Eco matemático ISSN: 1794-8231 (Impreso), E-ISSN: 2462-8794 (En línea) Volumen 11 (1) Enero-Junio de 2020, páginas 78-88

Structural Health Monitoring of Liquid Filled Above Ground Storage Tank Floors: A Time-Reversed Approach to Acoustic Emission Source Location

Monitoreo de salud estructural del fondo de tanques de almacenamiento sobre tierra llenos de líquido: Un enfoque de simetría temporal para la localización de fuentes de emisiones acústicas

Boris Adolfo Zárate-Hernandez[a]

[a*]PhD, Researcher, Grupo de Investigación en Ingeniería Sísmica, Eólica, Geotécnica y Estructural (G-7). Escuela de Ingeniería Civil y Geomática, Universidad del Valle. Boris.Zarate@yahoo.com. https://orcid.org/0000-0001-8141-05270000-0001-8141-0527, Cali, Colombia

Forma de citar: Zárate-Hernandez, B. A., Structural Health Monitoring of Liquid Filled Above Ground Storage Tank Floors: A Time-Reversed Approach to Acoustic Emission Source Location. Eco Matemático. *Eco Matemático,* 11 (1), 78-88

Recibido: 25 de octubre de 2019
Aceptado: 10 de diciembre de 2019

Keywords

structural health monitoring, acoustic emission, time-reversed acoustics, source location, tank floor acoustic monitoring

Abstract: Acoustic Emission (AE) is a proven successful Non-Destructive Testing (NDT) method to assess the state of storage tank floors. Traditional AE source location in tanks floors is performed using only the wavefronts that have traveled directly from the source to the sensor (direct hit). The wavefronts captured after reflected from the tank walls are identified and discarded. This paper proposes a new AE source location algorithm in tanks that considers a combination of reflections and direct hits. The proposed algorithm is based on time symmetry acoustics and ray theory. The methodology uses the concept of time symmetry acoustics in which a wave detected at any location can be directed back to the source when re-created at the detection place. Therefore, the developed approach takes the time at which each wave arrives to the sensor and sends it back as if time had reversed. Ray theory is used in the methodology to account for the way in which the wavefront is reflected when encounters an obstacle such as the walls of the tank. Then, the point of intersection of all wavefronts is identified using an optimization algorithm. This point where all wavefronts intersect is considered the location of the source. The location algorithm considers the first path or direct hits from the source to the sensors combined with reflections obtained by wavefronts bouncing from the tank walls. The proposed location algorithm was validated using numerical data from 176ft diameter tank and experimentally using AE data from a tank 55ft diameter.

*Autor para correspondencia: Boris.Zarate@yahoo.com

DOI 10.22463/17948231.2950

Palabras clave

control de la salud estructural, emisión acústica, acústica invertida en el tiempo, localización de la fuente, control acústico del suelo del tanque

Resumen: Emision Acústica (AE) es una metodología exitosa y que ha sido probada de Ensayos No-Destructivos (NDT) comúnmente utilizada para determinar daño en el piso de tanques de almacenamiento. Tradicionalmente la localización de fuentes de AE en el piso del tanque se realiza utilizando únicamente las formas de onda que han viajado directamente de la fuente al sensor (golpe directo). Las formas de onda capturadas después correspondientes a las reflecciones son identificadas y eliminadas. Este artículo propone un nuevo algoritmo de localización de fuentes de AE en tanques que considera una combinación de ondas reflejadas y golpes directos. El algoritmo propuesto se basa en acústica de simetria temporal y la teoría de rayos. La metodologia usa el concepto de acústica de simetria temporal en el cual una onda detectada en cualquier lugar se puede dirigir de nuevo a la fuente cuando se recrea en el lugar de detección. Entonces, la metodología desarrollada aquí toma el tiempo al cual la onda llega al sensor y la envía de vuelta como si el tiempo se hubiera devuelto. La teoría de Rayos se utiliza en la metodología para considerar la forma en la que el frente de onda se refleja cuando encuentra un obstáculo tal como la pared del tanque. El punto de intersección de todos los frentes de onda es identificado utilizando un algoritmo de optimización. Este punto donde todos los frentes se intercepta es considerado el punto de localización de la fuente. El algoritmo de localización considera el primer camino o el camino directo de la fuente a los sensores combinado con la reflecciones obtenidas por los frentes de onda que rebotaron de las paredes del tanque. El algoritmo de localización propuesto fue validado usando datos numéricos de un tanque de 176 pies de diámetro y datos experimentales usando datos de AE provenientes de un tanque de 55 pies de diámetro.

