AN APPROACH FOR FAULT DETECTION IN METALLIC STRUCTURES USING MILLIMETER WAVE IMAGING

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ABSTRACT

The detection of faults in any metallic structure in the industries is of great interest. Robust fault detection in different scenarios is necessary to predict the life of the structure. Penetration of the wave is possible through the rusted area at a frequency range 30- 300 GHz i.e. at millimeter wave frequency range. Non- Destructive Testing is very useful in industry since it provides the evaluation of the material without causing damage to the original part. This paper is about the millimeter wave image based fault detection in the metallic structure. Conventional fault detection techniques may give a false alarm for the intensities below the average values. A novel approach based on line enhancement filtering is introduced and developed images are compared with other image based processing techniques. Our proposed method gives satisfactory results for a fault like crack having different dimensions in the metal sheet.

Index Terms—Fault detection, millimeter wave imaging, line enhancement filtering, discrete wavelet transform.

1. INTRODUCTION

Metal is an integral structural part in many industrial applications such as an automobile, aviation, construction. Degradation of a metallic structure is a natural phenomenon due to corrosion, adverse climatical condition, pitting etc. [1]. The cost of replacing the structure suffers due to corrosion is not only high it also delayed the industrial production process. In civil and aviation industries damage of steel structure can cause loss of life. Non- Destructive Testing (NDT) technique based on MMW is a robust and effective solution for fault detection even though the resolution is poor compared to visible/ IR systems[2], [3]. Electromagnetic (EM) signals are very sensitive to the change in the dielectric properties of the structure [4]. Image resolution enhancement becomes necessary in many practical situations to improve the detection ability of MMW imaging system. Range resolution can be increased by increasing the bandwidth [5], [6] but it has practical limitations. To reduce the time and cost of real-time scanning, image enhancement techniques using signal processing can be used. In literature, very few studies are available for fault detection based on millimeter wave imaging. To reduce the computation time percolation method is used in [7]. To identify the crack on the concrete surface by removing the noise using shade correction is proposed in [3]. Canny edge detection algorithm is used in [8], but this method does not give satisfactory results in terms of false alarm.

This paper proposed a novel technique in the millimeter wave imaging using line enhancement filtering used previously for blood vessel detection in the biomedical field. Section II describes the experimental set- up and data collection. Conventional image enhancement and thresholding techniques are briefly explained in section III. Section IV provides details about the proposed line enhancement technique for crack like fault detection and section V concludes the paper.

2. EXPERIMENTAL SET-UP AND DATA COLLECTION

2.1 Set- up

In our experimental work metallic sheet of size *20 cm × 20 cm* is used for scanning in which grooves of sizes *3.5 cm × 10.5 cm* and *2 cm × 8.5* cm are made. Henceforth above sheet used in the experimental work, we will define as target. There are three types of scanning are used in radar imaging namely A- scan, B- scan and C- scan. A- Scan is a one dimensional scan which locate range bin for the target in the down range. B- Scan is a two dimensional scan that gives information about the length of the target in the cross range. Cross range resolution enables to detect two different targets in the horizontal direction while down range gives information in the vertical direction. Three dimensional information i.e. shape of the target can find out with the help of C- scan. In our experimental set- up target is mounted on 2- D wooden frame as shown in Fig.1 for scanning and is placed at a standoff distance $R = 50\ cm$ from the antenna. To develop C- scan raw image, target makes to slide over 2- D wooden frame in the horizontal and vertical direction with an equal distance of $S = 2\ cm$. The frequency range we choose for millimeter wave imaging is in the range of *60-62 GHz* i.e. having bandwidth of *2 GHz*. The resolution in the horizontal direction can be improved by moving the target in the lateral direction. At above frequency range the cross range resolution $\Delta CR = \lambda R/D = 4.17\ mm.$ and down range resolution is $\Delta R = C/2\ B.W. = 7.5\ cm.$

Figure1. 2-D structural setup

2.2 Data collection

A transceiver is used to generate the number of frequency points *N = 201* for the *2GHz* bandwidth and data are collected for the reflections from the target in the form of S11 coefficients. The number of horizontal and vertical scanning points (*M = 30* and *Ns = 16*) are selected respectively.

