Ultrasonic Scanner for Heat Treatment Qualification in CNG Cylinder Fabrication

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Abstract: Designing and manufacturing of an automatic ultrasonic testing system (scanner) for flaw detection of compressed natural gas (CNG) cylinders, particularly in heat treatment quality assessment, is explained in this paper. Ultrasonic scanners have been installed on 5 different CNG production lines in the territory providing a fast and reliable test of cylinders with the capability of logging results according to customer demands. The paper explains both the machine specifications and the challenges faced during the manufacturing and starting up stages. A questioner was designed to collect the opinions of operators in different sites about handling easiness and performance of the scanners. It was proved that the ultrasonic scanners efficiently identify defects caused in different stages of CNG production line especially in heat treatment furnace. Besides the innovations applied to overcome the practical matters in machine manufacturing, the knowledge of ultrasonic interpreting has been transferred to operators and they earned enough proficiency to distinguish between flaws and noise signals.

Keywords: CNG production line, Heat treatment, ISO 11439 standard, Ultrasonic scanner

1 Introduction

Iran was increasingly intending to substitute gasoline with gas in vehicles for last 5 years. Compressed natural gas (CNG) cylinders are mainly considered in this approach. It is essential to assure on the quality of CNG cylinders since the gas pressure is high enough (almost 200 bar) to cause an explosion and severe accident in case of any abnormality. Moreover, monitoring of used cylinders should be repeated every 5 years. ISO 114391 has been approved as the mandatory standard for the CNG cylinder production process in Iran2. Other complementary standard, ISO 190783 (with the national code: ISIRI-9426) is also considered applicable since it has the main concepts of inspecting, monitoring, and destructive and nondestructive testing (DT & NDT)4.
Steel, aluminum, and composite materials are the main materials used in the body of CNG cylinders which are divided into four categories as Table 1.
Three different types of testing including the prototype testing, batch testing, and whole testing are applicable in CNG production lines. Prototype testing shall be conducted on newly designed cylinders. Finished cylinders representing the normal product of this type are tested and engraved with appropriate identification marks. Batch testing shall be conducted on finished cylinders which are representative of normal product of an approved type. The cylinders required for testing shall be randomly selected from each batch. All the cylinders of the bach receive the related identification marks provided that the representatives pass the test statistically. In whole test, the test shall be carried out on all cylinders of a batch. In all of these three types of testing, nondestructive examinations shall be carried out in accordance with a standard acceptable to the regulatory authority.

Table 1: Different types of compressed cylinders

Type 1	Metal	Complete Steel, 34CrMo4 alloy
Type 2	Hoop wrapped	Metal liner reinforced with resin impregnated continuous filament
Type 3	Fully Wrapped	Metal liner reinforced with resin impregnated continuous filament
Type 4	All Composite	Resin impregnated continuous filament with a nonmetallic liner

Table 2 shows a summary of different test types offered by ISO 11439.Ultrasonic test is one of the important examinations recommended by ISO 11439 to be implemented on every cylinder for determining the position and depth of flaws. An ultrasonic wave is sent into the metallic body and the echoes are received. In order to assure the preciseness of the test, four different artificial flaws (reference notches) made on internal and external surfaces of a cylinder's sidewall in accordance to annex B of ISO 11439 (Figure 1) are used as the calibration reference.

Table 2: Different test types for CNG production line

Type of examination		Examples
Test on every cylinders (Whole test)		Hardness test, Ultrasonic test, Hydrostatic test
Prototype and Batch test	Tolerance strain examination	Bonfire test, impact tests
	Environmental examination	hydrostatic pressure burst, tensile test, coating batch test, Penetration test, Sulfide stress cracking resistance test, material tests
	Cyclic examination	Leak before break test(LBB), Burst test, Ambient temperature pressure cycling test, Corrosion tests

The ultrasonic system shall detect internal and external flaws with equal amplitude and along with flaw length clearly. Cylinders with indications which are equal to or greater than the indications from the reference notches shall be withdrawn. The thickness of whole sidewall is investigated and shall not be less than the minimum acceptable figure according to the standard.

