

On the performance of nondestructive testing methods in the hydroelectric turbine industry

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Abstract. Welded joints of turbine runners are one of the most critical parts of Francis turbines due to the presence of welding discontinuity and high stress. Because of thermal cycles, solidification, cooling distortion and residual stresses, welded joints always include discontinuities of different types and sizes. Some specific parameters will limit welding flaw dimensions in some or all direction based on the joint geometry, material and welding procedure. If discontinuities of critical size remain undetected, fatigue cracks might initiate and propagate in these zones because of dynamic in-service stresses leading to high repair costs and long down times. Therefore, reliable NDT methods and good knowledge of the probability of occurrence of welding flaws is important for fatigue life estimations. Every NDT method has its weaknesses; therefore, even after meticulous inspections it is likely for some discontinuities of critical sizes to remain in the welded joint. Our objective is to clarify the probability of detection and occurrence of different types of welding flaws in hydroelectric turbine runners. Furthermore, an overview of current nondestructive inspection methods and their capability in characterizing flaw dimensions will be discussed. Finally, advanced NDT techniques, for the characterization of welded joints integrity, will be proposed.

1. Introduction

The replacement and repair of hydraulic turbines requires large-scale field works and high down time. To reduce the cost associated with unplanned outage, it is desirable to obtain more accurate life estimation of these power generation equipments. One of the most important inputs in life estimation model is the distribution of manufacturing flaws size [1]. This distribution is normally determined using NDT methods. A better knowledge of NDT methods reliability, based on the detectable discontinuity types and characteristics, would help to increase the detection capability of critical flaws. Our objective is to discuss the capability of the NDT methods currently used in the hydraulic turbine industry and propose some alternatives.

The damage tolerance approach used by Hydro-Québec for fatigue life estimation is based on the propagation of existing flaws [2]. With this approach, the characteristics of remaining flaws in the runner significantly affect the life prediction. Therefore, more reliable NDT methods would decrease the risk of cracking and provide a better characterization of the discontinuities in terms of their size, orientation, and location. Ishii et al. [3] studied ultrasonic tip-echo, time-of-flight-diffraction and phased-array ultrasonic techniques as well as the conventional ultrasonic technique for the cast material of the hydraulic turbines. They found that using advanced ultrasonic techniques provides



more accuracy which has a direct impact on fatigue life estimation. It is believed that using inappropriate flaw characterization methods will either overestimate the flaws size or miss some critical defects. In the first case, the fatigue life will be underestimated which leads to more time, money and non-essential repair while an overestimation leads to unplanned down times or failure during service.

Fatigue failures are more likely to occur at the trailing edge of the runner welded joints mainly as a result of the combined effect of dynamic hydraulic load fluctuations and material discontinuities. Furthermore, the welded joints are likely to contain flaws which may act as favourable sites for fatigue crack propagation. Therefore, the use of appropriate NDT methods in those areas is critical.

This paper is structured as follows, common welding flaws, their dimensions and orientation, as well as their probability of occurrence in the runner joints are discussed. In addition, an overview of current nondestructive inspection methods and their capability in characterizing flaw dimensions will be covered. Finally, advanced NDT techniques, which might be better suited for the characterization of welded joints integrity, will be proposed.

2. Different types of welding flaws in turbine welded joints

2.1. Probability of occurrence

The multipass welding technique used for turbine runner joints, inevitably generates some slag inclusions. Inadequate interpass cleaning of the slags of previous passes of flux-cored arc welding (FCAW) as well as inadequate heat for subsequent passes will prevent slag to reach the surface of the newly made pass generating slag inclusions in the remaining weld structure, as depicted in Figure 1. Generally, cleaning problem happens at the toe of the weld beads as a result of accessibility difficulties. Radiographic and conventional ultrasonic records will typically report the presence of some slag inclusions in the as-welded joints. Since slag inclusions may prevent the previous weld bead from being melted by the subsequent layer, some lacks of fusion (LOFs), more critical planar flaws, are also expected to occur.

