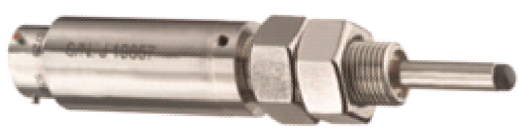
LVDT selection, handling and installation guidelines

Preamble

LVDTs (Linear Variable Differential Transformers) are extremely robust, linear position/displacement transducers; they are frictionless and 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 1200°F (650°C), in harsh environments, under high vibration and shocks. These are the main reasons why LVDTs, including those from Measurement Specialties Inc. (MEAS), have been widely used in very demanding applications such as in power turbines, hydraulics, factory automation, commercial and military aircraft, satellites, nuclear reactors and many others. More information on LVDTs is available in the Linear Displacement Sensors section of our Application Notes in our web site library.

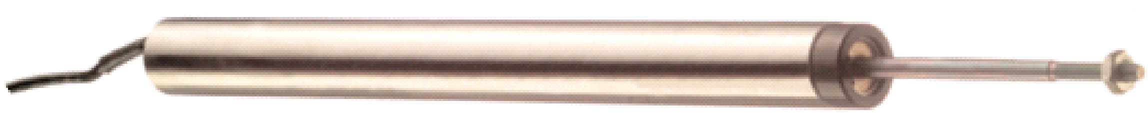
There are two main types of LVDTs: AC operated (no electronics) or DC operated (integral signal conditioning circuit). The moving *Core* (the sensing element) can be coupled to a C*onnecting Rod* to attach to the application *Target* (the moving part to be measured).

Spring loaded LVDTs, also known as *Gage Heads,* can be used for blind installations, for interfacing with target surfaces that rotate/slide 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 MEAS 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).

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- **Environment:** Temperature, pressure, fluid exposure, vibration, shock, contamination, humidity, sun UV exposure, hazardous atmosphere, proximity of high magnetic fields or magnets, EMI, radiation, etc. – MEAS 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, CE, Atex, FM/UL, CSA, etc.

- **Package:** Mounting, dimensions, weight, type of electrical connections, core guiding, captive core, spring loaded, 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 MEAS 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 only limited by the electronics it is connected to. For DC LVDTs, the resolution is the noise level and it is normally specified on MEAS data sheets.

- **Loads** connected to the LVDT output(s): 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).

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

- **Need for custom features or design** – MEAS customize its LVDTs even for small quantities

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

MEAS 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.

MEAS LVDTs for OEMs

The unique requirements of OEM applications, including the technical requirements, annual quantities and price affordability level, can dictate the design of a custom LVDT. While the majority of our catalog products are designed for the widest possible range of applications, they could be over-designed for a specific OEM application, or they may not be able to satisfy all of the requirements. Therefore optimization to the OEM's unique application requirements can result in the most cost effective solution. MEAS will either use an existing design, a variation thereof, or create a totally new design depending on the quantities and other factors.

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LVDT core handling and installation

The core is a small diameter rod made of a Nickel-Iron alloy, and is typically much shorter than the LVDT length or stroke. An LVDT should **never be operated without the core** or with the core sticking out of the LVDT boreliner, as the input impedance could drop considerably and the excess current through the LVDT 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 MEAS process, to relieve stresses due to machining; this annealing provides core homogeneity and higher permeability to magnetic fields. As a result, **the core is sensitive to mechanical stresses such as bending, clamping, dropping, filing, grinding, machining**, etc. MEAS packages the core individually in a rigid plastic tube to avoid damage during transportation. Once it is out of the tube, care must be taken to preserve its condition and to avoid LVDT performance degradation.

MEAS 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 adversely affected. MEAS cores have a **red mark** at one end; this end needs to be **facing the front face** of the LVDT (opposite side from electrical connection). The test data supplied with each MEAS LVDT is for this specific core orientation. If the core is reversed, then linearity and/or other performance parameters may be degraded.

MEAS LVDT Cores

Most MEAS cores are threaded each side, and both imperial and metric threads are available. The reason for having threads each side is primarily because 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).

MEAS 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, it 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, use a thread-locker adhesive or an epoxy. MEAS Applications Engineers can recommend brands and types. For OEM applications MEAS can provide custom designed core assemblies with the connecting rods already secured to the cores, with the length and end features (such as threads, hex, flats, etc.) necessary for interfacing.

For customers who decide 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 resisitivity metals** (conductors 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 usually exhibit much larger coefficients of expansion than metals and therefore will create LVDT output zero/offset shifts with temperature.

