Simulation of Process Conditions for Calibration of Fisher® Level Controllers and Transmitters—Supplement to 249 Sensor Instruction Manuals

Displacer / torque tube sensors are transducers that convert a buoyancy change into a shaft rotation. The change in buoyancy is proportional to the volume of fluid displaced, and the density of the fluid. The change in rotation is proportional to the change in buoyancy, the moment arm of the displacer about the torque tube, and the torque rate. The torque rate itself is a function of the torque tube material, the temperature of the material, the wall thickness, and the length. If the density of the process fluid, process temperature, and torque tube material of the sensor are known, simulation of process conditions may be accomplished by one of the following means[1]:

1. Weight or Force Method:

The interface application is the most general case. The level application can be considered an interface with the upper fluid SG = 0, and the density application can be considered as a variable SG application with the interface at the top of the displacer. The buoyancy for a given interface level on the displacer is given by:

$$F_B = \rho_w {}^* V_D {}^* \left[SG_U + H_{disp} {}^* \left(SG_L - SG_U \right) \right] \quad (1)$$

Where:

F_B = buoyant force

ρ_w = density of water at 4°C, 1 atmosphere = 1.0000 Kg/liter (0.03613 lb/in^3)

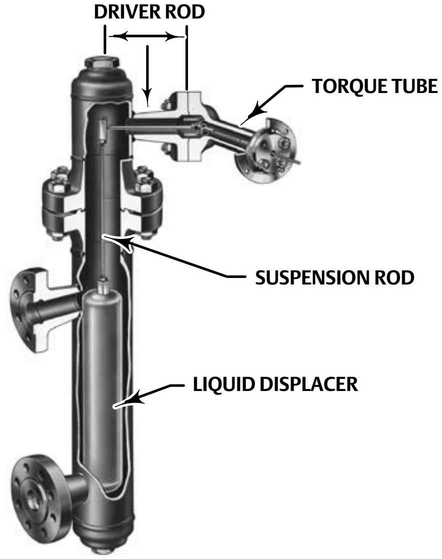
V_D = displacer volume

H_{disp} = height of interface on displacer, normalized to displacer length

SG_U = specific gravity of upper fluid (0.0 for Level)

SG_L = specific gravity of lower fluid

Figure 1. Cutaway View of Fisher 249 Displacer Sensor



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[1] Note that this document does not consider the effects of the thermal expansion of the moment arm, or the thermal expansion of displacer volume.

Figure 2. Fisher 2500 or 2503 Level Controller Transmitter on Caged 249 Sensor

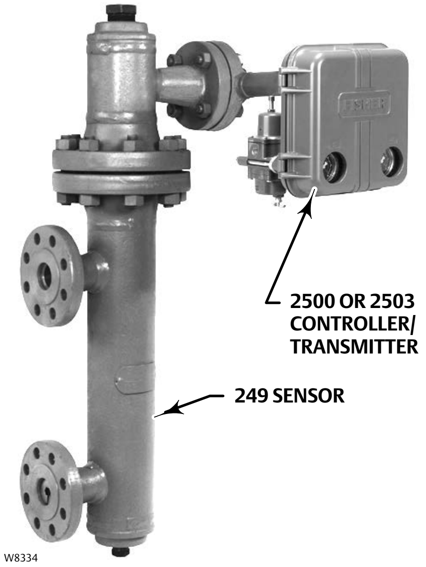


Figure 3. FIELDVUE™ DLC3010 Digital Level Controller

For the density application, $H_{disp} = 1.0$, SG_u = lowest expected density, and SG_L becomes the independent variable, the actual process density.

