LVDT SELECTION, HANDLING AND INSTALLATION GUIDELINES

APPLICATION NOTE

Preamble

LVDTs (Linear Variable Differential Transformers) are extremely robust, linear position/displacement transducers; inherently frictionless, they have a virtually infinite cycle life when properly used. As AC operated LVDTs do not contain any electronics, they can be designed to operate at cryogenic temperatures or up to 1,200°F (650°C), in harsh environments, under high vibration and shock levels. These are the main reasons why LVDTs, including those from TE Connectivity, have been widely used in the most demanding applications such as in power turbines, hydraulics, automation, commercial and military aircraft, satellites, nuclear reactors, and many others. More information on LVDTs is available on our web site, in the Linear Displacement Sensors section of our Application Notes.

There are two main types of LVDTs: AC operated (no electronics) or DC operated (integral signal conditioning circuit). The moving *Core* (the sensing element) can be coupled to a C*onnecting Rod* to attach to the application *Target* (the moving part to be measured).

Gage Heads (Spring loaded LVDTs) are used for blind installations, to interface with target surfaces that rotate or slide sideways while displacing linearly (for example when measuring the run-out of a rotor), or if no rigid attachment feature is available.

GC Series Gage Head

Guided Core LVDTs are used when sagging of the extension could cause the core to drag inside the LVDT Boreliner (the tube inside which the core slides) and cause wear under very high displacement cycling.

DC-SE LVDT with Guided and Captive Core

LVDT Selection Criteria

Selecting an LVDT for a specific application is not always as simple as it seems, as many factors need to be considered. Selection criteria include (but are not limited to) the following:

- **Electrical stroke:** The stroke to be measured accurately – This stroke needs to include all tolerances including accuracy, temperature effects and zero position adjustment range.

- **Mechanical stroke:** The maximum mechanical stroke of the equipment the LVDT is mounted on – Some of TE Connectivity LVDTs have a through bore; others have plugged (blind) boreliners, in which case the selected LVDT must have sufficient mechanical stroke (refer to the data sheet).

- **Environment:** Temperature, pressure, fluid exposure, vibration, shock, contamination, humidity, sun UV exposure, hazardous atmosphere, proximity of high magnetic fields or magnets, electromagnetic interferences (EMI), radiation, etc. – TE Connectivity has pressure resistant as well as hermetically sealed models (HC Series, for example the HCD model). We also offer LVDTs with Mild Radiation Resistance (MRR option) and the high radiation resistant XS-ZTR Series.

- **Certifications :** RoHS, REACh, CE, ATEX, FM/UL, CSA, etc.

- **Package:** Mounting type, dimensions, weight, type of electrical connections, core guiding, captive core, spring loaded or air actuated, open boreliner for fluid draining, etc.

- **AC or DC operated** – For DC operated there are many options: unipolar or bipolar DC voltage, DC current, digital, etc.

- **Availability of separate signal conditioning electronics** – See TE Connectivity selection of Instrumentation Products on our web site.

- **Required accuracy, linearity, precision** – Note that resolution is not applicable to AC LVDTs as its resolution is virtually infinite; resolution is limited by the electronics it is connected to. For DC LVDTs, the resolution is the noise level which is normally specified on data sheets.

- **Loads** connected to the LVDT outputs: Resistive, Capacitive, and cable length.

- **Proximity of multiple LVDTs in application:** May require AC LVDTs and external signal conditioning with synchronized excitation frequencies to avoid beat frequencies (heterodyning).

- **Required life cycle:** Determines need for and type of core guiding (PTFE or brass bushing; linear ball bearings).

- **Need for special features or custom design** – TE Connectivity customize its LVDTs even for small quantities.

Our Product Guide will also help with basic selection, and Applications Engineers are always available to assist customers and discuss their specific application requirements.

TE Connectivity Catalog LVDT models

The suitability of a standard catalog LVDT model depends on the application. Our Applications Engineers are available to discuss customer's requirements to avoid common mistakes and to offer the best possible solutions.

