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Leak detection of shock absorber tubes with acoustic emission

THESIS WORK

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Preface

This thesis is dedicated to all the people who accompanied me on the way of this research. Special thanks deserve to prof. dr. ir. Martine Wevers, ing. Johan Vanhulst, ir. Kasper, ir Stefan Peerenbooms (Tenneco Europe) and my co-student Federico Garza.

Abstract

This thesis is aimed to study the feasibility of using Acoustic Emission (AE) for leak detection after the welding of tubes for shock absorbers, in order to replace the current bubble technique employed in the production. These tubes were pressurized and subsequently analyzed using the Vallen Visual AE system AMSY4. The trials that were carried out with AE in air showed a low reliability due to the high background noise that hides the sound of the leak. Therefore a variable threshold level and some filtering techniques were used to avoid this situation. Thanks to the energy, amplitude, hits, RMS and frequency graphs' information, the trials carried out in water in a lab environment provided results that were a bit better than those done before in air. However for the trials carried out in water and in a production environment did not provide a great reliability.

List of figures

List of tables

Table of contents

1. General introduction

The detection, location and discrimination of growing defects is of great importance nowadays, not only to avoid final failures during service, but also for economical reasons. The concept of a defect is not standardized, and depends on quality and functionality which can be different for each situation. NDT methods do not require the disabling or sacrifice of the system of interest, and therefore they are highly valuable techniques that save both money and time in product evaluation, troubleshooting, and research. One of these methods is Acoustic Emission (AE).

In this master thesis the feasibility of using AE for leak detection of tubes for shock absorbers will be investigated. The advantages offered by the industrial applications of this technique are manifold: Testing of large areas at a reasonable effort, testing virtually in-service, early warning or defect localisation for economic follow-up. These features make AE useful in a production environment [1].

This research will be done for Tenneco Europe, a company that produces these shock absorbers. During the production process, possible leaks can be introduced by the welding operation. At this moment the bubble technique is used to detect which tubes are leaking. This technique consists on pressurizing the piece that is being tested and diving it into water, detecting visually the bubbles formation. Since this technique lacks reliability and turns out to be quite expensive (labor), they search for a better technique for leak detection. Additionally, it would be good to decrease the checking cycle time since it has a big influence on the complete production time. AE used for leak detection could prove to be a better technique. Therefore Tenneco Europe requested to check the feasibility of this technique.

2. Literature. Overview of leak detection techniques

2.1. Non-destructive testing.

Non-destructive testing [NDT] refers to those methods used to examine or inspect a part or material or system without impairing its future usefulness. As the physical system is not to be damaged by NDT, such techniques are valued for saving time and money [2]. NDT is used for in service inspection and for condition monitoring of an operating plant. It can be applied on small to large components and for the measurement of physical properties such as hardness, elasticity modulus and internal stress. The subject of NDT has no clearly defined boundaries; it ranges techniques such as visual examination of surfaces, radiography, ultrasonic testing, thermography, etc. Moreover, NDT methods can be adapted to automated production processes as well as to the inspection of localized problem areas [3].

Leak testing is a form of NDT. It is used for the detection and the localization of leaks, and for measurement the leakage amount in either system (pressurized or evacuated). However, leak testing techniques cannot detect all anomalies, therefore, it leans on other NDT methods to find and evaluate basic material anomalies.

When the word "leak" is used, one refers to a hole, a crack, a crevice, a fissure or a passageway that admits water, air, or other fluids, or allows the fluids to escape. Anyway, the word "leak" does not refer to the quantity of fluid passing through the hole. The "leak" depends on the nature of the fluid flow, the leak geometry, and the fluid conditions: pressure and temperature [4].

2.2. Methods

Focusing on leak location, a primary classification can be the following [4]:

1. Leak location methods that are independent of any characteristic properties of the tracer gas/fluid:

- Chemical and liquid penetrant

- Bubble testing

- Ultrasonic leak test

- Acoustic emission

2. Leak location methods using tracer gases/fluids with easily detectable physical or chemical properties:

- Thermal conductivity

- Halogen

- Infrared

3. Leak location methods involving the use of tracer gases/fluids with atomic or nuclear properties providing easily detectable leak signals:

- Helium

- Mass spectrometer

- Radioactive isotopes

The techniques that are the most important are:

- Halogen tracer gas techniques

Leak testing with halogen vapor tracer gases uses leak detectors that respond to most gaseous compounds that contain halogens such as chlorine, fluorine, bromine, or iodine. If the system is pressurized with one of the halogen tracer gases, or a mixture of a halogen gas with air or nitrogen, a halogen vapor leak detector can be used to locate leaks and to measure the rate of leakage.

- Pressure change tests for measuring leakage rates

The fluid pressure serves to create pressure differentials across walls. This pressure differential, in turn, causes the pressurizing gas to flow, by various mechanisms, through leaks in the containment walls. The higher the differential pressure is, the greater the rate of leakage, so the sensitivity of leak detection is increased.

-Mass spectrometer leak detector techniques

Those techniques are used on high vacuum systems. The mass spectrometer leak detector provides almost ideal leak detection characteristics, including very high sensitivity and a basically rapid response. Two categories are available, the helium mass spectrometer leak detector, that is adjusted to respond only to helium gas, and the residual gas analyzer, that can be adjusted to respond to any gas in a fairly wide mass range.

