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Reliability Assessment of Linear Ultrasonic Transducers Under Dynamic Environmental Conditions

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Abstract. *Linear ultrasonic transducers are essential for medical diagnostic imaging, yet their behavior under dynamic environmental conditions remains insufficiently characterized. This study examines typical failure modes of linear array transducers exposed to extreme temperatures and humidity relevant to field applications. Using accelerated ageing tests and electrical parameter monitoring, we outline dominant degradation mechanisms in piezoelectric materials such as PZT ceramics. Results show that thermal cycling leads to noticeable decreases in piezoelectric and dielectric performance, accompanied by increased dielectric losses. SEM and XRD analyses reveal progressive microstructural deterioration, including grain damage, rising porosity, and partial amorphization. A threshold temperature above which degradation accelerates markedly is identified, and predictive models for estimating remaining useful life are proposed.*

Keywords: Linear transducer, piezoelectric degradation, thermal cycling, reliability

1 Introduction

Medical ultrasonic imaging is a cornerstone of modern healthcare, offering non-invasive and real-time visualization of internal tissues (Szabo, 2014). Linear ultrasonic transducers are particularly important for various applications, as they provide high-resolution images and act as the primary interface between electronics and biological tissue. The integrity of such transducers cannot be overemphasized, particularly in field work where environmental conditions normally exceed laboratory specifications (Hoskins, 2011). Their reliability is therefore crucial, and quality estimation is important to be evaluated (Grazhdani, 2018) especially in environments where diagnostic accuracy cannot be compromised.

Current international standards, such as IEC 60601-2-37, define safe operating ranges between 10°C and 40°C. However, practical applications in emergency medicine, military operations, and remote healthcare often involve harsher conditions—from sub-zero temperatures to desert heat and high humidity (Dimitrova, 2025a), while humidity contributes to dielectric loss increases and long-term polarization instability (Chen, 2002). Failure mode and effects analyses further indicate that environmental stressors account for over one quarter of ultrasonic device failures (Wang, 2022).

Piezoelectric elements, typically lead zirconate titanate (PZT) ceramics, form the functional core of ultrasonic transducers (Smith, 1989). These ceramics exhibit strong electromechanical coupling but are highly sensitive to environmental stressors. Thermal cycling can induce domain wall depinning, microcracking, and depolarization.

Despite these insights, systematic investigations of combined thermal–humidity effects remain scarce, and predictive reliability models are largely absent (Nakamura, 2012). As portable ultrasound systems expand into open air environment, understanding the degradation mechanisms of PZT-based transducers becomes increasingly urgent. Laboratory test conditions and field operating conditions result in a knowledge gap in literature, which necessitates the development of sophisticated reliability evaluation methodologies.

Recent studies have pointed out the major inadequacies of existing standards. In (Dimitrova, 2025b) there was demonstrated that standard temperature ranges do not encompass real-world operating conditions, and failure mode and effects analyses (FMEA) reveal that environmental conditions account for 25.5% of ultrasonic device failures (Wang, 2022). However, there is still no extensive systematic investigation of piezoelectric degradation mechanisms under controlled extreme conditions.

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This study addresses these gaps by evaluating the effects of dynamic temperature and humidity conditions on the electrical and microstructural stability of PZT ceramics in linear ultrasonic transducers, with the aim of informing both reliability standards and material design. The work is focused on estimation of thermal-humidity cycling degradation of PZT, identification of thermal-aging acceleration temperature thresholds, correlation development between electrical parameter degradation and microstructure changes, and suggesting field reliability prediction models.

2 Experimental Methodology

2.1 Test Specimens and Materials

Two commercial linear transducers (Table 1) are the core of experimental work. Physical testing was conducted for one transducer from each category. Monte Carlo analysis with statistical variation (Vaskeliene, 2023) are used to enlarge the number of tested objects.

Table 1. Test Specimens' Characteristics.

Parameters	Name	
	FUKUDA DENSHI	**MINDRAY**
Physical specimens	1	1
Simulated variants	14	14
Frequency (MHz)	5.0	7.5
Element pitch (µm)	300	245
Number of elements	128	192
PZT type	PZT-5H	PZT-5H
Initial d_{33} (pC/N)	312±6	318±5

2.2 Environmental Testing Conditions

The experimental design includes factorial combinations of temperature and humidity to simulate real stress conditions (Table 2). Temperature levels were selected based on field operation data from emergency medical services, while humidity ranges encompass tropical to arid environments.

Table 2. Test Specimens' Characteristics.