TE Connectivity LVDTs for OEMs

The unique requirements of OEM applications, including technical, quantitative, and economical, can dictate the design of a custom LVDT. While the majority of our catalog products are designed for the largest possible variety of applications, they could be over-designed for a specific OEM application, or they may be unable to satisfy all of its requirements. Therefore optimization to the OEM's unique application requirements can result in the most cost effective solution. TE Connectivity will either use a variation of an existing product or create a totally new design depending on the quantities and other factors.

LVDT core handling and installation

The core is a small diameter rod made of a Nickel-Iron ferromagnetic alloy, and is typically much shorter than the LVDT. **An LVDT must never be operated without the core** or with the core sticking out of the boreliner, as the input impedance would drop considerably and the excess current through the primary coil could damage the windings from overheat. This is especially true with miniature or short stroke LVDTs with low input impedances.

To obtain the best performance of an LVDT, the core is annealed according to a special TE Connectivity process, to relieve stresses due to machining; this annealing provides core homogeneity with higher permeability to magnetic fields. As a result, **the core is sensitive to mechanical stresses such as bending, clamping, dropping, filing, grinding, machining**, etc. TE Connectivity packages the core individually in a rigid plastic tube to avoid damage during transportation. Once it is out of the tube, **it must be treated with extremely care** to preserve its condition and to avoid LVDT performance degradation.

TE Connectivity LVDTs and their cores are supplied as a matched pair. If cores are interchanged between different LVDT serial numbers, linearity and/or other performance parameters may be affected. TE Connectivity cores have a **red mark**; this end is oriented towards **the front face** of the LVDT (opposite side from electrical connection) when we test the LVDT at the factory. If the core is reversed, then the LVDT will still perform within specifications, but slight differences with the supplied test data are possible.

TE Connectivity LVDT Cores

Most TE Connectivity cores are threaded each side, and both imperial and metric threads are available. The main reason for having threads each side is that the core has to be mechanically symmetrical for best LVDT performance. For LVDTs that have a through boreliner, this feature also allows having a core connecting rod coming out from either end of the LVDT (or from both ends).

TE Connectivity offers threaded Core Connecting Rods of various lengths and thread sizes, to attach to the cores and to the applications. When threading a connecting rod into a core, tightening must be done **by hand** ("finger-tight") and not with a tool, to avoid damage to the core which would affect LVDT performance. To lock the core in-place, a thread-locker adhesive or an epoxy can be used. TE Connectivity Applications Engineers can recommend brands and types. For OEM applications TE Connectivity can provide custom designed assemblies with the connecting rods already secured to the cores, with the length and features (such as threads, hex, flats, etc.) necessary for interfacing.

For customers who prefer to use their own connecting rods, **ferromagnetic metals** (such as AISI 400 series stainless steels for example) **must not be used** as they will severely interfere with the LVDT operation. **Low resistivity metals** (such as aluminum, brass, etc.) **must also be avoided** as they will draw more energy (in the form of eddy currents) from the LVDT and significantly deteriorate its performance. Also be aware that some non-magnetic stainless steels such as AISI 304 can exhibit permanent magnetization (like a weak magnet) and must be **demagnetized** before attaching them to the core. Non-metallic, non-conductive materials such as composites, plastics, etc. can be used but they often exhibit much larger coefficients of expansion than metals and therefore will produce LVDT output zero/offset shifts with temperature.

To achieve frictionless operation and long cycle life, the core should not rub against or make direct contact with the LVDT boreliner in normal operation. Therefore alignment is important; however the core doesn't need to be centered inside the boreliner as LVDTs are not sensitive to transverse position. Our LVDT datasheets include core outside diameter and boreliner inside diameter information so that the interface can be designed to maintain clearance over the stroke. LVDTs with longer strokes may experience connecting rod "sag", due to the weight of the core and the flexibility of the connecting rod. In cases such as this, TE Connectivity can provide LVDTs with the *Guided Core* option, where the core is protected by self-lubricating bushings or a PTFE sleeve.

