Application Note 221101D

Dynamic Torque Measurement

Background

Rotary power sources and absorbers have discrete poles and/or pistons and/or gear meshes, etc. As a result, they develop and absorb torque in a pulsating rather than a smooth manner. Furthermore, a driveline consists of several inertias and torsion springs which resonate at one or more frequencies. Finally, even when running at "constant" average speed, every drive has some angular acceleration which, in combination with shaft inertias, generate dynamic inertia torques.

Thus, real world driveline torque is never constant. Instead, it consists of an average torque with superimposed oscillatory components. The oscillatory components can excite driveline resonance(s). These effects are exacerbated during transient load conditions. Accurate measurement and/or control of dynamic driveline torque requires an understanding of how the Torquemeter and other drive components interact. This note provides insight into those interactions from theoretical and practical viewpoints.

Torque Measurements Under Steady State Conditions

Consider a drive consisting of a Motor, a Torquemeter and a Pump. Assume the couplings and shafts are infinitely stiff, and the Torquemeter and couplings have negligible inertia. Then, the shaft network consists of the Motor Inertia ($\mathbf{J_m}$), the Pump Inertia ($\mathbf{J_p}$), the Torquemeter spring constant (**k**), and system damping (Ω); damping is assumed to be viscous.

Undamped Frequency Response

With no damping present, equation [1] defines the drive's frequency response, i.e., the ratio of pump input torque to motor output torque. At the drives natural frequency ($\mathbf{F_r}$) the output torque becomes infinite. When damping is present, infinite multiplication can't occur. Nonetheless, the **frequency response defined by equations** [1] **and** [2] **is always higher than that of a drive with damping.** Thus, these equations will quickly **reveal the measurement bandwidth and natural frequency limits.**

$$\frac{\text{Pump Input Torque}}{\text{Motor Output Torque}} = \left| \frac{\frac{1}{J_m}}{\frac{1}{J_m} + \frac{1}{J_p} - 4\pi^2 \frac{f^2}{k}} \right| \qquad \underline{1}$$

Setting the denominator of equation [1] to zero and solving for frequency yields $\mathbf{F_r}$. $\mathbf{F_r}$ is in hertz when $\mathbf{J_m}$ and $\mathbf{J_p}$ have in-lbf $\mathbf{s^2}$ units, and **k** has in lbf-in/rad units.

$$F_r = \frac{1}{2\pi}\sqrt{k\,\frac{(J_m + J_p)}{(J_m J_p)}} \qquad \underline{2}$$

Figure 1 is a plot of the undamped frequency response of the Motor-Torquemeter-Pump drive with:

- J_m = **100 in-lbf s²**
- J_p = **172 in-lbf s²**
- **k = 309,000,000 lbf-in/rad for an MCRT 87007V(25-3) Torquemeter, and**
- **k = 28,412,000 lbf-in/rad (3,210 kNm/rad) for a competitive Bearingless Torquemeter**
- **Motor Torque = 20,000 lbf-in**

The stiffer MCRT device has a significantly higher undamped natural frequency than the competitive device. Frequencies above about 1.5Fr are attenuated. At 6 kHz the attenuation is 290 times for the MCRT Torquemeter and 3,160 times for the competitive device. With damping present, the drive's resonant frequency and measurement bandwidth will be lower; see following discussion.

When torque is input to the undamped network, no power is delivered or absorbed. As a result, the drive will accelerate the

Figure 1. Undamped response with MCRT 87007V(25-3) and 3kNm competitive device.