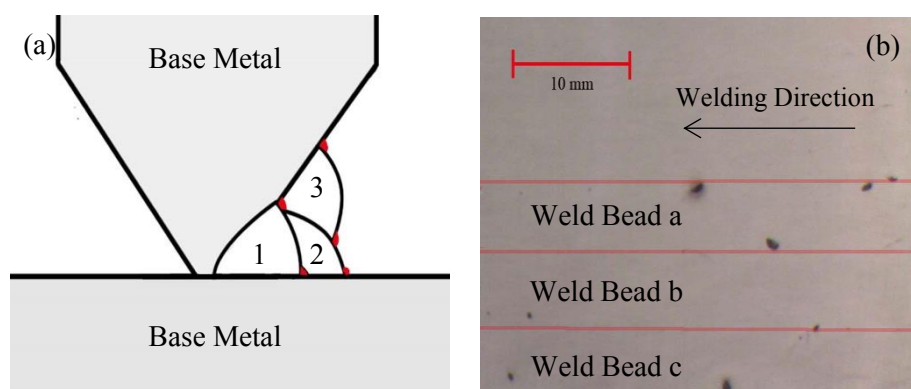


Figure 1. (a) Slag inclusions occurring in the areas of low accessibility, (b) Cross section of weld beads with slag inclusions occurring at their surfaces

Hot cracking rarely happens in the martensitic stainless steel runners due to solidification of the weld metal in delta-ferrite phase [4]; ferrite solubility is high for sulphur and phosphorus so that it does not allow low-melting compounds to form in the weld metal. In the case of porosity formation, it is highly depended on the welding parameters and stability of protection offered by the shielding gas. Normally, the manual FCAW process used for runner production will inevitably have instabilities due to torch manipulation and low joint accessibility. Furthermore, the preheated joint in turn increases the accessibility difficulties and leads to formation of porosities. Radiography commonly reports the presence of porosities.

Based on the study by Thibault et al. [5], weld metal and heat affected zone (HAZ) has roughly the same hardness; accordingly, since there is high longitudinal residual tension in the weld metal under the last weld layer, weld metal is more susceptible than HAZ to subsurface cold cracking. Although these transversal cold cracks are not oriented normal to the direction of high in-service cyclic stresses, if they are not detected by NDT methods, they may propagate leading to fatigue cracks. The propagation will then be in the direction normal to the highest cyclic working loads. It is noteworthy that heat treatment decreases the risk of cold cracking by lowering residual stress levels and the hardness of fresh martensite formed in the weld metal. An example of subsurface cold crack created during Tekken test is represented in Figure 2. Although the metal is under tensile residual stresses in the base metal and in the last layer of HAZ adjacent to the base metal, the low hardness in these areas render the occurrence of cold cracks not critical [5]. In Figure 3, we show an example of a fatigue crack which has originated from the welded joint of a Francis turbine runner.



Figure 2. Subsurface cold crack profile created by Tekken test



Figure 3. A fatigue crack initiated from trailing edge of blade/crown joint

2.2. Dimensions of flaws and their orientation

Normally the height of welding flaws such as porosities, slag inclusions, hot cracks, lack of fusion and solidification cracking cannot be larger than the dimensions of the weld bead. In contrast, cold cracks may practically extend across several weld beads [6]. However, since there is no constraint in the longitudinal direction, welding flaws may have larger dimensions parallel to the joint axis, as shown in table 1. Notice that the distribution of residual stresses is not favourable in this direction [5, 7]; therefore, they are not expected to be prevalent. Since it is difficult to determine the height of discontinuities in turbine joints using conventional ultrasonic data, studies are more focused on finding the length of discontinuities.

Table 1. Distribution of discontinuities in Francis runner

Discontinuity	Height	Length	Type	Description
Slag inclusion	< WBH ^a	No constraint	Volumetric	Detectable by RT and UT
Porosity	< WBH	No constraint	Volumetric	Detectable by RT, but UT may miss it due to its circular profile
Transversal Cold Crack	Can extend several beads	No constraint	Planar	RT and currently used UT has difficulty detecting this type of crack
Hot Crack	< WBH	No constraint	Planar	Detectable by UT
LOF	< WBH	No constraint	Planar	Detectable by UT

