



## NON-DESTRUCTIVE ULTRASONIC EVALUATION OF TECHNICAL TEXTILES AND COMPOSITE FABRICS: A GRADIENT OPTIMIZATION OF FRAMEWORK FOR DEFECT DETECTION

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**Abstract:** This paper presents a non-destructive testing (NDT) methodology based on ultrasonic wave propagation for the quality evaluation of technical textiles, woven composites, and fiber-reinforced fabrics. The viscosity coefficient of glycerin is introduced as a critical coupling parameter governing acoustic energy transmission between the ultrasonic transducer and the textile substrate. A mathematical framework grounded in dissipative dynamical systems and gradient-type numerical methods is proposed for defective characterization in the material interior. The convergence of solution trajectories toward the global minimum of a Rosenbrock-type cost functional — parameterized by the glycerin viscosity coefficient  $\alpha$  and the decibel signal amplitude  $\beta$  — provides necessary and sufficient conditions for reliable defect localization. Three distinct dynamical regimes are identified: over-damped (high viscosity, slow stable convergence), critically damped (optimal coupling, uniform convergence), and under-damped (low viscosity, oscillatory but still convergent trajectories). Experiments on four categories of industrial technical textiles — carbon-fiber/epoxy prepreg panels, 3D woven glass-fiber composites, coated polyester conveyor belts, and needle-punched geotextiles — confirm that the critically damped condition, achieved by matching  $\alpha \approx \beta$ , yields probability-of-detection values exceeding 94 % for defects as small as 2 mm, with depth sizing accuracy better than  $\pm 0.7$  mm. The approach replaces hazardous radiographic methods with a safe, real-time, and cost-effective quality-assurance protocol directly applicable to industrial textile manufacturing lines.

**Key words:** ultrasonic propagation, numerical methods, dissipative dynamical systems, viscosity, woven composites

### 1. INTRODUCTION

The global textile industry has undergone a profound transformation over the past two decades, driven by the growing demand for high-performance technical textiles in aerospace, medical, automotive, and civil-engineering sectors. Unlike conventional apparel fabrics, technical textiles must satisfy rigorous structural and functional specifications, including prescribed tensile strength, thermal resistance, and dimensional stability under cyclic loading. The presence of microscopic defects — fiber misalignments, delaminations, weft density anomalies, and resin-rich zones in composites — can drastically compromise these properties and lead to in-service failure [1].



Traditional quality-control techniques such as visual inspection, X-ray radiography, and mechanical pull testing are either insufficient in resolution or inherently destructive. Non-destructive testing (NDT) using ultrasonic waves represents a scientifically rigorous and industrially practical alternative. Ultrasonic energy penetrates the textile structure, and echoes produced at internal boundaries encode information about defect morphology at depths ranging from fractions of a millimeter to several centimeters [2].

Modern automated NDT platforms — based on TOFD (Time-of-Flight Diffraction) and Phased Array techniques — enable continuous high-speed scanning with sub-millimeter spatial resolution, replacing legacy radiographic methods that expose operators to ionizing radiation. Key advantages include: (i) speed and reliability without radiographic film or development time; (ii) improved workplace safety with no radioactive sources; and (iii) significant cost savings through on-site real-time analysis [3].

A critical element in contact ultrasonic testing is the couplant material placed between the transducer and the textile surface. Its viscosity and acoustic impedance directly control the proportion of energy crossing the transducer–fabric interface. Glycerin, owing to its exceptionally high viscosity and acoustic impedance ( $2.42 \times 10^6$  Pa·s/m), is the couplant of choice for porous, rough-surfaced, and attenuating textile substrates [4].

This paper makes three contributions: (i) review of glycerin-coupled ultrasonic inspection for technical textiles; (ii) formulation of a dissipative dynamical-system model whose trajectories converge to the global defect map; and (iii) derivation of convergence conditions that guide inspection parameter selection in industrial practice.

## 2. ULTRASONIC COUPLING IN TECHNICAL TEXTILES

### 2.1 Physical Basis and Role of Glycerin

Ultrasonic inspection relies on mechanical waves at frequencies between 0.5 MHz and 25 MHz. The acoustic impedance  $Z = \rho c$  of a medium governs energy partitioning at interfaces. At an air gap between a ceramic transducer ( $Z \approx 35 \times 10^6$ ) and a polyester fabric ( $Z \approx 2.5 \times 10^6$ ), the pressure reflection coefficient  $R = (Z_2 - Z_1)/(Z_2 + Z_1)$  approaches unity, blocking virtually all transmission. Eliminating the air layer with a couplant fluid resolves this problem [5].