2.2.1 Pre- processing

After collecting the data some pre- processing steps are required. A complete flow chart for the pre- processing is given in[9].

Step 1) Conversion of the Frequency domain to Time domain
Data collected by the transceiver is generally in frequency domain this data is converted to the time domain by using Inverse Fast Fourier Transform (IFFT).

Step 2) Conversion from Time domain data to spatial domain
To acquire the information about the range bin of the target, time information is converted into distance by using $z = c*t/2$

Where, *C* is the speed of light and *t* is the delay for the wave propagation.

Step 3) Calibration using a metal plate
To nullify the effect due to antenna reflections metallic plate is placed in front of the antenna and collected S11 reflections are subtracted from the observations.

2.2.2 Signal modeling

We received a signal from *M* and *Ns* number of positions in horizontal and vertical directions. Consider *Q* number of targets is present in the scene then

$$x(n,t) = \sum_{q=0}^{Q-1} \sigma_q s(t - \tau_{n,q}) + Noise \tag{1}$$

Where *s(t)* is the transmitted signal get convolved with reflections from the *Q* targets. During the propagation of the EM waves, additive noise gets added in the signal. $\tau_{n,q}$ is the delay between the antenna and the Q^{th} target given by

$$\tau_{n,q} = \frac{2}{c}\sqrt{(x_p - x_n)^2 + (z_p - z_n)^2} \tag{2}$$

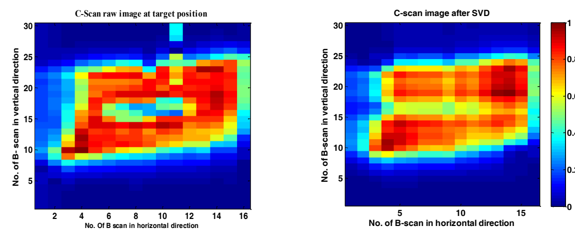
Where, *c* is the speed of light, (x_p, z_p) and (x_n, z_n) are the coordinates for the targets and antenna position respectively in the cross range and down range. In discrete form eq. (1) can be represented as

$$z[m,n] = \sum_{q=0}^{Q} \sigma_q \exp\{-j2\pi f_n \tau_{n,q}\} \tag{3}$$

2.3 Development of raw C – scan image and de- noising

After above pre- processing steps to acquire full information about the target and to detect the grooves we required C- scan, which is a 3-D data retrieve from lateral movement of the target in the horizontal direction and stepwise movement in the vertical direction. The size of 3-D data for S11 will be of dimension 201×30×16 in our case. We have collected 20 sets of data for the metal plates having grooves of different dimensions. Raw C – scan image is developed using back-projection beam forming technique by stacking the raw data [14], Fig. 2a shows raw image for a metal plate having a single groove after pre-processing.

Received data is generally corrupted with noise, to de- noise the data various techniques are available in the literature using singular value decomposition (SVD), wavelet transform etc. SVD technique separates the data into left and right singular matrix along with singular values associated with target and noise.



(a) (b)

Figure 2.(a) Raw C- scan image (b) C- scan image after SVD

Received data matrix ***R*** consists of signal component ***S*** along with random noise ***Noise.***

$$R = S + Noise \tag{4}$$

The optimum estimation for signal component ***S*** can be acquired by optimization.

$$\min \|P\|_F^2 \; s.t. rank(s) = n \tag{5}$$

Where ***P*** is the rank constrained for data ***S***. $\|\cdot\|_F$ is the Frobenius norm of ***R***.SVD can be represented by the equation.

$$R = \sum_{i=1}^{q} \sigma_i u_i v_i^T \tag{6}$$

Where σ_i is the eigen values associated with the target and noise, u_i is the left singular matrix and v_i is the right singular matrix. The de- noised image using SVD is shown in Fig. 2b.It can be observed that the crack like fault is visible in Fig. 2a, cannot be detected in Fig. 2b, hence another efficient technique for de- noising is required. Recently in [10]*opt-shrink* algorithm is proposed to optimize the singular values optimally. Different steps for *opt-shrink* algorithm are as follows.