^a Weld bead Height

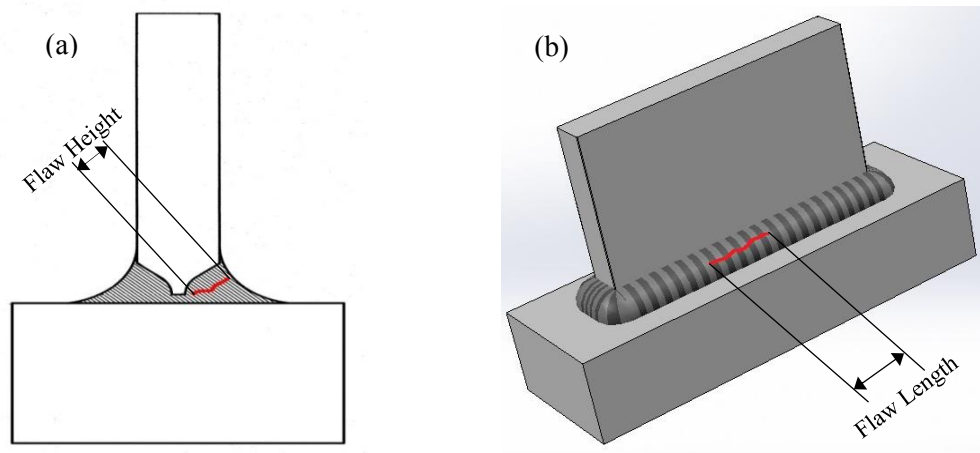


Figure 3. Flaw dimensions: (a) height, (b) length

3. Capabilities and weaknesses of different NDT methods in hydraulic turbine industry

3.1. Currently used conventional ultrasonic methods

Due to high sensitivity of ultrasonic waves to the material internal discontinuities, this is an appropriate method for detecting welding flaws. In the currently used angle beam shear wave inspection method, different beam angles have to be used in order to make sure that discontinuities with different orientations and location are detectable. If the beam angle does not have correct orientation relative to the flaw, either no indication from that flaw is reflected back to the probe or the indication is so weak that it cannot be discriminated from the background noise. Considering the limitation caused by the geometry of the runner joints, it is not possible to strike lower beam angles directly into the weld bead, as shown in a simplified form in Figure 4; therefore, the inspection pattern changes into second-leg inspection which means longer sound path and more attenuation and scattering along the path which in turn degrades the quality of received signal and decreases signal to noise ratio.

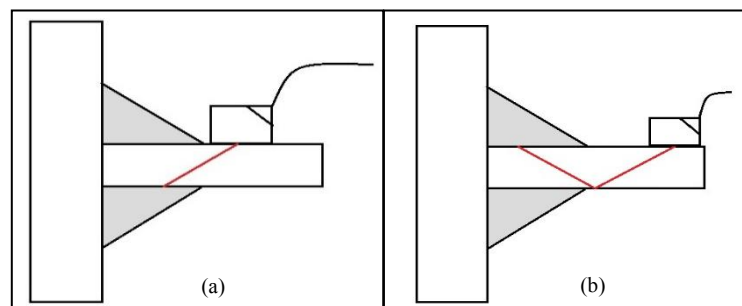


Figure 4. (a) First leg (b) second leg ultrasonic inspection.

This method is very dependant to the inspectors' ability since the indications should be judged directly from the signal displayed by the instrument. Couplant layer variations under the probe also need to be taken into account. Couplant variations will result in different signals received from analogous reflectors. Furthermore, for turbine runners, due to the limited accessibility to the welds, the inspector often cannot conduct the inspection in the most convenient conditions leading to more human errors. Notice that generally, with the exception of written reports, no raw data is stored. For further analysis, it is then required to do the inspection again.

3.2. *Conventional radiography (RT)*

RT is favourable for volumetric flaws including porosities and inclusions. It gives a picture of the profile of flaws as well as their dimensions and position on the film plane. Moreover, understanding RT results is easier than the signals of conventional UT.

Nonetheless, RT has the following limitations. This method has poor probability of detection (POD) for planar flaws if they are not well-oriented relative to film plane. In addition, the outcome of RT is a 2D projection of a 3D joint which conveys no information on the depth of detected indications. Besides, long exposure time is required for the turbine joints section thickness. This also requires the evacuation of the inspection area preventing any other type of work. Furthermore, the film processing time as well as the chemical products used in this step should also be listed as limitations of conventional RT.

3.3. *Magnetic particles testing (MT) and liquid penetrant testing (PT)*

These two techniques are quite useful for detection of surface breaking flaws such as undercuts. MT is also capable of revealing those discontinuities which are close to the surface but not surface breaking. Normally, where MT is applicable (e.g. ferromagnetic materials), its use is recommended due to faster application and setup time as compared to PT. In cases where austenitic stainless steel is used MT is not applicable. Both of these techniques can be used as a complement to UT and RT.