Introducción

Above ground liquid-filled tanks are indispensable in many industries such as oil refineries, chemical plants and power plants. The bottom of above ground tanks are made of steel and are exposed to different chemicals and vibrations. The floor of these tanks are subjected to different stresses and susceptible to the development of cracks and corrosion. The bottom of the tank results very difficult to inspect while the tank is still in service using most Non-Destructive Methods (Cole and Gautrey 2002). In order to access the floor, the tank has to be emptied and cleaned, which can make the inspection very expensive. Traditionally the floor of the tank is inspected in a "Leak-based" or a "Time-based" maintenance practice. In the "Leak-based" practice, tanks are taken out of service and inspected when a major problem such a leak appears. This practice is banned in most countries. In the "Time-based" approach tanks are inspected periodically. The result is that many tanks are emptied and cleaned without a real need. For instance, Saudi Aramco reports possible savings of more than US$50M if the unnecessary emptied and cleaned of tanks is avoided (Cole and Gautrey 2002). There has been a lot of research on trying to develop a reliable method of inspection of the tank bottom that does not require emptying the tank, including robots with ultrasound probes that scan the bottom (Schempf, Chemel et al (1995), da Cruz, and Ribeiro (2005)) or using guided waves that travel along the shell of the tank floor (Rizzo, Han et al (2010), Chen, Su et al (2010), Mazeika, Kazys et al (2011)). One very successful method to assess the state of the floor of the tank while in service is by using Acoustic Emission (AE).

AE is a passive Non-Destructive Testing (NDT) method that has successfully been used for Structural Health Monitoring applications (Zárate and Caicedo et al 2012, Zárate and Pollock et al 2015, Momeni and Koduru et al 2013, Aggelis and Barkoula et al 2012). AE uses acoustic waves typically in the range of 100 kHz to 1 MHz, propagating through a material. These waves are created by events in the material such as the formation or growth of a crack (Scruby 1987) or a chemical process such as active corrosion. The transient waves are converted into a voltage by AE sensors, and digitalized by the data acquisition system. The waveforms obtained are processed and hit features such as waveform maximum amplitude, duration, absolute energy, and rise time are calculated (Nair and Cai 2010). An amplitude threshold is used to trigger the "hit" (the processing of an individual AE waveform) and determine the time of arrival. AE has gained popularity within the NDT community because of several advantages (Shigeishi, Colombo et al. 2001) compared to other NDT methods including: i) allows in-service online monitoring; ii) geometric independence; iii) simple and economic installation; and iv) wireless nodes available in the market (Godinez-Azcuaga, Inman et al. 2011).

AE is used as a method for global qualification and inspection of above ground storage tanks floors. The sensors are located at the outer surface of the tank along the inferior circumference at a distance of 3 to 6 feet above the bottom knuckle as shown in Figure 1. Notice that in this specific application the acoustic event is started at the floor of the tank by the active leak or corrosion, then the wave goes to the liquid in the tank and from there to the outer shell or wall of the tank. Therefore, the medium for the wave to travel from the source of the event to the shell or wall of the tank is the liquid filling the tank. AE tests are designed so that AE detects a discontinuity and determines the region where is suspected. The AE method then grades the tank and evaluates the need to empty the tank for further inspection. The method relies on the location of the events in the plane of the floor of the tank for its grading. The events are localized based on the difference of arrival time of the hits that compose the event. The assumption in here is that each hit correspond to a direct arrival of the wave coming directly from the source. However, waves traveling in liquid filled structures can travel a long distance because of the low attenuation. The wave bounce of the walls of the tank creating reflections that can be mixed with the direct hits. The result is a combination of direct hits and reflections in the times of arrival, which causes errors in traditional location algorithms.

