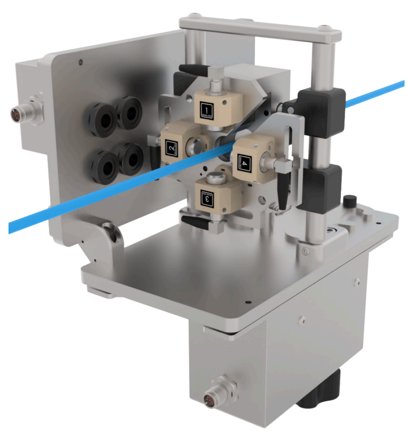
WHITE PAPER

Continuous Measurement of Wall Thickness and Concentricity in Medical Tubing Manufacturing

For Plastics, Nitinol, Stainless Steel, and Other Engineering Materials using Modern Ultrasonic Systems



LaserLinc AutoPilot

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Abstract

Tube wall thickness and concentricity are among the most critical quality attributes in extruded medical tubing. Variation in these parameters drives waste, while out-of-tolerance products lead to patient safety risk. This paper reviews the operating principle and value of in-process ultrasonic measurement for medical tube extrusion.

Less common but equally critical measurements of tube wall thickness and concentricity for stainless steel and specialty metal alloys such as Nitinol for medical products like stents, hypotubes, and cannulas are also covered.

1. Introduction

The performance and safety of extruded round products—polymer medical tubing, multi-layer catheters, drawn metallic hypotube—depend directly on the geometric uniformity of the wall surrounding the lumen. Two parameters dominate: wall thickness, the radial distance between inner and outer surfaces, and concentricity, the degree to which that wall is distributed evenly around the central axis. A common challenge in medical tube extrusion is dimensional characteristics drifting in real time during production as a function of extrusion die alignment, melt pressure, line speed, cooling profile, and many other process variables.

Upon process initialization, operators typically modulate key production variables—including line speed, die bolt alignment, and internal air or vacuum pressure—to bring the product within target dimensional tolerances. However, as the production run progresses, inherent process drift inevitably introduces geometric variance. The result is lower yield and escalating risk of nonconforming, potentially hazardous products reaching the end customer.

Historically, manufacturers have monitored these parameters by cutting samples, taking the samples to a bench, and measuring with optical comparators or manual thickness gauges. The approach is destructive, slow, sample-limited, and inherently retrospective: by the time a deviation is identified, an unknown amount of out-of-specification product may already be in post-production.

By placing immersion transducers in the process, modern production quality systems generate a live cross-sectional image of the wall, supporting immediate manual operator adjustment or, if desired, closed-loop control of the extrusion process.

2. Principles of Ultrasonic Wall Measurement

2.1 Acoustic Fundamentals

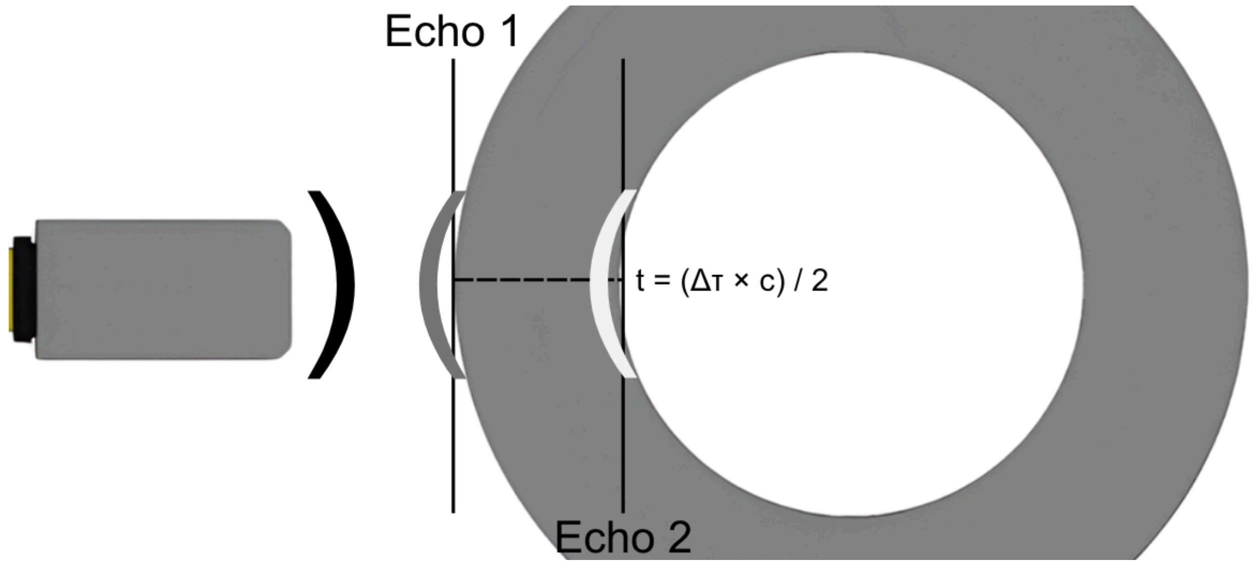
The theory of ultrasound for material thickness measurement is complicated. There are many sources available on-line to gain a deeper understanding. This paper only discusses aspects of the physics of ultrasound sufficient to understand its application for gauging material thickness.