In terms of flaw dimensions, none of these techniques can precisely quantify the depth of detected indications.

3.4. *Capabilities and weaknesses phased-array ultrasonic testing (PAUT) and time of flight diffraction (TOFD)*

PAUT is a recently developed technique employing several electronically controlled transducers in a probe in order to generate different patterns of beam angle and focus. Therefore, several incidence angles can be generated while the probe is fixed on its place which in turn causes the time required for setup of new probes with new angles of incidence to be significantly saved [8] and hence more material is inspected in less time. Since the variation of beam angle is almost continuous with small intervals, PAUT covers a vast range of angles and orientations enabling the detection of randomly oriented flaws while a conventional UT inspection of 45/60/70 degrees has a high probability of missing misoriented flaws [3, 9]. For in-service inspections, the preparation of large area is also eliminated because the PA probe can be fixed on a point and still cover a large part of the weld reducing the time and cost of inspection [10].

With PAUT we obtain more or less a picture of the reflector in the form of sectorial scan, which is easier to interpret, rather than radio waveform A-scan signals. Above all, this technique has the capacity to be automatized hence reduce human factors. Moreover, in terms of flaw sizing, PA probes give more accurate results. Ishii et al. [3] developed a technique for turbine casing and stay vanes which visualizes the outcome of PAUT and localizes the indication in the structure by employing a 3D-CAD program. This eliminates the need to interpret ultrasonic raw results.

TOFD is a new technique which uses the difference in the time of received waves, instead of their amplitude, for flaw sizing. This technique is precise for characterization of the height of flaws since the background noise does not affect its accuracy. TOFD uses the diffracted waves emitted from the edges of the intended flaw, which render it relatively insensitive to the orientation of the flaw. Additionally, diffracted waves propagate in greater range of angles, therefore the position of the receiver probe is not as important [11].

Notice that different standards now include advanced ultrasonic testing methods. As an example in the most recent edition of CSA W59 code [12], both PAUT and TOFD are included as alternative ultrasonic systems.

4. Discussion

Currently, most of Francis runner suppliers use conventional shear wave ultrasonic testing, radiographic testing combined with either MT or PT in order to be able to detect manufacturing flaws. Since during manufacturing the grinding process might mask existing surface breaking flaws and transform them into subsurface flaws, it is recommended to perform MT and PT inspections both before and after post-weld grinding. In fact, when compared with surface breaking flaws, the newly generated subsurface flaws are more difficult to detect and are more prone to propagate due to the interaction between the free surface and the close-to-surface flaw [2].

Due to the possibility of subsurface cold cracking of martensitic stainless steel runners [5], ultrasonic testing is mandatory. Radiography can also be helpful but its low sensitivity to planar flaws as well as long down times due to manufacturing site evacuation can limit its use. Please note that since the most probable orientation of the cold cracks is normal to the weld axis, currently applied ultrasonic methods are likely to miss this type of crack. Although normal to the weld axis is not favourable for crack propagation, if these cracks are missed during the inspections, they may change orientation as they propagate under the service loading and reduce the fatigue life of Francis runner.

As stated by Anandamurugan et al. [13], PAUT technique gives better results in length sizing as compared to RT; in addition, it gives 3-dimensional data on the dimensions and location of discontinuities. More accurate sizing of the flaws obtained by PAUT leads to more reliable remaining life estimation. Furthermore, the human resources and time required for PAUT inspection is normally lower than for RT. This technique is also more efficient than conventional UT. As an example, using PAUT technique on the mock-up samples of Figure 5, the welded joint of the turbine runner can be inspected from one side while using the conventional UT technique the full coverage of weld can only be obtained by applying the 45 and 60 degree probes from one side and the 70 probe from the other side. Moles [14] mentions that for T-joint inspections where multiple shear wave angles are necessary, early investigations showed that PAUT is 5 times faster than conventional manual UT; besides the operator's interpretation of a waveform is no longer such a key factor. Notice that the results of PAUT can be recorded and saved to be interpreted later reducing the human error.

