



## **Full Length Research Article**

### **PHASED ARRAY ULTRASONIC EVALUATION OF ULTRA HIGH STRENGTH STEEL WELDMENTS FOR AEROSPACE APPLICATIONS**

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#### **ABSTRACT**

Ultra high strength steels viz. Maraging 250 grade steel, that are used for realising rocket motor casings have a tendency to undergo brittle fracture in the presence of cracks. Thus, it becomes imperative to resort to fracture mechanics for determination of critical crack sizes that could cause a catastrophic structural failure. The flaw sizes that are characterised as critical are then taken as the minimum detectable flaws for NDT. Ultrasonic NDT is an effective method to detect small tight cracks available in weldments. Weld defects are sized/evaluated by comparison with standard reference notches listed in AMS 2632 viz. E, F and G Notches. The weld defects occur with a wide spectrum of geometric shapes and orientation. Hence there is possibility of missing defects of certain orientation and depth when carrying out Ultrasonic inspection with a single angle UT Probe. To overcome this problem during conventional ultrasonic inspection, multiple probes of various beam angles viz. 45deg, 60deg and 70 deg are used to inspect the same weldment. This results in multiple scanning of weldments which is further time consuming. Moreover certain type of defects that have a favourable orientation to the beam may not give the right amplitude echo so as to size it with the above said standard notches. An advanced Ultrasonic Inspection using Phased Array Ultrasonic Testing is implemented where sectorial scanning using various angles is performed on maraging steel weldments. The detection of the various SAE AMS standard reference notches are demonstrated on the welded plates. Phased array Sector scan result is compared with local A-Scan result to arrive at the geometric attributes of the defect.

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#### **INTRODUCTION**

The Solid rocket motors are one of the significant propulsion hardware. The present day solid rocket motors are being realized with ultra high strength steels like maraging steels in order to gain efficiency. The advent of high strength maraging steels which are highly fracture prone has brought a change in the design philosophy as well as in quality assurance methodology. The manufacturing technology being followed presently for maraging steel rocket motor casings involve welding which is the prime source of defects. Complete elimination of defects is both difficult and un-economical. NDT is an effective tool to identify such manufacturing defects and to take a judicious decision for repair.

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Conventional NDT methods like radiographic testing complimented with ultrasonic testing are being employed in detecting the flaws in welding and heat affected zones (Krautkramer, 2008 and Pugalendhi, 2013). Sometimes certain defects like tight cracks with certain orientations may go undetected by these methods due to either the limitations of the technique. Phased Array Ultrasonic Inspection is a fast maturing NDT tool ideally suited for detection of defects in thin weldments (Colin, 2012). The unique capability of the technique lies in its ability for scanning the weldment with multiple angle ultrasonic rays. An added advantage being that, a recorded Sectorial Scan (S-Scan) or C-Scan along with corresponding individual angle A-Scan is possible (USA, 2004). Phased Array technique has taken greater significance owing to the usage of fracture prone maraging steel materials for realization of rocket motor casings. In many cases, it has been reported that PAUT was able to detect flaws that escaped

detection using conventional UT inspection (Michael, 2008 and Wolfram, 2012). Thereby, Phased Array Ultrasonic Testing technique plays an effective role in assuring quality of rocket motor systems.

### Phased Array Ultrasonic Testing

Phased arrays have been put into practical use for some time now. The medical industry has been pioneering many of the industrial imaging systems for years and phased arrays are no exception. The industry however has been relatively slow to grasp the new technology, most of which can be attributed to two main factors, computer power and cost. Only this last decade have we more readily been utilizing the phased array technology to expedite inspection solutions previously unobtainable. The advent of this technology could be quite useful for inspection of Rocket motor casings in terms of accuracy and time. In comparison with the ultrasonic conventional examination of welded joints the phased array technique presents a series of facilities and specific advantages of these new examination technique, between which we can mention: a higher examination speed, a better probability of detection of discontinuities, better performances of sizing of discontinuities, bi-dimensional images, storage of all data, a high reproducibility and reduced security risks. Ultrasonic phased arrays are a novel method of generating and receiving ultrasound. They use multiple ultrasonic elements and electronic time delays to create beams by constructive and destructive interference. As such, phased arrays offer significant technical advantages over conventional single-probe ultrasonics; the phased array beams can be steered, scanned, swept and focused electronically.

