QUANTIFYING AND SPECIFYING THE DYNAMIC RESPONSE OF FLOWMETERS

David Wiklund
Sr. Principal Engineer
Rosemount, Inc.
Chanhassen, MN 55317

Marcos Peluso
Director of Temperature and Plantweb Development
Rosemount, Inc.
Chanhassen, MN 55317

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Abstract

The dynamic response characteristics of flowmeters are often incompletely or incorrectly specified. This is often the result of inadequate dynamic testing. This paper describes a robust method for determining the dynamic response characteristics of flowmeters. The results of frequency response tests on a number of flowmeter technologies are presented. A concise way of specifying the dynamic performance of flowmeters is presented.

Introduction

A common method for selecting a flowmeter is to compare the performance specifications of the devices under consideration. The performance parameter most often used in these comparisons is the uncertainty in the measurement of the flow rate. It is generally specified by flowmeter manufacturers and is relatively easy to verify in the laboratory under controlled steady state conditions. However, because real world flow applications are not steady state, a more meaningful comparison of candidate flowmeters can be made if their response to flow transients is included as one of the metrics in the evaluation. Such a comparison is often complicated by incomplete and sometimes incorrect specification of the dynamic characteristics of flowmeters. This paper will describe a method for quantifying the dynamic response of flowmeters as well as a concise way of specifying their dynamic performance.

Step Response Tests

The step response test is often used to determine the dynamic response characteristics of instruments. In conducting a step response test the input to the device under test is abruptly changed while the output is monitored. During such tests it is highly desirable to have a fast responding, independent device to monitor and provide as true a representation of the input as possible.

The response of many instruments to step inputs looks similar to that shown in Figure 1. For an increasing step input the output of the device asymptotically approaches its final value in a decaying exponential fashion. This behavior is characteristic of devices whose time response can be described mathematically by a first order differential equation. They are called first order devices or first order lags. A single parameter, the time constant, τ, is sufficient to completely describe the response of a first order lag to transient inputs. The time constant is the time required for the output of the device to reach approximately 63% of its final value.

When the results from a step response test look similar to those shown in Figure 1 it is natural to assume that the behavior can be described by one first order differential equation. That this is not always the case is illustrated in Figure 2. Here a step input and the response of a device described by a pair of first order lags are shown. Determining the 63% point of the output response results in a time constant of approximately 0.67 seconds. Using this time constant the time response of this single lag approximation is also shown in Figure 2. The single lag approximation is seen to be a poor estimator of the time response of the real device. The underestimation of the order of a flowmeter and resulting incorrect specification of the dynamic performance has ramifications in flow control applications [1, 2].

In addition to underestimating the order of the device, the step response test has three other serious shortcomings for testing flowmeters. First, pumps and valves cannot change instantaneously. The typical input becomes a ramp input rather than a step input. This complicates the interpretation of the data and makes it even more important to have a fast responding monitoring device to properly characterize the ramp input. Second, since many flowmeters make use of digital circuitry, the flowmeter output will exhibit dead time. The timing of the step input relative to the sampling of the digital circuitry will affect the apparent dead time. Repeated tests need to be performed with the largest measured value of dead time interpreted as the flowmeter dead time. Finally, step tests often consist of large amplitude, unidirectional inputs. Such inputs are unrepresentative of real world inputs and make it difficult to identify any asymmetrical or non-linear behavior of the device under test.

Frequency Response Tests

The evaluation of step response test results in the time domain, while it may seem familiar and intuitive, is not the best way to quantify the dynamic response characteristics of flowmeters. A far more reliable method for determining the dynamic response characteristics of any device is to perform a frequency response test. In such a test a sinusoidally varying input is applied to the device and the output is compared to the input. Figure 3 shows that the two parameters of interest are the gain and the phase shift. The gain is a measure of how much the output of the device is amplified or attenuated compared to the input. The phase shift is a measure of the time lead or lag as the device output follows the input.

The gain and phase shift values vary as a function of the frequency of the input. Consequently, it is more convenient to look at the data in the frequency domain. To make the leap from the time domain to the frequency domain requires the use of some mathematical tools used in automatic control theory [3,4]. One of these tools is the Laplace transform of a function of time, f(t), defined as:

$$F(s) = \int_0^\infty f(t) e^{-st} dt \qquad (1)$$

where: F(s) = Laplace transform of f(t)
f(t) = time function
s = Laplace transform variable
t = time.