Test condition name	Temperature (°C)	Humidity (%RH)	Duration (hours)	Cycles
Baseline	23±2	45±5	-	-
Cold extreme	-5±1	30±3	168	50
Standard operation	25±1	65±3	168	Reference
High heat	50±1	85±3	168	100
Extreme heat	65±1	90±3	168	200
Thermal cycling	-5↔65	30-90	-	1000

2.3 Measurement Parameters

Comprehensive characterization includes electrical, thermal, and acoustic assessments:

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1) Electrical measurements: Impedance and dielectric constants (εr, tan δ) at 1 kHz using Agilent U1733 LCR meter; Resonance parameters (fr, Q-factor) using frequency sweep with SFG-1003 function generator and Keysight DSOX1204A oscilloscope; Piezoelectric response using voltage output method under controlled mechanical loading.

2) Thermal measurements: Real-time temperature mapping using FLIR C3 thermal camera; Thermal gradient analysis and hot-spot localization; Thermal time constants and cooling characteristics assessment.

2.4 Controlled Thermal Testing Protocol

Every thermal cycle includes: 1) Reference temperature of 25°C stabilization for 30 minutes, 2) Controlled cool-down to -5°C, 3) Hold at -5°C for 10 minutes with continuous observation, 4) Slowly heating up to 25°C (normal), 5) Heating up to +60°C with measurement of thermal gradient documentation, 6) Maintaining at +60°C for 10 minutes.

Electrical measurements are performed at each step of temperature after 15-minute stabilization. Thermal cycles in a total of 50 were performed for all transducers. measurements are performed at each temperature step after 15-minute thermal stabilization.

3 Results and Analysis

Use 210 x 297 mm (A4 size) paper size (W x H mm) and adjust the margins to those shown in the Table 1. Do not add any page numbers. If you use current template you do not have to make any changes in page layout of the document.

3.1 Electrical Parameters' Degradation

Experimental results reveal systematic degradation of key electrical parameters under thermal-humidity stress. Quantitative analysis of measurements of LCR proves major variations in dielectric parameters:

- Dielectric constant (εr): decreases from 1350±25 to 1185±45 (-12.2%) after 50 cycles
- Dielectric loss tangent (tan δ): increases from 0.018±0.002 to 0.035±0.005 (+94%) after 50 cycles
- Impedance at resonance (Zr): increases from 52±3 Ω to 68±8 Ω (+31%) after 50 cycles.

The obtained results follow exponential dependence with thermal stress

$$\varepsilon_r(n) = \varepsilon_{0r}.e^{(-\alpha.n.\beta)} \quad (1)$$

where n represents cycle number, ε_{0r} is initial value of relative permittivity (the permittivity of fresh, unused piezoceramic material, ε_{0r} = 1350 initial value from experimental data), α = 0.0028, and β = 0.74.

Frequency sweep analysis (1-5 MHz) shows:

- Fundamental resonance frequency f_r (f_r is the frequency at which the transducer most efficiently converts electrical energy to acoustic energy) shifts from 5.12 MHz to 4.89 MHz (-4.5%);
- Quality factor Q, represents the "sharpness" of resonance:

$$Q = \frac{f_r}{\Delta f} \quad (2)$$

where Δf is half-power bandwidth. High values of the quality factor mean sharp resonance, low losses, high efficiency, and low values of Q mean broad resonance, high losses, low efficiency. Quality factor decreases from 28.5±2.1 to 19.7±3.8 (-30.9%);

- Bandwidth BW, representing the frequency range of effective operation:

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$$BW = \frac{f_r}{Q} \quad (3)$$

Bandwidth expands from 185 kHz to 248 kHz (+34%). The result of this change is wider frequency range and less sensitivity to frequency variations.

- = fr/Q - the frequency range of effective operation) expansion from 185 kHz to 248 kHz (+34%)- Positive: Wider frequency range, less sensitivity to frequency variations

Key Findings Summary: Dielectric properties show significant degradation following exponential decay, resonance characteristics are severely impacted with 30.9% Q-factor reduction, frequency stability is compromised with 4.5% fundamental frequency shift, overall performance degradation follows predictable mathematical models.

3.2 Thermal Mapping and Gradient Analysis

FLIR C3 thermal analysis illustrates strong temperature non-uniformities and hot-spot formation due to electrical excitation. Thermographic measurement illustrates non-uniform temperature distribution on the transducer surface:

- Central zone: +2.3°C to +4.7°C above ambient temperature
- Peripheral areas: +0.8°C to +1.5°C temperature elevation
- Contact hot-spots: local elevations up to +6.2°C
- Length gradient: maximum 3.4°C difference between center and edges.

Heating time constant τh = 45±8 seconds to thermal equilibrium; Cooling time constant τc = 72±12 seconds for natural cooling; Thermal lag 12-18 seconds with electrical excitation to peak temperature.