1) Effective rank for SVD matrix is estimated.
2) Compute SVD for **R** by $\hat{R} = \sum_{i=1}^{q} \hat{\sigma}_i \hat{u}_i \hat{v}_i^T$
3) Compute $\sum_{\hat{r}} = diag(\hat{\sigma}_{r+1} \dots . \hat{\sigma}_q) \in R^{(n-\hat{r})\times(m-\hat{r})}$
4) Compute D – transform for $\widehat{D}(\hat{\sigma}_i, \sum_{\hat{r}})$ and $\widehat{D'}(\hat{\sigma}_i, \sum_{\hat{r}})$

$$\widehat{D}(z,x) = 1/n\,Tr(z(z^2I - xx^H)^{-1}).1/m\,Tr(z(z^2I - x^Hx)^{-1})$$

$$\widehat{D}'(z,x) = 1/n\,Tr\big((z(z^2I - xx^H)^{-1}).1/m\,Tr(-2z(z^2I - x^Hx)^{-2}) + (z^2 I - x^H x)^{-1}\big) + 1/m\,Tr\,(z\,(z^2 I - x^H x)^{-1}).1/n\,Tr(-2z^2(z^2I - xx^H)^{-2} + (z^2 I - x^H x)^{-1}$$

5) Compute $\omega_{i,\hat{r}}{}^{opt} = -2\,\widehat{D}(\hat{\sigma}_i, \sum_{\hat{r}}) / \widehat{D'}(\hat{\sigma}_i, \sum_{\hat{r}})$
6) Evaluate $\widehat{R_{opt}} = \sum_{i=1}^{\hat{r}} \omega_{i,\hat{r}}{}^{opt}\, \hat{u}_i \hat{v}_i{}^T$

After implementing the above steps on raw data processed image is shown in Fig. 3.

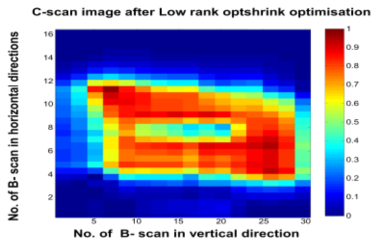


Figure3.Processed raw image using *opt- shrink* algorithm

3. IMAGE ENHANCEMENT AND THRESHOLDING USING CONVENTIONAL METHODS

Image enhancement can be done using different conventional filtering techniques, in this section image enhancement using Spatial filtering, Gaussian filtering, wavelet filtering is analyzed. Filtering is a 'shifting and multiplying' operation with filter transfer function. If input image is *I(i,j)* then it will be convolved with filter transfer function *H(x, y)* to produce new image *I'(I,j)*

3.1 Spatial filtering

Spatial filtering is an image processing technique to change the intensities of the pixels according to the neighboring pixels in the image. In this paper median filtering is used for this purpose.

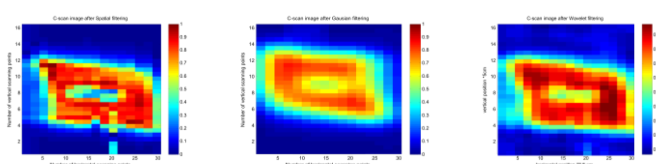
3.2 Gaussian filtering

Different types of filters are tried and find out that among Gaussian, average, log, Laplacian, Prewitt and disk, Gaussian filter gives good results.

3.3 Wavelet filtering

Wavelet filtering allows emphasizing and de- emphasizing the image in to the certain spatial domain. It is similar to the IFFT and breaks the image in to low, high or mid-frequency components. These frequency components further can be emphasized into detail components.

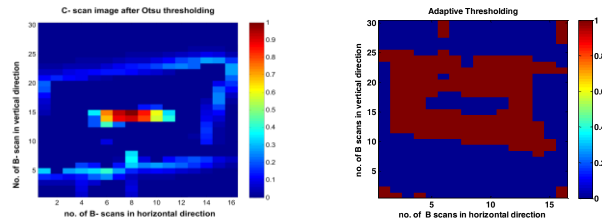
The images obtained after applying the above filtering techniques are as shown below.



(a) (b) (c)

Figure 4.(a) C- scan image after Spatial filtering (b) C- scan image after Gaussian filtering (c) C- scan image after Wavelet filtering

Our objective is not only to enhanced the image resolution by de- noising but also to detect the crack like fault in the metal sheet, for this purpose Otsu thresholding and adaptive thresholding proposed in[11]are investigated. The images using the above thresholding methods are shown in Fig.5. After thresholding different edge detection methods such as Canny, Sobel and Prewitt are used to extract the groove, among this Canny is a popular technique for edge detection.