Both contact and immersion probes may be used, therefore, surface should be clean without any tiny pieces stuck on it. The procedures for ultrasonic examination are valid for sidewall zone and the neck and bottom areas cannot use ultrasonic examination due to thickness alteration in transition between sidewall to neck/bottom. Operators shall have ultrasonic level 2 certificate in accordance to the IRISI-ISO-9712 training method 5,6.

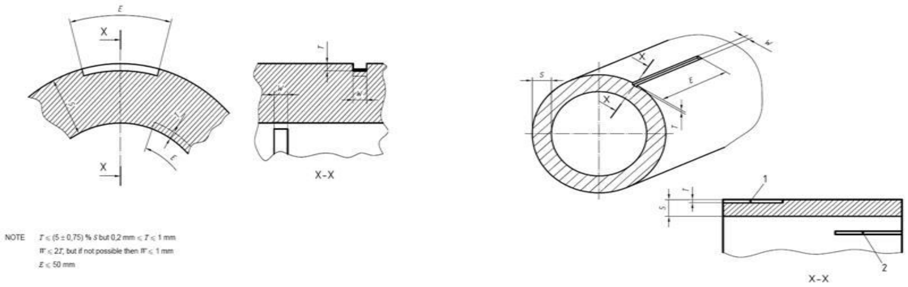

Fig. 1. Calibration block for checking the performance of ultrasonic testing system.

2 System Description

2.1 Mechanics & electrics

Cylinders are put horizontally on two parallel shafts equipped with 10 plastic wheels. A three-jaw chuck holds the neck of cylinder and keeps it in horizontal position during the rotation. Once the rotation starts, probe holder is descended on the initial position of the sidewall and starts the horizontal movement up to the end of the sidewall while the cylinder is rotating7 .The probe holder consists of 5 probes; 2 longitudinal, 2 transversal, 1 thickness and a plexiglas shoe. A suspension system with spring and shock absorber holds the probe holder and keeps a fixed distance between the holder and cylinder's outer surface. This mechanism is important to keep the examination reliable and repeatable. Probe holder has a space for water reservoir to supply the necessary couplant for the test. Used water is gathered in a repository tank to be used again after a filtration stage. The shoe of probe holder is made of a wear resistant material in different radiuses of convexes for different cylinders.

The scanning start/stop point and rotational and horizontal speeds are controlled by an industrial PC to ensure that not only all surfaces are scanned but also a 10% overlap between every two adjacent scans is guaranteed. The total testing time is about 3.5 minutes for a 40 litter water capacity cylinder; from which 2 minutes is for scanning and 1.5 minutes is for the load/unload process. The load and unload mechanism can be designed differently in accordance to the production line requirements. The mechanical and rotational system is installed in a stainless steel tank which serves as used-water collecting system. This tank is equipped with a filtration system for cyclic usage of the water too. Figures 2,3,4 show 3 different types of mechanical designs.

Two electric cabinets contain automation and control parts. They include all necessary tools for controlling the horizontal and rotational speeds and provide signal conditioning and analyses. An operator panel is the interface between operator and the machine (for manual commands). An industrial PC captures the ultrasonic signals from the used multichannel analyzer and presents them in several informative forms.

Fig. 2. The mechanism of type ‘a’ for ultrasonic testing system

Fig. 3. The mechanism of type ‘b’ for ultrasonic testing system

Fig. 4. The mechanism of type ‘c’ for ultrasonic testing system

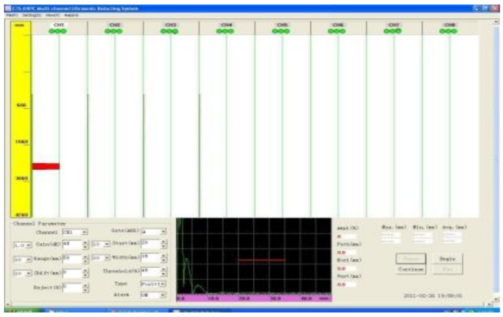

Fig. 5. Software overview

2.2 **Software**

The software of the system, written by visual C, enables the real time showing of the probes' signals, determining the flaw position, flaw length, and thickness measures (Figure 5). Information of each test is saved into a database for reporting purposes. Any specific request by the user can be considered in the software as well.

