systems or closed loop. Our discussion starts with open loop systems because they are easier to understand and because they present some useful concepts that can be applied to the discussion of closed loop systems and the selection problem at hand.

Figure 1 shows a generic open loop process control system where the electro-pneumatic instrument has not yet been selected. Notice how the components in this system are connected in a single string where the output of the preceding component is the input to the following component. One suspects that the over-all performance of this system, both from static and dynamic response standpoints, is the summation of the static and dynamic response characteristics of the individual components in the string. Indeed this is the case. The overall performance of this type of control system is no better than the performance of the worst component in the string.

Let's stop here for a moment and look at dynamic performance of processes, actuators and valves, and associated equipment in general terms. Some generic characteristics of performance need to be discussed, the first one being *gain.*

All elements in a control system have gain. Gain is the ratio of the size of the output response from a component to the size of the input stimulus and sometimes is known as sensitivity.

Figure 2 shows two examples of gain measurements made on an element using a fluctuating input. As indicated, gain changes as the rate of the periodic disturbance increases. In this case, the output starts to get smaller, or attenuate, as the frequency of the input disturbance increases. Gain is broken down into static gain and dynamic attenuation categories, but before we discuss them, let's talk about *phase shift.*

Figure 2 shows that there is a retardation or lag in time of the output response relative to the input at higher fluctuation frequencies. This effect is called phase shift and is measured as the number of degrees of shift between the output and input, where –360 degrees means a retardation of the output by one complete cycle relative to the input. Phase shift is normally not seen when a component's input changes slowly, but becomes more significant as the disturbance frequency is increased.

Figure 3 shows the gain and phase shift characteristics of an example component over a wide range of frequencies, from low to high. This figure illustrates some terminology which will help later when we discuss electro-pneumatic devices: *static gain, corner frequency,* and *dynamic attenuation.*

Static gain is the gain that you set when you calibrate an instrument such as an electro-pneumatic positioner or transducer. The static gain for a transducer that has been calibrated for a 4-20 milliamperes (mA) input and a 3-15 psig output is 0.75 psi/mA. Instruments like these maintain their static gain up to a certain rate of fluctuation or frequency and then begin to exhibit distortion of their output due to dynamic attenuation.

Dynamic attenuation is the effect of losing gain as the speed of the input fluctuation increases. The rate or

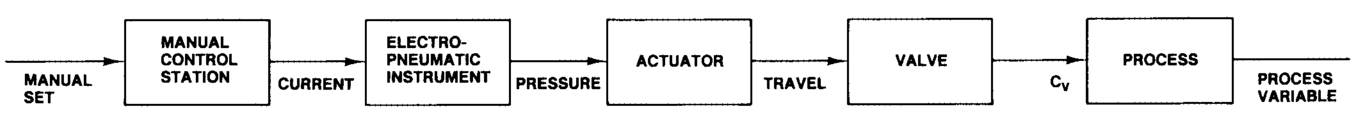

Figure 1. An open loop control system

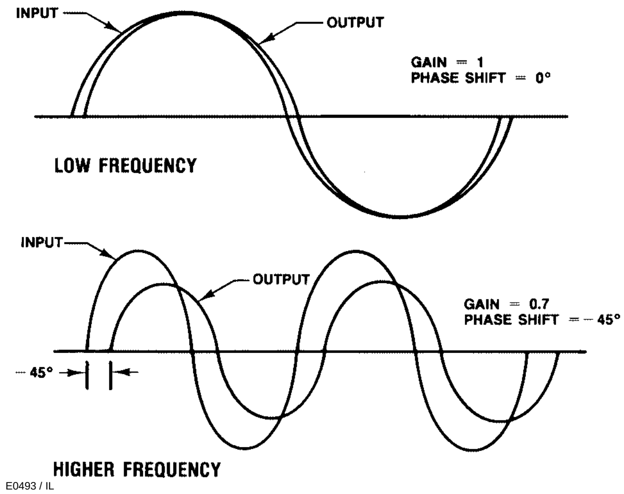

Figure 2. Gain and phase shift of an example element

frequency that corresponds to the place where dynamic attenuation starts to occur is called the corner frequency of the component because the component's gain "turns the corner" from its static value and begins to change to lesser values. Inputs that occur at rates faster than the corner frequency experience dynamic attenuation. The faster the input changes, the more the output is attenuated.

Notice in Figure 3 that a maximum negative phase shift is reached at frequencies well above the corner frequency. The value of this limiting amount of phase shift, –90 degrees in this particular case, depends upon the design and construction of the element under consideration. Limiting values of phase shift for elements in a process control system usually come out to be exact multiples of –90 degrees, i.e., –90, –180, –270, etc.