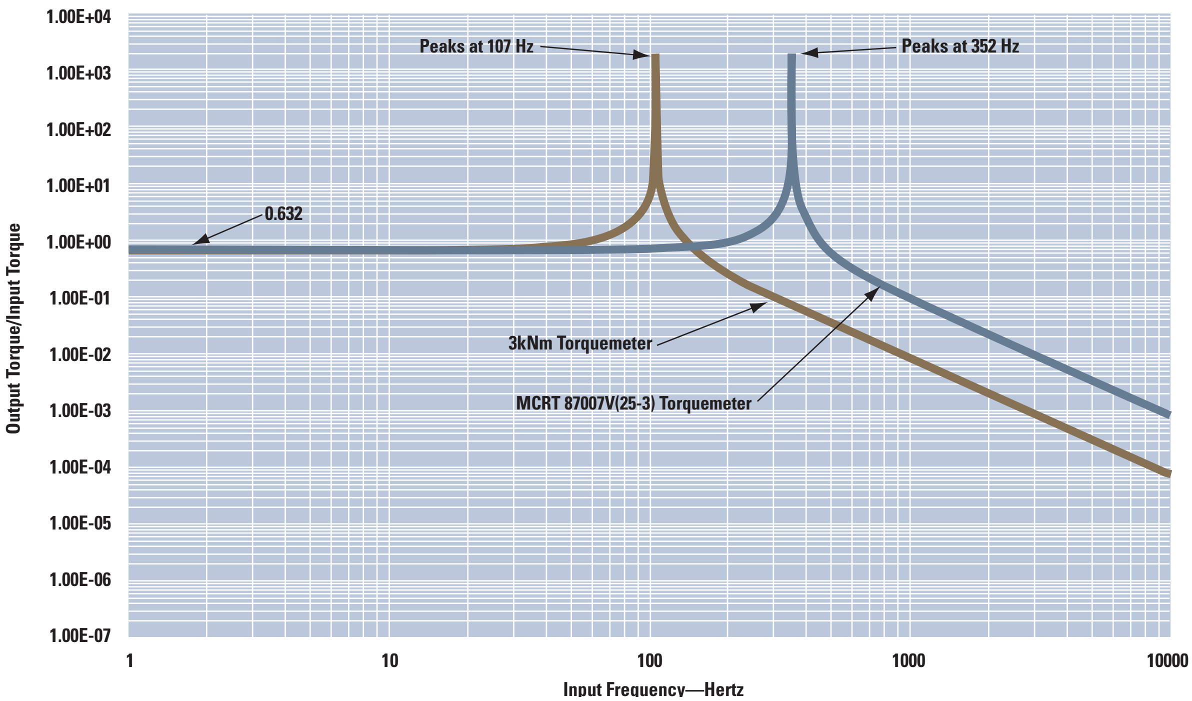
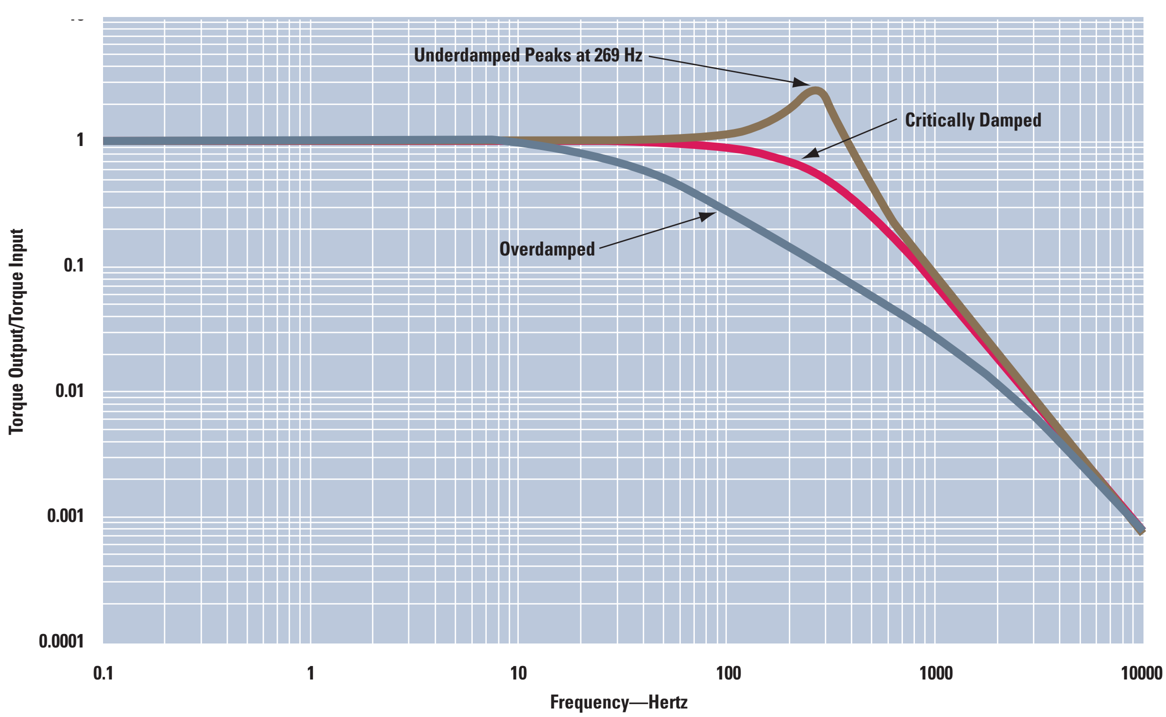