When the installation or application require that the core must never come out of the LVDT, TE Connectivity offers the *Captive Core* option (refer to our LVDT data sheets).

LVDT mounting

As most LVDT housings are cylindrical, they can be installed with clamping (split) blocks. Some versions are designed for bulkhead mounting; for example on the back of a hydraulic actuator (XS-C Series LVDTs), or bolted onto a surface (TE Connectivity MP and PTS-420 series).

XS-C Series LVDT

MP series LVDT

PTS-420 Series LVDT

Clamping forces must be controlled to avoid distortion of the LVDT housing as they could stress the internal components and thus damage them. TE Connectivity offers special mounting blocks available for all our LVDT sizes. They allow axial adjustment of the LVDT for zero position.

TE Connectivity Mounting Blocks

Installations with **set screws** that press onto the surface of the housing **must never be used** as they could deform it, and therefore damage the internal components.

LVDTs with a plugged (blind) boreliner should be installed with the **probe facing down** at an angle so that the tube can drain in condensing areas or in if there is a risk of being splashed with (compatible) fluids. If downwards orientation is not possible, LVDTs with an open boreliner should be used. TE Connectivity offers both types.

As discussed above (LVDT core handling and installation), the boreliner and the core should be aligned to achieve frictionless operation and long cycle life.

Electrical connections

TE Connectivity offers LVDTs with various electrical connection features: Individual lead-wires, cables, screw terminals, or connectors. TE Connectivity also offers mating connector kits, connector options for LVDTs with cables, as well as cable assemblies (mating connector and cable pre-wired) for ease of interfacing with our electronic instrumentation.

We recommend shielded cables for all installations. Cable length has an influence on both AC and DC LVDTs. There is no strict guideline for cable length between AC LVDTs and the instrumentation, as many variables and unknowns exist. As the AC LVDT is an R-L-C (resistance-inductance-capacitance) circuit, it is therefore sensitive to capacitive loading, which can affect linearity and other parameters. In general, cables lengths should be kept as short as possible, and/or the use of low-capacitance cables is strongly recommended.

For DC LVDTs it is a different matter. The length of the cable affects the amount of noise superimposed onto the DC output voltage and generated by the EMI (Electro-Magnetic Interference) waves, function of the electromagnetic environment: For example a factory environment can be electromagnetically noisy due to machinery, and an airport can be RF noisy due to radar. Therefore it is up to the user to decide what level of noise meets the application requirements knowing the environment to which his application will be subjected. The noise level defines the resolution (the smallest measureable output signal that can be read as representative of position). It can be reduced by proper cable shielding techniques (twist the wires, increase percentage of shield coverage, double shielding, grounding, etc.). If noise is still an issue, it is best to use a DC current output LVDT (i.e. 4-20mA DC) rather than a DC voltage output LVDT. Currents are much less sensitive to EMI.

DC LVDTs and Signal Conditioners use synchronous demodulation (rectification) which is excellent at rejecting symmetrical noise as it synchronizes to the excitation frequency.

Maximum excitation voltage/current/power for AC LVDTs

Our rule of thumb for the current through the LVDT primary windings is **25mA RMS maximum and 150mW maximum** for the input power. This is for LVDTs with primary wire gages no smaller than AWG 40 (See NASA specification EEE-INST-002 for maximum current function of gage); therefore lower currents may need to be specified for subminiature LVDTs that use even smaller gages.

In reality, what is important is the amount of power that the LVDT can dissipate without significantly self-heating and without damaging the windings. **TE Connectivity LVDT windings are vacuum-impregnated** with a specially formulated, flexible resin and the coil assembly is potted into the housing with a two-component epoxy; therefore **heat transfer is dramatically improved** compared to non-impregnated coils.