To achieve frictionless operation and long cycle life, the core should not slide 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. MEAS LVDT data sheets include core outside diameter and boreliner inside diameter information so that the application 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, MEAS 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, MEAS offers the *Captive Core* option (refer to our LVDT data sheets).

LVDT mounting

As most LVDT cases (housings) are cylindrical, they can be installed with clamping (split) blocks. Some versions are designed for bulkhead mounting; for example the back of a hydraulic actuator (MEAS XS-C Series LVDTs),

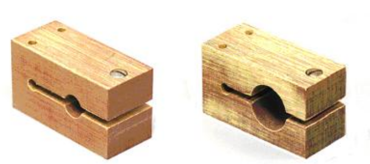
XS-C Series LVDT

or bolted onto a surface (MEAS MP and PTS-420 series).

MP Series LVDT

PTS-420 Series LVDT

Clamping forces must be controlled to avoid distortion of the LVDT housing tube as they could stress the internal components. MEAS has special mounting blocks available for all our LVDT sizes. They allow axial adjustment of the LVDT for zero position.



MEAS Mounting Blocks

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

LVDT selection, handling and installation guidelines

LVDTs with plugged (blind) boreliners should be installed with the **probe facing down** at an angle so that the tube can drain, in condensing areas or in applications where they can be splashed with (compatible) fluids. Otherwise, LVDTs with open boreliners should be used. MEAS offers both types.

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

Electrical connections

MEAS offers LVDTs with various electrical connection features: Individual lead-wires, cables, screw terminals, or connectors. MEAS also offers mating connector kits, connector options for LVDTs with cables, as well as cable assemblies (mating connector and cable pre-wired) for LVDTs with connectors to easily interface 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/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 electrical noise superimposed onto the DC output voltage, generated by EMI (Electro-Magnetic Interference) waves, depending on 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, etc. Therefore it is up to the user to decide what level of noise meets the application requirements. The noise level defines the resolution (the smallest measureable output signal that can be read as representative of position). Electric noise can be reduced by proper cable shielding techniques (twist the wires, increase the percentage of shield coverage, double shielding, grounding, etc.). If noise is 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.

MEAS 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

MEAS' rule of thumb for the maximum current through the LVDT primary is **25mA RMS 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 smaller gage magnet wires.

In reality, what is important is the amount of power that the LVDT can dissipate without significantly self heating and without damaging the windings. **MEAS LVDT windings are vacuum-impregnated** with a specially formulated, high temperature 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.

With an LVDT that has very low input impedance, for example 40 Ohms, the maximum excitation voltage should not exceed 1 VRMS. The power will be limited to 25mW, therefore very safe.

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If the LVDT has a 240 Ohm input impedance, the maximum excitation voltage is 6 VRMS and the input power is 150mW. With higher impedances, the power should not be higher, to avoid damage; therefore excitation voltage should be limited.
In the case of an LVDT with 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. With 150mW maximum power, the excitation voltage would be limited to 12.2VRMS.

MEAS signal conditioners provide very safe excitation voltages within 0.5 to 3.5 VRMS, and no more than 25mA of current, allowing safe operation with all LVDTs. The input (primary) impedances of all MEAS AC LVDTs are specified on the data sheets.

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

Excitation frequency versus frequency response of AC LVDTs

Occasionally there is 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 than (usually $1/10^{th}$ of) the excitation frequency.

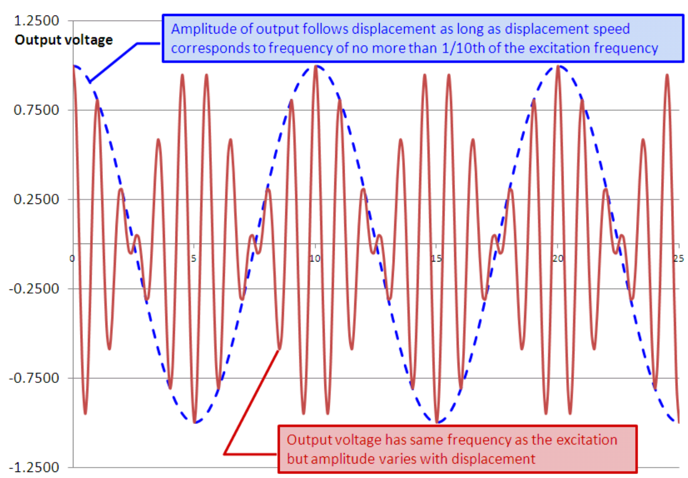

Figure 1

Signal conditioning consists of a sine wave oscillator to excite (power) the LVDT *Primary* coil (LVDT input), a rectification circuit (*Demodulator*), an amplifier circuit, 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. The filter frequency cutoff (typically $1/10^{th}$ of the excitation frequency) determines the maximum response of the DC output. If the filter is set at a higher frequency then the response is improved but the noise level increases and accuracy/resolution are degraded as the filter doesn't have enough rectified sine waves to integrate within the shorter displacement time.