The effects of static gain, dynamic attenuation and phase shift for each component in an open loop string can be added together to determine the overall static gain, dynamic attenuation and phase shift for the open loop system. With regard to the open loop control system, elements in the system which have the lowest corner frequency characteristics produce the most significant effect on the overall dynamic performance in the system because they contribute most to the overall dynamic attenuation and phase shift characteristics. These elements with the lowest corner frequencies are called *dominant lags* because their slow response has a dominant effect on overall dynamic performance.

As we look back at the open loop system in Figure 1, we need to consider which components have the most undesirable performance characteristics, from both static and dynamic standpoints.

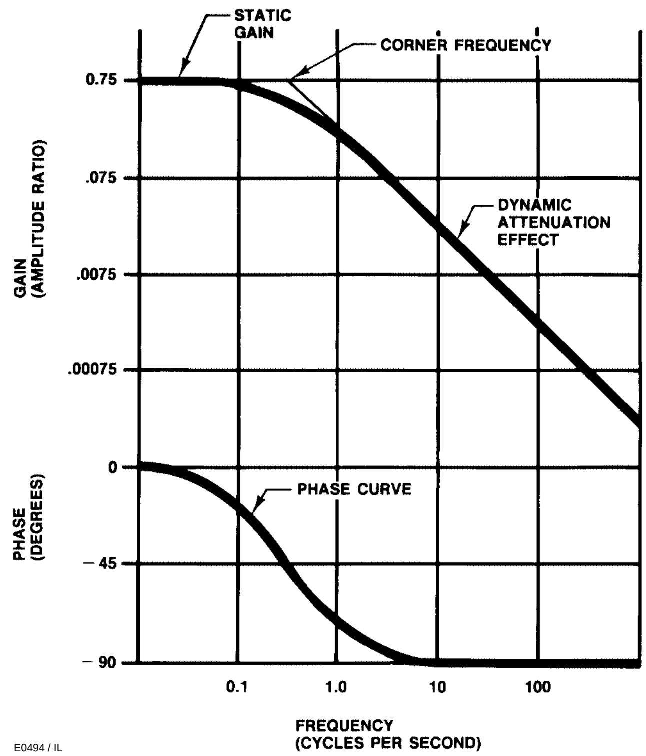

Figure 3. Gain and phase shift characteristics of an example component

The process can certainly be a potential source of undesirable performance in the open loop system. Here the static performance characteristics like linearity, hysteresis-plus-deadband, repeatability or drift due to load changes will all affect the overall control performance of the open loop system directly.

The dynamic behavior of the process also needs consideration. If the process is the dominant lag, the phase shift produced by the process will be very large relative to that produced by the control equipment in the string. The quickest dynamic response for this system will be achieved when the control equipment is selected to have dynamic response characteristics that are faster than the process. In this way, the overall phase shift of the open loop system will not be increased significantly by the control equipment, and the system's response will be no slower than the process.

On the other hand, a process that generates a small amount of phase shift, sometimes called a fast process, will cause the dynamic response of the open loop control equipment to be dominant. In this case the control equipment limits how fast the open loop system can respond.

The dynamic response characteristics of the valve and actuator are normally considerably faster than the other elements in the system, so they produce very

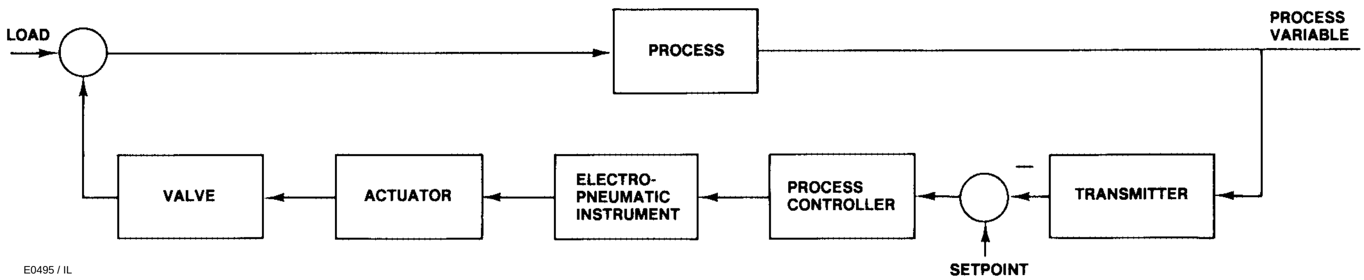

Figure 4. A closed loop control system

little dynamic attenuation or phase shift relative to the dominant lags. The size of the actuator's case volume will have an effect on the dynamic response of the electro-pneumatic instrument that is selected and may make the actuator appear to have slow response. However, it is really the electro-pneumatic instrument that is producing the slow response because of its inability to produce rapid pressure changes into the actuator casing.