- Electronic scanning permits very rapid coverage of the components, typically an order of magnitude faster than a single probe mechanical system.
- Beam forming permits the selected beam angles to be optimized ultrasonically by orienting them perpendicular to the predicted defects, for example Lack of Fusion in welds.
- Beam steering (usually called sectorial scanning) can be used for mapping components at appropriate angles to optimize Probability of Detection. Sectorial scanning is also useful for inspections where only a minimal footprint is possible.
- Electronic focusing permits optimizing the beam shape and size at the expected defect location, as well as optimizing Probability of Detection. Focusing improves signal-to-noise ratio significantly, which also permits operating at lower pulser voltages.

Overall, the use of phased arrays permits optimizing defect detection while minimizing inspection time.

Phased arrays offer significant advantages over traditional UT of welds as well:

- Better defect detection and sizing
- Great flexibility in parameter range
- Compliant with all known codes
- Many special feature/techniques are possible.

### Type of Phased Array UT Scanning

**Sectorial scanning of Welds:** As welds are typically inspected with probe angles of  $45^\circ$  to  $70^\circ$  beam steering with a phased array

probe can be set between  $35^\circ$ - $80^\circ$ . Knowing the weld geometry (type, width and thickness) the optimum probe distance can be calculated to the weld. Start with a distance, at which the minimum angle ( $35^\circ$ ) hits the edge of the HAZ (heat affected zone) at one skip, Fig. 1.

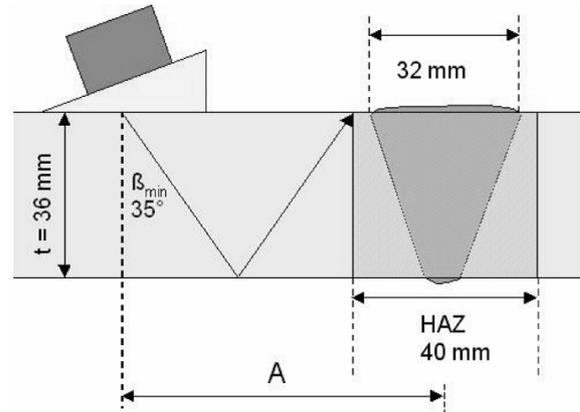


Fig. 1. Probe position for weld inspection

Now looking at all larger angles ( $35$ - $80$ ), the whole cross section of the weld plus the HAZ will be covered, fig. 2. In a sectorial scan with scanning at constant distance the gain should be increased, so that echoes from flat defects will be received. In order to increase the probability of detection, a second scan at a larger distance may be performed in order to optimize the scan angle with respect to the weld. The huge advantage of sectorial weld inspection is the test speed, and the easy differentiation of real defects and geometrical echoes, e.g. from the root and the weld cap: At a typical test speed of  $100$  mm/s the scan of  $6$  m weld (one side) is performed in almost a minute. A magnetic guiding strip or ruler supports the scan. Whenever a defect echo occurs, the operator has to locate and evaluate the defect. Maintaining the high scanning speed for weld inspection, the test results of a weld inspection with an additional encoder fixed to the probe will generate an uncorrected scan image only. However, all important information on detected defects are contained in this image. Offline evaluation will allow to calculate the real defect location in the weld, and evaluate the echo amplitudes.

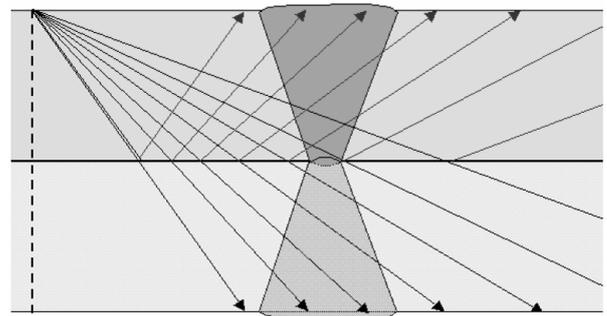


Fig. 2. Full Coverage of weld cross-section

### Linear Scanning of Welds

Manual ultrasonic weld inspections are performed using a single probe, which the operator “rasters” back and forth to cover the weld area. Many automated weld inspection systems use a similar approach (see Figure 3a), with a single probe scanned back and forth over the weld area. This is time consuming, since the system has dead zones at the start and finish of the raster.