Techniques using a mass spectrometer have as a necessary consequence the passage of a tracer gas through a presumed leak from one side to the other side of a pressure boundary and subsequent detection of tracer gas on the lower pressure side. There is usually one helium leak testing technique for each practical application that gives optimum results. It depends on the size, the shape, the location of the equipment, the pressure (or vacuum), the leakage rate, the degree of automatic leak testing operation required and the number of parts or complexity of the system

-Bubble techniques

In bubble techniques, a gas pressure differential is first established across a pressure boundary to be tested. A test liquid is then placed in contact with the lower pressure side of the pressure boundary. Then, gas leakage through the pressure boundary can be detected by observation of bubbles formed in the detection liquid at the exit points of leakage. This method provides immediate indications of the existence and location of large leaks, and with a longer time, the detection of small leaks, whose bubbles form slowly.

Bubble techniques can be divided into three classifications:

1- Liquid immersion technique, where the bubbles form and rise toward the surface after the immersion.

2- Liquid film application technique, where a thin layer of test liquid is flowed over the low pressure surface of the test object. Useful for structures that cannot be immersed.

3- Foam application technique, where the escape of gas blows a hole through the foam, revealing the leak location. Useful for large leaks [4].

-Acoustic Emission technique

According to ASTM E1316 - 08a Standard Terminology for Nondestructive Examinations, Acoustic Emission is defined as "the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material, e.g. plastic deformation, crack propagation, erosion, corrosion, impact, leakage. [5]" Acoustic Emission is the energy emitted in form of mechanical vibrations as a result of sudden change in most structures. Because bubble techniques and AE technique were investigated more thoroughly in this master thesis, the paragraphs 2.4 and 2.5 focus a bit more on these techniques.

2.3. Technique selection

There are several leak detection techniques. The selection of a specific leak testing technique depends on three important issues: the applicability taking into account all service conditions, the cost and the sensitivity of leak testing. Leak sensitivity refers to the minimum detectable amount of leakage that will occur in a specific period of time, under specified leak test conditions. Increasing the sensitivity increases the accuracy and the reliability. Therefore, the costs will be much higher, because the sensors and the equipment will be more expensive. Occasionally, it is desirable to locate every existing leak irrespective of size because stress leaks can grow during operation [2]. High temperature leaks may be very small at test temperatures but have higher leakage rates at system operating temperatures. Also, high T cycling can create stresses that result in changing leakage rates.

The choice of the method will also depend on the test finality (leak detection, leak location, leakage measurement); and depending on the application to focus on, a different method will be used. The first question in order to choose the best leak testing method is: “does the test reveal the presence of a suspected leak?” or “does it have to show the location of a known leak?” And the second question would be: “is it necessary to measure the rate of leakage at the specific leak?” The final selection of the leak method is made from only three or four possible test methods. The special conditions under which the test must be carried out can become a decisive factor in this final test selection [6].

2.4. Bubble techniques

2.4.1. Immersion technique

The immersion method of bubble testing for leaks is applicable for specimens whose physical size allows their immersion into a container of liquid. The test objects could be hermetically sealed or sealed off during the test. This technique involves pressurizing the system or component under test with a gas, before and during the period the component is immersed in an inspection liquid. The source of the leak is indicated by the bubbles of gas that are formed when the gas under pressure emerges from a leak into the surrounding liquid. The appearance of a bubble gives immediate indication of the opening through which the gas passes. The bubble or the bubbles stream, issuing from a leak opening, locates the exit point of leakage. The immersion procedure of bubble leak testing serves to locate the leak as well as to indicate that a leak exists. The major attributes of bubble leak testing are its simplicity and its ability to locate leaks very accurately.

2.4.2. Advantages of bubble techniques

Bubble leak testing has the obvious advantages of being relatively simple, rapid, and inexpensive. It is a fairly sensitive leak detection technique and enables the observer to locate the exit points of leaks very accurately. Another major advantage of bubble testing is that very large leaks can be detected readily. Some more sensitive leak testing methods often have responses so slow that leak may be missed while probing. With bubble tests, it is not necessary to move a probe or sniffer from point to point. In immersion bubble tests, the entire pressurized component can often be examined simultaneously for leaks on exposed surfaces visible to the observer. In some cases, test components may have to be turned over to expose to view the underside, so that leaks from this area can be seen. All leaks are revealed independently in immersion bubble leak testing. If it is desired, large leaks can be first detected with rapid bubble test methods.

In addition, during bubble leak tests it is not necessary that all connection pipes and valves be free from leaks. However, detection of small leaks requires operator patience and additional test time for the bubble to form. Care is required to ensure that all detectable bubble indications present are observed [7].

2.4.3. Factors influencing the bubbles sensitivity

The basic principle of the bubble emission leak test consists of creating a pressure differential across a leak and observing bubbles formed in a liquid medium located on the low pressure side of the leak or pressure boundary. The accuracy of the bubble emission test method can be influenced by factors [7] such as:

1. *The pressure differential acting across the leak.*
2. *The tracer gas probing medium that passes through the leak.*
3. *The contamination on surfaces being tested (oil, dirt).*
4. *The ambient weather conditions (rain, wind).*
5. *The test liquid used for bubble formation*

This last one needs special care. The process of forming bubbles that result from gas flow through a given leak into an immersion liquid depends on the physical properties of the liquid and on the tracer gas. Thus, by a suitable combination of the liquid and the gas selected for testing, the sizes of the bubbles and the rate of formation of bubbles can be modified [7].

For purposes of leak detection and location, it is desirable that the bubbles be clearly visible to the human eye. The sensitivity of the immersion is determined by the operator's ability to observe bubbles formed at the outlet end of small holes [7].