The net load on the driver rod is then computed from the equation:

$$W_{net} = W_D - F_B \tag{2}$$

Where:

W_{net} = net load on driver rod

W_D = weight of displacer

To simplify equations in the following discussion, let us define a few intermediate terms:

The minimum buoyancy, developed when the interface level is at the bottom of the displacer, is given by:

$$FB_{min} = \rho_w * V_D * SG_U \tag{3}$$

The change in buoyant force as the normalized interface level rises on the displacer is:

$$\Delta F_B = \rho_w * V_D * (SG_L - SG_U) * H_{disp} \tag{4}$$

The maximum change in buoyancy, developed when the interface level is at the top of the displacer is:

$$(\Delta F_B)_{max} = \rho_w * V_D * (SG_L - SG_U) \tag{5}$$

Temperature Effect

As process temperature increases, the torque rate decreases due to the change in modulus of rigidity. This effect can be represented by normalizing the modulus vs. temperature curve for a given material to the room temperature value, and using it as a scale factor on the torque rate. See figure 4 and table 1 or 2.

Because we can simulate the rotation of a more compliant torque tube by increasing the load, the weight value may be divided by the same scale factor to simulate the process condition:

$$W_{net\_test} = \frac{W_D - F_B}{G_{norm}} \tag{6}$$

Where:

W_{net_test} = net load adjusted to simulate process temperature effect

G_{norm} = normalized modulus of torque tube material, a function of temperature.

Displacer Rise Effect

Note that equation 6 simulates the process level on the displacer. The actual level in the cage or vessel will be different, due to the rise of the displacer as the torque tube load is decreased by the increasing buoyancy.

On a 14-inch displacer, or on a 249VS with a long driver rod, the displacer rise can become a significant fraction of the span. If the torque tube rate and driver rod length are known, change in rotation can be computed by dividing the torque change by the rate.

$$\Delta Angle = \frac{\Delta F_B \; * \; Driver}{R_{amb} \; * \; G_{norm}} \; * \; (\pi / 180^\circ) \tag{7}$$

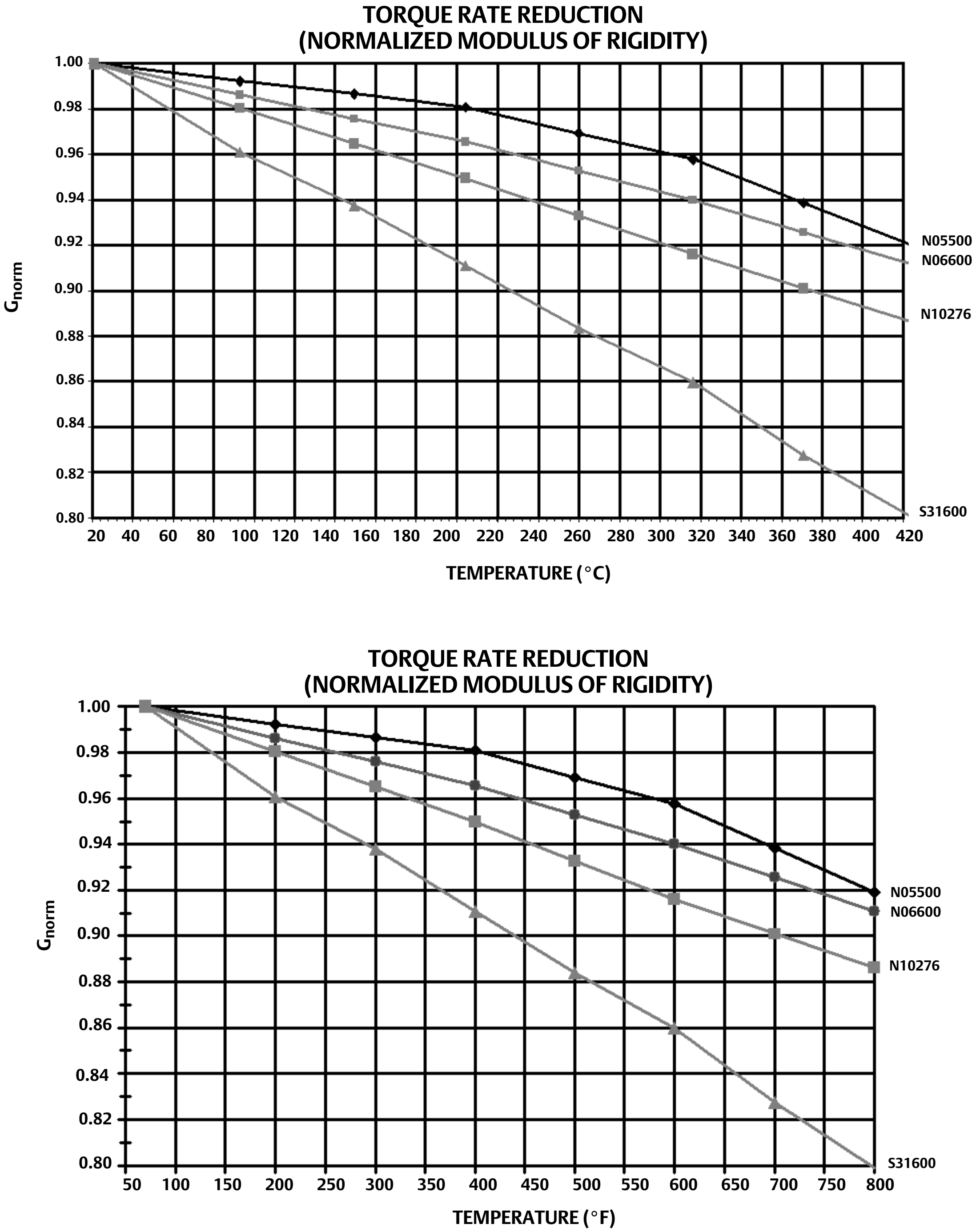
Where:

$\Delta Angle$ = resulting change in torque tube angle in radians

Driver = driver rod length

R_{amb} = Torque rate (torque per °rotation) at ambient temperature

Figure 4. “Gnorm”: Theoretical Temperature Effect on Torque Rate for Most Commonly Used Materials



NOTE: THIS CHART DEPICTS THE REVERSIBLE CHANGE ONLY. THE IRREVERSIBLE DRIFT IS A FUNCTION OF THE NET LOAD, THE ALLOY, AND THE LEVEL OF STRESS EQUALIZATION ACHIEVED IN MANUFACTURING. (THE IRREVERSIBLE EFFECT CAN ONLY BE COMPENSATED BY PERIODIC ZERO TRIM.) N05500 IS AN APPROPRIATE SPRING MATERIAL FOR TEMPERATURES BELOW AMBIENT AND UP TO 232°C (450°F). ABOVE 260°C (500°F), THE INDUSTRY DOES NOT RECOMMEND USING IT AS A SPRING MATERIAL. N06600 IS CONSIDERED ACCEPTABLE TO APPROXIMATELY 399°C (750°F) WITH PROPER STRESS EQUALIZATION.

Recognizing that the displacer rise is the side opposite this changing angle, in a triangle of which the drive rod is the hypotenuse, the displacer rise can be approximated applying the small-angle sine approximation to the result of equation 7.

$$\Delta Rise_{disp} = \frac{\Delta F_B * (Driver)^2}{R_{amb} * G_{norm}} * \frac{\pi}{180^\circ} \qquad (8)$$

The above expression may be factored to produce an ambient-temperature displacer-rise rate.

$$RiseRate_{amb} = \frac{(\pi / 180^\circ) * Driver^2}{R_{amb}} \qquad (9)$$

The net rise is then restated with aid of the temperature correction term Gnorm.

$$\Delta Rise_{disp} = \frac{\Delta F_B * RiseRate_{amb}}{G_{norm}} \qquad (10)$$

The digital instrument firmware makes an internal correction for the displacer rise, so we must account for it in our weight calculation to make sure that we get the expected digital value of interface level in the cage. (Analog electronic and pneumatic devices don't have this correction capability, but the accuracy of the calibration would still be improved by accounting for the effect during simulation.) The ratio of the level change on the displacer to the level change in the cage needed to produce it is:

$$\frac{\Delta H_{disp}}{\Delta H_{cage}}_{proc} = \frac{L_D}{L_D + (\Delta F_B)_{max} * RiseRate_{amb} / G_{norm}} \qquad (11)$$

Where:

L_D = length of displacer
H_{cage} = interface level in cage, normalized to displacer length.