One advantage of using the Laplace transform is that it transforms differential equations into algebraic equations making them much easier to manipulate and solve.

Another convenient mathematical concept is the transfer function, defined as the ratio of the Laplace transform of the output divided by the Laplace transform of the input. Using the Laplace transform notation the transfer function of a first order lag is:

$$TF = \frac{1}{1+\tau s} \tag{2}$$

where: TF = transfer function
τ = time constant (typically in seconds)
s = Laplace transform variable.

This transfer function expression is characteristic of all first order devices. It is only τ that changes from device to device.

A final useful mathematical tool is the Bode plot. The Bode plot is a two-part graph that plots the gain vs. frequency and the phase shift vs. frequency. For both graphs the frequency is plotted on a logarithmic scale. The gain is generally converted to decibels using the following equation:

$$G_{dB} = 20 \times Log_{10} G_{numerical} \tag{3}$$

where: $G_{numerical}$ = numerical value of gain
G_{dB} = gain in decibels.

For all results presented here the phase shift will be in degrees and the frequency will be in Hz.

A powerful feature of transfer functions is that when the output of one element serves as the input to another the transfer functions of the two elements are multiplied. Because of the logarithmic nature of the Bode plot, the gain and phase shift values of the two elements are additive. An example of a Bode plot for a device whose transfer function is given by two first order lags and dead time is shown in Figure 4a and 4b. The transfer function is given by:

$$TF_{composite} = \frac{e^{-\tau_d s}}{(1+\tau_1 s)(1+\tau_2 s)} \tag{4}$$

where: $TF_{composite}$ = composite transfer function

τ_d	=	dead time (seconds)
$\tau_{1,2}$	=	time constants of the two first order lags (seconds)
s	=	Laplace transform variable.

It should be noted that the dead time makes no contribution to the gain. It only contributes to phase shift, a fact that has important ramifications in control applications [1, 2]. In Figure 4a the gain contributions of the two first order lags add to produce the composite gain curve. Similarly, in Figure 4b the phase shifts from the two first order lags and the dead time add to produce the composite phase shift curve.

Experimental Test Setup

The experimental apparatus used to conduct frequency response tests on flowmeters is shown in Figure 5. It consisted of a recirculating water flow loop with 3-inch pipe. The mechanical parts of a 3-inch turbine meter were used as the reference meter. The pulses from the turbine meter were sent to a fast Frequency–Voltage converter to produce an analog signal representative of the flow rate. Two identical 3-inch globe-style valves with positioners were installed downstream of the flowmeters. They were the fastest available industrial control valves. One was held constant at 50% open. The position of the other valve was modulated to provide the sinusoidally varying flow rate. A HP 3563A control systems analyzer was used to generate the sinusoidal signal, to process the data and to produce the Bode plot data. The analyzer swept the frequency from 0.01 Hz to 10 Hz. The input to the valve was 12 mA ± 0.5 mA (50% of travel ± 3%). At the low frequency end the nominal flow rate and variations were approximately 96 gpm ± 6 gpm. The control systems analyzer performed a fast Fourier transform on the inputs from the flowmeter under test and the fast turbine meter/F-V converter to generate the gain and phase shift values. The attenuation of the valve travel causes the sinusoidal changes in flow rate to stop at approximately 2 Hz. The HP3563A continues to sweep through the frequency range and perform the FFT in an attempt to generate phase shift and gain data. The result is that both the gain and phase shift curves become very noisy for frequencies above approximately 2 Hz. The experimental test setup is described in more detail elsewhere [5].

Frequency Response Test Method and Results

The flowmeter technologies on which the frequency response tests were run included differential pressure/orifice, vortex, electromagnetic and coriolis. The tests involved eleven different models of differential pressure transmitters from five manufacturers, six different models of vortex meters from four manufacturers and three different models of magmeters from two manufacturers. A single coriolis meter was also tested. The same orifice meter run ($\beta = 0.67$) was used for all differential pressure/orifice meter tests.