Due to surface tension, these passages often may set up a high resistance to the passage of tracer gas. High surface tension of the test liquid may restrict the formation of bubble indications. The more readily the bubbles are evolved, the more easily they are observed. It is possible to change the sensitivity of the bubble leak test by changing either the tracer gas or immersion liquid. It is desirable to use a bubble forming testing liquid with low surface tension and low viscosity. The pressure differential acting across the leak should be made higher for detection of capillary leaks of a small diameter. In addition, the use of a low viscosity, low molecular weight tracer gas will increase the gas flow rate through the capillary leak. Regarding the testing liquid there are commonly three options to leak at [7]:

1- Immersion in water baths

If water is used, it must be treated to reduce the surface tension. This reduces the bubble size and reduces the tendency of bubbles to cling to the surface of test objects. Bubbles in a water bath cling to the surface of the test component and build up to a relatively large size before breaking loose and rising to the liquid surface. This means that small leaks forming bubbles in water would require a long response time produce a bubble that would be visible on the surface. Under these test conditions, a component might erroneously be passed as acceptably sealed because insufficient time was allowed for bubbles to form a conclusive test indication.

2- Immersion in oil bath

When objects with leaks are submerged in an oil bath, a steady stream of fine bubbles appears. This provides highly visible bubble indications with short response times. However, a disadvantage of the immersion bubble tests using an oil bath is the fact that test components must be degreased after being tested to remove the oil from their surfaces. It is also expensive.

3- Immersion in alcohol

The advantage of methyl, ethyl and isopropyl alcohol is the alcohol's cleaning properties. This eliminates the degreasing process, and cleans foreign matter introduced by production processes from surfaces of test objects. After the test parts are removed from the alcohol bath, no alcohol remains on the parts because of the rapid evaporation rate of alcohol. On the other hand, it is dangerous due to explosion hazards.

Another factor that affects the accuracy of bubble testing is *the size of the bubbles involved*. The size of bubbles increases with an increase in surface tension of the immersion testing liquid. For generation of large numbers of small bubbles, it is desirable to use liquids with small surface tension. Bubble size can also be affected by vibration. If the test object is subjected to increased levels of vibrations, the bubbles break off before they would have been released with a stationary test object. This could be useful since vibration increases the bubble emission rate for a given gaseous leakage rate [7].

If the pressure acting upon the surface of the immersion liquid is reduced below the atmospheric pressure until bubbles just emerge from the end of the leakage path, limitations are imposed by the tendency of the liquid to boil under conditions of reduced pressure. Immersion liquid with a high boiling point (low vapor pressure) allows reasonably low pressures to be used within the detection liquid without boiling. To enable detection of smaller leaks, it is desirable to use immersion liquids having low values of surface tension. However, such low tension liquids also have lower boiling points. These liquids may boil spontaneously before the pressure over the liquid could be reduced sufficiently to significantly improve gas flow through the leaks, or to enlarge the bubbles so as to increase their visibility [7].

2.4.4. Methods to increase the bubble test sensitivity

The sensitivity of a leak testing procedure must be adequate to permit detection of all leaks of a certain size and larger so that all detected leaks can be repaired. The hole or crack that constitutes the physical leak is usually characterized in its size of leak by the amount of gas passing through it as leakage. With certain combinations of tracer gases and detection liquids, sensitivities of 10^{-8} Pa m^3/s have been attained with calibrated leaks operating under laboratory conditions. Under excellent industrial immersion bubble leak testing conditions, maximum sensitivity of bubble testing is in the range of 10^{-5} to 10^{-6} Pa m^3/s. The sensitivity of a bubble emission leak test can be increased by [7]:

1. Increasing the time allowed for bubble formation and observation.

2. Improving conditions for observing bubble emission.

3. Increasing the amount of gas passing through the leak.

Despite of these methods, it is not always easy to put them into practice due to the time importance in a production environment. In addition, it also depends upon the observation and alertness of the leak test operator. Practically, under excellent industrial test conditions, there is no question that leakage of 10^{-6} Pa m3/s can be observed by the immersion bubble testing procedure. However, it is a different matter when the operator does not know that a leak exists and has to examine a long weld seam for a possible bubble. Conceivably, he might not wait long enough for bubbles to form, or he might fail look carefully after sufficient time, at every portion of every area where a potential leak might exist. Thus, provision of optimum bubble observation conditions and continuing training and motivation of bubble test operators to achieve and maintain their best observational capabilities are essential if the reliability and sensitivity of bubble emission leak testing are to be ensured.

2.5. Acoustic Emission

2.5.1. Concept and process

Acoustic emission is the energy emitted as high frequency mechanical vibrations as a result of a sudden change in the stress/strain field in most structures. This is usually due to a defect-related phenomenon, such as cracking or plastic deformation [8].

This method can be applied to locate leaks in pressurized systems. It is based on the detection and conversion of high frequency elastic waves, emanating from the source (leak), to electrical signals. Measurements are carried out using coupled piezoelectric sensors on the surface of the structure under test. The structure has to be loaded (mechanical, thermal…) in order to create acoustic emission. The output of the piezoelectric sensors is amplified through a preamplifier, filtered to remove any background noise, and then processed by the Central Processing Unit (CPU) of the AE-equipment. The acoustic emission technique can predict early failure of structures as a nondestructive method. Moreover, a whole structure can be monitored from a few locations and this can be done while the structure is in operation. These are major advantages of the technique [9].

2.5.2. Equipment

The sensors used in leak detection are piezoelectric. They have the feature of converting a mechanical distortion into an electrical signal. The sound vibrations are sent to the transducer of the object, becoming an electrical signal that can be stored and analyzed. There are several materials which behave piezoelectric, which are used as ultrasonic sensors such as Quartz crystal and Lithium sulfate [10].