2.1.1 Ultrasound Definition

Ultrasound is a mechanical pressure wave with a frequency above the upper limit of human hearing, approximately 20 kHz. Industrial wall-thickness gauging for measurement of plastics, certain rubber compounds, and metals typically operates between 1 MHz and 50 MHz, with the higher frequencies reserved for thin-wall and metal applications where short wavelengths and high temporal resolution are required.

2.1.2 Transducer Operation

A measurement cycle begins when a brief electrical pulse excites a piezoelectric crystal in the transducer. (Other types of transducers and wall measurement technologies are discussed in Section 8.) The crystal then emits a mechanical compression wave that propagates outward. The frequency of the wave and the properties of the medium–primarily elasticity and density–through which the wave is traveling impact its transmissibility. After emitting the wave, the transducer transitions to “listening mode” where reflected wave energy is converted back into an electrical signal that varies with the amount of energy received.



2.1.3 Acoustical Impedance

When the wave emitted by the transducer reaches a different medium, the relative acoustical impedance of the two media dictates what happens to the energy of the wave. The greater the difference in acoustical impedance, the greater the amount of the wave’s energy that is reflected. (This is why air is particularly problematic in the applications discussed in this paper. Its acoustical impedance is much lower than the materials being measured. More on this later.) In this paper, reflected energy is referred to as an echo. The most common medium chosen to “couple” the transducer and the material under test is water as its properties are well suited to transmitting pressure waves in the frequency range used for measuring medical tubing. In the case of a single-layer tube of a homogeneous material, the wave will travel through the water medium until it encounters the outer surface of the product. Assuming the material has an acoustical impedance sufficiently different from that of water, an echo will be produced. A portion of the wave’s energy will continue to propagate outward through the tube until it reaches the air filling the lumen. As air has a significantly lower acoustical impedance than any of the materials used in medical tubing, virtually all of the wave’s remaining energy is reflected back as a second echo.

2.1.4 Making the Wall Measurement

The time-of-flight difference between these two echoes, multiplied by the speed of sound in the wall material, and divided by two (because the wave travels through the tube wall twice), yields the wall thickness.

$$t = (\Delta\tau \times c) / 2$$

In this equation, t is the wall thickness, $\Delta\tau$ is the time difference between successive echoes, and c is the longitudinal acoustic velocity in the material. Calibration on a known sample of the same material establishes c for the material with properties at the point of measurement, after which the ultrasonic measurement technique becomes a fast, repeatable, and non-destructive measurement [1].

2.1.5 Frequency Selection and Wavelength

The general rule for resolving a wall echo is that the wall thickness must be greater than roughly half the acoustic wavelength in the material. If the acoustic wavelength is too long, identifying the echo from the inner boundary of a thin wall becomes inconsistent or impossible to discern, resulting in imprecise measurement or an error.

2.1.6 Focal Specifications

After the sound wave has been produced by the piezoelectric crystal, the beam of sound can be further manipulated. Focusing can be applied to the sound field to provide more energy and sensitivity at targeted locations. The primary types of focusing used for immersion transducers are:

1. Point focus (spherical) - Point focus transducers are conically focused to a specified focal distance. At the focal distance, the beam diameter is at its smallest and most sensitive. This is ideal for small targets, such as smaller diameter tubes.

2. Line focus (cylindrical) - Line focus transducers are similar to point focus, but the end result is a triangular prism, where the resulting beam focus resembles a line. This provides a less intense sound wave at the focal length, but one that covers a larger area. These transducers are ideal for larger targets or surfaces that need more analysis per reading. For instance, a braided wire with a plastic coating could benefit from a line focus transducer as the peaks and valleys produced by the coating and braided interface can be analyzed together.

3. Unfocused (natural focus) - Unfocused transducers are not focused to any particular focal length. The sound beam comes out at the element diameter defined for the transducer, and the beam terminates at the end of the near field. The sound wave intensity remains fairly consistent and stable through the near field, but weaker than the focused field counterparts. All of the immersion transducers are governed by their near field, as the far field of the sound field becomes more unstable. The unfocused transducers have a longer near field, making them ideal for applications where the distance to the target can fluctuate a lot. The focal point for the focusing transducers is very close to their effective near field.

2.1.7 Measurement Rate

For each wave emitted, the transducer begins listening for echoes. Once the expected echoes are received (or the max time to wait for them has expired), the process repeats. The rate at which this repeats is referred to as the ping rate**.**

Typically, before a measurement is reported, the data from a configurable number of pings are averaged together for stability. The ping rate and the averaging determine the measurement rate of the system.

2.2 Multi-Layer Measurement

When the product comprises multiple bonded layers—for example, a tie-layer construction in catheter tubing—each interface between materials of differing acoustic impedance generates an echo. The time between successive echoes is proportional to each layer's thickness. Properly configured systems can resolve two or more discrete layers (provided that adjacent materials have sufficiently different acoustic impedance) and report individual layer thicknesses as well as the total wall.