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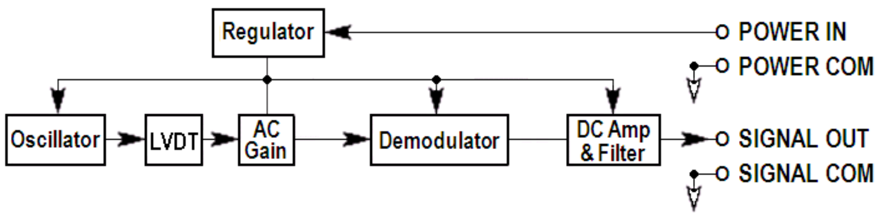

Figure 2

In the case of a spring loaded LVDT (Gage Head), the **mass of the moving assembly** (spring loaded probe) creates inertia, and therefore adds another **limiting factor to the frequency response**. If the target moves at higher speed/frequency than the probe dynamic (mechanical) response capability, even if this target movement frequency is lower than the frequency response of the electronics, the tip will not stay in contact with the target and significant errors will result. 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 factor that must be considered.

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

All MEAS data sheets for DC LVDTs, LVDT 4-20mA transmitters, and DC Gage Heads specify the maximum frequency response.

Sources of accuracy and precision error

Accuracy is how close a measured value is to the actual (true) input. Precision (reproducibility and repeatability), is how close to each other repeated measurements are under the same actual (true) input. There are many contributors to the accuracy and the precision than one could imagine including (but not limited to) the following:

- Non-linearity
- Temperature effects on zero and scale factor
- Phase shift between excitation and output voltages (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 and cable length (AC LVDT)
- Distortion of the excitation sine wave (do not use triangular or square waves)
- Misalignments on short stroke LVDTs (affects precision)
- Speed of displacement (versus LVDT frequency response)
- Tolerance of the calibrated output (at 2 position points as far apart as possible, in the application)

But there are solutions to reduce the effects of most of these sources of error, some of which are discussed in the previous sections herein. Distortion of the sine wave can be alleviated 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).