Figure 2. Response with Himmelstein MCRT 87007V(25-3) Torquemeter installed.



shaft system to the motor's no-load speed. Since both inertias are subjected to the same acceleration, equation [3] describes the frequency response to about 20 percent of $\mathbf{F_r}$.

$$\frac{\text{Output Torque}}{\text{Input Torque}} = \frac{J_p}{(J_p + J_m)} \qquad 3$$

For the case being discussed, equation [3] confirms the 0.632 ratio observed in Figure 1.

Frequency Response With Damping Present

Figures 2 and 3 show the frequency response of the drive with damping present. Since torque is input directly to the motor inertia ($\mathbf{J_m}$)—think of it as the developed motor torque — and power is absorbed by the pump, then the ratio of output to input torques is unity well below resonance.

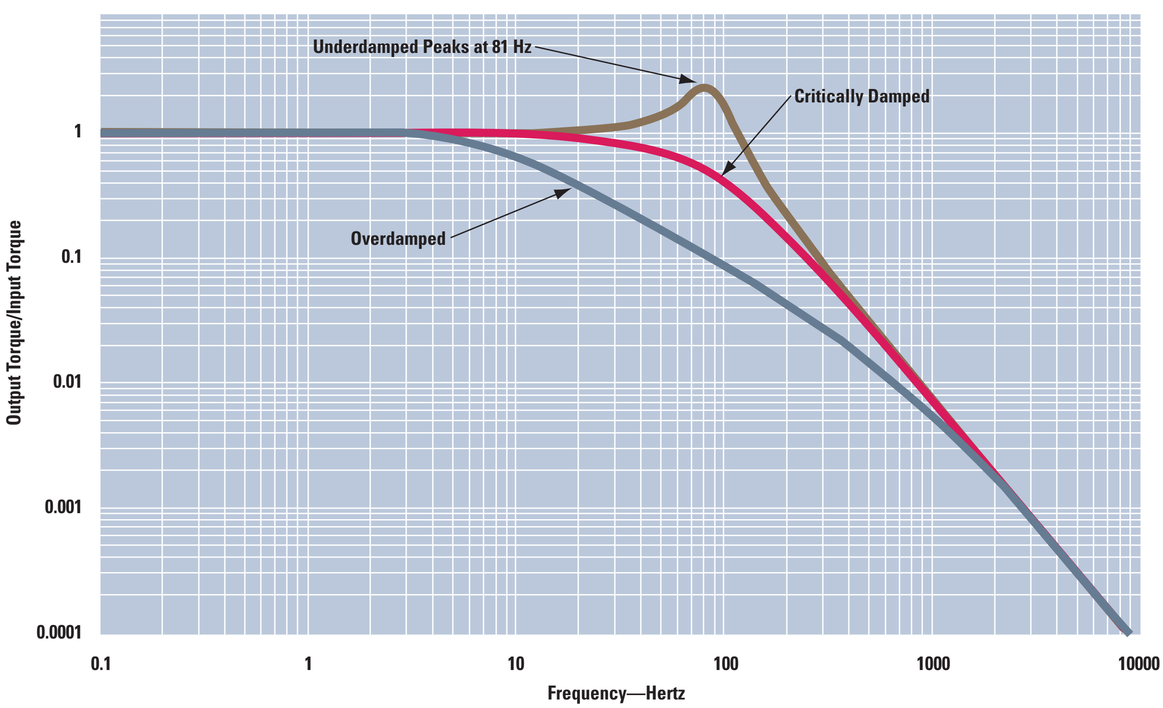
Depending on damping, three response types are possible. We define **Critical Damping** as the lowest damping that avoids oscillatory torques *and* overshoots when the drive is excited by a step function. A network is **Underdamped** if its damping is less than critical. Oscillations and overshoots will occur when the drive is underdamped. When damping is greater than critical it is **Overdamped**. Figures 2 and 3 plot critical, 0.2 times critical and 5 times critical responses. See Tech Memo 221201 for details on computing damped system response.