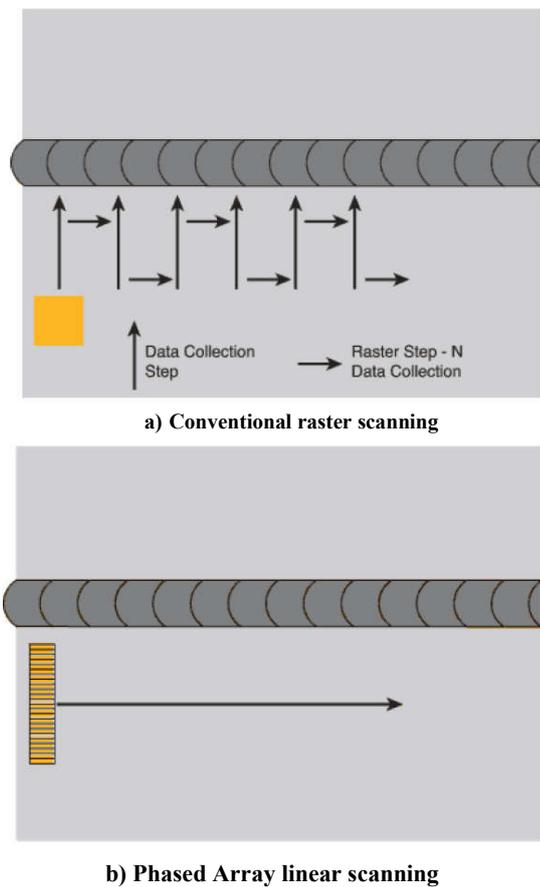


Figure 3. Linear Scanning of welds

In contrast, most multi-probe systems and phased arrays use a “linear scanning” approach (see Figure 3b). Here the probe pan is scanned linearly round or along the weld, while each probe sweeps out a specific area of the weld. Phased arrays for linear weld inspections operate on the same principle as the multi-probe approach; however, phased arrays offer considerably greater flexibility than conventional UT. Typically, it is much easier to change the set-up electronically, either by modifying the set-up or reloading another; often it is possible to use many more beams (equivalent to individual conventional probes) with phased arrays; special inspections can be implemented simply by loading a set-up file.

### Combined Scans

Combining linear scanning, sectorial scanning and precision focusing leads to a practical combination of displays. Optimum angles can be selected for welds and other components, while electronic scanning permits fast and functional inspections. For example, combining linear and L-wave sectorial scanning permits full ultrasonic inspection of components over a given angle range. This type of inspection is useful when simple normal beam inspections are inadequate, e.g. for titanium castings in aerospace where defects can have random orientations. A related approach applies to weld inspections, where specific angles are often required for given weld geometries; for these applications, specific beam angles are programmed for specific weld bevel angles at specific locations.

### Practical Applications of Phased Array Technique

From a practical viewpoint, ultrasonic phased arrays are merely a method of generating and receiving ultrasound; once

the ultrasound is in the material, it is independent of generation method, whether generated by piezoelectric, electromagnetic, laser or phased arrays. Consequently, many of the details of ultrasonic inspection remain unchanged; for example, if 5 MHz is the optimum inspection frequency with conventional ultrasonics, then phased arrays would typically start by using the same frequency, aperture size, focal length, and incident angle. While phased arrays require well-developed instrumentation, one of the key requirements is good, user-friendly software[7]. Besides calculating the Focal Laws, the software saves and displays the results, so good data manipulation is essential. As phased arrays offer considerable application flexibility, software versatility is highly desirable. Phased array inspections can be manual, semi-automated (i.e. encoded) or fully automated depending on the application, speed, budget etc. Encoder capability and full data storage are usually required. Though it can be time-consuming to prepare the first set-up, the information is recorded in a file and only takes seconds to re-load. Also, modifying a prepared set-up is quick in comparison with physically adjusting conventional probes. Phased arrays are very flexible and can address many types of problems. Consequently, ultrasonic phased arrays are being used in a wide variety of industries, where the technology has inherent advantages. These industries include: aerospace, nuclear power, steel mills, pipe mills, petrochemical plants, pipeline construction, general manufacturing and construction, plus a selection of special applications. All these applications take advantage of one or more of the dominant features of phased arrays (Jerome, 2008):

- **Speed** : scanning with phased arrays is much faster than single probe conventional mechanical systems, with better coverage;
- **Flexibility** : set-ups can be changed in a few minutes, and typically a lot more component dimensional flexibility is available;
- **Inspection angles** : a wide variety of inspection angles can be used, depending on the requirements and the array;
- **Small footprint** : small matrix arrays can give significantly more flexibility for inspecting restricted areas than conventional probes
- **Imaging** : showing a “true depth” image of defects is much easier to interpret than a waveform. The data can be saved and re-displayed as required.

