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Infrared Non- Destructive Testing Using Image Processing: A Survey

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Abstract: Non-destructive Testing (NDT) is a wide clump of analysis techniques. These techniques are used in industries and sciences to calculate and guesstimate the properties of material, substance or a system without damaging it. NDT is highly valuable technique as it does not enduringly change the substance being scrutinized and hence can save the money and time in product evaluation, troubleshooting and research. Infrared and Thermal testing is one of the many Non-destructive Testing techniques provided by the American Society for Non-destructive Testing (ASNT). This paper has concentrated the study towards Infrared Thermography which is the science of measuring and mapping surface temperature. It has proven to be an effective, expedient, and economical method of testing.

Keywords: NDT, TNDT, Image processing techniques, image processing approaches, IRNDT

I INTRODUCTION

Non-Destructive Testing implies to estimation methods for inspecting an article, material or system without altering its rudimentary properties and affecting its future usefulness. Thermography Non-destructive Testing (TNDT) refers to a non-contact inspection tool which custom the heat emitted by objects to swiftly inspect the surface and detect internal voids, cracks, delamination's and discontinuities inside the object or in material.

An Object with internal thermal equilibrium has no net heat flow throughout its volume. Once an object surface is bring in contact to thermal excitations results in manifestation of thermal front on surface which proliferates within the material until it reaches material internal defects. If a thermal excitation is smeared evenly over the surface of object, heat will flow in only one direction which is perpendicular to the surface and toward the interior of the material. However, if the object is homogeneous in nature, the material supposes to cool evenly after the application of thermal excitation. But due to interaction of heat diffusion amid regions having dissimilar thermal properties will results in different behaviours of the temperature decay during the cooling progression. This diverse and dissimilar temperature decay behaviours can be observed with an infrared camera. If the artefact slows heat movement, for example in case of insulating anomaly, the spot will appear warmer than the surrounding which implies that the warm spot is cooling down more sluggishly as compared to surrounding area. On the other hand, if anomaly is more conductive, heat will flow in the anomaly faster as compared to surrounding area which creates cooler spot on the surface. The greater the thermal disparity, the greater will be the surface temperature difference which can be observed over the area causing the disruption.

The inspection approach has numerous advantages which makes it outstanding are its swiftness and easiness, its ability to use it on several types of materials (example: composites, metals and polymers), its non-contact measurement, it can quickly inspect comparatively large area, it can measure moving or rotating objects, security of personnel since there is no detrimental radiation involved, wide span of application, results are easy to interpret since they are obtained in image format. Difficulties to Infrared thermography are Effects of thermal loses which produce fake contrast affecting the reliability of the interpretation, cost of equipment, emissivity problem. A limiting factor of thermography is the use of heat conduction to probe the structure. Heat conduction is a diffusion process which infers that the deeper the heat diffuses into the body the weaker it gets. Moreover there is a relationship between the depth and diameter of an anomaly. A large anomaly near to the surface will create a larger temperature variation then a smaller anomaly. Generally the diameter to depth ration should be equal to or greater than 1.

On the top of it, the signals acquired with the infrared camera are usually contaminated with noise from emissivity variation, reflections and non –uniform heating caused during the application of external thermal excitation. The non-uniform heating is the most harmful and unavoidable problem. However, most of the problems that arise due to application of non-uniform heating can be eliminated to some extend through the application of processing techniques on the temperature signatures obtained with the infrared camera. Image processing techniques are used to enhance image contrast and also the visibility of voids defects or cracks in material.

Most of the processing techniques transform the temporal data to some different domain for the simplification of data analysis and obtaining a new variable which may mend the defect detection. The defect detection capability of this new variable is more effective to those that are more sensitive to the effects of lateral heat diffusion.

II LITERATURE SURVEY

Roy et al. [1] had investigates the energy absorption efficiency and signal-to-noise ratio of photo thermal lock-in experiment setup. The LED was used as an excitation source instead of usually used higher power (of kilowatts range) halogen lamps for lock-in experiment. The LED excitation makes the setup much more energy efficient because of low power consumption. As compared to halogen lamps LED has low IR contents which is an advantage as IR contact cause unpredictable changes to phase image in lock-in thermography due to its reflection in IR camera. Moreover the IR contents in LED increase linearly thus it don't affect the phase image of lock-in thermography.