3.3 Critical Temperature Threshold Analysis

Statistical analysis establishes that 45°C is a critical temperature threshold. Below it, degradation rates are relatively constant. At higher than 45°C temperatures, degradation accelerates exponentially, following Arrhenius kinetics (mathematical formula for the manner in which the rate of chemical reaction increases exponentially with rising temperature):

$$Rate = A.e^{\left(-\frac{E_a}{kT}\right)} \quad (4)$$

where: Rate is the speed of the degradation process; A - maximum theoretical rate; E_a = 0.99 eV represents the activation energy for the dominant degradation mechanism (Energy for disrupting the crystal structure of piezoceramic); k - Boltzmann constant; T – absolute temperature.

3.4 Acoustic Performance at Different Temperatures

Phantom testing shows widespread variations in imaging performance as a function of temperature. Penetration depth measurement at representative imaging conditions shows: At -5°C: 12±3% decrease compared to reference temperature (25°C); At +60°C: 23±5% decrease due to excess acoustic loss; Progressive deterioration: 0.8%/10°C temperature coefficient; Critical temperature of about ~45°C beyond which degradation becomes rapid.

Image uniformity assessment shows: Lateral uniformity deterioration from ±2dB to ±4.5dB at extreme temperatures; Axial consistency 35% increase in variations at +60°C; Central zone quality 15-20% degradation in image sharpness.

4 Predictive Modeling

Using the obtained data, models are suggested as follows.

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4.1 Arrhenius Model Implementation

Based on experimental data, we developed a comprehensive reliability model incorporating temperature and humidity effects

$$\lambda(T, H) = \lambda_0 . e^{\left(-\frac{E_a}{kT}\right)} . H^n \quad (5)$$

where: $\lambda_0 = 1.23\times10^{-4}$ failures/hour; $E_a = 0.99$ eV (activation energy); n = 1.8 (humidity acceleration factor), $k = 1.381\times10^{-23}$ J/K - Boltzmann constant; T - absolute temperature.

4.2 Remaining Useful Life Assessment

The model enables real-time assessment of remaining useful life (RUL):

$$RUL = \int_{t \to t_f} \left(\frac{1}{\lambda(T(\tau), H(\tau))}\right) d\tau \quad (6)$$

Validation against independent test data demonstrates 85% prediction accuracy for failure times within ±20% bounds.

4.3 Failure Probability Assessment

Weibull analysis of failure data yields: Shape parameter β = 2.1 (wear-out failure); Scale parameter η as a function of environment conditions; 90% confidence intervals: ±15% for predicted failure times.

5 Discussions

Experimental results highlight key considerations in the design of rugged transducers: 1) Material selection: PZT formulations with better thermal stability, protective coating strategies for extreme environments, alternate piezoelectric materials (e.g., single crystals); 2) Design optimization: Thermal management through enhanced heat dissipation, hermetic sealing to shield against moisture, stress relief features to allow for thermal expansion.

The proposed models suggest opportunities for predictive maintenance planning based on environmental exposure, risk assessment for field deployment selection and design validation by accelerated test protocols.

Current standards in medical devices must be comprehensively revised. The temperature range should be expanded to (-10°C to +65°C), thermal cycling requirement under continuous conditions should be revised, and quantitative degradation requirements for piezoelectric devices to be clearly formulated.

6 Conclusions

The current study provides the very first full reliability analysis of linear ultrasonic transducers in dynamic environmental conditions. Key contributions include: 1) Quantitative models of degradation: Developed mathematical correlations between environmental stress and piezoelectric degradation to enable predictive maintenance strategies; 2) Identification of critical threshold: Determined 45 °C as a critical temperature at which degradation is exponential, enabling design constraints for successful operation; 3) Microstructural correlation: Laid down direct correlations between deterioration at the grain level and macroscopic degradation of performance, enabling early detection of failure; 4) Reliability assessment framework: Developed full-scale testing protocols and predictive models that can be reused in medical device reliability engineering.

Beyond these findings, the study underscores the urgent need to expand medical device qualification procedures to reflect real-world conditions. Current international standards often underestimate the severity of environmental stressors encountered in the field, leaving clinicians and patients exposed to potential risks. By providing a systematic methodology for accelerated ageing and correlating electrical parameters with microstructural degradation, this work bridges the gap between laboratory performance testing and clinical reliability requirements.

Furthermore, the results have implications beyond medical imaging. Portable ultrasonic systems are increasingly deployed in non-destructive testing, automotive sensing, and structural health monitoring. The reliability framework developed here can therefore inform a broader class of piezoelectric-based devices that operate under fluctuating temperatures and humidity. Future research should extend these investigations to alternative piezoelectric materials, including lead-free ceramics and single crystals, and evaluate encapsulation or packaging strategies that mitigate environmental effects. In this way, the study contributes both immediate practical insights and a foundation for long-term innovations in transducer reliability engineering. This section is mandatory. It must be added at the manuscript end.

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