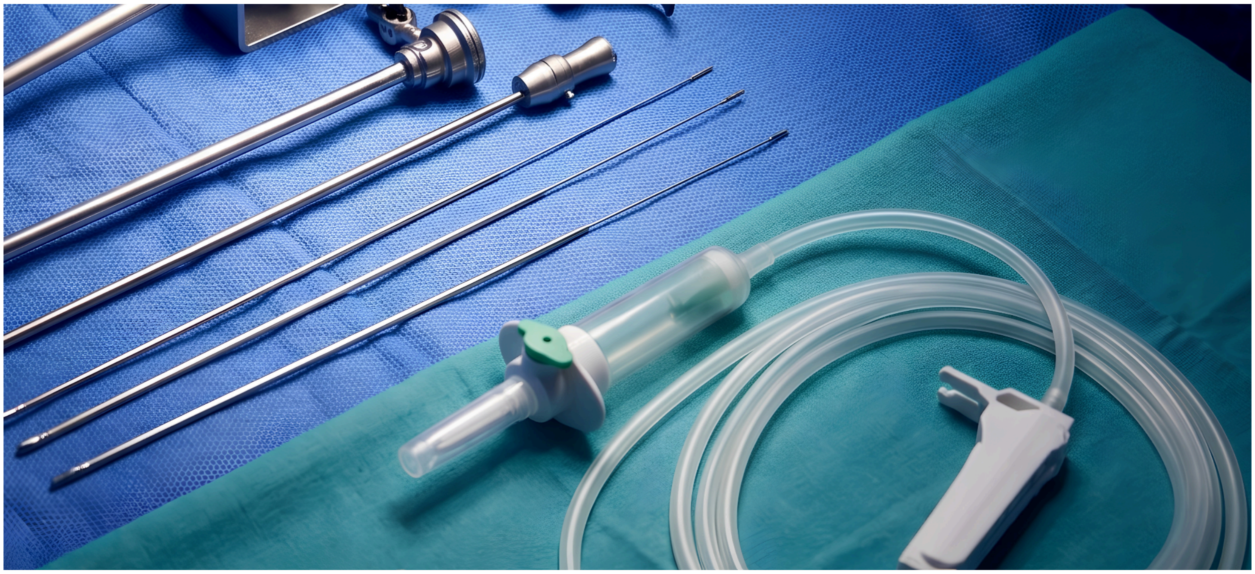
2.3 Concentricity from Multi-Point Arrays

A single transducer measures the wall only where its acoustic axis intersects the product. To obtain concentricity—how close the central axis of the tube's inner diameter (ID) and central axis of the outer diameter (OD) are to each other—an array of transducers is arranged in a circular pattern around the product. Four transducers spaced every 90° are sufficient for most polymer and metal medical tube extrusion applications. Higher angular resolution can be achieved with additional transducers, typically up to eight, providing an improved concentricity measurement and better detection of uneven walls.

2.4 Bubble-Free Operation

Air will attenuate ultrasonic signal propagation. Even a small air bubble on the transducer face will scatter the wave, causing a signal dropout. Therefore, industrial systems pump a stream of water across the face of each transducer with sufficient flow to break the surface tension between any pockets of air and the face of the transducer.

3. Application: Medical Tubing Manufacturing



3.1 Why Wall and Concentricity Matter

Industry standards for the importance of wall thickness and concentricity vary based on the product. Determining the importance of these characteristics is reliant on understanding what a failure can mean. Below are some potential failures for wall and concentricity.

Why Wall Thickness Matters:

- Burst strength - critical for balloon catheters and high-pressure delivery products.
- Fatigue cracking - thin walls under strain, but not pressure, can result in cracking.
- Kink resistance - failures can occlude flow or trap a guidewire.
- Coil and braid defects - a reinforcing material can press or break through thin spots, destroying the integrity of the end product.
- Fitment issues - an oversized or undersized wall can cause a downstream processing failure.

Why Concentricity Matters:

- Asymmetric stiffness - off-center ID (inner diameter) translates to inconsistent behavior during torque transmission and bias during straightening
- Fitment issues - if one product is centered properly and a mating piece is not, the assembly cannot be completed.

Tolerances are correspondingly critical. Metal alloy tubing for medical applications typically have an outer diameter as small as 0.254 mm (0.01 in) with wall thickness as thin as 0.013 mm (0.0005 in) [4, 5]. Industry specifications typically demand dimensional verification with tolerances on the order of ±0.0025 mm (0.0001 in) [3, 7].

Polymer medical tubing covers a comparably wide dimensional envelope. Precision catheter and microbore tubing is routinely extruded with outer diameters from roughly 0.25 mm (0.010 in) to about 4 mm (0.155 in) and with wall thicknesses ranging from ultra-thin sections near 0.0127 mm (0.0005 in) up to roughly 0.13 mm (0.005 in), increasing toward 0.2 mm (0.008 in) at larger inner diameters [22]; conventional fluid-management and drainage tubing extends to larger bores still. Dimensional control is correspondingly demanding: precision extrusion commonly holds outer-diameter and wall tolerances near ±0.0127 mm (±0.0005 in) [23], while the tightest microbore, multi-lumen, and coextruded products reach diameter tolerances as small as ±5 μm (±0.0002 in) [24].