The use of a LED lamp as a photo thermal source instead of halogen lamps improves the defect detection capability for lock-in thermography. F.Lopez et al. [2] presented in−depth analysis of three of the most popular techniques for processing Pulse thermographic images: differential absolute contrast, pulsed phase thermography and thermographic signal reconstruction and also reviewed the fundamental concepts of these techniques and analysed their application on thermal data obtained from the Pulsed thermographic inspection on a carbon fiber reinforced specimen. Furthermore, a new technique named as partial least square thermography is introduced and evaluated which is based on multivariate statistical analysis. The signal to noise ratio at maximum signal contrast is obtained to evaluate the performance of different processing techniques. Wadhwa et al. [3] presented Lock-in thermography and its application in finding low ohmic waves in 28nm Graphics processing unit and witnessed three case studies where lock-in thermography was used to isolate defects in 28nm graphic processing unit packaged device. Lock-in thermography was proven to provide reliable, fast and successful non-destructive failure analysis, on the basis of those case studies. Huang Jianxiang et al. [4] had summarized the various algorithms for infrared thermal wave sequences image processing. The basic principle of each algorithm was introduced along with presentation of the experiments and 3D visual display. The image processing results were quantitatively evaluated and compared on the basis of few parameters: Entropy, Signal to Noise ratio (SNR), Spatial Frequency (SF), average gradient of image (AGI) and Root-Mean-Square-Error (RMSE). Hernan et al. [5] discussed two image processing techniques for Thermography Non-destructive Testing (TNDT) for improvement of images contrast and visibility of cracks and voids in materials. Commonly these techniques are compared subjectively but experts visually compared the outcomes of thetechniques and the number of visible defects determines which technique is better for some given parameters.

The outcomes of comparisons help in evaluating and explaining why a new technique is much better or more convenient than previous techniques. Even after being a local and variable with time, SNR (Signal to Noise Ratio) is a quantitative measure of defect's visibility. Image Quality Assessment (IQA) based metrics have been proposed to measure the contrast enhancement on application of image processing techniques in TNDT. X. Maldague et al. [6] had presented a survey of active infrared thermography for non-destructive testing. It defined the important parameters like radiometry, emissivity, and temperature measurement, heat transfer etc. They have also discussed about infrared camera technologies, properties, advantages and areas of improvement. The deployment principles of pulsed thermography, step heating, lock-in thermography and vibrothermography are presented. Few applications, advantages and drawbacks of IRNDT are discussed as well. BartoszKunka et al. [7] presented an eye tracking technique using visible light. This technique eliminates the requirement of additional hardware equipment as in the infrared eye tracking system. Existing eye tracking techniques examples, proposed algorithm of image processing and the process of determining the eye position are described. Through the test of eye tracking application it is analysed that it enables a reliable localization of eye region and accurately detect the iris contour. Still it needs improvement especially for inner corner detection. Gonzalez et al. [8] proposed a new algorithm based on the Random Transform. The purpose of this algorithm is to minimize human intervention in the field of Thermography for defects. The each pixel decay of surface temperature within the image, human intervention is reduced to -0.5 slopes. Using common techniques of computer vision, an algorithm is developed so as to look for the -0.5 slope in the temporal temperature decay profile of each pixel, furthermore random transformation can be used to detect these -0.5 slope lines.

As a final result of this algorithm an image is obtained which visualizing the different voids and defects. This image contains all the necessary information required in it, as all the information is contained in one image this provides the qualitative analyses of depth detection as this algorithm supported by a one dimensional Fourier diffusion equation so the specimen should be limited to the semi-infinite homogeneous sample. Gupta et al. [9] proposed a technique of a non-destructive thermal imaging technique for the detection of defects in integrated part of advance microprocessors. With the help of high speed infrared camera this technique can capture the surface infrared emission response as a function of time.

By modelling of results it was noticed that by mapping the defective regions this technique can isolates the faults in case of the package thermal failure, also the thermal performance of the package can be quantatively evaluated in the transient mode. Paula Lopez Martinez et al. [10] proposed a 3D thermal model to deal with the problem of the detection and identification of buried landmines by studying the effect of presence of landmines in the thermal signature of bare soil. Depending on the model a

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procedure is proposed which identifies, detect and classifies the anomalies from the thermal signature of soil to identify the target. Whereas landmines acts as a thermal barrier in the heat flow through the soil and this can be identified on the thermal pattern of the surface in the form of perturbation, and these perturbation put evidence of the presence of potential mine target. Wen-Hung Liao et al. [11] proposed an image formation model for near-infrared images. In this model low cost camcorder with a Night Shot function is used to capture the images of objects in the total darkness and then homomorphic processing techniques are developed to reduce the artefact of captured images because the resulted images were prone with non-uniformity due to irregularity.