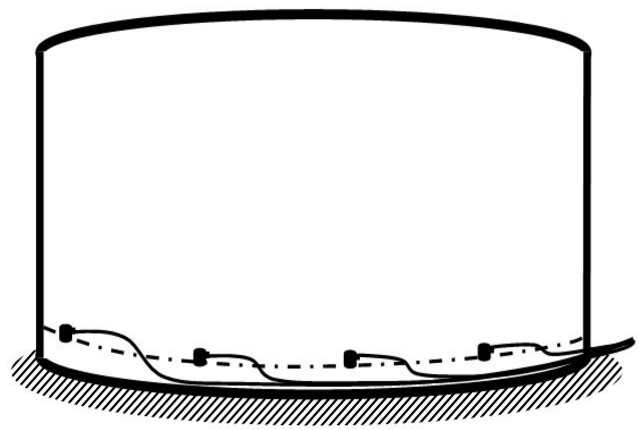

Figure 1. Schematic of above ground storage tank instrumented with AE sensors

Reflections caused by the wave bouncing from the tank wall can be considered into the location algorithm by using time reverse acoustics. The concept of time-reversed acoustics is based on the reciprocity property of the wave equation and expresses that a wave detected at any location can be directed back to the source when re-created at the detection place. Taking the time at which each wave arrives to the sensor and sending it back as if time had reversed. The point where all wavefronts intersect is considered the location of the source. Applications of time reversal for damage location in active sensing have been proposed in the literature. For instance, Anastasi (2011), Xu and Giurgitiu (2007), Wang and Rose et al (2004), and Sohn and Park et al (2007) developed methods for damage location using time reversal with guided waves. These algorithms allow locating damage in plates using an array of sensors some of them acting as receivers and others as sources. Algorithms for the location of sources considering the fact that the arrival wave may not be directly coming from the source have been developed in the literature as well. For instance, Parot (2006) developed a methodology for locating sources in an open space assuming obstructing rigid bodies between the source and the receiver. The concept of time reversal was used to locate the source based on the waves arriving to the receivers. The methodology was tested numerically using different propagation models including a ray tracing model and a full diffraction model. In all cases the source was located showing that the time reversal technique can be used to located sources with very few transducers. Albert and Liu et al (2005) developed an algorithm for source location in an urban environment that considers the wave being reflected from rigid objects before reaching the receiver. The urban environment was modeled using a Finite Element Model. By setting the receivers as sources, the sound refocuses in the vicinity of the original source. This indicates that with few non-line-of-sight sensors the source of the emission can be located. Nevertheless, the use of time reversal in passive methods such as AE for damage location is scarce in the literature. Horn (1996) developed an algorithm for the location of AE sources in structures that use time reversal. The methodology is designed to work in plates assuming the wave does not take a direct path from the source to the sensor. The methodology uses azimuth AE sensors which detect the orientation of the wave. Then, the measured wave orientation is used to direct a ray tracing model along the structure, which is used to find the location of the source. Even though methodologies for source location that do not assume a direct path between sensor and source are available in the literature, there is no methodology available for locating AE sources on the floor of liquid filled tanks that considers reflections.

Traditional location algorithms locate sources on tank floors using only direct arrival wave data. Reflections of the wave bouncing at the tank wall are discarded by choosing a proper Event Definition Value (EDV). However, very often the EDV is large enough to allow the inclusion of reflections within the wave arrival data confusing the location algorithm. This paper proposes an algorithm for locating AE events at the floor of tanks considering a mixture of reflections and direct paths wave arrivals. The proposed algorithm is formulated using concepts of time-reversed acoustics and ray theory. Ray theory is used in here to model the wavefront reflected when encounters an obstacle such as the walls of the tank. The concept of time-reversed acoustics is used to allow sending back the waves detected by the sensors to the source. Then, the point of intersection of all wavefronts is identified using an optimization algorithm. This point where all wavefronts intersect is considered the location of the source. The proposed time location methodology is validated using numerically generated data from a tank 176ft in diameter filled with gasoline and experimental data with a tank 55ft diameter tanks filled with AVGas.

Wave propagation in liquid filled tanks and time reversal

AE Sources located at the bottom of liquid filled tanks generate waves that propagate through the shell and passes to the liquid. The liquid creates a medium for the wave to leak away from the solid. A portion of the energy makes it in to the water generating waves that can travel a long distances in the low attenuation of liquid. The waves propagating in the liquid are governed by the equation: Please notice that in this particular application the assumption is that the wave travels thru the liquid to the outer shell or wall of the tank, not from the metallic bottom directly to the wall of the tank.

$$\nabla^2 \mathrm{F} = \frac{1}{V^2}\frac{\partial^2 \mathrm{F}}{\partial t^2} \qquad (1)$$

where V, is the velocity of the sound in the liquid, F, is the acoustic pressure field and t, is time. Notice that time appears only once in a second derivative term. This implies that if F(r;t) is a solution of the equation, then F(r,-t) is a solution as well (Fink 1992). In other words, if S(r;t)is a wave generated at the source, which is detected at the receiver as R(r,t). Then R(r;-t) generated at the receiver will be detected as S(r,-t) at the source (Parot 2008). Therefore, in order to obtain the location of the AE source the waves detected by the receivers have to be replayed back and the place where all waves intercept correspond to the location of the source.