3.2 Why Conventional Approaches Fall Short

Ultrasonic measurement technology is a response to the identification of limitations in traditional medical tubing inspection.

1. Destructive testing is slow and wasteful.
2. Statistically based sample inspection can miss out-of-tolerance defects that occur between samples.
3. Manual checks and contact measurement methods are error-prone. Manual methods introduce error through the handling, preparation, and placement of products for inspection while contact measurement is often subject to operator-dependent reproducibility error.

Each of these limitations is addressed through continuous, non-destructive ultrasonic monitoring over the full length of the production run.

3.3 Thin-Wall Capability

One of the defining metrological challenges in modern medical extrusion is measuring ever-thinner walls. Current ultrasonic technology supports wall thicknesses as small as 0.025 mm (0.001 in) for micro-polymer medical tubing and 0.075 mm (0.003 in) for metals, composites, and alloys, such as Nitinol stent tubing utilizing high-frequency transducers [8].

Thin walls result in a faster return of the sound wave from the inner wall. Lower-frequency transducers produce waves that overlap in thin materials such that the entry signal and return signals are difficult or impossible to discern. High-frequency transducers solve this through fewer cycles per pulse, creating the separation between waves necessary for an accurate measurement.

3.4 Off-Line Sample Measurement Verification

Off-line sample measurement remains essential for periodic verification, quality records, and regulatory documentation. Modern ultrasonic platforms address this by linking in-line and off-line measurements through a common software architecture. An example would be an off-line measurement system for OD, ID, and wall thickness, capable of measuring thin-walled tubes and using NIST traceable calibration standards.

These two measurement systems play complementary roles. Because the off-line bench is calibrated against NIST-traceable standards, it serves as the metrological anchor—the accurate reference of record—even though it is slower and limited to discrete samples. The in-line system is the inverse: it measures continuously at production speed but functions best as a relative gauge that is tied back to that reference. Linking the two transfers the bench's traceable accuracy to the production-speed measurement, so the reference establishes verification and the in-line system carries it across every meter of product between samples.

A sample is taken from production and measured with the off-line device. An HMI or other software solution automatically compares and adjusts the in-process system based on the off-line measurements, with the software serving as a uniform architecture for seamless integration. The result is a closed measurement loop that simplifies verification of in-line systems and provides traceable evidence of conformance.

4. Measuring Metals and Alloys

4.1 Why Metals Are Acoustically Different from Polymers

From the perspective of an ultrasonic transducer, metals and polymers are fundamentally different media. Longitudinal acoustic velocity through a material, such as austenitic stainless steel, is approximately ~5740-5920 m/s, and in Nitinol, ~4,500–5,800 m/s, compared with ~1,500 m/s in water and ~1350–2,700 m/s in typical thermoplastics. Acoustic impedance — the product of density and velocity — is roughly 10 to 20 times higher in metals than in polymers (acoustic impedance is expressed in megarayls, MRayl, where 1 MRayl = 10^6 Pa·s/m). This produces strong, well-defined front-wall echoes but tightly compressed time-of-flight differences for thin walls [1, 2]. Resolving those compressed time differences requires high-frequency transducers and high-speed digitization of the signal (~250 MHz or higher).

4.2 Frequency Selection

At 30 MHz in Nitinol ($c \approx 4{,}500$ m/s), the wavelength is approximately 0.15 mm (0.006 in), yielding a theoretical lower-resolution limit of approximately 0.075 mm (0.003 in) [2]. This places the system at the lower end of this practical range, with the high-frequency configuration used to achieve the demonstrated 0.075 mm (0.003 in) measurement on Nitinol stent tubing [8]. For stainless or nickel-alloy hypotubes and other metal tubing with thicker walls, utilizing a lower-frequency configuration (2.25–10 MHz) provides better acoustic penetration with adequate resolution.

4.3 Nitinol-Specific Considerations

Nitinol presents unique measurement challenges beyond those of steel, other alloys, and composite materials. Phase structure (austenite, martensite, rhombohedral (R-Phase)) shifts with temperature and stress, producing measurable changes in acoustic velocity [9]. Measurement verification against a Nitinol reference of the same thermomechanical state is therefore essential.

Nitinol stent tubing typically has outer diameters of 0.25–4.5 mm (0.010–0.177 in) and walls of 0.013–0.5 mm (0.0005–0.0197 in) [6]. At the thin end, those walls approach—and can fall below—the practical lower limit of ultrasonic measurement, while the tight radius of curvature leaves little margin for error in transducer position, angle, and focal distance [1, 8].

4.4 Other Alloys and Non-Ferrous Products

The same physical principles apply to a broader family of metallic round products. Stainless steel hypotube used in catheter shafts [5], nickel-alloy tubing for chemical processing, zirconium tube for nuclear applications, titanium tubing for aerospace and medical applications, and even small-diameter aluminum and brass tubing have all been measured with comparable ultrasonic techniques.