Each feature generates its own applications. For example, “speed” and “Flexibility” is important in pressure vessels and pipeline welds due to the size and geometry changes. “Inspection angles” is the key for some pressure vessel and nuclear applications. “Small footprint” is applicable to some turbine applications. “Imaging” is useful for weld inspections. NDE phased array technology is relatively new and still requires some set-up effort, especially for complex 3D applications. 2D set-ups are generally straightforward. Phased array systems are often more costlier than their single channel counterparts; however, the economy gained due to higher speed, data storage/ display, smaller footprint and greater flexibility offset such higher costs.

### SAE AMS Acceptance Standards for Ultrasonic Testing

For weldment inspections using angle-beam technique SAE AMS 2632 is predominantly used [9]. The Acceptance level is

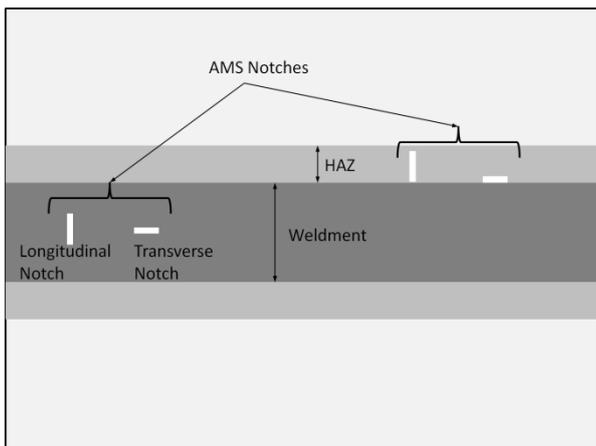
selected from E,F,G and H notches. The Notch acceptance criterion is chosen to correspond to critical crack size arrived by fracture design. The various AMS notches are tabulated in Table 1 below.

**Table 1. Dimensions of different AMS notches**

SAE AMS Notch	Length in mm	Depth in mm	Width in mm	Area in mm <sup>2</sup>
E	1.02	0.51	0.25 max	0.52
F	1.27	0.76	0.25 max	0.97
G	2.54	1.27	0.25 max	3.23
H	4.06	2.03	0.25 max	8.24

**Experimental Evaluation**

Notch are prepared by EDM process on a welded coupon plate of the thickness equivalent to that of the pressure vessel to be inspected. Notches are created in both longitudinal and transverse direction . For the purpose of Ultrasonic Inspection, notches were made on parent metal and welded plates in the manner shown in Fig. 9. Notches are made in both Weld region and Heat Affected Zone (HAZ) region and in transverse and longitudinal direction as shown. Scanning of this reference notch is carried out with the angle probes to establish the Distance Amplitude Curve (DAC) for various angles (45<sup>0</sup>, 60<sup>0</sup> and 70<sup>0</sup>) and for Phased array Inspection.



**Figure 4. Typical Ultrasonic Welded Reference Plate**

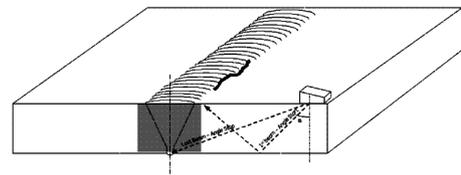
**Table 2. Weld Specimens with SAE AMS Notches**

S. No.	Thickness	Joint Type	Notch
1	3.82	Single V Butt joint	E
2	3.62	Single V Butt joint	F
3	3.66	Single V Butt joint	G
4	4.80	Single V Butt joint	E
5	4.76	Single V Butt joint	F
6	4.85	Single V Butt joint	G