It was postulated that some of the flowmeter technologies would have part of their dynamic response performance determined by elements whose characteristics would not change as the flowmeter damping was changed and part that would vary with the damping. An example of this is the differential pressure transmitter. It was anticipated that the oil-filled sensor would have fixed dynamics. It was further postulated that the filtering due to the user-adjustable damping would result in variable dynamic performance. Consequently, the differential pressure/orifice flowmeters were modeled mathematically as two first order lags and dead time. Since the user-adjustable damping value was known there were two parameters to be determined – the fixed time constant and the dead time. Similar mathematical models were postulated for the other flowmeter technologies.

Multiple frequency response tests were conducted on each device with the user-adjustable damping set to different values for each test. Mathematical models based on the postulated transfer function were plotted with the experimental data. The values of the time constants and dead time were adjusted until all of the mathematical models fit the experimental data. The equations used for the mathematical models were:

$$Gain_{1stOrder} = 20Log_{10}\left[\frac{1}{\sqrt{1+[\tau(2\pi f)]^2}}\right]; \qquad PhaseShift_{1stOrder} = Tan^{-1}[\tau(2\pi f)] \qquad (5), (6)$$

$$Gain_{DeadTime} = 0; \qquad PhaseShift_{DeadTime} = -\tau_d(2\pi f) \qquad (7), (8)$$

where: Gain = gain (decibels)
f = frequency (Hz)
τ, τ_d = time constant and dead time (sec)

The gain values are in decibels and the phase shift values are in degrees. An example of the how the mathematical models fit the experimental data is shown in Figure 6a-b. As was previously noted, the attenuation of the valve travel at frequencies greater than approximately 2 Hz was the cause of the noise shown in Figure 6a-b (identified as the "System Limit"). This phenomenon was observed in all tests. It was an artifact of the test system and should not be considered representative of the behavior of any of these devices. The mathematical models are seen to fit the experimental data very well and revealed that the dead time was 0.050 sec and the fixed time constant was 0.030 sec. The user-adjustable damping was set at the values listed in the legend of Figure 6a-b.

The transfer function parameters for all flowmeters tested are summarized in Tables 1 through 4. The nomenclature for designating the meters in the tables is DP, V, M and C for differential pressure/orifice, vortex, electromagnetic and coriolis, respectively. This is followed by a numerical indicator to designate the manufacturer and then by a letter to differentiate meters from a given manufacturer. For example DP1B indicates the second differential pressure/orifice meter from manufacturer #1. Table 1 shows the results for the differential pressure/orifice meter tests. Table 2 shows the results for the vortex meters, Table 3 shows the results for the magmeters and Table 4 shows the results for the coriolis meter. It should be noted that for some of the flowmeters there were discrepancies between the settings of the user-adjustable damping values and the values used in the mathematical models. This is probably related to the software implementation in those particular devices.

The test results show that for all differential pressure/orifice meters the dynamic response is characterized by two first order lags, one with a fixed time constant, and dead time. Four of the six vortex meters were characterized by a single first order lag with a time constant that varied with the user-adjustable damping and dead time. For the other two vortex meters, both from the same manufacturer, an additional first order lag with a fixed time constant was required to fit the experimental data. The magmeters were all characterized by two first order lags, one having a fixed time constant with the other varying with the user-adjustable damping and dead time. Since only a single coriolis meter was tested it is difficult to generalize the results. However, the physics of these devices demands a different type of model to fit the experimental data. The coriolis meter tested was characterized by a critically damped second order lag with a fixed natural frequency and damping ratio, a variable time constant first order lag and dead time. The time constant of the first order lag and the dead time were both found to vary with the user-adjustable damping. These results can be summarized in general transfer function notation using the following expressions:

For differential pressure/orifice meters, vortex meters and magmeters:

$$TF = \frac{e^{-\tau_d s}}{(1+\tau_{fixed}s)(1+\tau_{adj}s)} . \tag{12}$$

For the coriolis meter:

$$TF = \frac{e^{-\tau_d s}}{[(s/\omega_n)^2 + (2\varsigma/\omega_n)s + 1](1+\tau_{adj}s)} . \tag{13}$$

where:

TF	=	transfer function
s	=	Laplace transform variable
τ_d	=	dead time (sec)
τ_{fixed}	=	fixed time constant (sec)
t_{adj}	=	adjustable damping time constant (sec)
ω_n	=	undamped natural frequency (rad/sec)
ζ	=	damping ratio.