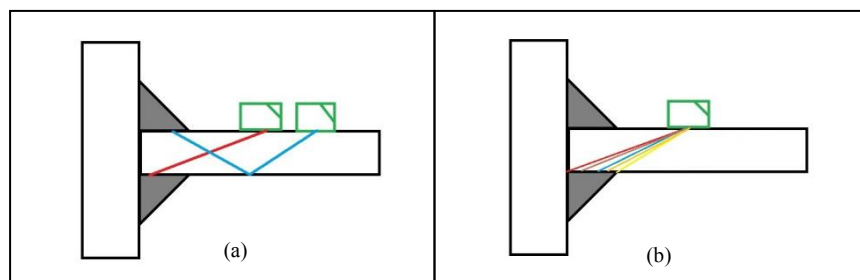


Figure 5. (a) Different beam angles on both sides required for conventional UT and (b) PAUT which covers the whole joint from one side

TOFD seems to be the most favourable for life assessment models since it sizes the flaws in a more accurate manner and it is based on signal timing with disregard to both wave amplitude and background noise [11]. Considering the high thickness of turbine blades, it is expected that the amplitude-base techniques suffer from attenuation and noise. However, for complicated joints such as Y-shape joint of runners, TOFD is difficult to apply and further investigations are required. According to Charlesworth et al. [11], in complicated joints, detection of the flaws is a straightforward process but good knowledge of the technique, physics of sound waves, and the geometry of the joints is needed in order to be able to precisely locate and size the indications.

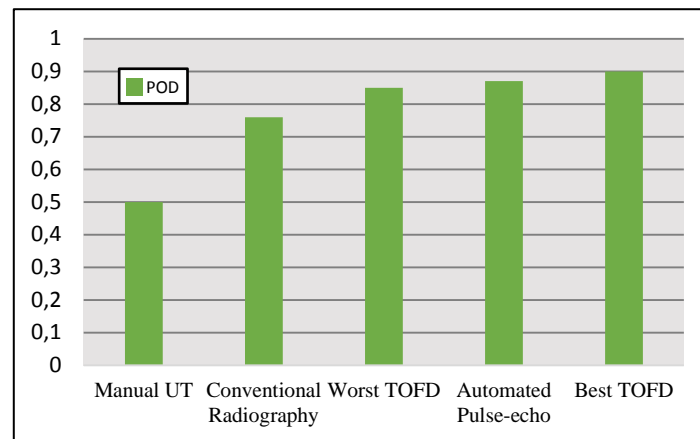


Figure 6. Improvement of inspection capability of steel welded plates by eliminating the human factors (data taken from [15])

Basically using automated inspection process instead of current manual UT would reduce the effect of human factors and working environment leading to improvement in accuracy and POD [15]. Automatization is sometimes not economical due to its costs. Nonetheless, the costs can be sometimes compensated by better POD and lower probability of false indication (POFI), see Figure 6. Lower POFI means lower repair costs and less downtime for repairing false indications [16]. In order to compare quantitatively two NDT techniques, laboratory studies on mock-up samples have to be carried out. In such cases, there is always some discrepancy between the capability of laboratory and real in-site inspection. These differences should be lower for automatic inspection since the environment and human factors are less significant.

Finally, it is important to define and categorize the structure of common flaws, as discussed by Pitkänen et al. [17]. In fact, knowing beforehand the expected common flaws in hydroelectric turbine joints could help better train inspectors and improve their analysis of detected indications. Such knowledge also helps the NDT experts in the design of more effective inspection plans specific to those types of flaws which eventually improves the POD.

5. Conclusion

- The multipass FCAW process used for turbine runners tends to produce slag inclusions which conventional UT and RT results can report.
- Porosities are likely to happen as a result of difficulties caused by preheat temperature and low accessibility of some welded joints.
- High longitudinal residual tensions in the martensitic stainless steel weld metal, promote transversal cold cracks. Currently used UT method has low POD in this detection.
- The dimensions of slag inclusions, porosities, hot cracks, and lack of fusion are restricted to the dimension of weld bead; but in longitudinal direction there is no barrier to limit their size.
- Conventional RT has radiation hazard, poor ability in detecting planar flaws and it requires high radiation time.
- PAUT eliminates the need for several ultrasonic probes, reduces the setup time and a vast area can be inspected from a fixed point. This technique also gives 3D overview of flaws, has higher probability of detection and better detects randomly oriented flaws.

In our current research, the dimensions of most common flaws in the welded joints of martensitic stainless steel runners are investigated and we try to quantify the capability of commercially available NDT techniques for hydroelectric turbine industry, in terms of POD. The knowledge of POD will

allow us to compare the reliability of different NDT methods and get a better picture of the integrity of welded joints by a better characterization of existing discontinuities.

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