4.5 Practical Setup for Metal Measurement

Field-proven setup practice for metallic products includes the following:

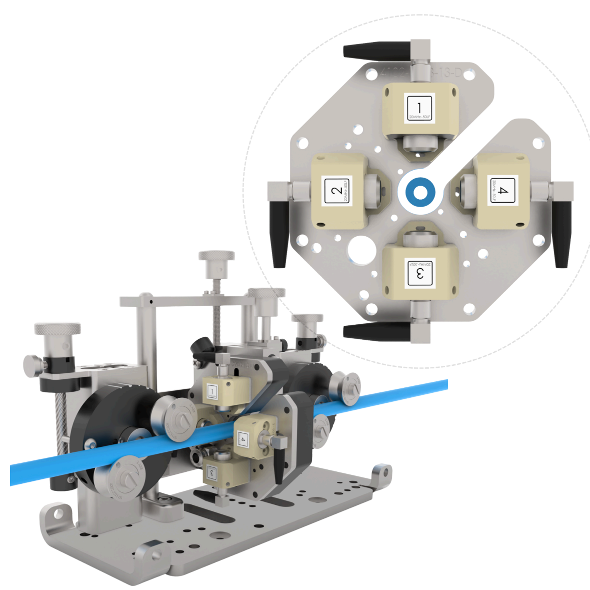
1. Select the transducer frequency consistent with the required acoustic penetration.
2. Align the measurement plane to be orthogonal to the product's surface.
3. Verify waveform response from the transducers.
4. Test and adjust the velocity of propagation for the product’s material in m/s on a dimensionally verified reference of the identical alloy and thermomechanical state.

When these conditions are satisfied, ultrasonic measurement is a repeatable, accurate, non-destructive option for metallic round products with wall thicknesses equal to or greater than 0.075 mm (0.003 in), depending on the material.

5. Ultrasonic System Architecture

5.1 Sensor Assemblies

By sensor assembly we mean a fixture that includes the transducers, transducer mounting, cable management, a method for purging air from the faces of the transducers, mounting of the entire sensor assembly in the process, and often some method for guiding the tube or for aligning the sensor assembly to the tube. The most common configurations include four or eight transducers arrayed around the measurement area every 90° or 45° degrees, respectively.



UG412 with a zoomed view of the transducer assembly

A variety of guiding mechanisms have been deployed with the most common being roller or clamshell guides. Guides are needed to ensure that the transducers are aligned perpendicular to the longitudinal axis of the tube. Roller guides offer flexibility in the shape, material, and positioning to suit the product and the process. Clamshell guides offer extreme simplicity.

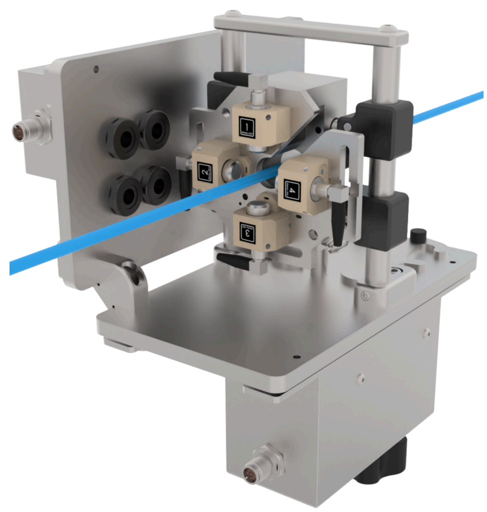
There are tradeoffs. Roller guides often require some positional adjustment. Roller guides are often used elsewhere in the process so operators are accustomed to this. Clamshell guides must be made-to-size to guide a given diameter tube. If not sized right, they can abrade the tube or even break the extrudate or result in inconsistent alignment and poor measurement quality.

Sensor assemblies are available for mounting in vacuum tanks, cooling troughs, or in a tank added to the production line solely for holding the sensor assembly.

5.1.1 Advanced Designs

Advanced designs for special requirements are also available.

Some manufacturers prefer a solution that requires no operator adjustment for guiding and aligning the sensor assembly with the tube. LaserLinc's AutoPilot™ assembly provides automatic and dynamic positioning. The operator activates positioning through the HMI as soon as the line is up and running, taking a couple of minutes or less for measurement to begin. This type of design is fast, requires no operator manipulation, and avoids any risk of damaging the tube.



LaserLinc AutoPilot

Since most nitinol and other specialty metal tubing is made in discrete lengths, the tube is open at both ends. This presents challenges with immersion. A sensor assembly is needed that ensures water doesn't enter the tube. An example of this is integral to LaserLinc's BenchLinc UT™ product line.

5.2 Signal Analysis

A DSP (digital signal processor) is used to digitize the electrical signal generated by the transducer. This processing capability must be reasonably close to the sensor assembly to avoid signal loss so this is usually packaged in an IP-rated housing so it can survive a wet environment. It has sufficient connections for the transducers in the assembly and it contains the circuitry to generate the excitation pulse to drive the transducer.