Specifying Dynamic Performance

The typical way of specifying the dynamic performance of flowmeters is to state the dead time and a range of values for the user-adjustable damping time constant. The implications of this are that the dead time is constant and that a single first order lag will adequately describe the dynamic performance. For most of the devices tested the assumption of a constant dead time is a good one. The second assumption, that the dynamic performance can be quantified with a single first order lag, will often result in a misstatement of the dynamic performance. The test results show that an additional first order lag associated with the mechanical and/or electrical design of the devices contributes to the dynamic performance of many flowmeters. At minimum damping settings this additional lag is actually the main contributor to the dynamic performance.

A more robust and descriptive way of specifying the dynamic performance is to use the transfer function. The transfer function provides a way of unambiguously specifying the dynamic performance of flowmeters. It reveals all of the terms that contribute to the dynamic performance of the devices. It makes clear distinctions between elements common to all flowmeters (i.e., user-adjustable damping) and design-dependent elements (i.e., sensor and/or electronics design characteristics). This allows users to do a complete and comprehensive comparison of flowmeter performance.

Conclusions

The difficulties associated with using step response tests to quantify the dynamic response characteristics of flowmeters have been addressed. These include difficulties in providing a true step input, difficulties in quantifying the dead time and the tendency to underestimate the dynamic performance by specifying it with a single time constant. The frequency response test method has been shown to be superior to the step response test. It provides inputs to the flowmeter that are more representative of actual flow applications. Furthermore, it provides for easier quantification of the flowmeter dead time. In addition, the frequency response test method makes it much easier to completely quantify the dynamic response characteristics of flowmeters.

The test results show that within a given technology the mechanical and electrical design of the devices plays a large role in determining the dynamic response characteristics. The user-adjustable damping results in a first order lag for all flowmeters tested. For differential pressure transmitters the sensor mechanical design and electronics signal processing design contribute to both an additional first order lag time constant and the dead time of the device. For magmeters and vortex meters an additional first order lag is affected primarily by the electronics signal processing design. The physics of Coriolis meters leads to a different mathematical model than other flowmeters.

In general, the fastest flowmeters were the differential pressure/orifice meters, although there was much variation in response within this technology. One of the magmeters had comparable performance to the fastest differential pressure/orifice meter. The remaining magmeters, vortex meters and the coriolis meter were significantly slower in their response characteristics. It is also clear that, regardless of the flowmeter technology employed, setting the damping to the minimum value results in faster response.

Finally, the results of the frequency response tests show that the commonly used single time constant method of specifying dynamic performance is inadequate and inaccurate. A consistent method of specifying dynamic performance is required to allow users to comprehensively compare one flowmeter to another within a given type of technology and to make the same kinds of comparisons of flowmeters of differing technologies. The transfer function is presented as a means of specifying dynamic performance that would eliminate any ambiguity in the specification of dynamic response characteristics and allow the user to make a more informed decision when selecting flowmeters.

References

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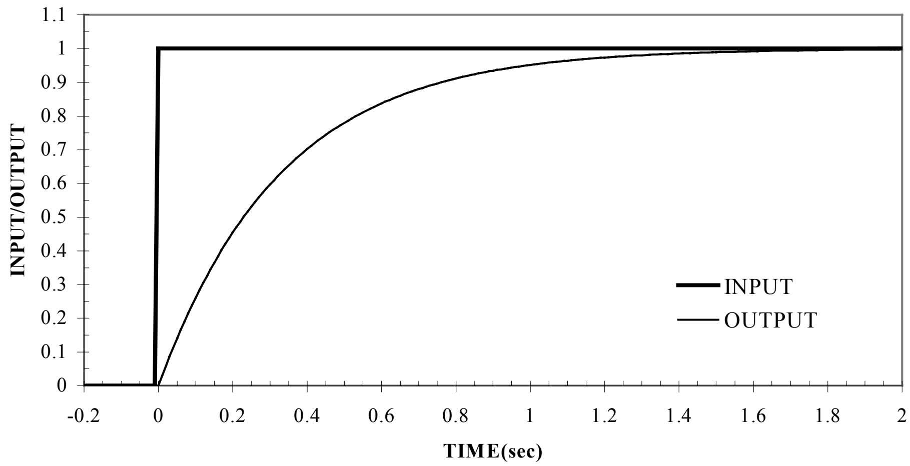