Ray tracing model

Ray tracing is a methodology to model wavefronts as they are reflected when encounter an obstacle like the wall of the tank. Ray theory is based on the simple assumption that wavefronts can be modeled as a series of discrete beams or rays that follow the reflection law. In other words, the continuous wave front is modeled by using a finite number of rays (Essl (2006)). Ray tracing has been successfully applied in different fields such as seismology (Bai, Hu et al (2014)), architectural acoustics (Serrano, Guillem et al (2014)) and graphics (Wald, Slusallek (2001)).

Let a ray front emanate from a point located at the circumference at the equator of a circle of unitary radius. Then, the position of the ray can be written to account for reflections as the ray bounces according to the reflection law as:

$$X_j = l_j \ cos(\theta) \qquad (2)$$

$$Y_j = l_j \ sin(\theta) \qquad (3)$$

where X_j, is the X position of the ray, Y_j, is the Y position of the ray, l_j, is the distance covered by the ray before being reflected at the tank wall, θ, is the angle measured from the radius of the circle to the path of the ray as shown in Figure 2. Once the ray hits the wall, the position of the ray can be calculated by rotating and translating Eqns. (2) and (3) accordingly. Therefore the position of the ray can be calculated at any instant of time.

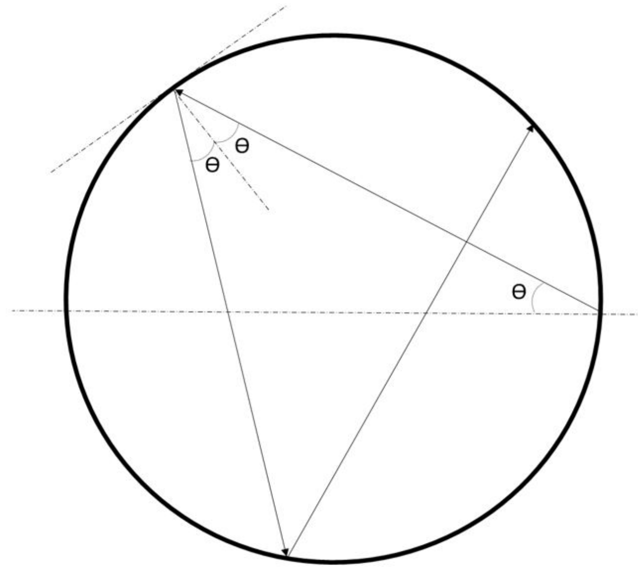

Figure 2. Ray tracing model of a wave in the bottom of a tank

This simple concept allows for the calculation of the position of the wavefronts at any instant of time, given the position of the source at the ring of the tank and the speed of the wave in the liquid. Notice that the ray tracing model used in here is limited to the position of the waveform at a given instant of time and does not consider attenuation, neither interference caused by the interaction of the different wavefronts. In consequence it is possible to obtain the time of arrival from this model, but not its amplitude.

Source location algorithm

Structural Health Monitoring of above ground storage tanks using AE relies in the proper location of the events. Leaks and corrosion at the bottom of the tank generate AE events that are captured by the sensors. Location algorithms find the position of the source based on the time of arrival of the wave to the different sensors. Then, the difference in time between the first arrival and all subsequent hit arrivals ΔT, is calculated. Traditional location algorithms use the Δt_i correspondent to the *i-th* hit to determine the location of the event, based on the theoretical time that would take the wavefront to arrive from the event location to the *i-th* sensor as expressed in the following

$$\Delta t_i = \frac{\sqrt{(x_i - x)^2 - (y_i - y)^2} - \sqrt{(x_1 - x)^2 - (y_1 - y)^2}}{V} \quad (4)$$

where x_1 and y_1 are the coordinates of the first sensor detecting the wave; x_i and y_i are the coordinates of the *i-th* hit detecting the wave; *x* and y are the coordinates of the source location; and *V* is the velocity of the wave in the liquid. Therefore, using the least square method the location that best matches the time of arrivals can be calculated.