Generally, the frequency of the leak noise has a wide bandwidth. In this case, the low frequency range was used (20-70 kHz), and the following sensors were used:

The VS375-M sensor, which Vallen Systeme advises to use it when the 150 kHz signal, is contaminated by noise. It is ideally suited to detect crack-growth signals in noisy environments.

The VS30-V sensor, high sensitivity low-frequency AE-sensor optimized for testing tank floors and other civil structures as well as leak detection.

Table 2.1- Sensor Models.

Sensor Model	Freq. Range/kHz	Case	Temp. Range/ºC	Capacity [pF]	Comments
VS375-M	250-700	M	-50 to + 100	390	Resonance at 375 kHZ
VS30-V	25-80	V	-5 to +85	140	Flat response

Table 2.2- Sensor Cases. Dimensions and Materials.

Case	Size DxH (mm)	Weight	Case Material	Connector	Wear Plate
M	20.3 x 14.3	12g	Aluminum	Microdot	Ceramics
V	20.3 x 37	44g	Aluminum	Microdot	Ceramics

The ceramics wear plate provides electrical isolation of the sensor's metallic case from the structure under test [11].

The use of frequencies over too wide a band is susceptible to excessive background noise, limiting sensitivity and resolution of the technique.

For adjustment of the sensors, the Hsu-Nielsen source is now widely accepted as a device to simulate an AE event. It uses the fracture of a brittle graphite lead to generate an AE signal to which the base settings of the AE testing set-up are adjusted.

For an acoustic emission sensor, the purpose of a coupling is to provide a good acoustic path from the test material to the sensor. Without a coupling or a very large sensor hold-down force, only a few random spots of the material-to-sensor interface will be in good contact because of the inherent surface roughness, and little energy will arrive at the sensor [5].

The output of each piezoelectric sensor is amplified through a low-noise preamplifier, filtered to remove any extraneous noise and furthered processed by suitable electronic equipment.

In this study it was used:

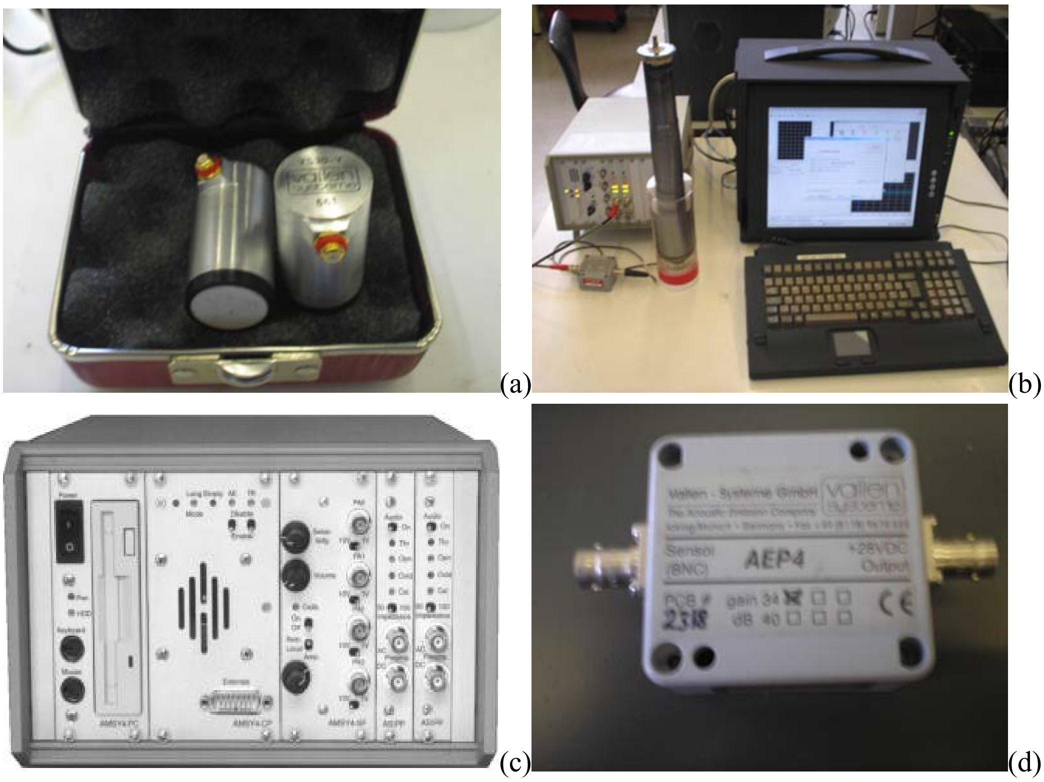
- The digital AE system AMSY4 with two channels.

- Vallen Visual AE, which is an advanced software for the acquisition and analysis of AE data using the digital AE system AMSY4.

- The AEP4 preamplifier, which has got two selectable gain settings and a wideband response from 2,5 kHz to 3 MHz.

- The sensors VS30-V and VS375-M.

Figure 2.1- (a) VS30-V sensors. (b) Full AE equipment. (c) Digital AE system AMSY4. (d) AEP4 preamplifier.



2.5.3. Applications and advantages of AE

The most important reasons for detecting leaks with acoustic emission technique are [9]:

1. To detect unreliable components.
2. To prevent environmental contamination.
3. To prevent material leakage loss that interferes with system operations.

Typical advantages of the AE technique are: real time monitoring in service structures, cost reduction, time reduction; high sensitivity, defect localization, global structures monitoring; control of non accessible zones (no need to access to the whole examination area), and can be used with other destructive and non-destructive techniques.