For an LVDT with a very low input impedance, for example 40 Ohms, the maximum excitation voltage should not exceed 1 VRMS. The current will be limited to 25mA and the power to 25mW, therefore very safe.

If the LVDT has a 240 Ohm input impedance, the maximum excitation voltage is 6 VRMS. With 6VRMS excitation voltage, the current is 25mA and the input power is limited to 150mW, therefore acceptable. But for lower impedances, the excitation voltage will have to be decreased to avoid damage.

In the case of an LVDT with a higher input impedance, for example 1000 Ohms, the maximum excitation voltage would be 25 VRMS if current was the only limiting factor. But the 625mW power dissipation could be excessive. For 150mW maximum power, the excitation voltage will have to be limited to 12.25VRMS.

Our Signal Conditioners provide very safe excitation voltages from 0.5 to 3.5 VRMS, and no more than 25mA of current, allowing safe operation with all our AC LVDTs. The input (primary) impedances of all TE Connectivity AC LVDTs are specified on the data sheets.

As these are very conservative guidelines, we recommend calling our Applications Engineers before selecting the LVDT and the excitation parameters.

Frequency response versus excitation frequency – Signal Conditioning

Occasionally there could be confusion between the *Frequency Response* needed for an application (how fast the core can move while maintaining LVDT output accuracy) and the *Excitation Frequency* (the frequency of the sine wave that is fed to the LVDT primary coil). The output signal of an AC LVDT is a sine wave with the same frequency as the excitation; its amplitude is modulated by the core displacement (See Figure 1). The signal conditioning electronics (external in the case of an AC LVDT) determines the frequency response which is much lower (usually 10 times less) than the excitation frequency.

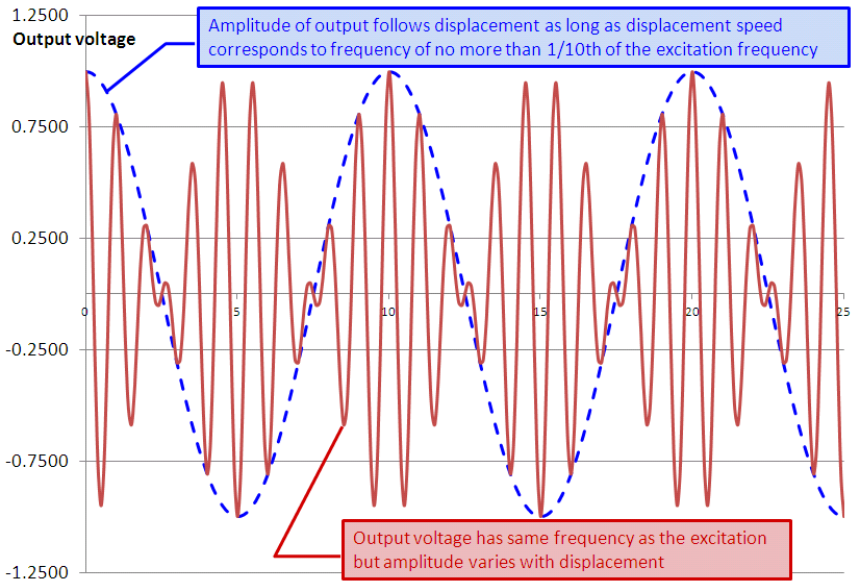


Figure 1

Signal conditioning consists of a sine wave oscillator to excite (power) the LVDT *Primary* coil (LVDT input), a *Demodulator* (rectification circuit), an amplifier, and a low-pass filter to finally generate the DC output signal (see Figure 2). The *Secondary* coil (LVDT differential output) generates a sine wave of the same frequency as the excitation, with amplitude proportional to core position; it needs to be rectified and then filtered (low-pass) into a DC voltage, proportional to the core position. The filter frequency cutoff (typically 1/10th of the excitation frequency) determines the maximum frequency response of the DC voltage output, and therefore the maximum LVDT core displacement speed. If the filter is set to a higher cutoff frequency, the response is improved but the noise level increases and accuracy/resolution are degraded as the filter doesn't have enough rectified sine wave periods to integrate within the shorter displacement time.