LaserLinc UltraGauge DSP

Analyzing the signal can be done in a variety of ways: finding transition points representing each echo using a traditional method such as curve-fitting, using Fast Fourier Transforms (FFT) to isolate the transition points, or one of the most recent advances, AI. Once the echo locations have been identified, the time between echoes is simple subtraction. Section 2.1.4 describes conversion from time to wall thickness.

An HMI, described next, includes tools for viewing the digitized signal and setting analysis parameters.

5.3 Software and HMI

Ultrasonic measurement systems are operated through a human–machine interface (HMI) and supporting software. Real-time measurement enables functions such as trending, tolerance checking, alarming, sorting, statistical process/quality control (SPC/SQC), closed-loop control, logging, and reporting. controlling signal analysis parameters that turn the raw output of the transducers and signal processor into actionable information.

One of the most useful features is a live cross-section display of the tube. The cross section shows each layer and visually represents each wall measurement and concentricity. This display provides almost immediate feedback to the operator as they adjust the extruder's die bolts to optimize concentricity and adjust the process to bring the average wall on-size.

5.4 Auxiliary Components

For ease of installation and ease of use, accessories can make the difference for successful adoption. If the existing equipment won't accommodate the sensor assembly or isn't located where needed, a separate tank for placing the sensor assembly is useful. Most sensor assemblies fit into a short tank, ~60 cm (two feet) or less. A full-featured tank accessory will include a height-adjustable stand, water management, and pumps to generate the flow needed to purge the transducer faces. Other nice-to-have options include an air-purge or other solution to remove water from the tube and an independent reservoir of water.

When frequent changeovers occur and equipment is rearranged as required for the job, a fully integrated mobile measurement system is particularly valuable. Everything required is mounted together on a mobile base with leveling and locking casters: a tank such as described above with the sensor assembly, the DSP, touchscreen HMI, discrete I/O, and input devices such as a keyboard.

5.5 Added Value Options

While technically possible, ultrasonics rarely provide an accurate measurement of outer diameter. Typically, a laser micrometer is added to the system to provide complete dimensional inspection: OD, ID, wall, ovality (eccentricity), and concentricity. For medical extrusion, a three-axis laser micrometer is the most common configuration as at least three axes are required to obtain an acceptable ovality measurement. Many ultrasonic systems are designed to integrate diameter measurement devices.

In-process, the tube is under tension and may not be fully set. Post-process measurement is needed to ensure quality. To establish quality as early as possible, adjusting the in-process measurement to match the off-line wall is necessary for optimal performance. Ideally, the off-line system offers seamless communication to deliver the off-line measurement data to the ultrasonic system.

5.6 An Example: The UltraGauge™ Line

The LaserLinc UltraGauge product line includes a range of sensor assemblies with multiple options for transducer frequency and focal characteristics, a DSP, and the Total Vu™ HMI. Sensor assemblies include options for four and eight transducers, mounting in vacuum or open tanks, and accommodate a range of product diameters.

To accommodate the diverse needs of medical extrusion—from micro-catheters to large hoses—the UltraGauge line includes different sensor assemblies sized for specific outer diameter (OD) and wall-thickness ranges. Across all models, the systems can be equipped with low-frequency transducers (2.25–10 MHz) for thicker polymer and elastomeric products, or high-frequency transducers (20–50 MHz) specifically reserved for precise thin-wall metrology. Table 1 below details the measurement capabilities of each model based on its frequency configuration.

Model	Outer Diameter Range	Wall Thickness Range (Low Freq.)	Wall Thickness Range (High Freq.)
UG412	0.2 – 11.4 mm (0.01–0.45 in)	0.254 – 5.08 mm (0.01–0.20 in)	0.025 – 1.27 mm (0.001–0.05 in)
UG430	0.5 – 29.2 mm (0.02–1.15 in)	0.254 – 12.7 mm (0.01–0.50 in)	0.025 – 1.27 mm (0.001–0.05 in)
UG460	6.3 – 60 mm (0.25–2.36 in)	0.254 – 25.4 mm (0.01–1.0 in)	0.025 – 1.27 mm (0.001–0.05 in)

Table 1. Example of ultrasonic measurement ranges for LaserLinc's UltraGauge system (low frequency: 2.25 -- 10 MHz; high frequency: 20 – 50 MHz). Source: UltraGauge datasheet [8].

5.6.1 BenchLinc ID/OD™ System with UltraLinc™ Option

The BenchLinc ID/OD is designed to measure the OD, ID, and wall of discrete tube samples. A sample is mounted on a PTFE-coated mandrel to support the sample and provide a reference surface for the wall measurement. A motor drives two bands that contact and rotate the sample at user-defined angular intervals and stops. At each stop, individual measurements of OD and wall are made. Average OD and wall are computed.

The UltraLinc option transfers the data to the in-process UltraGauge system. Because both systems operate with the same Total Vu platform, data is delivered in an optimized fashion and can offset the wall, and the OD, if included. (Note that since the BenchLinc system also operates on the Total Vu platform, its operation and capabilities are very similar to the UltraGauge system.)