Figure 1. Typical response of a device to a step input

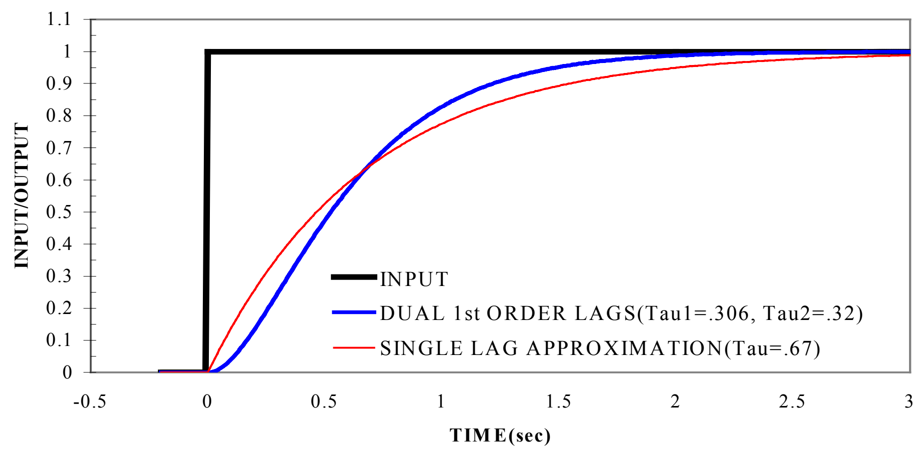

Figure 2. Step response of dual lag device and single lag approximation

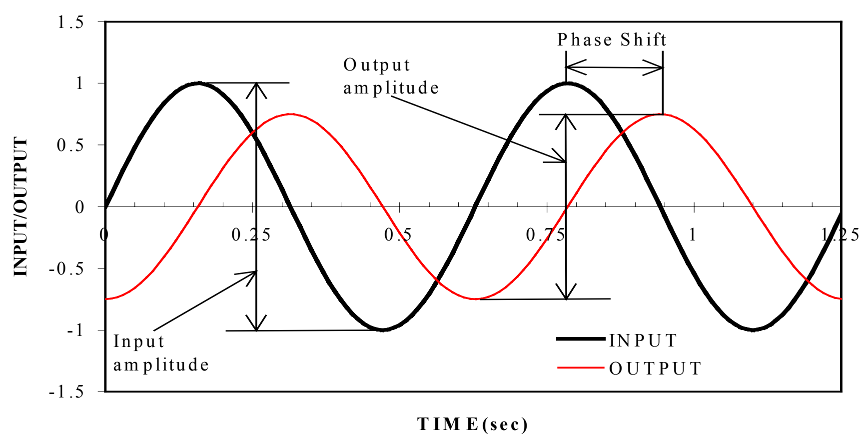

Figure 3. Time response showing attenuation and phase shift of output relative to input.

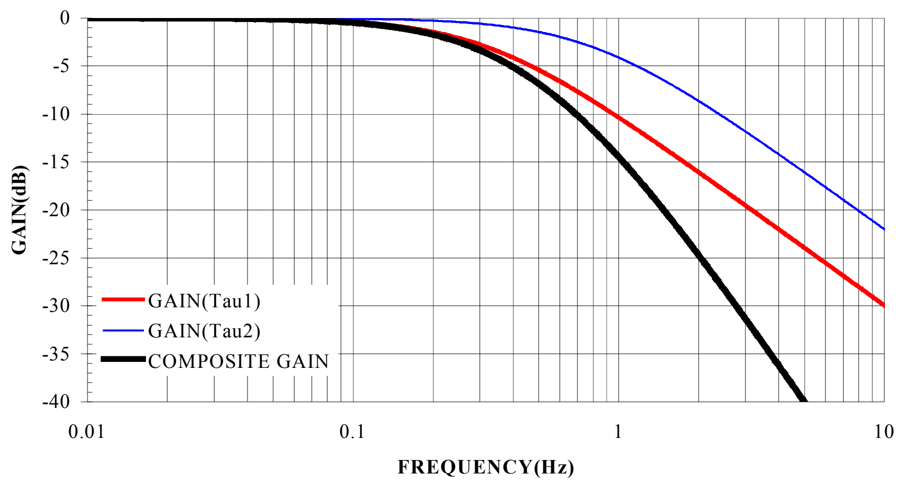

Figure 4.a. Gain part of Bode plot demonstrating the addition of gain contributions