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

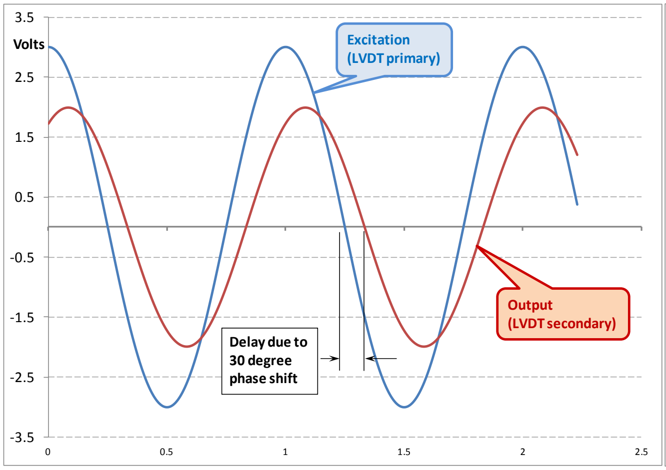

Figure 3

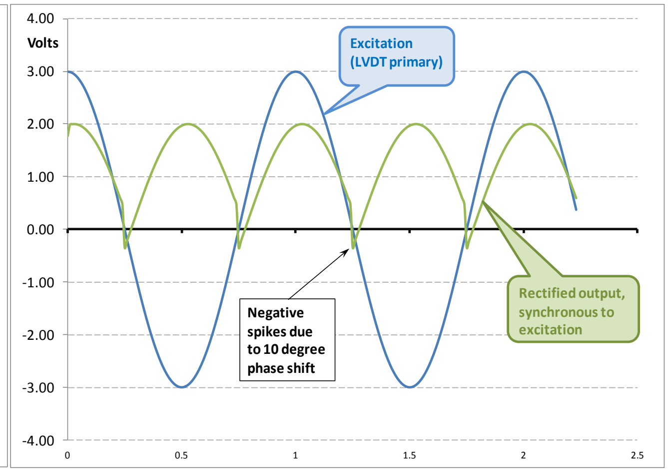

Figure 4

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

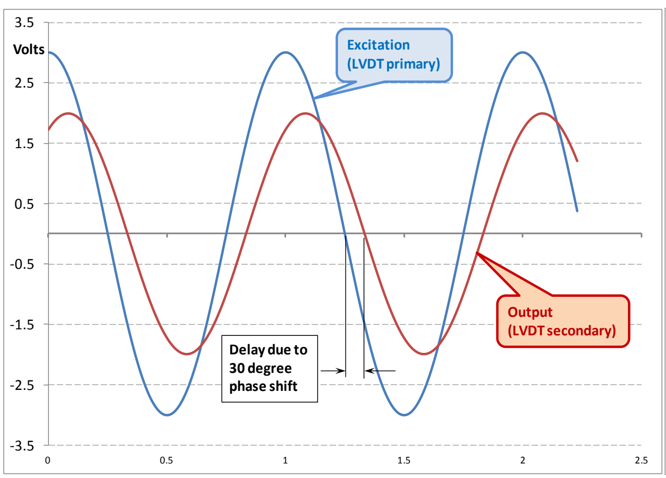

Figure 5

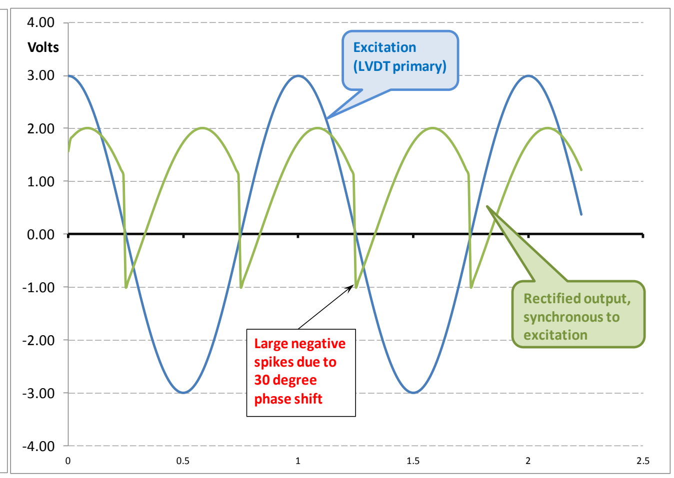

Figure 6

The spikes generated by a large phase shift are difficult to filter (noise level is increased) and more aggressive filtering results in a lower frequency response.

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

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

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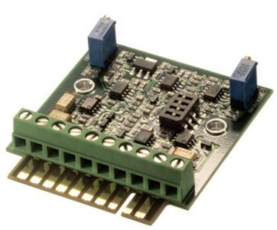
Electromagnetic considerations

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

When multiple LVDTs are used in close proximity, some *Cross-Talk* can occur, resulting in beat frequencies (heterodyning). Therefore double shielded LVDTs are preferable in this type of application, and cables should be shielded as well. However, if 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). MEAS offers a range of signal conditioners with "Sync" inputs and outputs for this purpose (LVM-110, LDM-1000, and ATA-2001).



LVM-110

LDM-1000

ATA-2001

Note on cross-talk:

Cross-talk happens when two or more AC LVDTs are excited with slightly different frequencies (usually due to oscillator frequency tolerance). The electromagnetic waves leaking out of the LVDTs or most likely from long cables, while very weak, can penetrate the other LVDTs (or their cables) thus inducing (superimposing) very low AC voltage signals. 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 any of the other LVDTs in proximity. The voltages with the frequency differences cannot be usually filtered out as they are typically have low frequencies.

Example: Say LVDTs are excited at 2.5 kHz and that the tolerance on this frequency is +/-5 Hz, then the maximum difference between the excitation frequencies of any two LVDTs would be 10 Hertz maximum. As the low-pass filter cutoff frequency of signal conditioners is usually set to 1/10th of the excitation frequency, or 250Hz in this case, the 10Hz cross-talk voltage would not be filtered and would show up on the DC output as low frequency noise or "beat".

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Unique electronic solutions

Over the years, MEAS 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 for OEMs that exceed the performance and functionality of many others. They 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 coil 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 precision
- Digital serialization
- Smooth power on/off circuitry
- Controlled power on time
- Voltage, current, PWM, and digital outputs such as CANopen and RS485

These solutions, and those we are working on, are part of what makes MEAS unique in the LVDT industry. From the Schaevitz Engineering times to today, we will continue to push the performance envelope by creating technology at an affordable cost.

MEAS acquired Schaevitz Sensors and the Schaevitz® trademark in 2000.