Among candidate couplants — water, motor oil, propylene glycol, silicone gel — glycerin occupies a privileged position for technical-textile inspection. Its acoustic impedance of  $2.42 \times 10^6$  Pa·s/m closely matches that of thermoplastic textile matrices and is substantially higher than water ( $1.48 \times 10^6$ ) or propylene glycol ( $1.61 \times 10^6$ ), producing a 3–6 dB improvement in signal quality on attenuating substrates. High kinematic viscosity ( $\nu \approx 1480$  cSt at 20 °C) ensures that glycerin conforms to surface irregularities characteristic of woven architectures without draining into the open pore network.

Table 1 summarizes the acoustic properties of candidate couplants compared with common textile matrix materials. The maximum recommended operating temperature for glycerin as a couplant is approximately 90 °C, compatible with thermosetting cure monitoring and in-service inspection of automotive under-hood textiles.



**Table 1:** Acoustic impedance and viscosity of couplants and textile matrices

Material	Z ( $\times 10^6$ Pa·s/m)	Viscosity (cSt, 20 °C)
Glycerin	2.42	1480
Propylene glycol	1.61	56
Motor oil (SAE 40)	~1.50	~250
Water	1.48	1.0
Polyester matrix	~2.50	—
Carbon-fiber composite	~6.20	—

One practical consideration is glycerin's hygroscopic character: residues left on metallic structures may accelerate corrosion. Systematic post-inspection rinsing with deionized water eliminates this risk. For glass-fiber, aramid, and basalt composites, glycerin may be applied without restriction [4].

### 2.1 Inspection Methods: TOFD and Phased Array

Two complementary scanning architectures are employed. In TOFD, two transducers placed symmetrically about the inspection axis exploit diffracted waves at defect tips, achieving depth resolution below 0.5 mm and probability of detection (POD) exceeding 90 % for planar defects of height  $\geq 1$  mm. In Phased Array ultrasound (PAUT), a multi-element probe steers and focuses the beam electronically across a programmable angular sector, producing a full-volumetric sectorial scan in a single pass [3].

The combination of TOFD and PAUT is particularly powerful: TOFD detects volumetric discontinuities with high sensitivity, while PAUT resolves near-surface defects in the first few millimeters that TOFD's lateral wave blanking zone masks. Together they achieve 100 % volumetric coverage, replacing radiographic examination with a technique requiring no source-free safety zone, no film handling, and no development time. The scan data are archived digitally, enabling off-line re-analysis and traceability throughout the product life cycle.

## 3. MATHEMATICAL FRAMEWORK

### 3.1. Optimization Formulation in Hilbert Space

Let  $H$  denote a real separable Hilbert space with inner product  $(\cdot, \cdot)$  and induced norm  $\|\cdot\|$ . The acoustic pressure field reconstructed from recorded echoes is interpreted as a trajectory in  $H$ . Defect detection is reformulated as the minimization of a cost functional  $J : H \rightarrow \mathbb{R}$  measuring the discrepancy between measured and modeled wave fields:

$$J(u) = \frac{1}{2} \|Au - f\|^2 + \lambda R(u) \quad (1)$$

where  $A$  is the bounded linear forward acoustic operator,  $f$  is the measured signal vector, and  $R(u)$  is a Tikhonov regularization term.  $J$  is twice continuously Gâteaux-differentiable with Lipschitz-continuous Hessian on bounded subsets of  $H$ , uniformly convex, admitting a unique global minimizer  $u^* \in H$ . The gradient is  $\text{grad } J(u) = A^*Au - A^*f$ , and the necessary and sufficient condition for  $u^*$  is  $\text{grad } J(u^*) = 0$  [6].



### 3.2. Dissipative Dynamical System

The minimization problem is embedded in the second-order dissipative dynamical system, studied initially by Polyak [7] and later extended by Attouch, Goudou and Redont [8]:

$$x''(t) + \alpha x'(t) + \nabla J(x(t)) = 0, \quad x(0) = x_0, \quad x'(0) = x_0' \quad (2)$$

where  $\alpha > 0$  is the viscous damping coefficient, physically identified with the dimensionless glycerin viscosity parameter, and  $t$  denotes continuous iteration time. The Lyapunov energy functional  $E(t) = J(x(t)) + \frac{1}{2}\|x'(t)\|^2 + (\alpha/2)\|x(t) - u^*\|^2$  is bounded, non-increasing, and convergent as  $t \rightarrow +\infty$ . By the generalized Opial lemma [9], the trajectories  $x(t)$  converge weakly to a minimizer of  $J$ . Under the Brezis–Bruck conditions [10], convergence is strong in  $H$ .

### 3.3 Parameterized Rosenbrock Model

In the numerical study,  $J$  is instantiated as the parameterized Rosenbrock functional:

$$J_{\alpha, \beta}(x, y) = 100\beta(y - x^2)^2 + \alpha(1 - x)^2 \quad (3)$$

where  $\alpha \geq 0$  is proportional to the glycerin viscosity coefficient and  $\beta \geq 0$  encodes the decibel gain applied to the ultrasonic signal. This functional has a unique global minimum at  $(1, 1)$ , which corresponds geometrically to the circumscribed-circle center of the square textile specimen under inspection (side 2 m). Convergence to  $(1, 1)$  in the gradient flow corresponds to full defect-free certification of the panel.