A device's measurement bandwidth is commonly defined as the frequency at which the response is down 3 DB or, has fallen to 70.79% of the start value. The following table lists drive performance with each Torquemeter installed versus network damping. For completeness the -3 DB frequency as well as the frequencies at which the response falls to 1%, 0.1% and 0.01% are included.

Whether you accept the 3 DB criteria or a more stringent definition, the stiffer MCRT 87007V Torquemeter clearly provides the widest measurement bandwidth. Its bandwidth is about 3.3 times higher than the other device. Note 3.3 is the square root of the two Torquemeters' stiffness ratio.

At low frequencies, the effect of damping is relatively small. At intermediate frequencies, torque can be multiplied or attenuated depending on system damping. Since damping is usually unknown, the precise torque value is indeterminate in this frequency region. Furthermore, ***data in this***

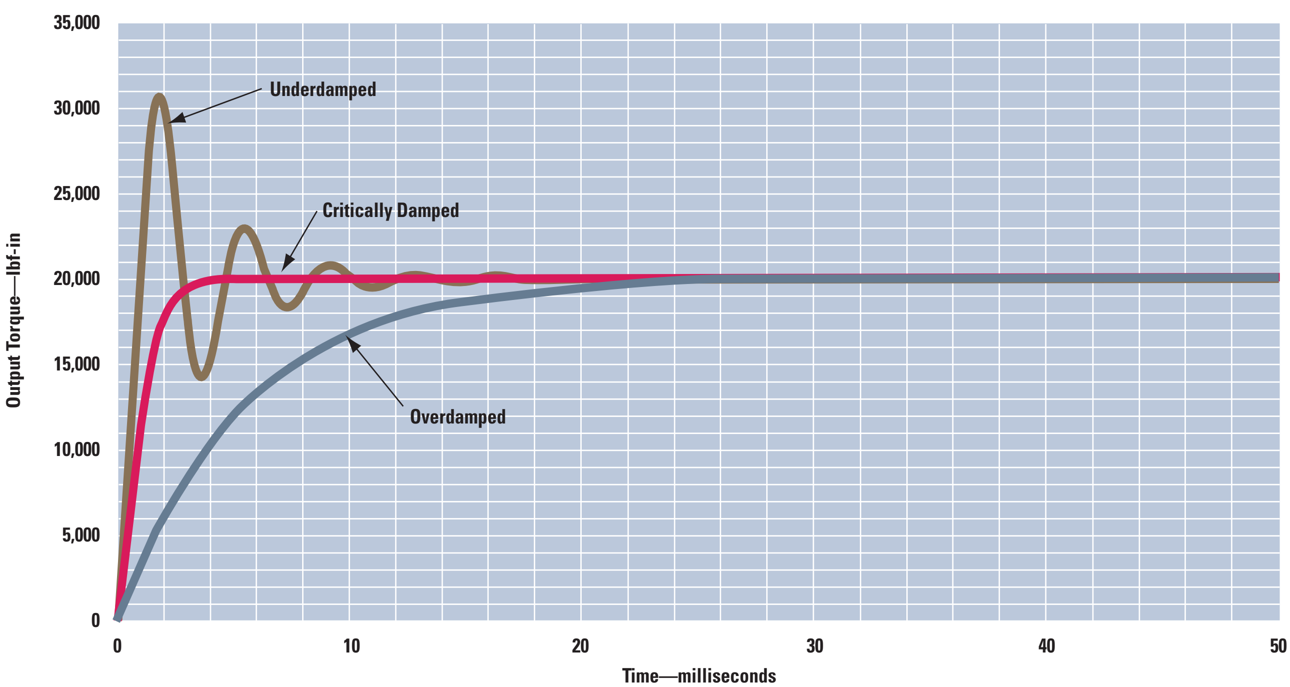
Figure 3. Response with competitive 3kNm torquemeter installed.