(a) (b)

Figure 5.(a) C- scan image after Otsu thresholding (b) C- scan image after Adaptive thresholding

The image using 'Canny' edge detection is shown in Fig. 6. It can be observed that the above thresholding methods and edge detection methods do not give satisfactory results hence more efficient image enhancement and adaptive thresholding is required to detect the fault.

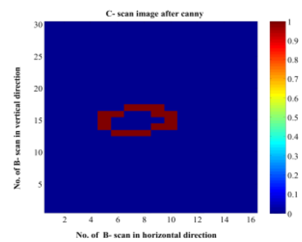


Figure 6. C- scan image after Canny edge detection method

4. PROPOSED FRANGI LINE ENHANCEMENT FILTERING METHOD

Techniques solely based on intensity does not give satisfactory results[12], the region of the image below the average intensities cannot be extracted if the improper threshold is set. A line enhancement filter is very effective in removing noise sources other than linear pattersand and widely used in the detection of blood vessels. Frangi line enhancement filter using Hessian based matrix is proposed in [13]and expressed by the eq. (7)

$$V_0(x)=\begin{cases} 0 \text{ if} \lambda_2<0 \\ \exp(-\frac{R_B{}^2}{2\beta^2})(1-\exp(\frac{s^2}{2\sigma^2})) \text{ if} \lambda_2\geq 0 \end{cases} \quad (7)$$

Where $V_0(x)$is the line enhancement filter, $S=\sqrt{\lambda_1{}^2+\lambda_2{}^2}$, $\beta = 0.5$, $R_B=\lambda_1/\lambda_2$, $\lambda_1 \ll \lambda_2$.S is the standard deviation and $\lambda_1$and λ_2 are the eigen values from the Hessian matrix. Hessian second order information and Gaussian kernel measures the contrast between inside and outside the range (*-S, S*). The smallest eigen value $\lambda_1$will represent the presence of the fault and other values from λ_2 to λ_k(k are the number of eigen values in Hessian matrix) represents the background [13]. To extract information related to the fault, we modify $S=\sqrt{\lambda_1{}^2+\lambda_2{}^2-\lambda_2{}^2}$ in our approach so that the effect of the background can be minimized. In our experimental work testing of the proposed algorithm is done on the metal sheet which do not have any fault, C- scan image for this case is shown in Fig. 7b. Then the algorithm is tested for one and two crack like faults. C- Scan images for these two cases are shown in Fig. 7c and 7d respectively. We have tested proposed algorithm on probable cracks in the different materials used in various structures.

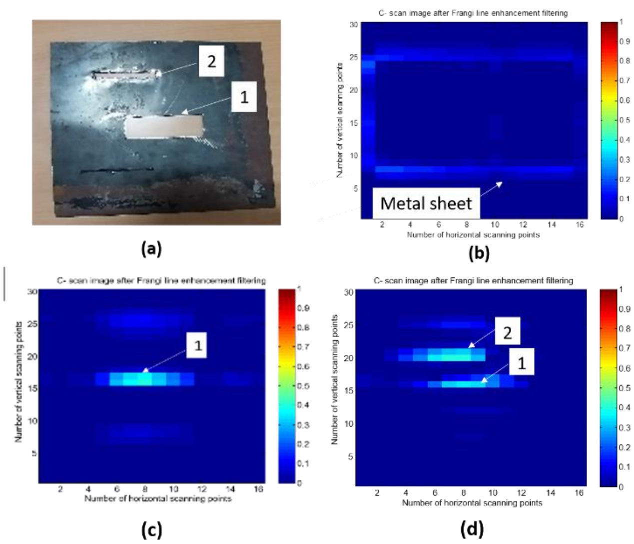


Figure 7.(a) Photograph of sample with two grooves (b-d) C- scan images without groove, single groove and two grooves after Frangi line enhancement filtering

5. CONCLUSION

Fault like crack detection in metallic structures in any industry is always a challenging task. Conventional methods solely based on image intensities do not give satisfactory results, if image intensities are less than the average value. Frangi line enhancement filter which is based on Hessian matrix and statistical values of the data is an adaptive approach. The performance of the Frangi line enhancement filter is very encouraging in terms of false alarm, and fault detection in the various structures compared to other methods.