The static performance of the actuator and the valve can also limit performance in open loop control. These elements can produce static input/output distortions such as nonlinearity, hysteresis-plus-deadband, and repeatability errors caused by frictions, lost motion and force load reactions coming back through the valve from the process. The combined effect of these errors varies over a wide range but nominally is in the area of 2% to 15% of input span. Because these errors can be rather large, the static performance of the open loop control system will be affected directly if nothing is done to reduce them.

If we were to summarize the characteristics of the electro-pneumatic instrument to be used for open loop control applications, we would come up with the following. First, the static performance of the instrument should be better than the combined static performance of the actuator, the valve, and the process. Second, the dynamic performance of the instrument should have minimal effect on the overall response of the open loop system, i.e., the electro-pneumatic instrument should have fast response.

The instrument that best fits this application is the electro-pneumatic valve positioner. The electro-pneumatic positioner makes use of stem position feedback which lets it reduce the effects of friction and other distortions produced by the valve and actuator by a tremendous amount, normally by 10 to 100 times. The transducer uses pressure feedback, but good control of actuator pressure doesn't guarantee that the valve strokes to the right position. The electro-pneumatic positioner is better here.

Also, positioners are designed to have fast response, normally faster than the pressure response of the transducer. In open loop applications this means that the electro-pneumatic positioner will have a smaller effect on overall dynamic attenuation and phase shift of the system.

Further discussion of the characteristics of electro-pneumatic positioners and transducers occurs in the sections that follow, but before that, we need to develop some understanding of closed loop control systems.

Closed Loop Control Systems

The closed loop control system, like the one shown in Figure 4, does not have the same accuracy and transient response limitations as the open loop control system. When the control equipment in the loop is properly selected, the closed loop system is better at controlling the process variable under varying load conditions.

Conversely, an improperly selected control device can result in a control loop with degraded steady state control and poorer transient response. Let's see how the characteristics of the electro-pneumatic instrument can affect the overall performance of the closed loop control system.

In Figure 4, notice that when a load disturbance occurs it immediately begins to disturb the process, which results in the beginning of a change in the process variable. The process variable is sensed by the transmitter which in turn starts a corrective feedback action back on load flow by way of the process controller, the electro-pneumatic instrument, the actuator and finally, the valve.

The valve makes a resulting change in flow that compensates in an opposite sense for increasing or decreasing values of load flow. The amount or degree of compensation that occurs depends on the gain or sensitivity of each component in the loop, and the more perfect the compensation becomes, the better the performance of the loop. In other words, higher gain around the loop will result in better compensation

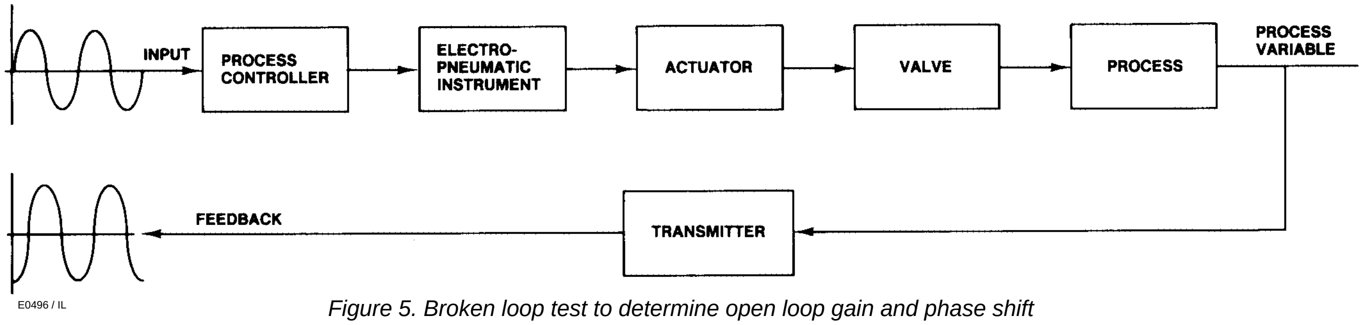

Figure 5. Broken loop test to determine open loop gain and phase shift

than lower gain around the loop. This is why high gain around the loop, or loop gain, is needed for good closed loop performance. Unfortunately, there is a limit to how much loop gain we can have.

As we add ever increasing values of gain to the loop, normally by adjusting the proportional band and reset adjustments on the process controller, we start to see signs of too much loop gain. The process variable will overshoot its correct value before it stabilizes and will start to exhibit nervous behavior. As additional increases in loop gain are made, the loop will become more oscillatory with the oscillations caused by the disturbance taking longer to die out. Continued increases in loop gain will eventually result in a loop that continually oscillates, and the disturbance in the process variable never dies out. Obviously there is a limit to how much gain can be put in a control loop, but why do control loops begin to oscillate when too much loop gain is present? And is there anything that can be done to maximize loop gain before signs of instability occur?