Table

Installed Torquemeter ▸	MCRT 87007V(25-3)			Competitive 3 kNm Device		
Specified Torquemeter Performance/Parameters						
Torquemeter Stiffness (lbf-in/rad)	309,000,000			28,412,000		
Full Scale Rating (lbf-in)	25,000			26,550		
Electrical Overrange Rating (lbf-in)	75,000			31,860		
Mechanical Overload Rating (lbf-in)	100,000			42,485		
Max Allowed Torque Oscillation (lbf-in, peak-peak)	100,000			42,485		
Torquemeter Signal Chain Bandwidth (kHz)	3			6		
Installed Torquemeter Steady State Performance						
Drive Natural Frequency — No Damping (Hz)	351			107		
Damping as a percent of critical (%)	20	100	500	20	100	500
-3 DB Frequency (Hz)	N/A	190.20	29.40	N/A	51.42	8.20
Frequency at which error =< 1% (Hz)	29.01	30.49	4.18	8.92	7.89	1.17
Frequency at which error =< 0.1% (Hz)	9.26	9.72	1.35	2.74	2.50	0.37
Frequency at which error =< 0.01% (Hz)	3.22	3.80	0.51	0.58	0.97	0.14
Torque Signal Reduction at 3 kHz (times)	113.9	115.7	153.5	1,250	1,252	1,306
Torque Signal Reduction at 6 kHz (times)	458.5	460.3	502.5	4,995	4,998	5,049

Figure 4. Step response with MCRT 87007V(25-3) Torquemeter installed.



frequency region only reflects the dynamic driveline response if the Torquemeter is permanently installed.

High frequencies are significantly reduced, asymptotically approaching 40 DB per decade. Assuming critical damping, with the MCRT 87007V installed, 3 kHz signals are reduced by 115 times. At 3 kHz the reduction is 1,250 times with the competitive device rendering any data useless. At 6 kHz signal reduction is 460 times for the MCRT 87007V(25-3) and 4,998 times for the more compliant competitive device. With either device installed, signals of 1 kHz are suspect, 6 kHz and higher torque signals are useless.

Despite both Torquemeters' wide signal chain bandwidth, actual installed measurement bandwidth is much less. It is primarily determined by the drive and load inertias and the Torquemeter stiffness and, to a lesser extent, by system damping. As long as the signal chain bandwidth is higher than the drives' natural frequency, it has no effect on measurement bandwidth.