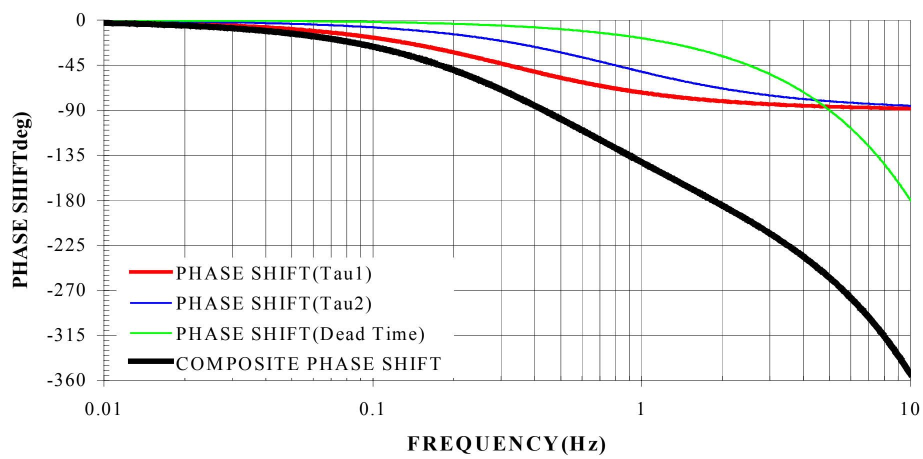

Figure 4.b. Phase shift part of Bode plot demonstrating the addition of phase shift contributions

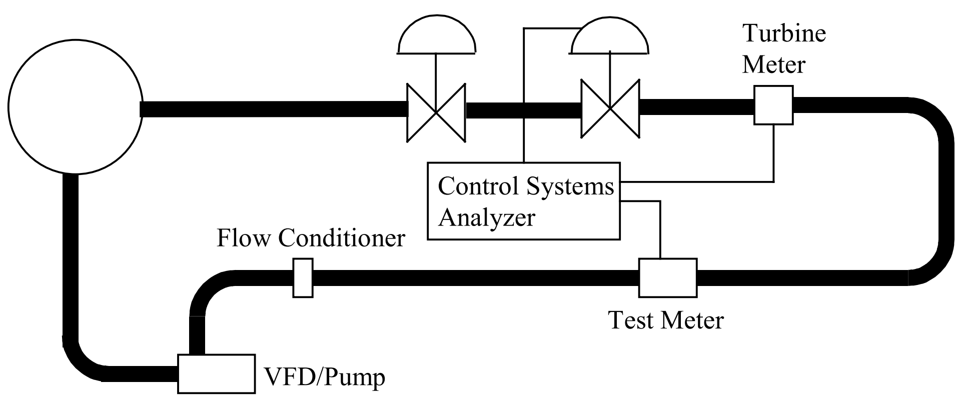

Figure 5. Experimental test setup.