The above equation is valid only for $0.0 < H_{disp} < 1.0$ (since interface level excursions above or below the displacer produce no additional change in buoyancy)

The % span error introduced by neglecting the displacer rise effect becomes smaller as the displacer length increases.

The displacer rise at the initial condition, (displacer completely submerged in the upper fluid), is given by:

$$Rise_{0proc} = \frac{FB_{min\_eff} * RiseRate_{amb}}{G_{norm}} \qquad (12)$$

Where:

FB_{min_eff} = $[\ FB_{min} - Max(\ (W_{disp} - W_{max}), 0.0)\ ]$
W_{max} = the load that will cause the linkage to contact the lower travel stop.

$Max(\ (W_{disp} - W_{max}), 0.0\ )$ = the amount of buoyancy required to lift the displacer off the travel stop so that rise can actually commence. The maximum available shift below the zero rest position at ambient temperature is also limited by this travel stop, so the value of W_{max} will be a function of temperature. To account for this, replace W_{max} by $(W_{max\_ambient} * G_{norm})$ in the FB_{min_eff} equation.

Note that $W_{max\_ambient}$ would have to be determined by experiment on the specific physical hardware, but for a first approximation, you could use the 'maximum un-buoyed displacer weight' value given in table 5.

Figure 5. Illustration of Displacer Rise Effect

Temperature-Induced Zero-Shift at Zero Buoyancy

If the physical zero reference was established at zero buoyancy and ambient temperature, there is an additional zero-shift to take into account. The zero buoyancy position of the bottom of the displacer at process temperature will be lower, because of the reduction in torque rate.

$$\mathrm{ZeroShift}_{proc} = \frac{W_D * \mathrm{RiseRate}_{amb} * (G_{norm} - 1.0)}{G_{norm}} \tag{13}$$

Note that the combination of:

a. the location of the displacer bottom relative to the external reference at ambient,

b. the zero-shift at process temperature, and

c. the initial displacer rise at process temperature,

will determine the extent of any unobservable region between the external zero reference and the displacer bottom.

We must decide what our process variable (PV) calculation is going to use for a zero reference. Since any interface level excursion below the bottom of the displacer cannot change the output, it is convenient to call the displacer bottom “zero” for the test, and this has been standard procedure in pilot mounting. In the digital level controller, Level Offset is used to adjust the digital output to zero at this condition.

Lowest Observable Cage Interface Level

If it is desired to line up the calculation with the physical external reference, the Level Offset (and range values) can be adjusted according to the following.

$$H_{cage0} = \frac{\mathrm{ZeroShift}_{proc} + \mathrm{Rise}_{0proc}}{L_D} \tag{14}$$

Where:

H_{cage0} = highest possible value of cage interface level (normalized to displacer length), relative to zero buoyancy, ambient temperature coupling point, when displacer interface level is 0.0 (bottom of displacer).

This is the physical interface level below which a change is unobservable. The range values or alarm values should be set within the observable range of PV to make sure that over- and under-flow conditions are reported to the control system.

Weight Calculation Procedure

To compute the weight required, at room temperature, to simulate a given process-condition cage interface level:

a. Start with an initial buoyancy based on the SG of the upper fluid,

b. subtract it from the displacer weight, and

c. correct the result for process temperature.

This will give the test weight for the lowest observable process condition.

$$W_{net\_test}\Big|_i = \frac{W_D - F_{Bmin}}{G_{norm}} \tag{15}$$

The change in weight for a process-temperature, cage (or vessel) interface level condition, one displacer length higher than the above state, is given by:

$$\Delta W\Big|_f = \frac{(\Delta H_{disp} / \Delta H_{cage})_{proc} * (\Delta F_B)_{max}}{G_{norm}} \tag{16}$$

The net weight for the 100% cage process condition is:

$$W_{net\_test}\Big|_f = W_{net\_test}\Big|_i - \Delta W\Big|_f \tag{17}$$

Other values of ΔW can be computed from:

$$\Delta W = \frac{\Delta H_{cage} * (\Delta H_{disp} / \Delta H_{cage})_{proc} * (\Delta F_B)_{max}}{G_{norm}} \tag{18}$$

Where:

$\Delta H_{cage} = H_{cage} - H_{cage0}$

Valid for $H_{cage0} < H_{cage} < [1/(\Delta H_{disp} / \Delta H_{cage})_{proc}]$

Remember that it is common to arbitrarily set H_{cage0} to zero for test purposes when using weights. (For water column calculations in the next section, it is more important to keep track of the initial process-condition cage level to simulate the initial buoyancy correctly.) The resultant net weights for the intermediate levels are given by:

$$W_{net\_test} = W_{net\_test}\Big|_i - \Delta W \tag{19}$$

This assumes that the net weights do not violate the maximum or minimum load for the torque tube. Refer to table 5.

2. Water Column Method:

It is possible to simulate a range of buoyancy adjusted for process temperature effect by using a water column at room temperature. At the ambient SG = 1.0 level application, the corrections should all cancel out, leaving H_{cage} = desired PV.

Cage Water Level Required to Simulate Interface Levels

If we have computed an equivalent weight for a given process condition in section 1, the ambient temperature water level on the displacer that will produce the same torque tube rotation is:

$$H_{disp\_eq} = \frac{W_D - W_{net}}{\rho_w * V_D} \tag{20}$$

For high temperatures and high SG, the range of conditions that can be simulated will contract, since we are limited by the actual displacer weight and the nominal density of water.

We must next convert this equivalent displacer level into an equivalent cage level using the inverse of the relationship in equation 11, without the temperature compensation.

$$\frac{\Delta H_{disp}}{\Delta H_{cage}}\,_{amb} = \frac{L_D + \rho_w * V_D * RiseRate_{amb}}{L_D} \tag{21}$$

The result is:

$$H_{cage\_eq} = \frac{(\Delta H_{disp} / \Delta H_{cage})_{amb} * (W_D - W_{net})}{\rho_w * V_D} \tag{22}$$

Process Interface Level Simulated by a Given Cage Water Level

We can also write a generic equation for the process-condition displacer interface level simulated by a given room-temperature displacer water level:

First, convert the ambient cage water level to an ambient displacer water level:

$$H_{disp\_eq} = \frac{H_{cage}}{(\Delta H_{cage} / \Delta H_{disp})_{amb}} \tag{23}$$

Next, define an intermediate variable to compute the apparent SG being simulated at process conditions by the ambient displacer water level:

$$SGapp_{sim} = (1 - G_{norm}) * \frac{W_D}{\rho_w * V_D} + G_{norm} * H_{disp\_eq} \tag{24}$$

Now use this apparent SG value to compute the simulated interface level on the displacer:

$$H_{disp_{sim}} = \frac{SGapp_{sim} - SG_U}{SG_L - SG_U} \qquad (25)$$

Finally convert the simulated process-conditions displacer interface level to simulated process-condition cage interface level, by the equation:

$$H_{cage_{sim}} = H_{cage0} + \frac{H_{disp_{sim}}}{(\Delta H_{disp} / \Delta H_{cage})_{proc}} \qquad (26)$$

Where H_{cage0} is either 0.0 or the value computed in equation 14, per the practice being followed for PV reference.

3. Tables of Nominal Values

If the calibration is being run per standard practice the values of the parameters for the above equations are generally available for observation in the instrument memory. For analog instruments, a table of nominal values may be consulted to generate good approximations.

Table 1. Gnorm for Common Torque Tube Materials Above Room Temperature

Material	**Gnorm**															
	°C	**°F**	**°C**	**°F**	**°C**	**°F**	**°C**	**°F**	**°C**	**°F**	**°C**	**°F**	**°C**	**°F**	**°C**	**°F**
	21	**70**	**93**	**200**	**149**	**300**	**204**	**400**	**260**	**500**	**316**	**600**	**371**	**700**	**427**	**800**
N05500	1		0.9923		0.9866		0.9808		0.9692		0.9577		0.9385		0.9192	
N06600	1		0.9861		0.9759		0.9657		0.9529		0.9401		0.9256		0.9111	
N10276	1		0.9802		0.9649		0.9497		0.9329		0.9161		0.9010		0.8859	
S31600	1		0.9609		0.9378		0.9108		0.8837		0.8597		0.8277		0.7993	
These values are approximations derived from various metal-alloy industry publications																

Table 2. Gnorm for 316 SST Below Room Temperature

Material	**Gnorm**									
	°C	**°F**	**°C**	**°F**	**°C**	**°F**	**°C**	**°F**	**°C**	**°F**
	-240	**-400**	**-184**	**-300**	**-129**	**-200**	**-18**	**0**	**21**	**70**
S31600	1.0836		1.0807		1.0635		1.0179		1	
Low temperature data for N05500, N06600, and N10276 not available at time of publication.										