Acoustic emission differs from most of other non-destructive methods in two significant respects. First, the energy that is detected is released from within the test object rather than being supplied by the non-destructive method, as in ultrasonic or radiography. Second, the acoustic emission method is capable of detecting the dynamic processes associated with the degradation of structural integrity [5].

2.5.4. Sources

Possible acoustic emission sources are: plastic deformation, dislocation motion, rupture of the inclusion, phase transformation, twin/slip deformation and different stages of crack propagation (static, fatigue, stress, corrosion). For weld defects: lack of penetration and fusion (which can often be detected by ultrasonic testing methods or by visual inspection during welding) [12]. Detecting and monitoring of active corrosion, hydrogen embrittlement, pitting corrosion fatigue, and intergranular stress corrosion cracking. Friction. Mechanical impact. Gas or liquid leaks. External noise: mechanical, electrical, and environmental [4].

Source location of an AE event can be calculated with respect to sound velocity in the investigated material making the difference between the recording time at sensor further away and at sensor closer, and multiplying by the sound velocity.

2.5.5. Interpretation of test data

AE signals

There are two types of acoustic emission signals, which are called either bursts or continuous signals. The waveform of a continuous AE signal is similar to Gaussian, but the amplitude varies with the applied load. In metals and alloys, this kind of emission is considered to be associated with the motion of dislocations. Bursts signals are short pulses and are associated with a discrete release of high amplitude strain energy. In metals, the burst type emissions are generated by twinning, micro yielding, and development of cracks [9].

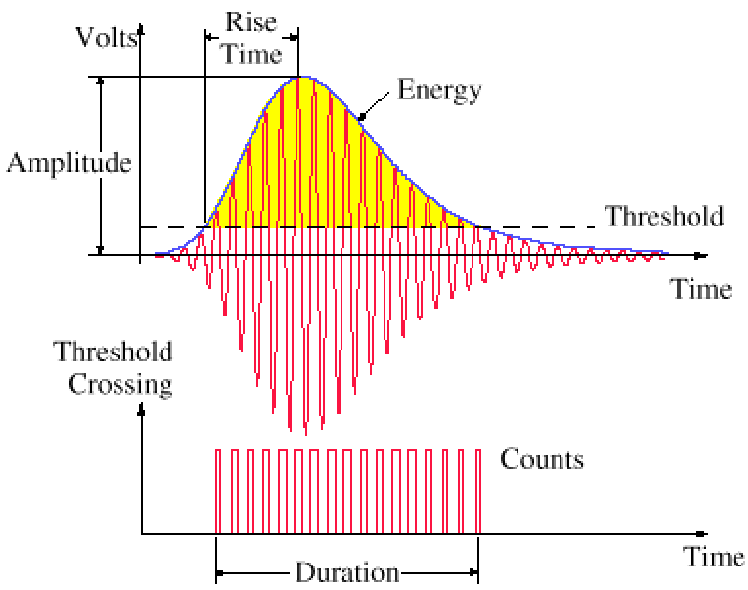
The AE signal features showed in Figure 2.2 are following detailed:

Amplitude, A, is the greatest measured voltage in a waveform and is measured in decibels (dB). This is an important parameter in acoustic emission inspection because it determines the strength of the signal. Signals with amplitudes below the operator-defined, minimum threshold will not be recorded.

Rise time, R, is the time interval between the first threshold crossing and the signal peak. This parameter is related to the propagation of the wave between the source of the acoustic emission event and the sensor. Therefore, rise time is used for qualification of signals and as a criterion for noise filter.

Counts, N, refer to the number of pulses emitted if the signal amplitude is greater than the threshold. Depending on the magnitude of the AE event and the characteristics of the material, one hit may produce one or many counts. While this is a relatively simple parameter to collect, it usually needs to be combined with amplitude and/or duration measurements to provide quality information about the shape of a signal

Figure 2.2- AE signal features.



Energy Counts, E, is the measure of the area under the envelope of the rectified linear voltage time signal from the sensor. This can be thought of as the relative signal amplitude and is useful because the energy of the emission can be determined. It is also sensitive to the duration and amplitude of the signal.

Threshold is the level from where an AE event is captured. Signals whose peak amplitude is not large enough to cross the threshold are not detected. Setting the threshold too high will prevent potentially important signals from being recorded. Setting the threshold too low will cause the background noise to cross the threshold and will result in a great deal of unwanted data to be recorded. In most cases, bursts with less than three threshold crossings and durations less than 3µs can be regarded as unwanted signals. Most of the bursts with low amplitudes and long duration are friction noise. Very short signals may indicate electrical noise peaks, especially, if they arrive at all channels at the same time.

Duration, D, is the time difference between the first and last threshold crossings. Duration can be used to identify different types of sources and to filter out noise. Like counts (N), this parameter relies upon the magnitude of the signal and the acoustics of the material. An event lasts D [13].

<u>*Ring-down counting analysis*</u>

Analysis of AE can be done as AE activity analysis which counts the number of hits registered per unit of time. These hits can be cumulated and then be related to the degree of damage in the sample. Furthermore, frequency and time domain parameters can be analysed. Therefore one has to measure the total time while the signal is above the threshold. During this time the ring-down counts which are the times when the wave signal crosses the threshold can be measured. The highest amplitude or peak amplitude for a signal also gives information on the damage. The time from beginning of the signal till this peak amplitude is called the rise time. From the ratio of peak amplitude to rise time, the slope can be calculated [14].

Energy analysis

Ring-down counting is now less common, and has been replaced by energy pulses. The measurement of the energy in a signal by means of electronic processing is, in principle, simple. The signal voltage is first squared, and then the area under the curve of voltage squared against time is measured. This area is proportional to the signal energy with the constants of proportionality being the amplifier gain and input impedance [15].

