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# Non-Stationary Thermal Wave Imaging for Osteoporosis Detection

**Badugu Suresh,**

Koneru Lakshmaiah Education Foundation, Vadedeswram, Guntur, AP, India,

Pin code:522302. suresh.nitr@gmail.com

**Abstract.**

Osteoporosis, a skeletal disorder resulting from a decrease in bone density, compromises bone strength and increases the susceptibility to fractures. Accurate diagnosis is imperative to identify individuals at risk of future bone fractures. Among the various non-destructive testing methods available, quadratic frequency modulated thermal wave imaging has recently emerged as a preferred choice due to its enhanced depth probing capabilities at lower frequencies compared to its linear counterpart. While this diagnostic approach is valuable, it does not provide direct bone density values. Therefore, a suitable post-processing technique becomes essential for accurate bone density estimation. In this study, an orthogonal kernel-based random projection post-processing technique is applied to the thermal response data to determine bone density. The resulting random projection coefficients are plotted against density, revealing a polynomial relationship that serves as the basis for osteoporosis detection.

**Keywords:** Quadratic frequency modulated thermal wave imaging; Orthonormal projection; Pulse compression; Hilbert Phase and Signal to noise ratio.

## 1.Introduction

Osteoporosis is the typical bone disorder occurs in most of the people with low calcium intake, eating disorders and gastrointestinal surgery and causes the loss of bone density, early bone loss which subsequently increases the risk of fractures. To prevent the risk of fracture with this osteoporosis a suitable diagnosing system is necessary, for this infrared non-destructive testing (IRNDT) makes an easy way due to its non-contact, whole field and non-destructive method of evaluation[1]. It uses the infrared spectrum to identify the in homogeneities present in the material, in which a temperature variation over the tested object

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surface is recorded using an infrared camera. In active thermography the test object surface is excited by an external predefined stimulus, the incident optical energy initiates thermal waves very nearer to the surface due to diffusion process, generated thermal waves travel to back end of the object. In this process the object dissipates energy to the surroundings and to reach equilibrium. The total temporal and thermal response of the object is captured by infrared camera. Among various available IRNDT methods pulse thermography (PT) and continuous wave thermography are popular; in PT[2,3] a short time high peak power stimulations are used further the thermal response is recorded by camera. But the captured thermograms are affected by non-uniform heating of object surface and usage of large power stimulus limits its usage. In contrast to PT in continuous modulated thermography uses low power periodic stimulations[4] and the captured thermal data is analysed by phase-based method due to less sensitive to non-uniform heating problems but it is limited due to depth resolution capability because of its single frequency analysis.

To overcome above two limitations R. Mulaveesala introduced non stationary thermal wave imaging methods[5-12], in these non-stationary imaging methods uses a low power suitable band of frequency stimulus is employed to energize the test object in a single experimentation cycle. Linear frequency modulated thermal wave imaging[5] (LFMTWI) uses a chirp like stimulation where as in digitized linear frequency modulated thermal wave imaging (DLFMTWI) uses a digitized version of LFMTWI by probing more harmonics compared to its analog version. It gives a better depth resolution than LFM. The recently introduced Quadratic frequency modulated thermal wave imaging[6] (QFMTWI) is attracted with the support of depth probing capability at low frequencies than its linear counterpart.

An orthonormal kernel based post processing[10] is adopted to determine the bone density variations with respect to the random projected coefficients. Further this is validated by conducting experiment over a simulated bone sample using QFMTWI and results of various post processing techniques are compared by means of detection and signal to noise ratio.

## 2.Methodology

In IRNDT the test object is energized by a modulated stimulus, this incident energy initiates thermal waves nearer to the surface which will further propagate into interiors of the object in order to reach equilibrium. The anomalies present in the object gives an abnormal behaviour

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to conduction process; it results in a temperature contrast over the surface at defect location compared to non-defective region. This total temporal thermal response recorded by infrared camera and anomalies are extracted by processing the captured temperature history.

In the captured data, thermal history is embedded with the experimental noise, non-uniform radiation and non-uniform emissivity which hides the defect signature. In order to extract fine defect details, various signal processing methods are used. Prior to the application of processing methods the captured thermal data is necessary to remove a response corresponding to DC offset[12] in excitation to get dynamic responses according to proposed excitation using a linear fitting procedure[13].

### 2.1 Phase Analysis

It is a frequency domain method, employing fast Fourier transform (FFT) for frequency unscrambling. Fast Fourier transform[14,15] applied over mean removed thermal profile of each pixel and phase values to each frequency component is calculated, phase images are formed by arranging phase values of corresponding frequency component into its respective pixel position. The constructed phase images exhibits phase contrast due to phase delay contributed from thermal waves of anomalies at different depths. The frequency corresponding to the phase image exhibiting the defects can be determined by

$$f = \frac{F_s n}{N}$$

$F_s$=Sampling frequency or Capturing rate

N=Total number of the samples in thermal profile

n=Number of the phase image

### 2.2 Hilbert phase

It is a multi-transform method, in which a reference profile is selected from pixel's profile, further Hilbert transform[16,17] has applied over it next fast Fourier transform has been employed over remaining pixel profiles and complex conjugate of it is calculated. Then inverse FFT is calculated over multiplication of referenced Hilbert transform profile and calculated complex conjugate profiles.