Then a selection criterion for homomorphic filter parameters was also discussed and the effectiveness of the proposed image processing technique is demonstrated with the help of experimental results. Clemente Ibarra-Castaneda et al. [12] reviewed whole acquisition chain including pre-processing levels which are required to restore images from degradations like dead pixels, vignetting and camera pixels.

Processing steps are discussed in two directions one qualitative imaging which requires image enhancement and another is quantitative imaging for thermal properties assessments, defects quantification, and defect detection. R. Hidalgo-Gato et al. [13] uses signal to noise (SNR) to identify the goodness of selected thermographic techniques. The assessment of the defects presented in the specimen is done through the comparison of SNR values.

III APPROACHES of IRNDT

The IR thermography can be classified in two approaches:
- Passive approach and
- Active approach

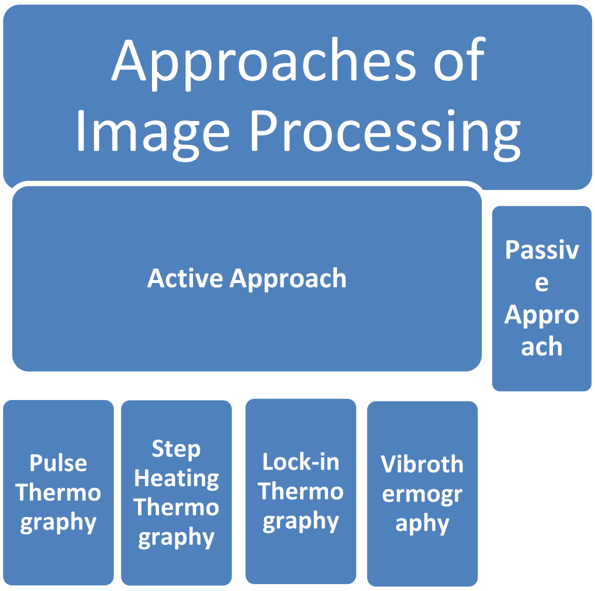

Fig.1. IRNDT approaches

A. Passive approach: In this approach test material or structures are naturally available at different temperature than ambient, usually at higher temperature. There are many important application of passive approach, such as, forest fire detection, production, medicines, predictive maintenance, building efficiency survey, agriculture and biology. In all above applications the abnormal temperature patterns obtained in the images indicated a potential problem to take care of.

B. Active approach: In this approach, an external simulation is required to apply on material and structure to generate relative temperature differences which are not present otherwise and known characteristics of this simulator help to obtain quantitative characteristics of structure or material. Example depth of defects, depth of disbond, level of defects, affected area etc.Different approaches of active thermography have been developed on the basis of the type of external stimulus as shown in figure 1.

(a) Pulse Thermography (PT):
Pulse thermography is one of the most popular methods among all thermal stimulation methods in IR thermography because of its quickness of the inspection relaying on thermal stimulation pulse. The duration of the inspection varies from few milliseconds for high thermal conductivity material like metal to few seconds for low thermally conductive material like plastics.

The basic advantage of using PT is the brief heating prevents damage to the components and quick thermal stimulation allows direct deployment on the specimen's floor with convenient heating sources.

In pulse thermography the specimen is heated briefly and its temperature decay curve is recorded. Firstly, the temperature of material rises due to application of pulse after the deployment of pulse it decays because the thermal front propagates by diffusion under the surface.

The presence of subsurface defects reduce the diffusion rate and hence these defects appears as an area of higher temperature as compared with the surrounding area and because this phenomenon occurs with time so deeper defects are observed later with a reduced spread thermal contrast. A relationship can be shown between the time and subsurface defects depth as [6]:

$$T \approx \frac{d^2}{\alpha} (1)$$

Where T is the temperature, d is subsurface defect depth and α is thermal diffusivity of the material. The above relation shows time as a function of defect depth.

According to the rule of thumb, the radius of the smallest detectable defect should be at least one or two times larger than its depth under the surface and it is useful for basic PT in homogeneous isotropic materials.