The advantage of energy measurement over ring-down counting is that energy measurements can be directly related to important physical parameters (such as mechanical energy in the emission event, strain rate or deformation mechanisms) without having to model the AE signal. Energy measurements also improve the acoustic emission measurement when emission signal amplitudes are low, as in case of continuous emission.

Narrow band signals direct energy analysis yields substantially the same information as ring down counts. However, for cases where the frequency does change, differences exist between energy and ring-down records, and energy analysis is sensitive to differences in the waveform whereas ring-down counts are not [16].

Another approach in determination of the energy of the signal is by measuring the root mean square (RMS) of the amplitude using an RMS voltmeter. For a continuous signal, such as that from a leak, with constant amplitude V_0, the energy rate is proportional to the square of the RMS voltage. RMS measurements are very suitable for continuous signals. If no threshold voltage is imposed, the background noise, which is generally of constant amplitude, will have an RMS value which remains constant and any variation of the RMS above this value will be indicative of emissions occurring from the material tested. Squaring the signal for energy measurement produces a simple pulse from a burst signal and leads to a simplification event counting. The RMS voltage measurement is simple and without electronic complications. However, a RMS meter response is generally slow in comparison with the duration of most AE signals. Therefore, RMS measurements are indicative of average AE energy rather than the instantaneous energy measurement of the direct approach [17].

Frequency analysis

Frequency analysis is usually performed to identify the sources of burst acoustic emission or when the signals are of the continuous type such those occurring during plastic deformation or in leak detection. In the latter case, the characteristic frequency peaks are identified and correlated to the presence of a leak, and they are caused by the flow of the air through the leak or by the bubble release.

2.5.6. Noises

Compensating for background noise

The ability to detect leaks acoustically depends on the physical mechanisms of the fluid flow in the leak, the sensitivity and selectivity of the detection instruments, and to what degree the leak is situated from the detection sensor. Noises can interfere in testing. The strategy to be followed in eliminating noise includes identifying the active sources of noise, characterizing the signals that they cause and setting up a procedure to eliminate the noise signals. The origin of noise can be electromagnetic interference, grip noise during laboratory testing, loose joints and environmental conditions. Electromagnetic interference can be identified by signal detection at both sensors at the same time and can be reduced through electrical shielding. Additional signals occurring due to the other origins of noise can be eliminated by raising the threshold of the detection system for low amplitude noise or applying filters for the different parameters.

When acoustic emission monitoring is used during hydrostatic testing of a vessel or other pressure system, the acoustic emission system will often provide the first indication of leakage. Pump noise and other vibrations, or leakage in the pressurizing system, can also generate background noise that limits the overall system sensitivity and hampers accurate interpretation.

Special precautions and fixturing may be necessary to reduce such background noise to tolerable levels. Acoustic emission monitoring of the production processes in a manufacturing environment involves special problems related to the high noise levels (both electrical and acoustical).

Preventive measures may be necessary to provide sufficient electrical or acoustical isolation to achieve effective acoustic emission monitoring.

Various procedures have been used to reduce the effects of background noise sources. Included among these are mechanical and acoustic isolation; electrical isolation; electronic filtering within the acoustic emission system; modifications to the mechanical or hydraulic loading process; special sensor configurations to control electronic counter-measures including autocorrelation and cross correlation [5].

Noise associated with welding

Welding requires heat which causes thermal expansion, followed by contraction and warpage with cooling. These movements, especially over a gritty surface, cause random noise bursts until the weldment reaches ambient temperature. Good welding practice is to wipe the weld piece, parts and work table clean before assembly [5]. It would be necessary to wait a couple of minutes until starting to record the acoustic emission.

2.5.7. Material

The tubes for shock absorbers are made out of low carbon steel (ferritic) which is seam or arc welded. The welds contain approximately 0.05–0.15% carbon, 0.25-1.5% manganese, 0.5% sulfur (maximum), nickel and chromium [18]. Material ductility is less than that of the austenitic grades. Steel with low carbon content has properties quite similar to iron. As the carbon content rises, the metal becomes harder and stronger but less ductile and more difficult to weld. Therefore these tubes are made out of low carbon steel, because they generally have good ductility and can be welded or fabricated without difficulty.

Figure 2.3- (a) Welding in which the leaks are difficult to observe. (b) Tube for shock absorber.


(a)

(b)

2.5.8. Test set up

In order to use AE for own our research, it is useful to study the literature at hand in order to make the right decisions for our own set up.

1. The European Committee for Standardization gives general principles of AE testing for the detection of corrosion damage within metallic surrounding filled with liquid [19]:

Duration: The recommended duration of the service period following the test is with respect to the service condition. The ideal conditions are: no rain, no wind no direct sun light and performing during night time.

Noise and threshold: The test result shall not be influenced by external or internal noise sources. The background noise level of the tank has to be monitored for every channel. If the noise interference is indicated, appropriate measures have to be taken in order to identify and eliminate the noise sources. If a test detection threshold greater than maximum detection threshold is required, the test has to be suspended. The standard detection threshold is 30 dB, and maximum detection threshold is 42 dB.

Sensors: When wave propagation through the liquid is used, the sensor frequency band is usually in the range from 20 kHz to 80 kHz. When wave propagation through the metal is used, the sensing frequency band is usually in the range from 100 kHz to 300 kHz. With respect to the coupling, the sensors may be directly attached to the structure using magnetic devices or a suitable adhesive. In a tank, the number of sensors applied shall not be less than 6 per row, and the distance of a sensor to a weld or a reinforcing plate shall not be less than 0.2 m. The correct functioning of the sensors and instrumentation must be checked using Hsu-Nielsen source at a distance of 0.05 m from centre of each sensor. Minimum peak amplitude of the Hsu-Nielsen source is 95 dB

Source location: In case of tank floor testing two rows of sensors and wave propagation through the liquid shall be used.