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7. REFERENCES

[1] S. B. Kumaar, “Stress Corrosion Cracking Guides to Good Practice in Corrosion Control.”

[2] S. Agarwal and D. Singh, “An Adaptive Statistical Approach for Non-Destructive Underline Crack Detection of Ceramic Tiles Using Millimeter Wave Imaging Radar for Industrial Application,” *IEEE Sens. J.*, vol. 15, no. 12, pp. 7036–7044, Dec. 2015, doi: 10.1109/JSEN.2015.2469157.

[3] Y. Fujita and Y. Hamamoto, “A robust automatic crack detection method from noisy concrete surfaces,” *Mach. Vis. Appl.*, vol. 22, no. 2, pp. 245–254, Mar. 2011, doi: 10.1007/s00138-009-0244-5.

[4] M. R. Jahanshahi and S. F. Masri, “A new methodology for non-contact accurate crack width measurement through photogrammetry for automated structural safety evaluation,” *Smart Mater. Struct.*, vol. 22, no. 3, p. 035019, Feb. 2013, doi: 10.1088/0964-1726/22/3/035019.

[5] L. Barazzetti and M. Scaioni, “Crack measurement: Development, testing and applications of an automatic image-based algorithm,” *ISPRS J. Photogramm. Remote Sens.*, vol. 64, no. 3, pp. 285–296, May 2009, doi: 10.1016/j.isprsjprs.2009.02.004.

[6] Hutchinson Tara C. and Chen ZhiQiang, “Improved Image Analysis for Evaluating Concrete Damage,” *J. Comput. Civ. Eng.*, vol. 20, no. 3, pp. 210–216, May 2006, doi: 10.1061/(ASCE)0887-3801(2006)20:3(210).

[7] “(14) Fast crack detection method for large-size concrete surface images using percolation-based image processing | Request PDF,” *ResearchGate*. [Online]. Available: https://www.researchgate.net/publication/225147330_Fast_crack_detection_method_for_large-size_concrete_surface_images_using_percolation-based_image_processing. [Accessed: 02-Jan-2020].

[8] “An Automatic Approach for Accurate Edge Detection of Concrete Crack Utilizing 2D Geometric Features of Crack | SpringerLink.” [Online]. Available: https://link.springer.com/article/10.1007/s11265-013-0813-8. [Accessed: 02-Jan-2020].

[9] “(14) (PDF) A novel neural network based image reconstruction model with scale and rotation invariance for target identification and classification for Active millimetre wave imaging,” *ResearchGate*. [Online]. Available: https://www.researchgate.net/publication/268236581_A_novel_neural_network_based_image_reconstruction_model_with_scale_and_rotation_invariance_for_target_identification_and_classification_for_Active_millimetre_wave_imaging. [Accessed: 02-Jan-2020].

[10] R. R. Nadakuditi, “OptShrink: An Algorithm for Improved Low-Rank Signal Matrix Denoising by Optimal, Data-Driven Singular Value Shrinkage,” *IEEE Trans. Inf. Theory*, vol. 60, no. 5, pp. 3002–3018, May 2014, doi: 10.1109/TIT.2014.2311661.

[11] D. Bradley and G. Roth, “G.: Adaptive thresholding using the integral image,” *ACM J Graph Tools*, pp. 13–21, 2007.

[12] “Image-Based Concrete Crack Detection Using Convolutional Neural Network and Exhaustive Search Technique.” [Online]. Available: https://www.hindawi.com/journals/ace/2019/6520620/. [Accessed: 02-Jan-2020].

[13] A. F. Frangi, W. J. Niessen, K. L. Vincken, and M. A. Viergever, “Multiscale vessel enhancement filtering,” in *Medical Image Computing and Computer-Assisted Intervention — MICCAI’98*, 1998, pp. 130–137.

[14] Y. Yamaguchi, M. Mitsumoto, M. Sengoku and T. Abe, "Synthetic aperture FM-CW radar applied to the detection of objects buried in snowpack," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 32, no. 1, pp. 11-18, Jan. 1994, doi: 10.1109/36.285184.