Table 3 provides the theoretical unloaded rate, and the composite or effective torque rate measured by the digital level controller at the end of the pilot shaft. The physical rotation at the far end of the torque tube may be a bit greater than what these tables would predict, due to some wind-up of the pilot shaft.

Table 3. Theoretical Room Temperature Torque Rates

Family / Wall	**Material**	**Torque Tube Part Number**	**Unloaded Rate[2]**		**Composite Rate**			
					W/O Insulator		**W/Insulator**	
			N•m/deg	**lbf•in/deg**	**N•m/deg**	**lbf•in/deg**	**N•m/deg**	**lbf•in/deg**
249, 249B, 249BF 249BP, 259B, 249P (CL150-600), 249W HEAVY	N05500[1]	1K4497X0012	1.48	13.1	1.90	16.8	2.01	17.8
	N06600	1P8662X0012	1.66	14.7	2.07	18.3	2.18	19.3
	S31600	1K4541000A2	1.76	15.5	2.18	19.3	2.29	20.3
	N10276	1K453140152	1.75	15.5	2.16	19.1	2.27	20.1

1. N05500 is the default material.
2. Appropriate for 2500 controllers only.

-continued-

Table 3. Theoretical Room Temperature Torque Rates (continued)

Family / Wall		Material	Torque Tube Part Number	Unloaded Rate(2)		Composite Rate			
						W/O Insulator		W/Insulator	
				N•m/deg	lbf•in/deg	N•m/deg	lbf•in/deg	N•m/deg	lbf•in/deg
249, 249B, 249BF 249BP, 259B, 249P (CL150-600), 249W STANDARD	249C 249CP 249PT 249VT HEAVY	N05500(1)	1K4493X0012	0.764	6.76	0.988	8.75	1.05	9.27
		N06600	1K4515000A2	0.758	6.71	0.952	8.42	1.00	8.87
		S31600	1K4503000A2	0.848	7.50	1.06	9.36	1.11	9.85
		N10276	1K4527000A2	0.799	7.07	0.993	8.79	1.04	9.23

1. N05500 is the default material.
2. Appropriate for 2500 controllers only.

Family / Wall		Material	Torque Tube Part Number	Unloaded Rate(2)		Composite Rate			
						W/O Insulator		W/Insulator	
				N•m/deg	lbf•in/deg	N•m/deg	lbf•in/deg	N•m/deg	lbf•in/deg
249B 249, 249BP, 259B, 249P (CL150-600), 249W THIN	249C 249CP 249PT 249VT STANDARD	N05500(1)	1K4495X0012	0.384	3.40	0.502	4.44	0.532	4.70
		N06600	1K4517000A2	0.405	3.58	0.513	4.54	0.540	4.78
		S31600	1K4505000A2	0.416	3.68	0.524	4.64	0.551	4.87
		N10276	1K4529X0012	0.427	3.78	0.535	4.73	0.562	4.97

1. N05500 is the default material.
2. Appropriate for 2500 controllers only.

Family / Wall	Material	Torque Tube Part Number	Unloaded Rate(2)		Composite Rate			
					W/O Insulator		W/Insulator	
			N•m/deg	lbf•in/deg	N•m/deg	lbf•in/deg	N•m/deg	lbf•in/deg
249K, 249L, 249N, 249VS, 249P (CL900-2500), STANDARD	N05500(1)	1K4499X0012	1.06	9.41	1.46	13.0	1.54	13.7
	N06600	1K4519000A2	1.20	10.6	1.58	14.0	1.66	14.7
	S31600	1K4507000A2	1.26	11.2	1.66	14.7	1.75	15.4
	N10276	1K9159X0012	1.26	11.2	1.65	14.6	1.73	15.3