The reason instability occurs is due to the phase shift characteristics that result from all the elements in the loop and the static gain and dynamic attenuation characteristics of these elements. To see exactly why this is, we can use a demonstration like the one shown in Figure 5.

If we break the closed loop open at some point like shown in Figure 5, we see a string of elements much like the open loop control system that we discussed earlier. By externally generating a periodic disturbance and injecting it into the system in this broken loop demonstration, the disturbance will progress around the loop (or through the string at this point) and pick up the combined effects of static gain and dynamic attenuation and phase shift distortions. If we compare the return or feedback response to the periodic disturbance we are injecting into the input of the system, we could determine the loop gain, more commonly known as *open loop gain,* and the total phase shift that is generated. The open loop gain that we observe is the combination of the static open loop gain and the total dynamic attenuation around the loop, where the *static open loop gain* is the product of the static gains for each element in the loop.

If we now change the frequency of the input disturbance in our demonstration, we can make another measurement of open loop gain and another measurement of phase shift. If we run enough of these tests at various frequencies, we would develop a good feel for the relationship between the input frequency, the loop gain, and the overall phase shift around the loop.

The important thing about the open loop data that we have recorded during the broken loop demonstration is that it can predict the stability of the control loop when the loop is reclosed. To do this we simply look for the input frequency in the data that we have collected that produces a full 360 degrees of delay around the loop. At this particular frequency the feedback disturbance that returns in our broken loop example is one full cycle out of phase with the input or, in other words, again exactly in phase with the input disturbance. If the size of this return disturbance is as large as or larger than the periodic input disturbance, then the open loop gain at this frequency is one or greater. It means the loop is dynamically unstable because the oscillations around the loop would sustain themselves if we were to suddenly disconnect the disturbance generator and quickly reclose the control loop. *What we are saying is that the stability of the control loop can be predicted by first finding the frequency where the phase shift around the loop is –360 degrees and then by seeing if the open loop gain at this frequency has a value of one or greater. If the loop gain is one or greater at this particular rate of disturbance, then the control loop is dynamically unstable.*

The particular frequency of disturbance that we are discussing is known as the *critical frequency* of the control loop because this is the rate at which the loop will oscillate if the loop gain is too high. Every control loop has a critical frequency which can be predicted if the static gain, dynamic attenuation and phase shift characteristics are known for each element in the control loop.

How does this relate to the selection of electro-pneumatic control equipment? The closed loop systems that we are discussing are *negative feedback control systems,* which means that they all have a feedback signal that is –180 degrees out of phase with the control signal from the controller. Negative feedback is why the closed loop control system compensates and minimizes deviations in the process variable when a disturbance or a load change occurs.

Because this type of control inherently has –180 degrees of phase shift to start with, the components in the loop need to contribute only another –180 degrees of phase shift to make –360 degrees and to determine the critical frequency of the loop. The electro-pneumatic positioners and transducers contribute to a portion of the –180 degrees of phase shift required to determine the critical frequency of the control loop. Depending on their dynamic response characteristics and how they are selected, better or worse control performance will occur.

More specifically, our discussion of stability indicates that the open loop gain of the closed loop control system must be less than one at the loop's critical frequency. Furthermore, if there is a way to maintain high open loop gain everywhere except at the loop's critical frequency, then the best case closed loop performance will result. This is where the proper selection of the electro-pneumatic instrument is important.

If the electro-pneumatic instrument is selected for a given application to maximize dynamic attenuation around the loop at the loop's critical frequency, then high values of static open loop gain can be realized by adjusting the process controller's gain upward. The result will be better overall closed loop control of the process.

How maximum dynamic attenuation is achieved by proper selection of the electro-pneumatic positioners and transducers is the topic of the next sections. The dynamic attenuation and phase shift characteristics of these two types of electro-pneumatic instruments prove most important.

Electro-Pneumatic Positioners

The electro-pneumatic positioner function is accomplished in process control systems in several different ways by manufacturers of this type of equipment. Figure 6 shows that some designs are composed of electric and pneumatic components combined into one device, while other types are actually a combination of an electro-pneumatic transducer coupled to a pneumatic input valve positioner. All of these designs have similar static and dynamic response characteristics, and for the discussion that follows, all yield the same conclusion.