On the other hand the proposed time reverse acoustic algorithm considers that the time t_{si} taken for each wavefront detected to travel from the source to the sensor can be calculated using the corresponding Δt_i as

$$\begin{aligned} l_1 &= t_{s1}\, V \\ &\;\;\vdots \\ l_i &= (t_{s1} + \Delta t_i)\, V \end{aligned} \quad (5)$$

where t_{s1} is the time that takes the wave to travel from the source to the first sensor that detects it; and and l_i is the distance traveled by the wavefronts from the sensors that detect it.

The arrival times are used to obtain Eqn. (5) and the wave is propagated from the sensor that detected it. The correspondent wavefront is calculated using the ray theory model of Eqns. (2) and (3) for an angle θ_j that varies between -π/2 to π/2. Then, the distance between wavefronts is minimized using an optimization algorithm. The source of the AE is located at the intersection of all wavefronts. Notice that in the proposed time reverse AE methodology the minimization process aims to find only one variable, the value of t_{s1} that represents the time at which all waves intercept, while traditional algorithms aim to find two variables x and y. Furthermore, in this methodology a minimum of 3 hits is required to locate a source. However, the 3 hits could be obtained from only 2 different sensors. Therefore, the methodology requires a minimum of 2 sensors to locate an AE source at the floor of a tank.

Numerical validation

The proposed methodology to locate AE events at the floor of tanks was validated numerically using simulated events from source located at x= 40ft and y= 20ft on the floor of a tank. The tank was monitored with 15 sensors equally spaced along the ring of the tank and assumed 176ft diameter and filled with gasoline, which has a wave speed of 4101ft/sec. The wave traveling through the liquid and being reflected from the walls was modeled by discretizing the differential equation (1).

Let us rewrite equation (1) as

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = \frac{1}{V^2}\frac{\partial^2 u}{\partial t^2} \quad (6)$$

where its components can be discretized as

$$\frac{\partial^2 u}{\partial x^2} = \frac{u(\mathrm{i,k+1,l}) - 2\,u(\mathrm{i,k,l}) + u(\mathrm{i,k-1,l})}{(\Delta x)^2} \quad (7)$$

$$\frac{\partial^2 u}{\partial y^2} = \frac{u(\mathrm{i,k,l+1}) - 2\,u(\mathrm{i,k,l}) + u(\mathrm{i,k,l-1})}{(\Delta y)^2} \quad (8)$$

$$\frac{\partial^2 u}{\partial t^2} = \frac{u(\mathrm{i+1,k,l}) - 2\,u(\mathrm{i,k,l}) + u(\mathrm{i-1,k,l})}{(\Delta t)^2} \quad (9).$$

Replacing Equations (7), (8) and (9) into (6), it is obtained

$$\begin{aligned} u(\mathrm{i}+1,\mathrm{k},\mathrm{l}) = {} & 2\,u(\mathrm{i},\mathrm{k},\mathrm{l}) - u(\mathrm{i}-1,\mathrm{k},\mathrm{l}) \\ & + b^2(u(\mathrm{i},\mathrm{k},\mathrm{l}+1) - 4\,u(\mathrm{i},\mathrm{k},\mathrm{l}) + u(\mathrm{i},\mathrm{k},\mathrm{l}-1) + u(\mathrm{i},\mathrm{k}+1,\mathrm{l}) \\ & + u(\mathrm{i},\mathrm{k}-1,\mathrm{l})) \end{aligned} \tag{10}$$

where b = $V\Delta t$, assuming Δx and Δy are unitary. This solution of the wave equation allows to obtain both the location and amplitude of the wave at any instant of time as shown in Figure 3.