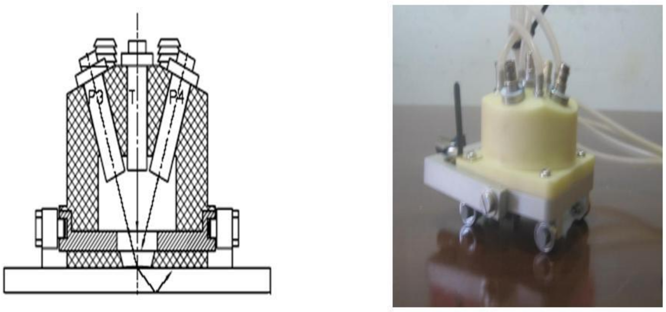

Fig. 6. Probe Holder design and sample

2.3 **Immersion probes:**

Four normal probes immersed in water send longitudinal waves to the cylinder surface obliquely. Mode conversion phenomena occurs on the boundary of water and steel and both longitudinal and transverse waves are produced. Since the incident angle is bigger than the first water/steel critical angle, only the transverse wave is propagated into the cylinder body. The fifth normal probe sends the ultrasonic wave normally into the cylinder body to measure its wall thickness. The probe holder is de

signed so that it keeps one pair of mirror probes parallel with the longitudinal axis of the cylinder for testing the transverse flaws. The probe holder also keeps the other pair of mirror probes perpendicular to the longitudinal axis of the cylinder for testing the longitudinal flaws as showed in Figure 6.

2.4 Manufacturing challenges

2.4.1 Cylinder unbalances

CNG cylinders in CNG production lines are usually made by forming billet, sheet or long length tubes. In these production methods, the section of cylinders is not perfectly round. Moreover, the metal forming and heat treatment process deform the shape of cylinders into asymmetrical shapes and degrades their tomographical circularity. The hot spinning machine which make the neck of cylinders do not have enough accuracy to perfectly center the neck on the longitudinal axis due to the chuck's (which holds the cylinder) vibration and bearings' forces during the rotational twisting8.

In automatic testing of moving parts, the stability of the pieces under examination and smoothness of the movement are the key factors. As it was explained above, the asymmetries caused in the production process of CNG cylinders cause considerable rotational unbalances during the ultrasonic testing of the cylinders. This in turn varys the distance between the cylinder wall and probe holder causing many error signals on the ultrasonic device. It also causes asymmetrical frictions on the probe holder shoe and depreciation of mechanical parts. In order to mitigate the unbalances problem, two extra supporting arms are designed that position on the top surface of the cylinder during the scanning process pushing it down. The end of each supporting arm has one highly abrasion resistant plastic wheel to avoid corrosion while compensating the swings.

2.4.2 Noise

The distance between the probes and ultrasonic multichannel analyzer (Reader) is about 10m owing to the cylinder length and the need to move the probe holder horizontally on the surface of cylinder. Ultrasonic signals are inherently weak, i.e., in the range of mV. They may thus be influenced by high voltage switching on/off of motors and pneumatic jacks. It is essential to consider noise reduction techniques such as using the shield wires, physical separation between low signals and power signals, separating digital and analogue grounds, establishing a proper earthing well, and using high quality probes.

2.4.3 Probes calibration

Immersion probes must be calibrated for angle, sensitivity and beam index carefully. For every probe in the angular position, receipt of one extra echo from the opposite probe shall be considered. The ultrasonic wave passes through both the water and steel mediums. The multichannel ultrasonic device uses sound velocity in steel as reference for sound path calculation. As an example, if the ultrasonic wave runs 30 mm in water and then incidents the steel with an angle of 24 degree, the echo in steel would be seen at 73mm in the screen for a flaw in 3 mm depth (figure 7 and formulas 1to 3).