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Configuration	Tools	Advantages	Disadvantages
Point Inspection	Laser, Focused light beam	Repeating heating, uniformity	Moving of inspection head for full inspection of surface slows down
Line Inspection	Line lamps, heated wire, line of air jets	Fast inspection rate, good uniformity	Only part of temperature history curve is available due to
Surface Inspection	Flash lamps, scanning laser	Complete analysis is possible	Non-uniformity of heating

Table1: Configuration of Pulse Thermography

(b) Step Heating (SH):
Contrary to the PT in this case stepped heating pulses or long pulses are applied. In Step heating sample is continuously heated at low power and temperature is monitored during and after the heating process. SH have various applications like evaluation of the composite structures, thickness evaluation of coating etc. SH technique sometimes also referred as TRIR i.e. time resolved infrared radiometry. For point heating and line heating the specimen argon laser is used as a tool and surface heating is obtained if the specimen is opaque at argon wavelength i.e. 0.514 μm. with the help of dedicated electronics the synchronization of laser heating with respect to IR camera frame rate can be obtained and this further help in obtaining three types of measurements first scan of temperature line at specific time after heating , second collection of temperature line scan as a function of time which actually shows the temperature development with time over an area of specimen and third is the reconstructed image at a specified time.

(c) Lock-in thermography (LT):
The lock-in thermography is based on thermal waves which are generated inside the specimen. In this case specimen is subjected with a periodic or sinusoidal thermal stimulation [6]. In this case highly attenuated and dispersive waves are found inside the material near its surface and these waves are named as thermal waves. An interesting term come into account is the photo thermal lock-in thermography in which waves can be detected and generated remotely by periodically depositing heat on the specimen surface with a lamp. The depth range of the amplitude image can be roughly calculated in the form of thermal diffusion length μ which is given as [6]

$$\mu = \sqrt{\frac{2k}{\omega\rho c}} \qquad (2)$$

Where k is the thermal conductivity, c is specific heat, ω is modulation frequency and ρ is mass density. As shown in equation (2) μ is inversely proportional to the modulation frequency it shows that the low modulation frequency will probe deeper effects.

(d) Vibrothermography (VT):
In VT the specimen is subjected to the external mechanical vibrations which are fixed at certain frequencies. Heat is generated within the structure and released by friction at the location of defects like cracks and voids. Here direct conversion of energy from mechanical to thermal takes place and defects or flaws are excited at some specified mechanical resonances this implies that delaminating in some area will be resonates independently of the rest of structure at some particular frequencies and may disappears at some other frequencies.VT have various advantages most significant are inspection of large area, it is capable to detects flawswhich are hardly visible by other IR thermography techniques where as it is difficult to achieve the mechanical loading.

IV IMAGE PROCESSINGTECHNIQUES

The use of signal processing techniques on thermographic Images needed to overcome the harmful effects occurred due to non-uniform distribution of the irradiation applied during thermal excitation which results in the appearance of abnormal thermal patterns that sometimes superimposed on the contrast produced by internal defects. The non-uniform heating results in the reduction of spatial resolution i.e. affecting smaller defects and also limit of detection i.e. affecting deeper defects. Because of these limitations infrared thermography is generally used for qualitative applications on large, near surface defects.
Many image processing techniques are practiced in thermography for non-destructive testing to improve image contrast and visibility of voids or cracks in materials. Commonly the ability of these image processing techniques is compare subjectively. The outcomes of the techniques are visually compared and determine which technique, for provided parameters, works well by analysing the number of defects made visible in a particular image. The result of these comparisons defines and explains why a new technique is better than previous one. However, SNR or detectivity of defect is a quantitative method for comparison, which can be defined as a ratio of the absolute value of the absolute contrast at the centre of the defect to the spatial noise in the non-defective.