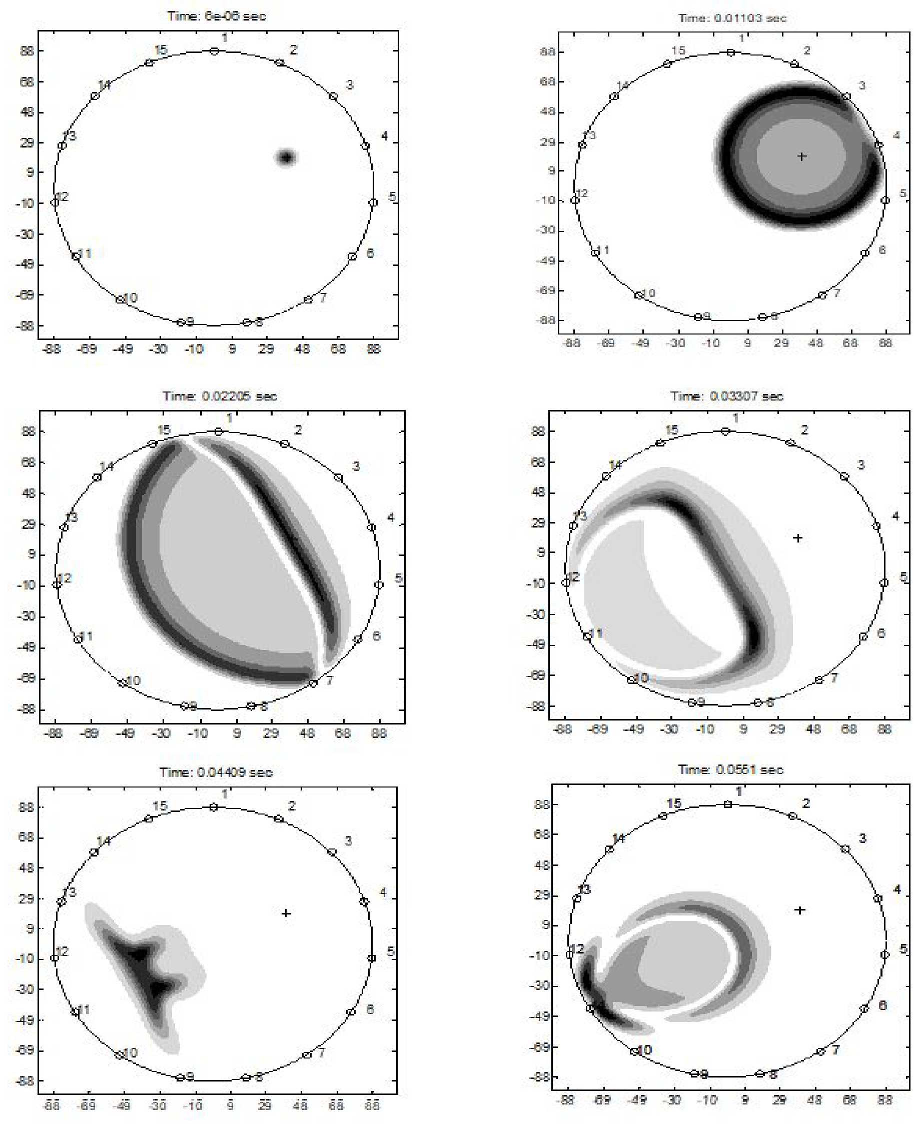

Figure 3 Wave simulation calculated by discretizing the wave equation

The times of arrival of the wavefront to the sensors was recorded and include direct paths as well as reflections. Table 1 shows a selected number of hits with the correspondent time the wave took to arrive to the sensors. Then the arrival times in Table 1 are used to feed the proposed time reverse AE and the traditional location algorithm for locating the source.

Table 1 Time of arrival and delta time of simulated event

Hit	Channel	Time of arrival (sec)	Delta Time (sec)
1	4	0.010799	0
12	13	0.030211	0.019412
13	12	0.031899	0.021100
15	11	0.055096	0.044297
18	13	0.063732	0.052933

Results

Table 1 shows a selection of numerically generated hits that correspond to direct paths and reflections. The source was located using three scenarios: i) only direct hits, ii) combination of direct hits and reflections, and iii) using only 2 sensors. Table 2 shows the results of the location for the traditional and the proposed algorithms. The results show that the time reverse AE location algorithm, is able to deal with a mixture of reflected waves and direct paths and present an error of about 0ft. While the traditional location algorithm pointed to complete different areas of the tank for the case that reflections were included and only two sensors were used. This shows that the proposed algorithm can be used with only 2 sensors as long as there are at least three hits.

Table 2 Location of the numerical event using traditional and proposed algorithms

	X (ft)	Y (ft)
Only direct hits - Traditional algorithm	40.0	19.7
Direct hits and reflections - Traditional algorithm	70.4	41.8
Only direct hits - Proposed algorithm	40.0	20.0
Direct hits and reflections - Proposed algorithm	40.0	20.0
Using two sensors (4 and 13) - Proposed algorithm	40.0	20.0
Using two sensors (4 and 13)- Traditional algorithm	80.1	43.2

Experimental validation

The time reverse AE location methodology proposed in here was validated experimentally using two events from a tank bottom test. The events were obtained from a 55ft diameter, filled with AVGas with wave velocity of 3608ft/sec. The test was performed using 6 AE sensors with a PCI8 system manufactured by Mistras Group. The sensors were installed equally spaced at a distance of three feet from the ground and AE data was captured for a period of 30 minutes. Table 3 shows the hit sequence that compose the events that include a direct hits and a reflection. Notice, that the sequence of channels and the similar difference in times indicates that both events point to the same location.