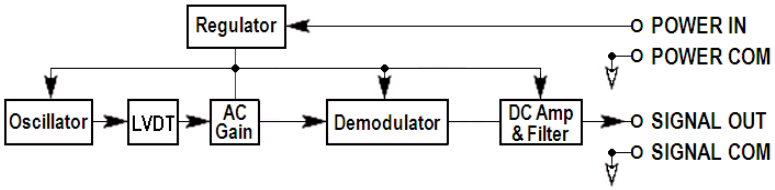


Figure 2

In the case of a spring loaded LVDT (Gage Head), the **mass of the moving assembly** (core + connecting rod + spring) creates inertia, and therefore **adds yet another limiting factor to the frequency response**. If the *target* (moving part which displacement is to be measured) displaces at higher speed/frequency than the (mechanical) frequency response of the moving assembly, the contact tip will not stay in contact with the target and significant measurement errors will result. This will happen even if the target movement frequency is within than the frequency response of the electronics, What it means is that the inertia of the probe and the stiffness of the spring determine the maximum frequency response, which is typically much less (as low as 15 Hertz) than the frequency response of the electronics. This is a very important factor which must be considered when developing the application.

If a high frequency response is needed (i.e. 250Hz), then a spring loaded LVDT should not be used and the core connecting rod should be secured to the application target.

The frequency response of our DC LVDTs and Gage Heads is specified on the datasheets.

Sources of accuracy and precision error

Accuracy is how close a measured value is to the true input. Precision (reproducibility and repeatability) is how close to each other repeated measurements are, for the same true input. There are more contributors to the accuracy and the precision than one normally think of, including (but not limited to) the following:

- Non-linearity
- Temperature effects on zero and scale factor
- Phase shift between excitation and output voltage (AC LVDTs)
- Null voltage (AC LVDTs used with signal conditioners that have non-synchronous demodulators)
- EMI and noise (DC LVDT)
- Proximity to high magnetic fields or magnets
- Cross-talk (multiple LVDTs)
- Loads connected to the outputs and cable length (AC LVDT)
- Distortion of the excitation sine wave (do not use triangular or square waves)
- Misalignments between core and boreliner for short stroke LVDTs (affects precision)
- Speed of displacement (versus LVDT frequency response)
- Tolerance on the calibrated output (at 2 position points as far apart as possible, in the application)

Fortunately, there are solutions to reduce the effects of most of these sources of error, some of which are discussed in the previous sections herein. The distortion of the sine wave can be reduced with a proper oscillator/shaper circuit design. Phase shift affects demodulators that rectify the LVDT output synchronously to the excitation (See Figures 3 through 6).

Effect of a moderate 10 degree phase shift between differential output and excitation on the rectified signal:

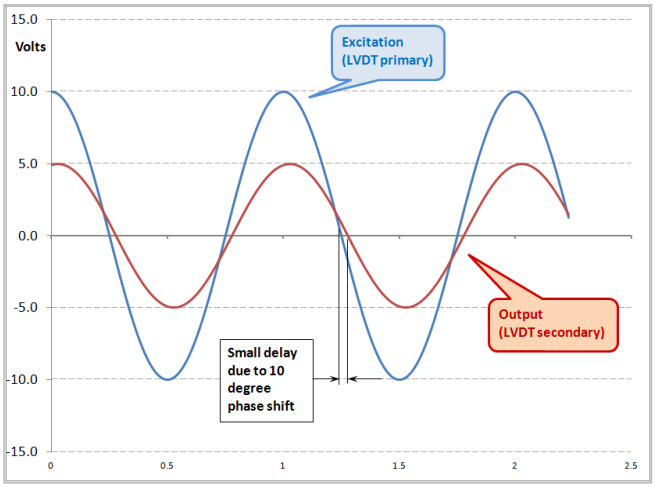


Figure 3

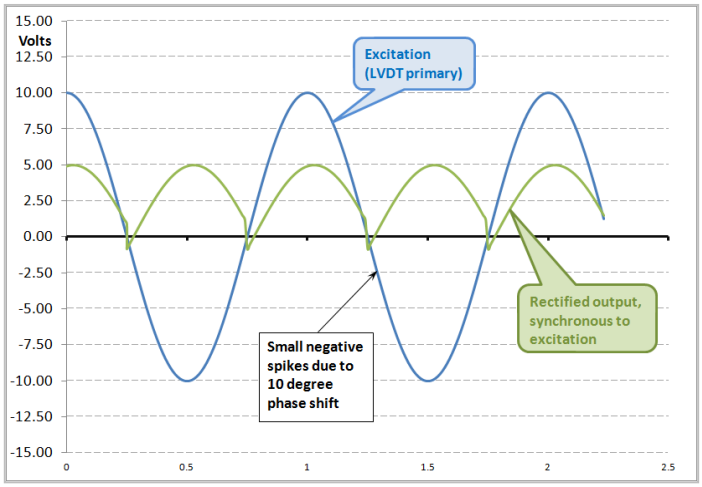


Figure 4

Effect of a larger 30 degree phase shift between differential output and excitation on the rectified signal:

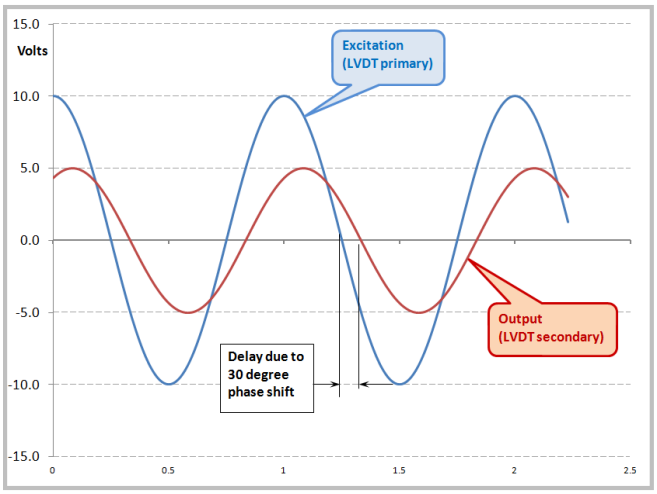


Figure 5

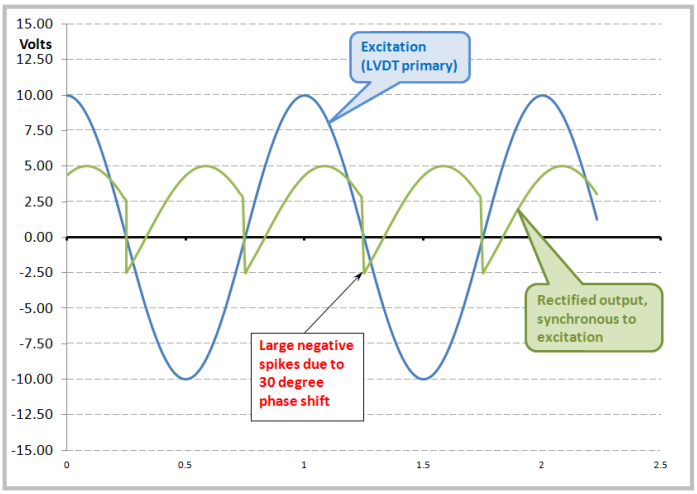


Figure 6

The voltage spikes (discontinuities) generated by a large phase shift are difficult to filter (noise level is increased) and more aggressive filtering can result in a reduced frequency response.