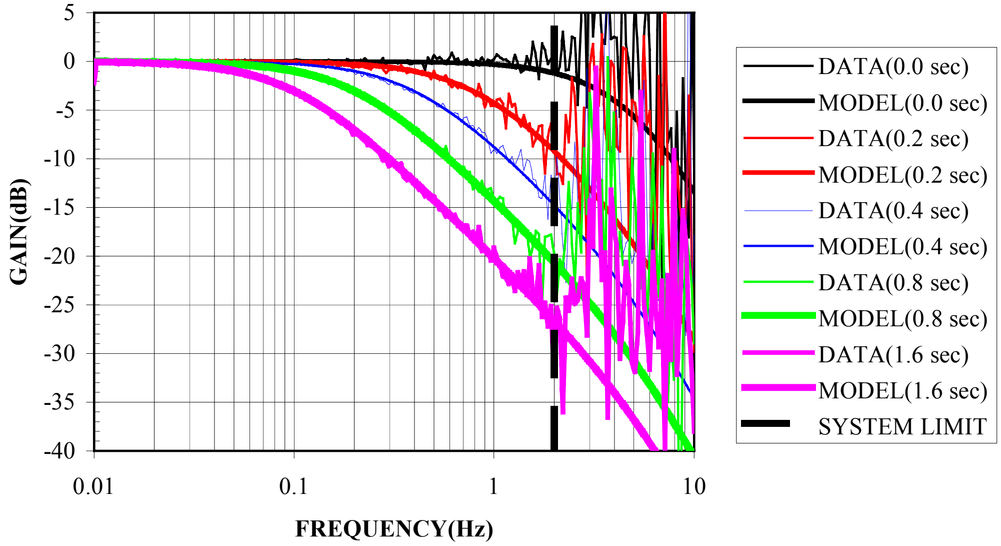

Figure 6.a. **Gain for a differential pressure/orifice meter, experimental and mathematical model data.**

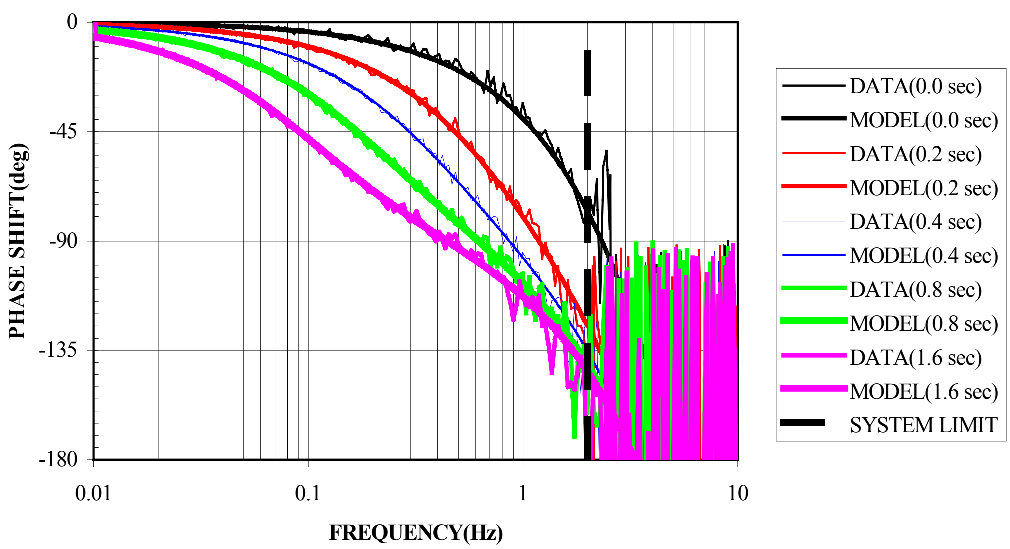

Figure 6.b. **Phase shift for a differential pressure/orifice meter, experimental and mathematical model data.**