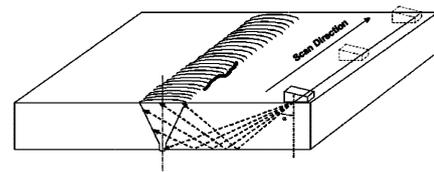
**Test Setup for weld Inspection**

In conventional ultrasonic testing generally we use the probe with the angle of 45°, 60° and 70° as a standard UT probes. Based on the weld geometry the ½ skip and full skip distance shall be marked on part. Inspector move the probe between ½ skip to full skip distance in the raster scan format. In phased array ultrasonic testing the probe has to be mounted on the prefixed angular wedge, hence it transmits shear wave inside the material for weld inspection. The ultrasonic beam can be steered from 35° to 80° for the entire weld coverage. Based on the weld geometry the scan plan has to be configured in the

phased array instrument. The coverage of weld can be assured with the help of an appropriate software tool. The scan plan has to be defined in such a manner that the optimum distance has to be calculated from the weld centre line (WCL) to the wedge front. With the fixed optimum distance the scan plan has to be designed such that the lower most angle hits at the top edge of heat affected zone (HAZ) with the full skip. Each beam will be steered at different angle and hit at the different depth of the weld specimen (Anandamurugan, 2009).



**a) Conventional UT scanning**

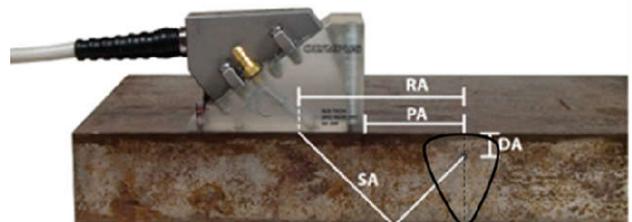


**b) Phased Array scanning**

**Figure 5. Scan Setup for Inspection**

By keeping the probe with reference to optimum distance moving the probe with line scanning will cover the entire weld. Hence it improves the scanning speed when compare to conventional A-scan inspection by line scanning instead of doing raster scanning. Based on the scan plan, the parameters of part, probe and scanning pattern has to be configured in the instrument. The weld dimensions has to be configured as weld overlay. The weld overlay will draw the profile of the weld on the sector image. This will be useful for the inspector to spot the weld location immediately, when there is a defect indication. Origin line will be used to locate the weld centre line. The leg lines and measurements will make the user to easily the interpret the depth of defect from the scanning surface and horizontal location of the defect from weld centre line. The advantage of sector scan inspection of weld is the scanning speed and easier differentiation of weld defects from the root and the weld cap. Whenever the defect occurs the user has to spot the location and evaluate the defect.

Scan Setup for Welded Specimen	Equipment Used
Scan Type : Sector Scan	Olympus Omniscan MX
Angle Start : 43°	Probe 5MHz 60 element probe
Angle Step 1°	Maraging Steel test plates with EDM Notches
Angle Stop 70°	



PA – Forward position of the reflector with respect to the tip of the wedge  
 DA – Depth of the reflector at Gate A  
 SA = Sound path length to the reflector  
 RA = distance between the wedge reference point and the reflector