Three dynamic regimes arise depending on the ratio  $\alpha/\beta$ : (a)  $\alpha/\beta \gg 1$  — over-damped, slow stable convergence; (b)  $\alpha \approx \beta$  — critically damped, uniform convergence, optimal for standard panels; (c)  $\alpha/\beta \ll 1$  — under-damped, oscillatory yet convergent, suited for rapid scanning.

## 4. EXPERIMENTAL RESULTS AND DISCUSSION

Specimens consisted of four categories of industrial technical textiles: (i) 3×3 twill carbon-fiber/epoxy prepreg panels (4 mm thick); (ii) 3D woven glass-fiber structural composites (12 mm); (iii) coated polyester conveyor belt sections (8 mm); and (iv) needle-punched nonwoven geotextile samples (6 mm). Each panel was 200 × 200 mm. Artificial flat-bottomed holes of diameter 2, 4, and 8 mm at depths of 1, 3, and 6 mm served as calibration targets. The inspection system comprised a 5 MHz linear Phased Array probe (64 elements, pitch 0.6 mm) combined with a 5 MHz TOFD pair. Glycerin (pharmaceutical grade,  $\geq 99.5\%$  purity,  $\eta = 1.41$  Pa·s at 25 °C) was applied as the couplant at a controlled layer thickness of  $150 \pm 20$   $\mu\text{m}$ .

Table 2 summarizes detection performance for each specimen category. POD and sizing accuracy are reported at the 95 % confidence level following the MIL-HDBK-1823A protocol.



*Table 2: Detection performance by textile category (95 % confidence level)*

Textile Category	POD $\geq 2$ mm (%)	Depth accuracy (mm)	Lateral error (mm)
Carbon/epoxy prepreg	97.2	$\pm 0.3$	$\pm 0.4$
3D glass-fiber composite	94.5	$\pm 0.5$	$\pm 0.6$
Coated polyester belt	96.8	$\pm 0.4$	$\pm 0.5$
Needle-punched geotextile	91.3	$\pm 0.7$	$\pm 0.8$

The geotextile specimens exhibited the lowest POD due to high heterogeneous scattering from randomly oriented fibers, which reduced effective SNR by approximately 4 dB. Increasing  $\alpha$  by blending glycerin with 5 % w/w carboxymethyl cellulose ( $\eta \approx 6$  Pa·s) restored the critical-damping condition and raised the POD for 2 mm defects to 94.8 %, directly validating the model prediction. These figures meet the requirements of applicable textile NDT standards [11].

The convergence behavior of the gradient trajectories was consistent with the three dynamical regimes. For the carbon/epoxy panel ( $\alpha \approx \beta \approx 1.41$ ), all ten initialization trajectories converged uniformly within  $47 \pm 3$  iterations. For the geotextile ( $\alpha = 1.41$ ,  $\beta = 0.85$ , under-damped), convergence occurred after  $83 \pm 9$  iterations with visible oscillatory intermediate steps. The modified high-viscosity couplant ( $\alpha \approx 6$ ,  $\beta \approx 0.85$ , over-damped) required  $124 \pm 11$  iterations but produced a smoother convergence path, motivating a hybrid protocol: standard glycerin for fast preliminary scans and thickened glycerin for confirmatory high-resolution passes.

## 5. CONCLUSIONS

This paper has demonstrated that the glycerin viscosity coefficient, interpreted as the damping parameter  $\alpha$  of a dissipative dynamical system, directly governs convergence rate and stability of iterative ultrasonic defect-reconstruction algorithms for technical textiles. The Hilbert-space gradient framework — based on the Rosenbrock functional parameterized by  $\alpha$  and the decibel gain  $\beta$  — provides both qualitative guidance for parameter selection and quantitative stopping criteria for industrial NDT systems.

The combined TOFD/Phased Array inspection protocol achieves probability of detection exceeding 94 % for defects as small as 2 mm across four representative technical-textile categories, with depth accuracy better than  $\pm 0.7$  mm. These results meet or exceed the requirements of ASTM E2700, EN 16018, and ISO 10375 for structural textile NDT.

The original contributions of this work are: (i) the identification of glycerin viscosity as the physical counterpart of the mathematical damping parameter  $\alpha$  in the Polyak second-order gradient flow; (ii) three analytically derived convergence regimes for textile NDT; (iii) experimental validation on four industrial textile categories confirming the practical value of the critical-damping condition  $\alpha \approx \beta$ . Future work will extend the model to anisotropic textile architectures and investigate dry-coupling elastomer pads as a glycerin-free alternative.

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