2. The European Committee for Standardization gives also a specific methodology and some general evaluation criteria in AE testing of fiber-reinforced polymers (FRP) [20]. Background knowledge: the properties of FRP relevant to AE testing are distinctly different from those of metals. Therefore, it will be focused on points in common:

Analysis of AE: Hit, Energy and RMS based processing are applicable types of analysis. The signal processing of acoustic emission from FRP does not differ significantly from that required for metals. The main differences are that high frequency signals are significantly shorter due to the absence of reverberation. Analysis of the AE waveforms may provide useful information on the source mechanism and the propagation path. The interpretation of the AE sources based on the frequency spectra of signals must consider strong wave distortions from the attenuation in the material, frequency dependent sensitivity of the AE sensors and the characteristics of the filters. This means that the identification of the AE source mechanisms using power spectra is essentially restricted to very short distances between source and sensor.

Sensors: 150 kHz sensors monitoring the high stress areas of the structure, and where the 150 kHz sensors do not provide the full coverage, 30 to 60 kHz sensors are used to monitor the remaining test areas, bearing in mind that these may be susceptible to extraneous noise. Suitable coupling agents are silicone-based high vacuum grease or adhesives, e.g., cold hardening silicone rubber. They guarantee a stable mechanical mounting of sensors and shall prevent noise signals resulting from sensor movement at the surface of structure.

Noise: Extraneous noise caused by loading process, e.g., pump noise or leakage from servo-hydraulic test machine or pressure equipment, rubbing between grips and test specimen etc. must be suppressed before the test. If it is not possible, correctly identified noise signals may be removed from data during post analysis using data filter or location procedures. Attaching of at least 2 sensors to the specimen (one to each clamp or support) and performing linear location, AE background noise (hydraulic, friction or electrical) can be removed by filtering. Often, features of signals with peak amplitudes $A \geq 60$ dB are shown in graphs only. The detection threshold is set above the peak background noise.

Load: The application of the load depends on the aim of the test, the test object and the fluid to be pressurized. Care must be taken with low strain rates and very long hold periods which can lead to creep (relaxation) effects.

3. Miller [21] makes a reference standard which was constructed for setting up and evaluating AE equipment to be used in pipeline leak detection:

Goal: Detect leaks on the order of 0.1 ml s^{-1} (0.1-0.2 mm diameter).

Problem: Pressures of 2-3 bar typically produce leak rates of several milliliters per second, far above the 0.1 ml s^{-1} target. Furthermore, openings with diameters of 0.1 mm or less are very liable to getting clogged by small particles in the flow. Below 7 bar, small leaks in flange gaskets and pipe threads may not be turbulent so the flow of the liquid itself may produce little or no AE. But source mechanisms associated with solid particles or entrained gas can produce quite high amplitude AE that will be detectable at substantial distances.

Results: Trials with clean water are irrelevant. With plain water and 2-3 bar of pressure leaks of 0.3 mm diameter are detected. Introducing air, it is noticed that the breaking of air bubbles emerging from the leak produced audible emission. The following increases in AE amplitudes are achieved by injecting air and/or raising the pressure:

Non-turbulent: Pressure 1 bar, 0.03 ml s^{-1}, amplitude 45 dB, burst type

Air injected: Pressure 1 bar, 0.03 ml s^{-1}, amplitude 60 dB, continuous type

Turbulent: Pressure 5 bar, 0.25 ml s^{-1}, amplitude 62 dB, burst type

Air injected: Pressure 5 bar, 0.25 ml s^{-1}, amplitude 70-80 dB, burst type, RMS 230 μV, threshold 68 dB.

Nitrogen is used. The basis of this approach is that when the nitrogen reaches the leak location, high-amplitude emission is produced by the mixture of gas and water passing through the leak path. Pressure 2 bar.

Sensors: The instrumentation consisted of a two-channel PAC MISTRAS system while the sensors are PAC Model PLS-1 resonant sensors (15 kHz peak sensitivity). Sensors are mounted with viscous coupling substances and hold in place with electrical tape. Hsu-Nielsen is used in this test.

4. Sharif and Grosvenor [22] make a detailed experimental study, which is conducted to determine the lowest detectable compressed air leakage rate through an industrial control valve that can be reliably detected using an acoustic emission (AE) technique.

AE sensors with a frequency range of 20-100 kHz are used. The attachment is made using an acoustic coupling compound. The Hsu-Nielsen source is used to indicate the good acoustic contact between the sensors and the valve flanges. The preamplifier is built into each of the sensor's in order reduce the losses of the AE signal detected by the sensors. Software used is data acquisition, processing and analysis.

Tests are carried out under laboratory conditions, in which the background noise is reduced to a minimum value. The experimental work starts by monitoring the background noise in order to determine the frequency components that are related to this type of noise and hence eliminate them from the frequency spectrum. The highest frequency value is produced at 42 kHz by an electro-pneumatic machine that is operating in the laboratory. The effects of the background noise on the measured AE signal are considerably reduced by using the real-time programmable filters that are part of the AE measurement system. Frequencies below 20 kHz are not significant in this study.

With respect to the leak, the most dominant frequency is around 70 kHz, and its amplitude is around 21 dB, but the amplitude increases with the leakage rate because it produces a higher level of turbulent flow, and values around 57 dB are reached.

Due to the nature of the waveforms, important conclusions cannot be drawn from this type of graph.