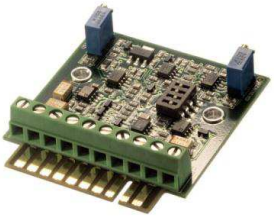
Usually the phase shift of an LVDT decreases with frequency. If the phase shift is, for example, +30 degrees at a specific frequency, it will be lower at a higher frequency. But there is a frequency at which it turns negative. A -30 degree negative phase shift has the same effect as +30 degrees.

TE Connectivity uses two methods to eliminate the effects of phase shift: In demodulators that synchronize LVDT differential output rectification to the excitation, we include a **phase compensation circuit** to allow adjustment of the phase shift to zero; in others (i.e. LVM-110 and LiM-420), **synchronization to the sum of the LVDT secondary** output voltages is employed (requires constant sum LVDTs), and phase compensation is not needed as there is no significant phase shift between the secondary differential and sum signals. The phase shift of TE Connectivity AC LVDTs is always specified on the data sheets. Some TE Connectivity LVDTs have specifications at two different excitation frequencies (i.e. MHR Series).

Electromagnetic considerations

TE Connectivity LVDTs incorporate a magnetic shield around and at each ends of the coil assembly. Some models even have two concentric shields. Shielding dramatically reduces but does not completely eliminate the adverse effects of intense magnetic fields coming from the outside. Therefore LVDTs should not be installed near electric motors, solenoids, magnets, or devices which generate high electromagnetic fields (i.e. MRIs).

When multiple LVDTs are used in close proximity to each other, some *Cross-Talk* can occur, resulting in beat frequencies (heterodyning). Double shielded LVDTs are preferable in this type of application, and cables should be shielded as well. If despite these precautions cross-talk is still an issue, the best solution is to use AC LVDTs with external signal conditioners and synchronize the oscillators so that the excitation frequencies are exactly the same (one master plus slaves). TE Connectivity offers a range of signal conditioners with “Sync” input and output for this purpose (LVM-110, LDM-1000, and ATA-2001).



LVM-110

LDM-1000

ATA-2001

About cross-talk

Cross-talk happens when two or more AC LVDTs are excited at slightly different frequencies (usually due to oscillator frequency tolerances). Despite shielding, some of the electromagnetic field leaking out of the LVDTs or most likely from long cables, while very weak, can penetrate the other LVDTs (or their cables) thus inducing very low AC voltages. The frequencies of these cross-talk voltages are heterodynes: They are the sum and the difference of the excitation frequency of the affected LVDT and that of each of the other LVDTs in proximity. The induced voltages at the differential frequency cannot usually be filtered out as these frequencies are too low.

Example: Several LVDTs in close proximity are excited at 2.5 KHz +/-5 Hertz; the difference between the excitation frequencies of any two LVDTs would therefore be 10 Hertz maximum. As the low-pass filter cutoff frequency of signal conditioners is usually set to $1/10^{th}$ of the excitation frequency, or 250 Hertz in this example, the 10 Hertz cross-talk voltage would obviously not be filtered and would therefore superimpose onto the DC output as low frequency noise or “beat”.

Unique electronic solutions

Over the years, TE Connectivity has developed innovative and very cost effective signal conditioning solutions using both analog and digital electronics, including microprocessors. We have been using these solutions to develop LVDTs that surpass the performance and functionality of many others, for OEM customers. These solutions include (but are not limited to):

- Digital linearity correction
- Extremely low temperature coefficients of output using “by design” temperature compensation schemes
- Detection of the presence of the core inside the boreliner to avoid winding overheating
- Monitoring of winding temperature
- Core interchangeability without significant loss of accuracy
- Field programmable zero and scale factor
- Failure detection circuitry
- Self-diagnostics
- Digital output calibrated to extreme accuracy
- Digital serialization
- Smooth power on/off circuitry
- Power management circuitry using controlled ON/OFF time
- Voltage, current, PWM, and digital outputs such as CANopen and RS485

These solutions, as well as those we are currently working on, and our ability to customize our sensors, are part of what makes TE Connectivity unique in the LVDT industry. We will continue to push the performance envelope by creating innovative technologies with affordable costs.

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