1. N05500 is the default material.
2. Appropriate for 2500 controllers only.

Family / Wall	Material	Torque Tube Part Number	Unloaded Rate(2)		Composite Rate			
					W/O Insulator		W/Insulator	
			N•m/deg	lbf•in/deg	N•m/deg	lbf•in/deg	N•m/deg	lbf•in/deg
249K, 249L, 249N, 249VS, 249P (CL900-2500) THIN	N05500(1)	1K4501X0012	0.550	4.87	0.762	6.74	0.804	7.12
	N06600	1P747040042	0.546	4.83	0.729	6.45	0.765	6.77
	S31600	1K450935072	0.611	5.40	0.809	7.16	0.848	7.51

1. N05500 is the default material.
2. Appropriate for 2500 controllers only.

Additional Information

Table 4. Moment Arm (Driver Rod) Length[1]

Sensor Type[2]	Moment Arm	
	mm	Inch
249	203	8.01
249B	203	8.01
249BF	203	8.01
249BP	203	8.01
249C	169	6.64
249CP	169	6.64
249K	267	10.5
249L	229	9.01
249N	267	10.5
249P (CL125-600)	203	8.01
249P (CL900-2500)	229	9.01
249VS (Special)[1]	See serial card	See serial card
249VS (Std)	343	13.5
249W	203	8.01

1. Moment arm (driver rod) length is the perpendicular distance between the vertical centerline of the displacer and the horizontal centerline of the torque tube. See figure 6. If you cannot determine the driver rod length, contact your Emerson Process Management sales office and provide the serial number of the sensor.
2. This table applies to sensors with vertical displacers only. For sensor types not listed, or sensors with horizontal displacers, contact your Emerson Process Management sales office for the driver rod length. For other manufacturers' sensors, see the installation instructions for that mounting.

Table 5. Maximum Unbuoyed Displacer Weight

Sensor Type	Torque Tube Wall Thickness	Displacer Weight, W_T (lb)
249, 249B, 249BF, 249BP, 249W	Thin Standard Heavy	3.3 5.0 9.5
249C, 249CP	Standard Heavy	4.0 6.4
249VS	Thin Standard	3.0 5.5
249L, 249P[1]	Thin Standard	4.5 8.5
249K	Thin Standard	3.8 7.3

1. High pressure CL900 through 2500.

Figure 6. Method of Determining Moment Arm from External Measurements

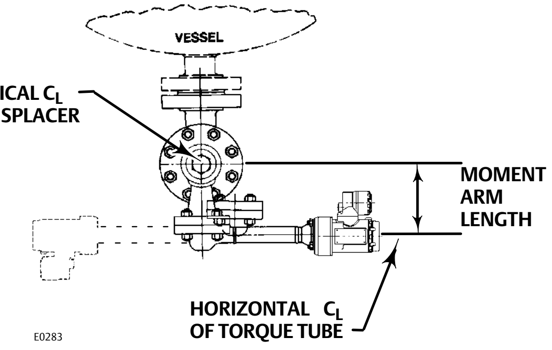


Table 6. Related Documents

Document	Part Number
249 Caged Displacer Sensors Instruction Manual	D200099X012
249 Cageless Displacer Sensors Instruction Manual	D200100X012
249VS Cageless Displacer Sensor Instruction Manual	D103288X012
249W Cageless Wafer Style Level Sensor Instruction Manual	D102803X012
2500 and 2503 Level Controllers and Transmitters Instruction Manual	D200124X012
DLC3010 Digital Level Controller Quick Start Guide	D103214X012
DLC3010 Digital Level Controller Instruction Manual	D102748X012
DLC3020f Digital Level Controller Quick Start Guide	D103434X012
DLC3020f Digital Level Controller instruction Manual	D103470X012
2502 Level Controller	D200126X012

These documents are available from your Emerson Process Management sales office. Also visit our website at www.Fisher.com.

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