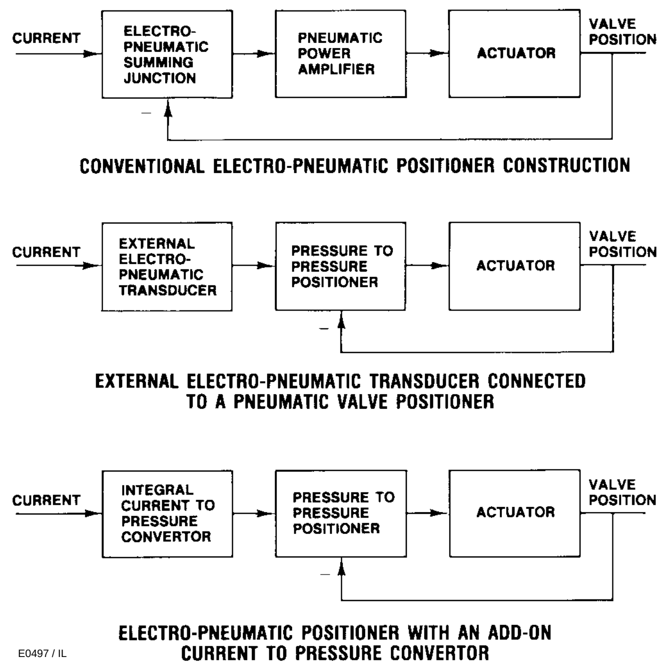

Figure 6. Some different constructions of currently available electro-pneumatic positioners

Positioners are actually closed loop valve stem position control systems that are mounted right on the actuator. The static gain of the valve positioner is determined when the instrument is calibrated. The corner frequency, dynamic attenuation and phase shift characteristics are determined by the particulars of the positioner design and also by the size of the actuator that the positioner is mounted on.

Because of the design of the pneumatic amplifiers in the positioner and because of the overall stem position feedback used in the positioner, the positioner has the ability to cover up the distortions caused by actuator and control valve friction. This is why some think that the best process control always occurs when a valve positioner is used. It turns out that this is true on some types of closed loop process control systems and not true on others.

Figure 7 shows actual time recordings of a slow responding gas pressure control process. This process was observed with an electro-pneumatic transducer installed on the actuator first, and then with the transducer removed and an electro-pneumatic positioner installed. Notice that the response of the control system to a step change in setpoint is faster with the electro-pneumatic positioner than with the electro-pneumatic transducer and no positioner. Also note that the proportional band and reset settings of the process controller are higher when the positioner is installed. Look as well at the state of the process pressure after the transient from the setpoint change has died out. The control system without the positioner

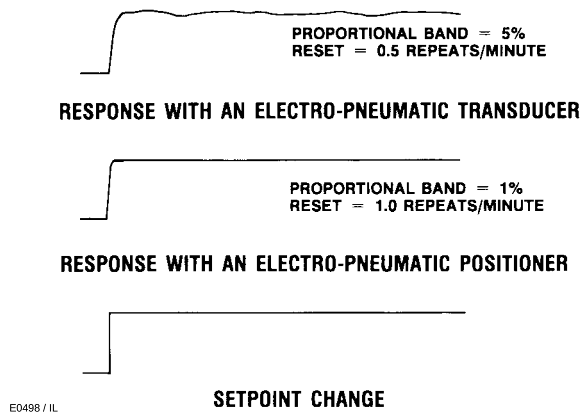

Figure 7. Comparison of the time response of a slow process control system using an electro-pneumatic transducer to one with an electro-pneumatic positioner

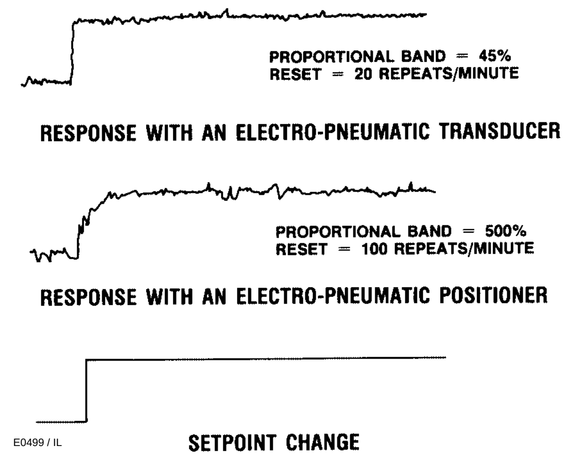

Figure 8. Comparison of the time response of a fast process control system using an electro-pneumatic transducer to one with an electro-pneumatic positioner

hunts around and never does completely stabilize. Continuous hunting of the control valve was observed when the transducer was installed, and none was observed when the positioner was installed.

It turns out that electro-pneumatic valve positioners work better than electro-pneumatic transducers alone when the process corner frequency is considerably less than the corner frequency of the electro-pneumatic positioner and actuator we are using. We can use our knowledge of process control systems to understand the reasons why.

The slow responding process is the dominant lag in the control loop and therefore has a considerable effect on the dynamic attenuation and phase shift that occurs in the loop at the systems critical frequency. By itself, however, the phase shift generated by the process is not sufficient to determine the critical frequency of the control loop as it generates a maximum amount of –90 degrees. The rest of the phase shift needed must come from the next slowest lag, which turns out to be the electro-pneumatic positioner or the transducer.