**Figure 6. Linear Scanning of welds**

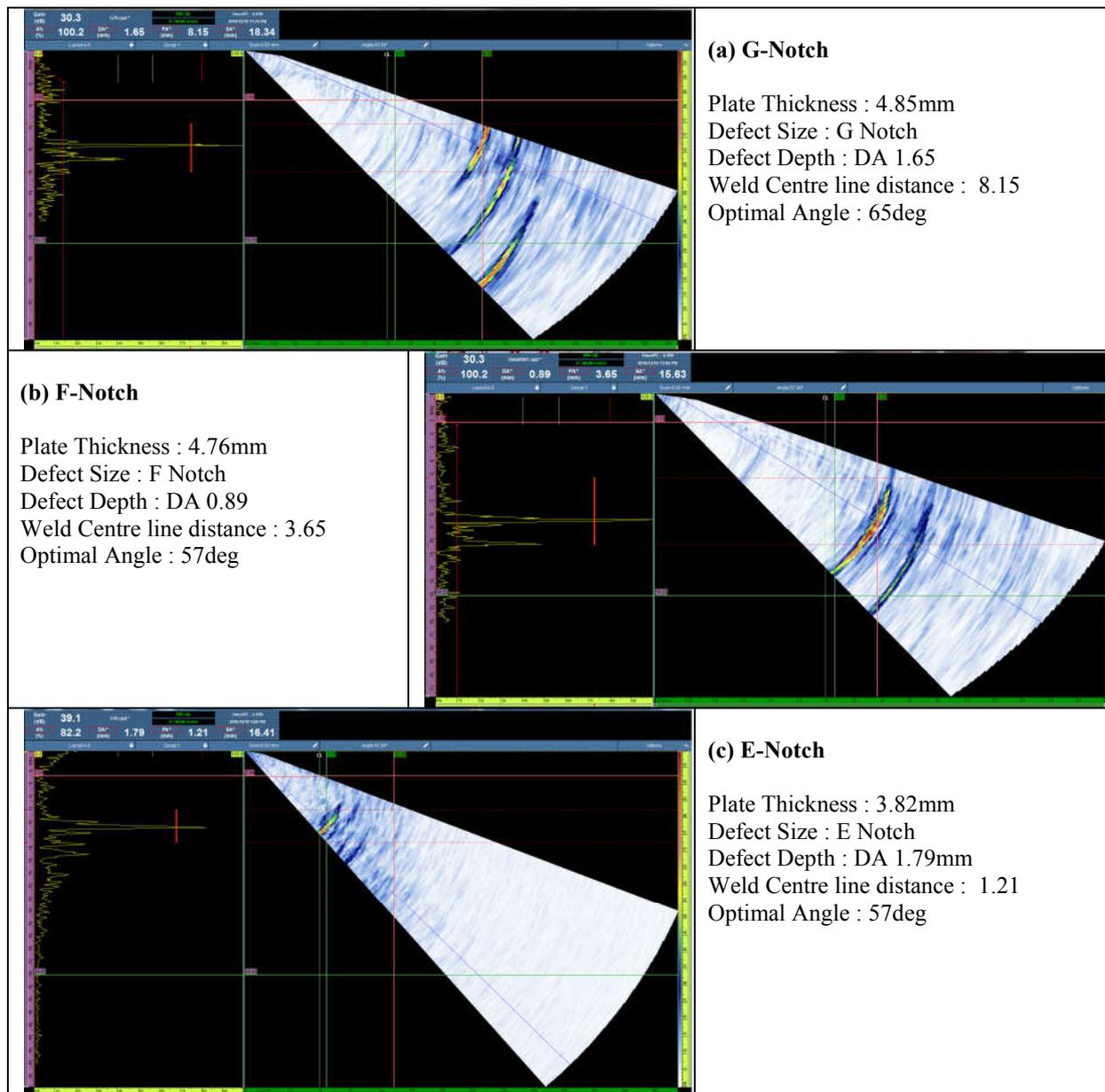


Fig. 7. S-Scan Image SAE AMS Notches

### Evaluation of defects

The representation and dimensioning of different type of weld defects on sector scan is given in Fig.6. The material depth and surface projection measurement will ease the user to spot the location of the scan. The sectorial image directly allows flaw location and sizing in depth direction, The S-scan image of a G, F & E Notches are shown in Fig(s). 7a, 7b and 7c. From these images it can be differentiated between the geometrical indications (front/backwall echo) and the real defect (notch), and from the dynamic behaviour of the flaw echo the geometric positioning of the defect can easily be found. However, the influence of the beam divergence has to be put into consideration, in order not to over evaluate the defect.

### Conclusion

Presently, three times UT is being carried out for the rocket motor casing welds. At first, UT is performed in as welded stage, then after Heat treatment stage and thirdly performed at post pressure test stage. Each time testing is being performed with three different probes (45 deg, 70 deg and normal probe) which makes the task tiresome and time consuming [11].

If instead, at all these stages phased array has to be implemented, a single Phased Array probe can scan the weld at various angles (sectorial scan). Inspection of thin sections are quite difficult as the number of mode converted signals reaching the receiver-transducer increases with decreasing thickness of the specimen. Moreover, in the case of sub-surface defects, the defect echo tends to merge with the frontwall and the backwall echo. The problem of inspection of thin sections can be tackled by using higher frequency ( $\geq 5$  MHz) transducers, which increases the resolution of the S-scan image. This may be acceptable since the accompanying higher attenuation is less of a problem in thin samples. Using the phased array, it is possible to increase the angular resolution and vary the gain dynamically to clearly separate the defect echo from the backwall. Enough trials have to be carried out on thin plates with standard notches (E, F & G notches). The smallest defect of E-Notch on 3.6mm plate is comfortably detected. Phased arrays offer considerable potential for weld inspections due to their flexibility and versatility. Scan patterns can be tailored to the code, the component and the customer's requests. Once set-up, the scan can be reloaded and used indefinitely. Phased arrays offer other advantages for pressure

vessels: no safety hazards, “immediate” inspections, digital archiving, advanced imaging, better defect detection and improved sizing.

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