5.6.1 BenchLinc-UT™ Piece-Part System

Measurement of nitinol, stainless steel, cobalt-chromium, and other specialty metal tubes is accomplished with this all-in-one compact system. A UT430 sensor assembly, similar to the UG430 specs in the above table, is an ultra-compact sensor assembly with its own immersion “tank,” and toolless changeover of a guide with built-in gaskets to contain the water.

To prevent water from entering the tube, the part is first inserted through the gaskets and then an integrated micro-pump turns on to quickly fill the sensor’s reservoir. Within seconds, the measurement cycle can begin. The sensor assembly is mounted on the front of a stainless steel package housing electronics and other hardware. A touchscreen PC running the Total Vu HMI mounts on the housing for easy operation.

6. Operational Benefits of A Modern Ultrasonic System

Measurable benefits of a modern in-process ultrasonic wall thickness measurement system can be described in three categories: Quality, Cost and Yield, and Safety and Compliance.

6.1 Quality

- Continuous, non-destructive verification of every meter of product instead of infrequent destructive sampling.
- Direct visibility of the cross-section, enabling immediate adjustment for concentricity and wall thickness.
- Per-layer measurement on multi-layer tube constructions, supporting independent control of each layer in the stack.
- Closed-loop verification by linking in-line readings with off-line measurements of samples after the material has set and is no longer under tension, ensuring that in-process measurement translates to finished quality.

6.2 Cost and Yield

- Faster startup, with operators centering the die within minutes rather than hours.
- Reduced material consumption (give-away) by eliminating the extra material margin that compensates for unverified concentricity and minimum wall requirements.

- Lower scrap rates from earlier detection of process drift resulting in dimensional variance.

6.3 Safety and Compliance

- Improved confidence in wall integrity for safety-critical medical devices.
- Documented dimensional conformance to support quality and compliance requirements, including ISO 13485 for QMS; ASTM F2633 for finished Nitinol tube [3, 10].
- Continuous measurement and SPC trend data for early detection of process drift before it produces non-compliant products. Virtually 100% inspection to prevent acceptance of defective products.

7. Limitations of Immersion Ultrasonic Measurement

As with any technology, wall thickness measurement using ultrasonics has limitations. Most center around the materials in the tube. Other factors include process conditions and some common requests that are beyond the practical capabilities of the technology.

- Immersion required: The transducer frequencies required in the applications addressed herein require a coupler much more dense than air, typically water. In processes where the extrudate cannot come into contact with water, immersion transducers are not practical. Other couplers can be used but they tend to have more or other adverse effects.
- Operating temperature range: Transducer life shortens as couplant temperatures approach or exceed spec, often in the range of 37.8° - 48.9° C (100° - 120° F).
- Porous and foamed (as with blowing agents) products: Small pockets of air, no matter how small, especially when there are a lot of them, reflect enough of the pressure wave that the wave never returns to the transducer to create an echo.
- Braided or coil-wrapped products: Multi-layer tubes with a braid or coil (particularly when the reinforcing layer is metal) often scatter too much of the pressure wave or interfere with measurement of deeper layers.
- Hydrophilic materials: If the material absorbs water, the acoustic impedance at the surface can vary, causing an inconsistent echo from the product's surface. An inconsistent echo leads to measurement variability.
- Highly viscoelastic materials: Similar to hydrophilic materials, these can absorb the energy of the soundwave, resulting in poor return and unreliable measurements.
- Uncured extrudate: In applications where the extrudate retains a lot of heat at the desired measurement location, the material temperature can vary such that the wall

measurement is inconsistent. (Material temperature affects the speed of sound through the material.)

- Similar acoustical impedance: Materials that have the same acoustical impedance as the coupler won't create an echo at the product's surface. Similarly, in a multi-layer construction where adjacent layers have approximately the same acoustical impedance, an echo won't be generated from the interface.
- Surface condition: A coarse surface will reflect the soundwave in many directions resulting in weak energy return to the transducer, preventing measurement.
- Flaw detection: gels and very short defects in the wall dimension, thick or thin, are unlikely to be detected as line speeds relative to ping rate are too high and even with sensors every 45°, defects can pass between sensors.
- Wall too thin: there are products where the wall is too thin to measure ultrasonically as covered herein. What constitutes "too thin" is dependent on the material.
- Certain multi-layer constructions: Where a "tie-layer" or bonding layer is used between two materials, that layer is almost always too thin to be measured ultrasonically. Another example is where an outer layer is too thick such that the higher-frequency required to measure an inner layer won't penetrate the outer layer.
- Multi-lumen products: Multiple internal chambers filled with air present two challenges: 1) unless the construction and orientation allow for consistent alignment with a region of an inner chamber that is clear of the internal structure, wall measurement is either highly variable or impossible, and 2) it is impossible to measure anything with an air pocket between it and the transducer.
- Inner diameter (ID) accuracy: The ID is a calculated measurement. All transducers are pulsed at the same time so the wall measurements are not of the same spot on the tube. Further complicating that issue is the fact that a separate device is typically used to measure outer diameter, at a different location in the process. Without a true cross section, ID measurement accuracy suffers.