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$$Q_1 = IFFT\left[\{FFT\left(Hilb(T_r)\right)\}*\{FFT(T)\}\right]$$

In the next stage ordinary cross correlation between reference thermal profile and temporal thermal profiles of all the pixels in view has been obtained as given as

$$Q_2 = IFFT\left[\{FFT\left(T_r\right)\}*\{FFT(T)\}\right]$$

Finally the time domain phase will be obtained using

$$\theta = \tan^{-1}\left(\frac{Q_1}{Q_2}\right)$$

Time domain phase images are formed by arranging above phase values in to their respective locations.

**2.3 Pulse Compression**

Pulse compression[1]is a time domain analysis, it uses group delay in the thermal profile to discriminate defective and non-defective regions. In the first stage a mean removed thermal profile is selected as a reference profile from the region of non-defective pixels. Cross correlation has been carried out between reference profile and to the remaining pixel profiles results in a data of normalized correlation coefficient sequence, further correlation images are formed by arranging the resultant coefficient sequence. Delayed instants are kept in to their respective spatial location. The correlation images exhibits correlation contrast due to the dependency on delay and attenuation of the defective profiles.

**3.Results and Discussion**

In order to validate the proposed methodology experimentation has carried out over bone sample of 240mmX55mmX4mm size consisting of skin, muscle and fat layers each with a thickness of 0.5mm covering a bone layer of 2.5mm thickness with 7 different density variations simulated as artificial anomalies shown in fig.1.and their thermal properties are presented in table 1. The skin side of the sample is excited by a 2KW, quadratic modulated heat flux for 100 seconds. Corresponding thermal response is recorded at 25 frames per second using FLIR camera as shown in the experimental set up fig.1. b.

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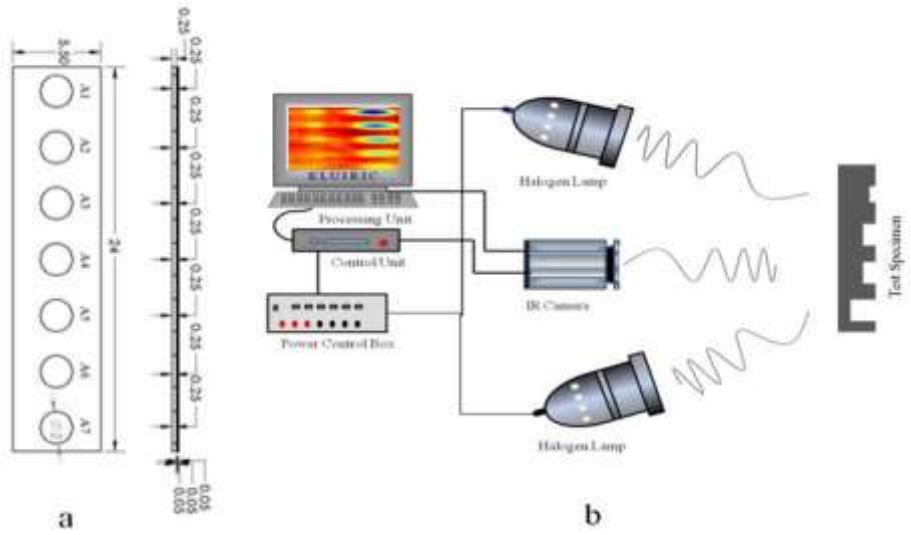


Fig.1.a. Sample layout (all dimensions are in cm) and b. Experimental setup for active thermography

Table 1 Thermal properties of Bone sample

| Region | Density | Thermal Conductivity | Specific heat |
|---|---|---|---|
| Bone | 2420 | 0.616 | 1430 |
| A1 | 148 | 0.25 | 1200 |
| A2 | 1908 | 0.32 | 1313 |
| A3 | 1200 | 0.34 | 1000 |
| A4 | 1980 | 0.504 | 1170 |
| A5 | 2090 | 0.532 | 1235 |
| A6 | 2200 | 0.560 | 1300 |
| A7 | 2310 | 0.588 | 1365 |
| Muscle | 1090 | 0.49 | 3421 |
| Fat | 911 | 0.21 | 2348 |
| Skin | 1109 | 0.37 | 3391 |