The electro-pneumatic positioner works better because the corner frequency of the positioner on the actuator is higher than the corner frequency of the transducer connected to the same actuator, i.e., the positioner has faster response than the transducer. This means that the slow dominant process lag will produce more dynamic attenuation at the critical frequency of the control system when the positioner is installed because there is more *dynamic separation* between the dominant process lag and the next slowest source of phase shift, the positioner. More dynamic separation between the dominant lag and the next most dominant lag means more dynamic attenuation from the dominant lag, and the loop will take on more static open loop gain before signs of instability occur. More static open loop gain means better control system performance.

Using an electro-pneumatic transducer instead of the electro-pneumatic positioner to control a slow process produces less dynamic separation between the dominant process lag and the next most dominant lag. The results are less static open loop gain and poorer overall control performance, which is why electro-pneumatic valve positioners should be always used on slow process loops.

A beneficial side effect of using a valve positioner in a loop that controls a slow process is the reduction of distortion presented to the loop resulting from the friction and other distortion characteristics of the valve and actuator. As mentioned in the discussion on open loop control systems, the positioner effectively reduces static valve and actuator distortions by 10 to 100 times. It therefore enhances the overall control system performance and reduces hunting of the process variable after all other external disturbances have died out.

In the next section, we will find out that positioners are not always able to reduce friction related distortions in a control loop and can even make things worse.

Electro-Pneumatic Transducers

We have already shown that electro-pneumatic positioners work better when the process to be controlled looks like a slow dominant lag. It turns out that electro-pneumatic transducers alone work best when we are controlling a fast responding process, like liquid pressure control or some flow control applications.

Figure 8 shows a comparison of the response of a fast process control system, first using an electro-

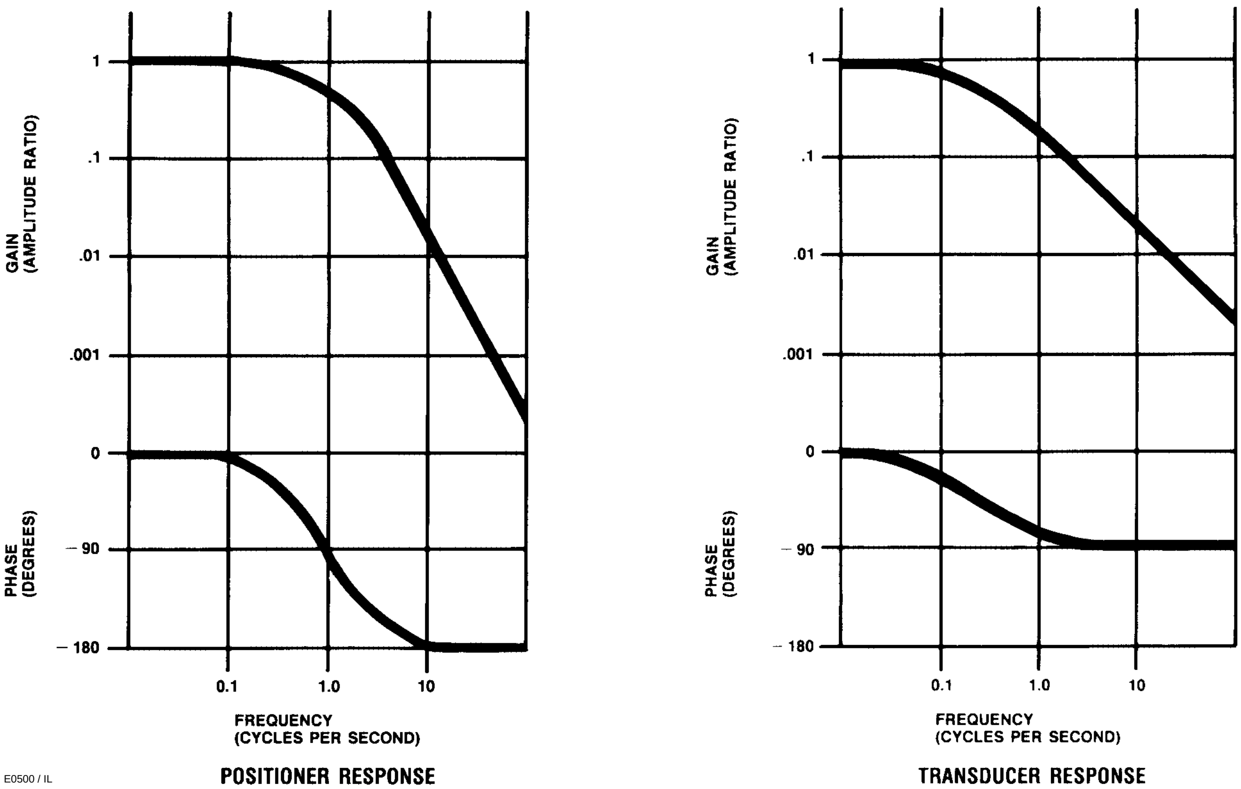

Figure 9. Gain and phase shift characteristics of an electro-pneumatic valve positioner and electro-pneumatic transducer