$$\frac{\sin 24°}{1473} = \frac{\text{Sin}\,\theta_{st}}{3251} \rightarrow \theta_{st} = 63.8° \qquad BP_{2st} = \frac{3mm}{\cos 63.8°} = 6.8mm \tag{1}$$

$$\frac{BP_{1w}}{V_w} = \frac{BP_{1i}}{V_{sst}} \rightarrow BP_{1st} = \frac{3251}{1473} \times 30 = 66.2mm \tag{2}$$

$$BP_{total} = 66.2mm + 6.8 = 73mm \tag{3}$$

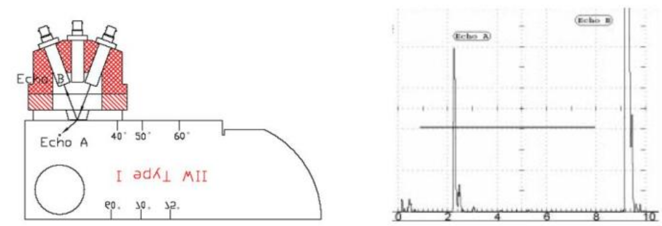

Fig. 7. Echoes of hole in Standard Block and mirror probe

3 Results

Ultrasonic nondestructive testing is a kind of NDT methods which needs experienced operators. The operators must be able to distinguish between noise and flaw pulses and shall be familiar with the standards and accept/reject criteria. That is why it is the only test which requires level II certified operators among all the other mentioned tests for CNG cylinder fabrication according to ISO 11439.

After three years of operation of the first ultrasonic scanner made by this group, a questionnaire was developed and distributed among the operators of 3 different workshops. The purpose of the questionnaire was collecting feedbacks from the users and technicians in technical and operational terms. The results are presented in Table 3. The result shows that all operators have enough knowledge for working with the scanner.

In this paper the applicability of automatic ultrasonic scanner in detection of flaws arising from ironing works (all the processes for making a steel pipe or plate) was validated. It was also proved that any damage caused by poor heat treatment is detectable by the ultrasonic test station immediately. These damages are often cracks arising from elongation and propagation of very small discontinuities. It clearly validates the good efficiency and performance of the scanner.

It was shown that the immersion technique is practically efficient for detecting the longitudinal and transverse flaws and for measuring the thickness of sidewalls. The system is able to operate in compliance with ISO11439 standard and to run a complete ultrasonic test within 2 minutes (excluded load/unload time) for a medium size CNG cylinder. Fortunately, with solving the hardware and software problems the scanners are successfully working in 3 cylinder manufacturing sites. Using of phased array probes9 and the C-scan presentation10 is considered for the future research.

Table 3: Views and comments of the users of the ultrasonic testing scanners collected from 3 different workshops.

Q1: How a flaw pulse is distinguishable from a noise pulse?	Answer 1: Flaw pulse is sharp and has a fix position. In contrast to the noise, it appears almost same by repeating the test. Answer 2: It is distinguishable in accordance with its place and operator's experience. Answer 3 :The noise pulse is happens on all 4 probes almost at the same position but the flaw pulse may not.
Q2: Where is often the flaws positions?	Answer 1: All the cylinder surface. Answer 2: All surface may have. Answer 3: On the central and near to neck area.
Q3: Where is the main place of noises?	Answer 1:No fixed position Answer 2:In middle and near to neck of cylinder Answer 3:No fixed position
Q4: How often is it necessary to change the water?	Answer 1: 2-3 days Answer 2: Every 3 months Answer 3: Each 3 weeks
Q5: To announce a flaw: both mirror probes indications are noticed OR one probe indication is enough.	Answer 1: The pulses of each probe is surveyed individually. Answer 2: Two pulses from mirror probes are surveyed simultaneously. Answer 3: Two pulses from mirror probes are surveyed simultaneously.
Q6: Quality of the ultrasoinc scanner's response to heat treatment furnace malfunction.	Answer 1: In case of heat treatment malfunction the rate of flaws increases considerably. Answer 2: The number of flaws increases whenever the heat treatment is not working properly. Answer 3: In case of bad operation in furnace, the cracks are expanded on body of cylinders and these are shown by the scanner.
Q7: Verification of flaws reported by the ultrasonic scanner with other NDT methods.	Answer 1: Verification of the flaws by magnetic particle testing (MT) and/or hydrostatic test approves them Answer 2: By MT and hydrostatic test is rechecked. They approve each other. Answer 3: By visual and Magnetic test is rechecked. They approve each other.

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