Torque Measurement During Transient Conditions

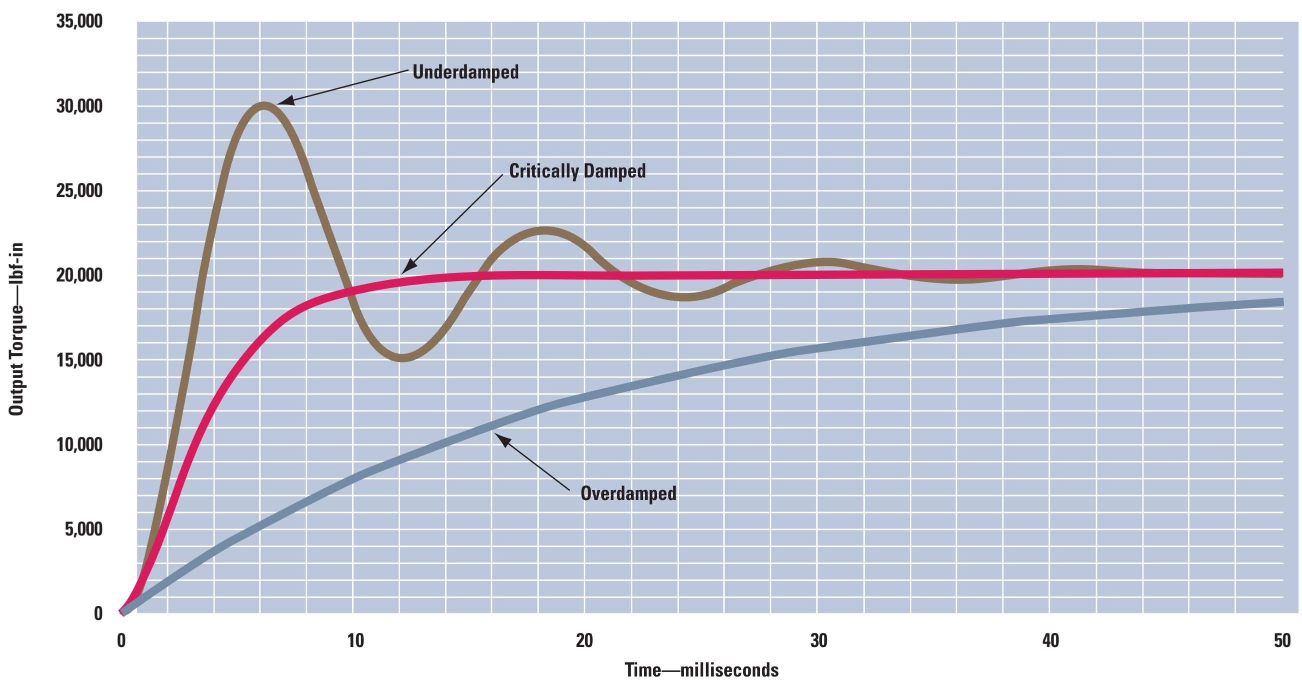
Starting, stopping, reversing, impact loads, etc. are transient occurrences that must be monitored and/or controlled in many applications. During transient conditions three system responses are possible. Which occurs depends on whether system damping is equal to, greater or less than Critical Damping.

Remember, Critical Damping (Ω_c) is the lowest that avoids ringing and overshoots when driven by step function. System response is fastest when damping is critical. When damping is below critical, oscillatory torques will be generated which can result in large torque overshoots and increase the time to reach equilibrium. When damping is greater than critical, oscillations don't occur, but the response time is increased.

Figures 4 and 5 show the drive response to a 20,000 lbf-in step input. The damping used is critical, five times critical and one fifth of critical. The much stiffer MCRT 87007V(25-3) has significantly faster response than the competitive product. The table that follows lists pertinent response times.

When the damping is 20% of critical, the peak overshoot is within the Mechanical Overload and Electrical Overrange ratings of both Torquemeters, but the competitive device is marginal on Electrical Overrange. The MCRT

Figure 5. Step response with competitive 3kNm torquemeter installed.



Table

Installed Torquemeter ▸	MCRT 87007V(25-3)	Competitive 3 kNm Device
Specified Torquemeter Performance/Parameters		
Torquemeter Stiffness (lbf-in/rad)	309,000,000	27,616,000
Full Scale Rating (lbf-in)	25,000	26,550
Electrical Overrange Rating (lbf-in)	75,000	31,860
Mechanical Overload Rating (lbf-in)	100,000	42,485
Max Allowed Torque Oscillation (lbf-in, peak-peak)	100,000	42,485
Torquemeter Signal Chain Bandwidth (kHz)	3.00	6.00
Installed Torquemeter Performance With 20,000 lbf-in Step Input		
Time for Error =<1% with Critical Damping (Ω_c) (ms)	3.45	13.60
Time for Error =< 0.1% with Critical Damping (Ω_c) (ms)	4.46	18.80
Time for Error =<0.01% with Critical Damping (Ω_c) (ms)	5.61	24.51
Time for Error =< 1% with Damping = 5*Ω_c (ms)	19.80	68.20
Time for Error =< 0.1% with Damping = 5*Ω_c (ms)	31.13	102.5
Time for Error =< 0.01% with Damping = 5*Ω_c (ms)	41.29	136.5
Frequency of Oscillation with Damping = 0.2*Ω_c (Hertz)	351.8	104.5
Maximum Overshoot with Damping = 0.2*Ω_c (lbf-in)	30,736	30,171
Time for Error =< 1% with Damping = 0.2*Ω_c (ms)	10.37	34.20
Time for Error =< 0.1% with Damping = 0.2*Ω_c (ms)	14.95	49.30
Time for Error < 0.01% with Damping = 0.2*Ω_c (ms)	20.54	68.00