pneumatic transducer alone, and then with an electro-pneumatic positioner. The process that we are controlling here is a liquid flow process with a high corner frequency, i.e., a fast responding process. Notice the response to the setpoint change of the two systems. The response of the system with the transducer installed is much quicker than the control loop with the positioner and the controller tuning with the transducer is dramatically higher. Also, the steady state response of the system after the transient has died out is less noisy and erratic when the electro-pneumatic transducer is installed. Continuous hunting of the control valve is much less when the positioner is omitted. This indicates that transducers do a better job controlling fast processes than do positioners.

During the control of a fast process, the dominant lag will be the transducer or the positioner because all the other lags in the loop are quicker responding. This means that we will experience the best overall control of the process when we select the electro-pneumatic instrument with the *slower* response and thereby provide for the greatest amount of dynamic separation between the dominant transducer lag and the next most dominant lag, the process.

Figure 9 shows typical response characteristics of an electro-pneumatic transducer and an electro-pneumatic positioner that have been installed on the same actuator. Figure 9 is of value because it shows that the electro-pneumatic transducer produces slower response into the actuator than the equivalent positioner. It also indicates that the transducer only produces –90 degrees of phase shift at frequencies above its corner frequency where the positioner produces –180 degrees of phase shift.

The transducer's response is known as *first order response* and is characterized by a maximum phase shift of –90 degrees at high frequencies. This type of response gives the transducer the best dynamic attenuation and minimum phase shift characteristics that make it best suited for a dominant lag when applied to the closed loop control of a fast process. In this application the transducer provides the slow dominant first order lag that provides for the dynamic separation required to produce good controller tuning and good control loop performance.

The positioner response shown in Figure 9 generates dynamic attenuation at a faster rate, but it also generates a lot more phase shift. A dynamic characteristic like this that generates a maximum of –180 degrees phase shift at high frequencies is said to have *second order response.* Second order positioner response is undesirable in fast process control loops because the positioner is the slowest lag in the loop, and because of its second order response characteristic, the positioner determines the critical frequency of the control loop by itself. The whole idea of increasing performance by increasing the dynamic separation between the dominant and second slowest lag is pointless when a second order characteristic is the slowest lag. Second order positioner response limits how much dynamic attenuation will occur at the critical frequency of the loop.

You may wonder about the positioner's valuable ability to reduce valve and actuator friction distortions that we mentioned in the slow process discussion. The fact is that valve positioners of any type are only able to reduce valve and friction related distortions at frequencies up to about one half of their corner frequency. Above one half of the positioner corner frequency, the amplifiers in the positioner begin to roll off or dynamically attenuate. This, in combination with the valve/actuator produced distortion, results in distortion of the control signal that is actually worse than that present when there is no positioner at all. This is the reason why we see more hunting in Figure 8 when the positioner is installed.

The Guidelines

Our preceding discussion focused on what happens in a control system when an electro-pneumatic positioner or an electro-pneumatic transducer is used. The following application guidelines result from these discussions.

For open loop control systems:

1. Always use an electro-pneumatic valve positioner.

For closed loop control systems:

1. If the system is relatively fast, such as is typical of liquid pressure, fast flow and small volume gas pressure control loops, best control performance will be achieved by selecting an electro-pneumatic transducer and by not using a valve positioner.

2. If the system is relatively slow, such as is typical of liquid level, blending, temperature, large volume gas pressure and slow flow control loops, best control performance will be achieved by selecting an electro-pneumatic positioner.

Guideline Application

Application of the guidelines stated above is usually just a quick reflection as to whether the process is to be in an open loop control system or a closed loop system and then, in the case of closed loop control, a determination of whether the process lag is fast (not a dominant lag) or slow (dominant). The proper electro-pneumatic instrument selection is then made according to the rule of the guidelines.

For closed loop control, the preceding guidelines help by providing examples of several generically fast and slow processes. A few extra pointers that relate to the practical application of the guidelines may be helpful.

1. In those applications where the use of an electro-pneumatic positioner is indicated, an electro-pneumatic transducer and a pneumatic input valve positioner, connected together in series, can be used as an equivalent substitute for the electro-pneumatic positioner. The dynamic response of the transducer, in this case connected to the input of the positioner, is very fast and will not change the results indicated by the guidelines. This point may be of benefit when it is desirable to not mount the electro-pneumatic instrument on the control valve.

2. There are systems where adequate control is quite easy to achieve or stringent performance requirements do not exist. In these cases, relatively loose control settings are acceptable and misapplication of the guidelines will produce quite tolerable results.