8. Other Wall Thickness Measurement Technologies

A range of non-contact technologies is available for tube wall-thickness measurement. Most, however, are specialized for particular materials or measurement conditions rather than being broadly applicable, and several impose practical constraints that limit their use to specific product types.

- **Air-coupled (air-gapped) transducers** operate at approximately 50 kHz to 2 MHz, though most practical measurements are performed below 1 MHz, where transmission through air and scattering losses remain manageable [11]. The measurable thickness range varies substantially with the material's acoustic impedance, attenuation, and sound velocity, so accommodating a diverse product range may require multiple transducer configurations or systems, rendering this method unsuitable for thin-walled metal and polymer products.

- **Electromagnetic acoustic transducers (EMATs)** generate the ultrasonic wave directly within the part through electromagnetic interaction — Lorentz forces in electrically conductive materials and magnetostriction in ferromagnetic (ferrous) materials — rather than coupling a wave across an interface. They require no couplant and can operate across a small air gap, but their low transduction efficiency and the resulting signal-to-noise ratio limit resolution, making them better suited to thicker sections and flaw detection than to precise thin-wall measurement [12].

- **Laser ultrasonics** is a fully non-contact, single-sided method in which a pulsed laser thermoelastically generates ultrasound in the surface, and an interferometric receiver detects it at a standoff distance. The operating principle is similar to ultrasonics, however, this method does not require a couplant like water, instead operating through the air. The limiting factor for widespread use is the poor signal-to-noise ratio created through this process. The dimensional scale of medical tubing is not compatible with this technology. It is well established for wall-thickness measurement of hot seamless steel tubes at temperatures from 800 °C to over 1000 °C (1472° to over 1832° F) in rolling-mill applications, where contact and immersion methods are not feasible [12, 13].

- **Optical coherence tomography (OCT) and low-coherence optical gauges** resolve wall thickness, inner and outer diameters, and individual layers of light-transmitting polymer tubing at micron-scale resolution, with reported accuracies in the ±0.1 μm class; they do not penetrate metals [14, 15].

- **Terahertz time-domain methods** measure wall and multilayer thicknesses in non-conductive polymers, including grades opaque to visible light, but do not penetrate metals [16].

- **Eddy current** provides non-contact thickness and flaw information for electrically conductive metals, but is sensitive to liftoff (variance in the distance to the product, due to size changes or movement) and geometry, and offers limited thin-wall accuracy [12].

- **X-ray and gamma radiometric gauges** measure opaque and pigmented tubing of essentially any material. Modern inline X-ray systems can resolve individual wall dimensions [21], whereas traditional gamma radiometric configurations often report a mean across two opposing walls rather than a single local wall. Because these methods rely on ionizing radiation, they also carry added radiation-safety, regulatory, and maintenance considerations that other techniques do not.

9. Conclusion

Ultrasonic measurement has matured from a periodic off-line manual inspection technique into a continuous in-process metrology solution that delivers real-time wall-thickness and concentricity data on polymer and metal products alike. For medical tubing manufacturers, the technology supports the tight-tolerance constructions that modern minimally invasive devices demand, with demonstrative capability down to 0.025 mm (0.001 in) for micro-polymer tubing and 0.075 mm (0.003 in) for metal, composite, and alloy tubing. Furthermore, systems can resolve multiple discrete layers simultaneously, often more reliably and easily than with off-line methods.

Beyond the physics of transducers and mechanics of sensor assemblies, the software included with modern ultrasonic platforms offers a myriad of valuable capabilities, including real-time trending and tolerance checking, SPC, closed-loop control, sorting, logging, reporting, and connectivity with the enterprise and other equipment on the line. In some cases, the platform allows for integration of other measurement devices and data streams to present a unified view of the product and the process. Connectivity to post-process measurement equipment supports traceable dimensional conformance required to meet stringent medical device standards, including ISO 13485 and ASTM F2633 [3, 10].

Looking ahead, the metrology requirements for medical tubing is poised to advance alongside ultrasonic transducer innovations. The anticipated industrial integration of Capacitive Micromachined Ultrasonic Transducers (CMUTs) [17], self-focusing high-frequency transducers capable of sub-100 μm spatial resolution [18], and directly deposited thin-film piezoelectric sensors [19, 20] promises to push measurement boundaries to even thinner walls and more complex geometries.

As medical tube production lines move toward higher speeds, smaller dimensions, and tighter tolerances, real-time wall thickness and concentricity measurements are no longer optional enhancements; they are often a precondition for cost-effective, compliant manufacturing.

About LaserLinc

LaserLinc is a privately-held U.S. manufacturer of ultrasonic and laser-based products for in-process and sample-based measurement and inspection solutions. Industries served include medical, industrial, aerospace, energy, and communications. Medical tube and device inspection, wire and cable, hose, pipe, are some of the most common applications. To learn more about LaserLinc's ultrasonic measurement capabilities and other manufacturing solutions, visit LaserLinc.com.

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