has much higher margins and is truly linear in both Mechanical Overload and Electrical Overrange. Since the competitive device is only repeatable in Electrical Overrange, it will have unknown errors in that region. When damping is lower, torque peaks increase exacerbating that situation. See Tech Memo 221201 for details on computing damped system response.

To summarize, like the steady state case, transient response speed is primarily a function of Torquemeter Stiffness and the coupled Drive and Load Inertias. Network damping plays a secondary but vital role. Provided it is higher than the drive's natural frequency, signal chain bandwidth has no effect on the measurement of transient phenomena.

Other Important Matters

Torquemeter Electrical Overrange

Without sufficient Electrical Overrange, when torque signals are large, torque peaks are clipped. That results in large errors in reported average torque and, also generates output frequencies not present on the drive. Modern Himmelstein Torquemeters have high (150 to 300%) Electrical Overrange to avoid these errors. Moreover, *to eliminate signal distortion and amplitude errors,* we g***uarantee maximum nonlinearity of 0.1% in the Electrical Overrange region.*** Many competitive Torquemeters have virtually no Electrical Overrange. Others, such as the one listed, have insufficient Electrical Overrange and don't specify nonlinearity in Overrange; they merely guarantee repeatability. See Application Note 20805B for more information on the critical importance of Overrange.

Signal Chain Bandwidth

The signal chain, rotor and stator electronics and rotor to stator signal transmission, should have a bandwidth well above the highest measurable shaft frequency. As a practical matter, their bandwidth is constant for any Torquemeter Series. For modern Himmelstein Torquemeters, it is well above the driveline torsional natural frequency. **Signal chain bandwidth never determines the maximum measurement bandwidth when a well-designed Torquemeter is installed. It is primarily determined by the drive and load inertias and the Torquemeter Torsional Stiffness.**

Torquemeter Length

Bearingless Flanged Torquemeters provide the highest stiffness, lowest deflection, shortest overall length and highest natural frequency. However, you should be aware a ***very short length carries an accuracy/performance penalty.*** That is, a very short sensor sacrifices isolation from the attachment bolts to the torsion element. The problem doesn't show up during static calibration. Nonetheless, in a typical installation, dynamic bending and thrust loads will induce error signals in very short devices. ***Because of this, even though a shorter length lowers material and machining costs, Himmelstein products are designed with enough length to provide inherent isolation during operation,*** and to provide the other characteristics needed for accurate static and dynamic measurements.

Ambient Electrical Noise

Dynamic torque measurements can be corrupted by electrical noise often present in industrial environments. Pulse Width Modulation based adjustable speed drives, which use carrier frequencies between 1 and 10 kHz, are a common noise source. Without proper grounding and adequate shielding , magnetic and capacitive coupling and leakage currents can induce high frequency noise in the torque instrumentation and data cabling. Himmelstein Torquemeters and Readouts include selectable low pass filters with at least ten cutoff frequencies. Those filters can optimize dynamic measurements by providing the widest useable bandwidth while eliminating high frequency noise.

Torquemeter Natural Frequency

For accurate dynamic measurements, the Torquemeter must have a ***natural frequency*** ($\mathbf{F_n}$) above the drivelines' natural frequency. Himmelstein production Torquemeters have natural frequencies from several hundred Hz to above 10 kHz. The resonance of practical drivelines virtually always falls between 5 and 500 Hz.

Flanged Torquemeters have the highest natural frequency ($\mathbf{F_n}$). You can estimate a Torquemeters' $\mathbf{F_n}$ using equation [2] and published values for Stiffness ($\mathbf{k}$) and Inertia. Himmelstein Torquemeters are axially symmetrical. That is, the input and output inertias are equal. Thus the Torquemeter is a torsion spring with half the total Inertia at each end; see relevant specifications.

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