Table 3 Time of arrival and delta time of experimental AE event

Hit	Channel	Time of arrival (sec)	Delta Time (sec)	Amplitude (dB)
1	1	1.553526	0	43
2	4	1.555424	0.001897	48
3	2	1.555927	0.002401	48
4	3	1.565293	0.011767	40
1	1	9.227154	0	44
2	4	9.228702	0.001548	46
3	2	9.229773	0.002619	47
4	3	9.238667	0.011513	41

Results

The events presented in Table 3 are composed of three direct hits and one reflection. The times of arrival of the hits presented in Table 3 were used to locate the event using the time reverse AE methodology proposed in here and the traditional location algorithm. Two scenarios were considered: i) only direct hits (hits 1 to 3) and ii) direct hits and the reflection (hits 1 to 4). Table 4 shows the calculated location for the event considering both scenarios and both proposed and traditional algorithm. Results show that both algorithms locate to the same region of the tank with a difference of less of 1ft when dealing only with direct hits. However, only the proposed time reverse AE algorithm can point to the same region of the tank within 3ft of difference when the reflection is included.

Table 4 Location of the experimental event using traditional and proposed algorithms

	Event	X (ft)	Y (ft)
Only direct hits - Traditional algorithm	1	-8.7	3.6
Direct hits and reflections - Traditional algorithm	1	-27.5	11.4
Only direct hits - Proposed algorithm	1	-8.7	3.6
Direct hits and reflections - Proposed algorithm	1	-11.5	3.9
Only direct hits - Traditional algorithm	2	-10.8	3.0
Direct hits and reflections - Traditional algorithm	2	-27.3	10.2
Only direct hits - Proposed algorithm	2	-10.7	3.0
Direct hits and reflections - Proposed algorithm	2	-12.0	3.3

Conclusions

This paper presents the formulation and validation of a time reverse acoustics methodology to locate the source of AE events at the bottom of liquid filled above ground tanks. The methodology uses the waveforms captured by AE sensors spread along a ring of the outer surface of the tank to locate the AE event. The proposed methodology considers the direct hits from the source to the sensor as well as the reflections from the tank wall. The outcome is the location of the event at the bottom of the tank without the need of identifying and eliminating reflections.

The proposed methodology uses a ray tracing model of the wavefront traveling through the liquid and accounts for the direct paths as well as the reflections caused by the walls of the tank. Then the time reverse acoustics is used to send the wave back to the source as if time had reverse and the point of intersection of the wavefronts is identified using an optimization algorithm.

The proposed methodology was validated using numerically generated data from a 176ft diameter tank and experimental data obtained from a 55ft diameter tank. Results show that the proposed framework calculates the location of the AE event including the reflections from the tank wall. Furthermore, the proposed methodology has the ability to locate the source of the AE event with fewer sensors than traditional AE location.

The development in accuracy obtained through the use of ray theory and time reverse acoustics, can eventually lead to significant improvements in source location technology for above ground storage tank floors. It is not proposed that this methodology replace the traditional location algorithms currently used in well-established test procedures. But in specific events where the traditional location algorithm fails to locate because of the inclusion of reflections, the proposed reversed acoustic source location can improve the location of the event.

References

Aggelis, D. G., Barkoula, N. M., Matikas, T. E., and Paipetis, A. S. (2012). Acoustic structural health monitoring of composite materials: Damage identification and evaluation in cross ply laminates using acoustic emission and ultrasonics. Composites Science and Technology, 72(10), 1127-1133.

Anastasi, R. F. (2011). Time Reversal Methods for Structural Health Monitoring of Metallic Structures Using Guided Waves, (No. ARL-TR-5716). ARMY RESEARCH LAB HAMPTON VA VEHICLE TECHNOLOGY DIRECTORATE.

Albert, D. G., Liu, L., and Moran, M. L. (2005). Time reversal processing for source location in an urban environmenta), The Journal of the Acoustical Society of America, 118(2), 616-619.

Bai, C. Y., Hu, G. Y., Zhang, Y. T., and Li, Z. S. (2014). Seismic wavefield propagation in 2D anisotropic media: Ray theory versus wave-equation simulation. Journal of Applied Geophysics, 104, 163-171.