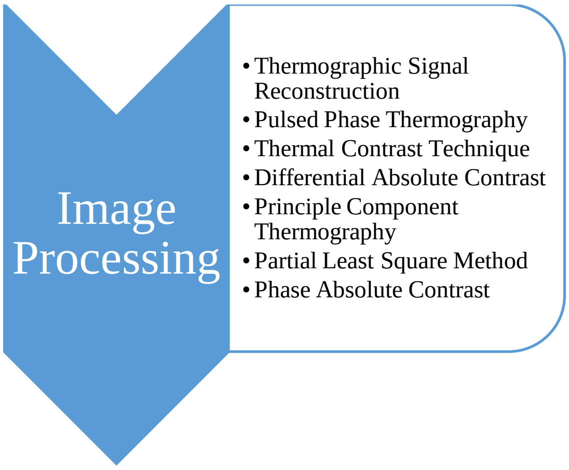

Fig.2. Image processing techniques

A. Thermographic Signal Reconstruction

Thermographic Signal Reconstruction (TSR) is an image processing technique use to process image sequences obtained from pulse thermography experiments. It brings important improvements over pulse thermography raw data. TSR is very simple and provide accurate results allowing the detection of defects, increase of spatial resolution and temporal, the reduction of data for processing, ability to produce time derivative images without generating additional noise and reduction of high frequency noise. The basic of TSR is the use of the one dimensional heat diffusion equation which describes the surface temperature fruition in a semi-infinite sample once it has been thermally stimulated with a Dirac pulse:

$$T = \frac{Q}{e\sqrt{\pi t}} \qquad (3)$$

Where, t is the time, e is the material effusivity and Q is the energy density at the surface [5]. This equation can be represented and rewritten in a double logarithmic form to approximate the time dependency of temperature at each pixel with a polynomial having the following form [5]:

$$\ln[T(t)] = a_0 + a_1 \ln(t) + a_2 ln^2(t) \ldots \ldots . a_n ln^n(t) \quad (4)$$

Normally, the value of N is set to 4 or 5 to avoid ringing and insure a good correspondence between signal de-noising and fitting accuracy for TNDT applications.

B. Pulsed phase thermography

Pulsed phase thermography (PPT) is another processing technique which is based on superposition principle which states that a time domain response may be obtained from a frequency response by applying Fourier expansion. PPT enables to transform the data from time domain to frequency domain using one dimensional discrete Fourier transform (DFT) [2]

$$F_n = \Delta t \sum_{k=0}^{N-1} T(k\Delta t) exp - \frac{j2\pi k}{N} = Re_n + Im_n \qquad (5)$$

Where Δt is sampling frequency interval, n is the frequency increment (n=0, 1, 2… N), j is some imaginary number, Re is the real part of transform and Im is imaginary part.

The process is as follow, using PPT analyze the time evolution of image sequence, then the one dimensional Fourier transform is applied to each pixel of image sequence results in obtaining two new image sequences, one of amplitude another is of phase. The amplitude and phase image sequences remains symmetric about the frequency of 0 Hz (f==0 Hz), which redundant the half of the data and further reduce the calculation time vital for processing. The phasegram is very significant amid the sequences resulted from applied PPT as it is minus affected by non-uniform heating, signal degradation, optical fluctuations and enable to estimate the depth of the defects of the body. PPT somewhere said to combine the advantages of both PT and LT. In PPT the body is pulse heated as in PT. the diffusion of heat from surface in to the body is better understood by considering it the thermal wave propagation into body away from surface. The mix of different frequencies components of thermal waves will suffer different amount of attenuation which results in increasing or decreasing the amount of penetration of each of thermal waves. Because of this dualism between the harmonic and transient problem PPT is consider as a connection among pulse thermography and lock-in thermography.

In PPT and LT it is possible to explore various frequencies. However, analysis in PPT is carried out in transient more where as in LT the signal recording is performed in stationary mode. In qualitative analysis of subsurface defects PPT is considered more effective in terms of accuracy and applicability whereas for instance the quality of image will be higher in LT because of the summation process in the computations.

C. Thermal Contrast technique

Thermal contrast techniques are used commonly for the processing of data. All thermal contrast definitions require a sound area denoted asS_a, which is a non defective region with in the area of view. The absolute thermal contrast, denoted as $\Delta T(t)$, defines [12]:

$$\Delta T(t) = T_d(t) - T_{Sa}(t)(6)$$

Where T_{Sa} (t) is the temperature at time t for sound areaS_a, T (t) is the temperature at time t, and $T_d(t)$ is the temperature of a pixel whether defective or non defective or can be an average value of the group of pixels. For the case,

$$\Delta T(t) = 0 \quad no\ defect\ can\ detected$$

S_a Come up as a drawback especially in few cases where there is no knowledge of the specimen or where automated analysis is required. Moreover change in the location of S_a brings considerable change on the results. Whereas the problem of location variation of S_a is resolved by another

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processing technique named as Differential absolute contrast (DAC).