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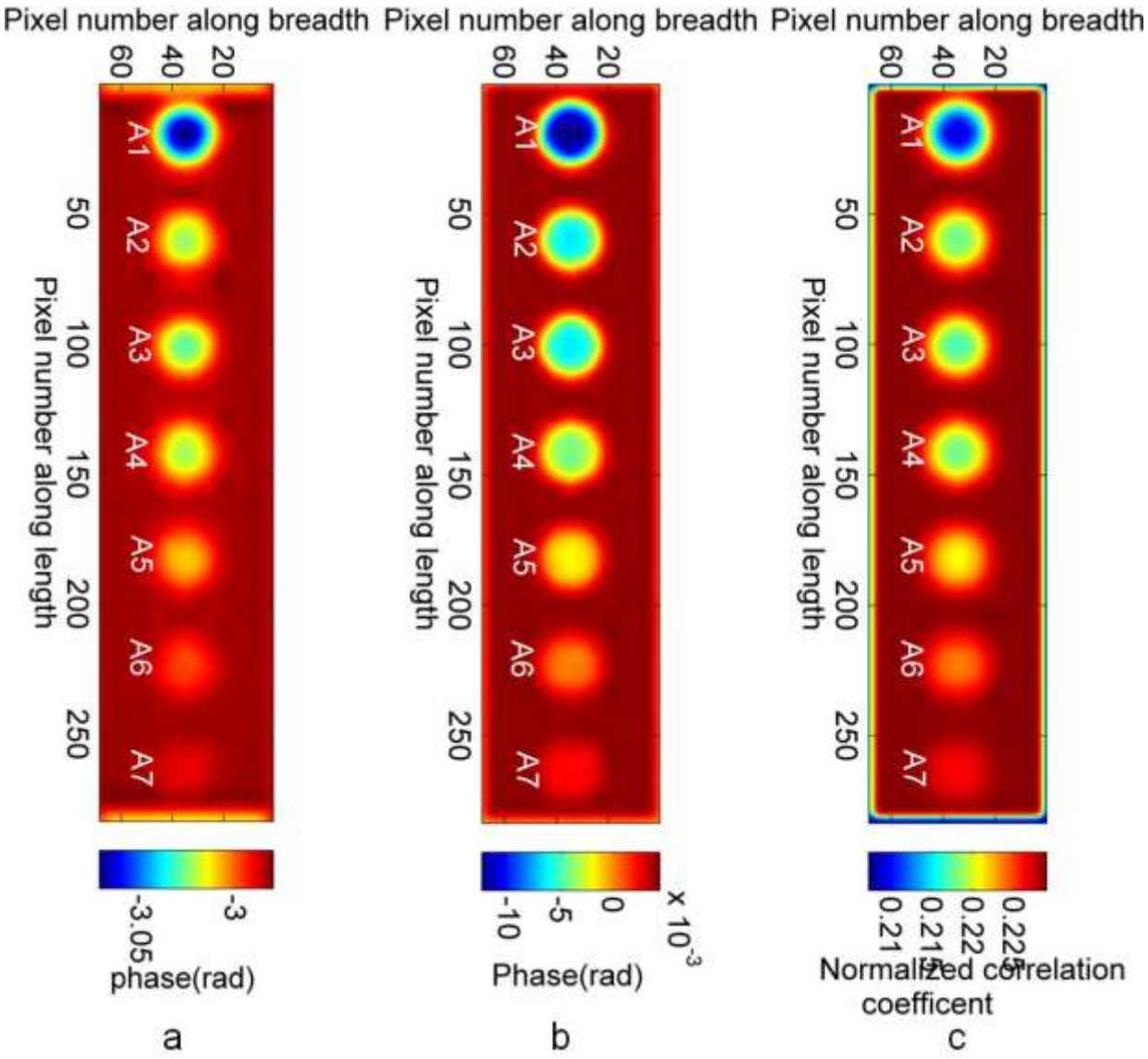


Fig.2. a. Phase image at 0.02Hz b. Hilbert phase image 16.5s c. Correlation image at 4.5s and

To extract fine subsurface defect details, captured thermal data has processed by phase, correlation, Hilbert phase and orthonormal projection transform methods. fig 2.a&b are the phase images obtained at 0.02 Hz and 16.5 s using FFT and HT based transforms respectively exhibits defect details of larger diameter only whereas in fig 2.c pulse compression images gives better details of smaller and deeper defects also due to its concentration of energy and noise minimization property.From fig.2it clearly shows the depth resolution capability of QFMTWI supported by orthonormal random projections.

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The detectability of these processing methods was compared using signal-to-noise ratios[24,25] (SNR) of the defects computed from below equation.

$$SNR=20\log\left(\frac{\text{mean of the defective area-mean of non defective area}}{\text{standard deviation of the non defective area}}\right)dB$$

## 4. Conclusions

This work uses quadratic frequency modulated thermal wave imaging to showcase the capability of the random projection-based post processing technique for simulated bone sample. The orthonormal based projection coefficients are used to discriminate the bone density variations and further characterize the edge of osteoporosis. A polynomial plot between the relative densities of bone with respect to random projection coefficients gives the severity of osteoporosis. Further SNRs are calculated to validate the random projection-based technique by comparing with the contemporary techniques.

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