Chen, J., Su, Z., and Cheng, L. (2010). Identification of corrosion damage in submerged structures using fundamental anti-symmetric Lamb waves. Smart Materials and Structures, 19(1), 015004.

Cole, P. T., and Gautrey, S. N. (2002). Development history of the Tankpac AE tank floor corrosion test. NDT. net, 7(09).

da Cruz, A. C., and Ribeiro, M. S. (2005). RobTank Inspec–in service robotized inspection tool for hazardous products storage tanks. Industrial Robot: An International Journal, 32(2), 157-162.

Essl, G. (2006). Computation of wave fronts on a disk I: numerical experiments. Electronic Notes in Theoretical Computer Science, 161, 25-41.

Fink, M. (1992). Time reversal of ultrasonic fields. I. Basic principles. Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on, 39(5), 555-566.

Godinez-Azcuaga, V., Inman, D., Ziehl, P., Giurgiutiu, V., Nanni, A. (2011) Recent advances in the development of a self-powered wireless sensor network for structural health prognosis. In: Wu HF, editor. 1 ed. San Diego, California, USA: SPIE; p. 798325-7.

Horn, M. (1996). Acoustic emission source location by reverse ray tracing. U.S. Patent No. 5,528,557. Washington, DC: U.S. Patent and Trademark Office.

Nair, A. and C. S. Cai (2010). Acoustic emission monitoring of bridges: Review and case studies Engineering Structures 32(6): 1704-1714.

Mazeika, L., Kazys, R., Raisutis, R., and Sliteris, R. (2011). Ultrasonic guided wave tomography for the inspection of the fuel tanks floor.

International Journal of Materials and Product Technology, 41(1), 128-139.

Momeni, S., Koduru, J. P., Gonzalez, M., Zárate, B., and Godinez, V. (2013, March). Online acoustic emission monitoring of combustion turbines for compressor stator vane crack detection. In SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring (pp. 86900B-86900B). International Society for Optics and Photonics.

Parot, J. M. (2008). Localizing impulse sources in an open space by time reversal with very few transducers. Applied Acoustics, 69(4), 311-324.

Rizzo, P., Han, J. G., and Ni, X. L. (2010). Structural health monitoring of immersed structures by means of guided ultrasonic waves. Journal of Intelligent Material Systems and Structures, 21(14), 1397-1407.

Schempf, H., Chemel, B., and Everett, N. (1995). Neptune: above-ground storage tank inspection robot system. Robotics and Automation Magazine, IEEE, 2(2), 9-15.

Shigeishi, M., S. Colombo, K. J. Broughton, H. Rutledge, A. J. Batchelor and M. C. Forde (2001). Acoustic emission to assess and monitor the integrity of bridges, Construction and Building Materials 15(1): 35-49.

Scruby, C. (1987) An introduction to acoustic emission, Journal of Physics E: Scientific Instruments 20: 946-953.

Serrano, P., Guillem, I., and Gómez, V. (2014). Ray Tracing Study of the Effectiveness of Acoustic Intervention in the Church of Santa Maria De La Valldigna Monastery. In Construction and Building Research (pp. 383-389). Springer Netherlands.

Sohn, H., Park, H. W., Law, K. H., and Farrar, C. R. (2007). Damage detection in composite plates by using an enhanced time reversal method. Journal of Aerospace Engineering, 20(3), 141-151.

Wald, I., Slusallek, P., Benthin, C., and Wagner, M. (2001, September). Interactive rendering with coherent ray tracing. In Computer graphics forum (Vol. 20, No. 3, pp. 153-165). Blackwell Publishers Ltd.

Wang, C. H., Rose, J. T., and Chang, F. K. (2004). A synthetic time-reversal imaging method for structural health monitoring. Smart materials and structures, 13(2), 415.

Xu, B., and Giurgiutiu, V. (2007). Single mode tuning effects on Lamb wave time reversal with piezoelectric wafer active sensors for structural health monitoring. Journal of Nondestructive Evaluation, 26(2-4), 123-134.

Zárate, B. A., Caicedo, J. M., Yu, J., and Ziehl, P. (2012). Probabilistic prognosis of fatigue crack growth using acoustic emission data. Journal of Engineering Mechanics, 138(9), 1101-1111.

Zárate, B. A., Pollock, A., Momeni, S., and Ley, O. (2015). Structural health monitoring of liquid-filled tanks: a Bayesian approach for location of acoustic emission sources. Smart Materials and Structures, 24(1), 015017.