3. An actuator without a spring, such as a piston actuator, always requires the use of a positioner. If your application requires the use of an actuator such as this and the application is on a fast process, you will have to accept looser controller settings and degraded closed loop control. The penalty that you pay in this case may not be serious, particularly if your control requirements are not extreme. The application of springless actuators with positioners on slow processes is in agreement with the guidelines.

4. There are cases in closed loop applications where the process corner frequency is in a range between one tenth and one half of the positioners corner frequency, and therefore the process is not clearly fast or slow. This case can be considered to be in the "grey" or transition range of the application guidelines. It turns out that in this situation either positioner or transducer can be used with similar closed loop results.

5. Electro-pneumatic transducers should be designed to have dynamic attenuation and phase shift characteristics that look like dominant first order response when they are installed on an actuator. This type of response gives the transducer the best dynamic attenuation and phase shift characteristics that make it best suited for application to the closed loop control of a fast process. *Be aware that not all transducers are designed to have first order response when installed on an actuator.*

The response characteristic shown in Figure 10 is of a currently available electro-pneumatic transducer that is connected to a popular actuator. Notice that this transducer generates more than –90 degrees of phase shift at high frequencies.

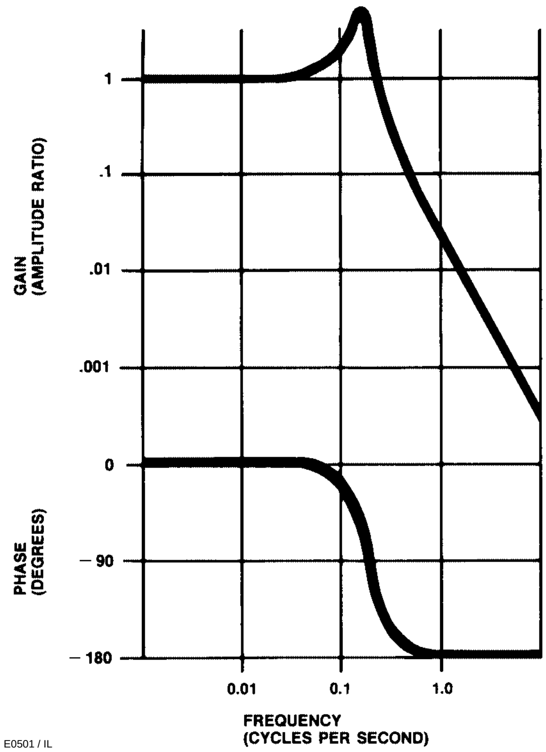

Figure 10. Second order response of an electro-pneumatic transducer connected to an actuator

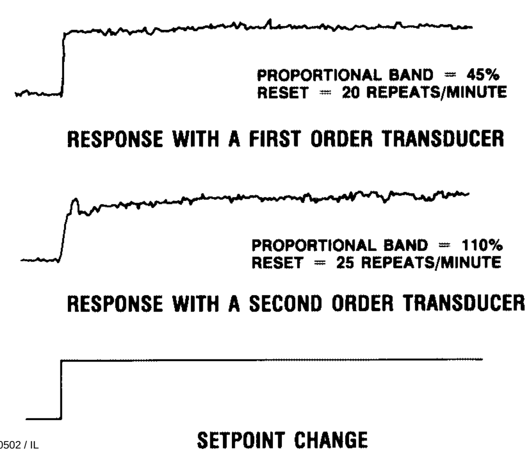

Figure 11. Time response of a fast process control system using two different types of transducers

When a transducer with a second order response characteristic is installed in a loop that is controlling a fast process, the controller gain settings are looser, and the control system response is slowed. This is demonstrated in Figure 11 where the response of a fast process control system using a transducer with a first order response characteristic is compared to the response of the same system using a transducer with a second order response characteristic. Notice the improvement in controller tuning and the crisper response of the system with the first order transducer response. Beware of the transducer with second order response characteristics when applied to fast processes as this type of transducer results in less than the best process control.

The last point to make is that *it is the dynamic performance characteristic of the electro-pneumatic positioner and electro-pneumatic transducer that is important in their successful application.* Too much emphasis on “on the bench” static performance such as linearity, hysteresis-plus-deadband, and repeatability will cause improper selections to occur.

Emphasis on reducing friction and distortion in the control loop by always using an electro-pneumatic positioner is unreasonable and unreliable.

Conclusion

The preceding guidelines for the application of electro-pneumatic positioners and transducers serve as easy-to-apply and reliable electro-pneumatic equipment selection tools for process control systems of all types. The discussion sticks to fundamental process applications and basic automatic control theory concepts. For the very few applications that may arise where a clear cut decision is not indicated, the outline of the discussion can be expanded to provide meaningful application guidance.

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