Table 1. Transfer Function Parameters for Differential Pressure Transmitters

Meter DP2B			Meter DP5A			Meter DP3A		
τ_d (sec)	Damping (sec)	τ_{adj} (sec)	τ_d (sec)	Damping (sec)	τ_{adj} (sec)	Dead Time(sec)	Damping (sec)	τ_{adj}(sec)
0.070	0.00	0.031	0.150	0.00	0.01	0.300	0.00	0.227
	0.20	0.20		0.25	0.25		0.25	0.227
τ_{fixed}(sec)	0.40	0.40	τ_{fixed}(sec)	0.50	0.50	τ_{fixed}(sec)	0.50	0.199
0.010	0.80	0.80	0.200	1.00	1.00	0.199	1.00	0.318
	1.60	1.60		2.00	2.00		2.00	0.796
Meter DP2A			**Meter DP1A**			**Meter DP2C**		
τ_d (sec)	Damping (sec)	τ_{adj} (sec)	τ_d (sec)	Damping (sec)	τ_{adj} (sec)	Dead Time(sec)	User Damping	τ_{adj}(sec)
0.070	0.00	0.005	0.170	0.00	0.02	0.400	0.112	0.079
	0.20	0.20	τ_{fixed}(sec)	0.16	0.16		0.224	0.159
τ_{fixed}(sec)	0.40	0.40	0.306	0.32	0.32	τ_{fixed}(sec)	0.448	0.398
0.050	0.80	0.80		0.48	0.48	0.010	0.896	0.796
	1.60	1.60		1.00	1.00		1.792	1.768
Meter DP2D			**Meter DP1B**			**Meter DP3B**		
τ_d (sec)	Damping (sec)	τ_{adj} (sec)	Dead Time(sec)	User Damping	τ_{adj} (sec)	τ_d (sec)	Damping (sec)	τ_{adj} (sec)
0.100	0.00	0.020	0.200	0.00	0.122	0.400	0.00	0.079
	0.10	0.10		0.16	0.318		0.50	0.159
τ_{fixed}(sec)	0.20	0.20	τ_{fixed}(sec)	0.32	0.455	τ_{fixed}(sec)	1.00	0.637
0.080	0.40	0.40	0.306	0.48	0.637	0.032	2.00	1.592
	0.80	0.80		1.00	1.224		4.00	3.386
	1.60	1.60						
Meter DP4B			**Meter DP4A**					
τ_d (sec)	Damping (sec)	τ_{adj} (sec)	τ_d (sec)	Damping (sec)	τ_{adj} (sec)			
0.125	0.10	0.06	0.270	0.20	0.20			
	0.50	0.50		0.50	0.50			
τ_{fixed}(sec)	1.00	1.00	τ_{fixed}(sec)	1.00	1.00			
0.100	2.00	2.00	0.250	2.00	2.00			

Table 2. Transfer Function Parameters for Vortex Meters

Meter V1A			Meter V4A			Meter V2A		
τ_d (sec)	Damping (sec)	τ_{adj} (sec)	τ_d (sec)	Damping (sec)	τ_{adj} (sec)	Dead Time(sec)	User Damping	τ_{adj}(sec)
0.170	0.20	0.15	0.300	0.00	0.15	0.630	0.00	0.01
τ_{fixed}(sec)	0.50	0.42	τ_{fixed}(sec)	0.50	0.20	τ_{fixed}(sec)	2.00	1.60
NA	1.00	0.90	NA	1.00	0.40	0.700	4.00	3.50
	2.00	1.90		2.00	0.90			
Meter V3A			**Meter V3B**			**Meter V2B**		
τ_d (sec)	Damping (sec)	τ_{adj} (sec)	τ_d (sec)	Damping (sec)	τ_{adj} (sec)	Dead Time(sec)	User Damping	τ_{adj}(sec)
0.250	0.20	0.20	0.400	0.20	0.20	0.630	0.00	0.01
τ_{fixed}(sec)	0.50	0.50	τ_{fixed}(sec)	0.50	0.50	τ_{fixed}(sec)	2.00	1.60
NA	1.00	1.00	0.700	1.00	1.00	0.200	4.00	3.50
	2.00	2.00	0.700	2.00	2.00		8.00	7.00

Table 3. Transfer Function Parameters for Magmeters

Meter M1B			**Meter M1A**		
Dead Time(sec)	User Damping	τ_{adj}(sec)	Dead Time(sec)	User Damping	τ_{adj}(sec)
0.070	0.01	0.05	0.220	0.01	0.05
τ_{fixed}(sec)	0.25	0.25	τ_{fixed}(sec)	0.25	0.25
0.05	0.50	0.50	0.05	0.50	0.50
	1.00	1.00		1.00	1.00
	2.00	2.00		2.00	2.00
Meter M2A					
Dead Time(sec)	User Damping	τ_{adj}(sec)			
0.200	0.20	0.053			
τ_{fixed}(sec)	0.50	0.265			
0.279	1.00	0.723			
	2.00	1.768			

Table 4. Transfer Function Parameters for Coriolis Meter

Meter C1A				
User Damping	Dead Time (sec)	Undamped Natural Freq, ω_n(rad/sec)	Damping Ratio, ζ	τ_{adj} (sec)
0.00	0.030	2.39	1.00	0.001
0.40	0.050	2.39	1.00	0.400
0.80	0.200	2.39	1.00	0.800
1.60	0.400	2.39	1.00	1.600