D. Differential absolute contrast

Processing technique using differential absolute contrast was developed as an alternative to the absolute thermal contrast technique, as defined in equation (4). DAC uses the 1D Fourier heat equations for a pulsed thermal wave. Instead of looking for a non-defective area, DAC locally compute an ideal S_a at the time t, assuming that on first few images at least one image at time t′ this local point behaves as a S_a. The local temperature for S_a[12]

$$T_{S_a}(t') = T_d(t') = \frac{Q}{e\sqrt{\pi t'}} \qquad (7)$$

The first step in the implementation of DAC techniques is to define t' as a given time value between the instant when the pulse is applied and the precise moment when the first defect spot appears on the thermogram , means at the time when there is enough contrast to detect the defect. At time t' there is no existence of the defect; therefore the local temperature of the sound area is found exactly the same as for a defected area, as shown in equation (5). On substitution of equation (5) into absolute thermal contrast equation (4) we obtain following expression:

$$\Delta T_{DAC} = T(t) - \sqrt{\frac{t'}{t} * T(t')}(8)$$

Equation (6) provides good approximation at earlier times as time passes it will diverge from the semi-infinite case. DAC deals with the problems like non-uniform heating, environmental reflections and emissivity variation.

E. Principle Component Thermography

Principle component Thermography (PCT) uses transformation technique for the processing of image sequence. PCT compactly extract the temporal and spatial information of the image sequence using orthogonal empirical function. For this e it first reduces the information from singular value decomposition and then extract the temporal and spatial information. For applying the decomposition it is required to transform the 3D matrix of image sequence to the 2D matrix. The row and columns contains the spatial and temporal dimensions respectively. The obtained complete sequence will be a 3D matrix denoted as $N_x \times N_y \times N_t$ where N_t is total number of images [13].PCT seems to face problem when very large defects are present and also time consuming when applying it to large data.

F. Partial least square method

The above techniques provides a great improvement in the quality of the images but it has been notices that their application is limited to certain criteria, like transient regime duration, depth of defect and thermo physical property of material, because all three are derived using one dimensional heat conduction equation. This indicates that the heat diffusion process will be more predominant in the transversal direction but this condition is not mandatory to be always satisfied and as a result usually deeper defects go through the consequences of the lateral heat diffusion. Whereas partial least square thermography (PLST) allow reconstruction of thermographic signature while maintain physical consistency on material. PLST is based on statistical correlation method in which it computes loading P and score T vector which are correlated to the predicted block Y while describing a large amount of variation in predictor matrix X. The surface temperature obtained during inspection is represented through matrix X. The observational time during which the thermal images were captured is defined by Y. For obtaining the PLS model X and Y are decomposed to form a combination of loading P and Q, scores T and U and residuals E and F [2], where Q is formed by orthogonal vectors and U is the projection of loading vectors which are linked with singular values. PLST separates the physical effects which is the main advantage of it. The first PLS component can be related to non- uniform heating through the detailed analysis of each latent variable. Once this latent variable is identified one can subtract it from the correlated data. This enhances the visibility of defects in material.

G. Phase Absolute Contrast

Phase absolute contrast (PhAC) is a hybrid processing technique. This technique basically combines three different processing techniques which are TSR, PPT and PhAC. The calculations for the Phase absolute contrast can be obtained from the phase sequences acquired from pulsed phase thermography. These sequences are previously filtered by applying TSR so as to reduce the signal noise. The half of the data is subtracted due to the symmetry with respect to the frequency of 0 Hz which phase sequence presents. Now DAC is applied to the resulting sequence using the thermograph previous to the appearance of first defect as a reference. PhAC improves the contrast between the sound area and defective area and hence resulting in better analysis and identification of defects.

V CONCLUSION

In this paper, we presented the brief overview about IR Thermography, its challenges and characteristics. Different thermographic approaches are discussed and differentiated on the basis of source used as an external simulation. As the images obtained by the camera are not clear they required processing so as to find out the defects so various processing techniques are discussed along with their advantages, disadvantages and applications. The basic difference between the various processing techniques is also discussed. This paper do not introduced any new processing technique by the have discussed the limitations of various techniques. In future we will propose improvements in techniques so as to improve the detection process by working on the various factors like SNR, RMSE etc.

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