The use of a band-pass filter with a restricted bandwidth between 50 and 300 kHz eliminates satisfactorily mechanical background noise and enables relevant results to be obtained in either the laboratory or the simulated industrial environment.

For industrial applications the sensor with the higher frequency response (100 kHz – 1 MHz) is more suitable in order to reduce the need for noise reduction filtering to a minimum level, despite it is less sensitive for the leak detection.

5. Kenichi Yoshida et al. [23] studied the frequency characteristics of AE waveforms during gas leak:

Set up: Each AE sensor (S2SG, 48 kHz) is placed at 10 mm from each pinhole to detect the leak signal. The test pressure is from 1 bar to 3 bar. The total gain of detected signal is 60dB. Threshold level is 40dB that corresponded to 100 µV at the preamplifier input voltage. AE signal is detected continuously from 1 bar to 3 bar.

Energy: If the energy release process due to air leak changes, the detected AE activity probably also changes. In order to clarify the energy release due to air leak, mean amplitude is numerically calculated from the digitized AE waveform. As a result, the calculated mean amplitude is certain to be the relative energy release due to air leak.

Frequency: The frequency spectrum of the AE waveform due to air leak is considered to be able to clear by indicate the different types of AE sources. The larger the pinhole diameter, the lower the peak frequency of detected AE waveforms becomes.

Table 2.3- Set ups distilled from the literature survey.

Nº	Load	Threshold	Sensor frequency	Sensor coupling	Hsu-Nielsen	Analysis
1	X	30/42 dB	Liq: 20-80 kHz Met: 100-300 kHz	Magnetic Adhesive	Yes	X
2	Depends on the aim	60 dB	30-60 kHz	Grease Adhesive	No	Hit/Energy/ RMS/Freq
3	1 – 5 bar	68 dB	~ 15 kHz	Viscous	Yes	Amplitude/ Wave signal
4	1 bar	X	Lab: 4-100 kHz Indust: 0.1-1 MHz	Coupling compound	Yes	Frequency
5	1 – 3 bar	40 dB	~ 48 kHz	X	No	Energy/Freq.

6. Other references for leak detection using AE techniques:

The Municipal Services Board of Brescia (ASM) [24] describes the experience with the application of leak detection using acoustic emission technique in several water systems. In the last years "noise loggers" have been used to identify leakage areas. Thus systems for acoustic noise monitoring and recording have been developed which can be permanently or time limited installed at hydrants, valves or house connections. These "noise loggers" record typical noises in the network during low consumption hours at night and identify areas of potential leakage for further investigation.

Germain et al. and Smith [25, 26] report reliable results when infrared was used to detect low gas leakage rates through various types of control valves. The lowest pressure that Germain et al. use to detect gas and steam leakage through is around 14 bar.

Drouillard [27] presents a review in which he reports the work of a large number of researchers in the field of AE. He also includes a description of applications in leak detection, although he does not provide any result of his tests using the AE techniques.

Delarue [28] uses successfully AE techniques to detect leakage in process pipelines. The reported results indicate that AE is a very powerful leak detection method that can be used not only to detect small leakage rates pipelines, but also to detect the initial symptoms of a micro-crack that may lead to leakage if not detected.

Williams [29] provides a description of the applications of AE to detect growing cracks and leakage in pressurized vessels.

Dickey et al. [30] say that the amplitude of certain frequency components in the AE frequency spectrum increases with the leakage rate, although pressurized air leakage is only detectable very high pressures (276 bar), but this was due to the limitations of the instrumentation at that time.

Lord et al. [31] say that the nature of the AE signal also needs to be considered. The signal is attenuated as it travels from the point of leakage to the detecting sensor, since it travels through the valve body, which is metal. In order to reduce this attenuation, it is necessary to position the sensors as close to the source of leakage as possible.

Gerald Lackner et al. [32] mention the successful use of Vallen AMSY5 equipment for testing the pipelines connecting the refinery on the right side of the river Danube with the storage facility on the other side.

AE technique selection

Welds may be tested using NDT techniques such as industrial x-ray radiography or using neutron radiography, liquid penetrant testing and other methods such as acoustic emission or bubble techniques. In a perfect weld, these tests would produce known results (such as a known radiographic response, or a clean penetrant surface), and tests that produce differing results may indicate flaws that would otherwise cost money, time, and even lives in the case of vehicles. But the decision of using the AE technique is mainly based on its better industrial application than radiography, apart from its reasonable price. Its usefulness in this field will be investigated.

3. Experimental. The use of AE for leak detection

Tenneco Europe uses the bubble technique to detect which tubes are leaking at the weld (see point 2.4). After welding the bottom of the tube, the tube is pressurized and dived into water while an operator observes the bubbles formation. If the tube has a leak, the tube is scrap material. The cycle time for checking one tube is around 8 sec.

In order to carry out the feasibility study to analyze the use of AE for leak detection, Tenneco Europe provided MTM with eight shock absorber tubes made out of low carbon steel, with a thickness of 3 millimeters, a length of 39,5 millimeters and a diameter of 4,8 millimeters (Figure 3).

3.1. Trials in air

3.1.1. Coming into contact with AE.

Firstly, the tubes for shock absorbers were observed in the lab using X-ray computer tomography with data-analysis and image processing system to detect any flaw, but it was impossible due to the high amount of iron in the welded area, thus it was decided to perform the AE measurements. In first instance six-pack tubes were tested. Tenneco Europe had made trials with the bubble technique to detect the leaks before sending the tubes, and the half of them were supposed to be all right (without leak), and the other half were leaking.

Figure 3.4- Pressure pump in the lab.

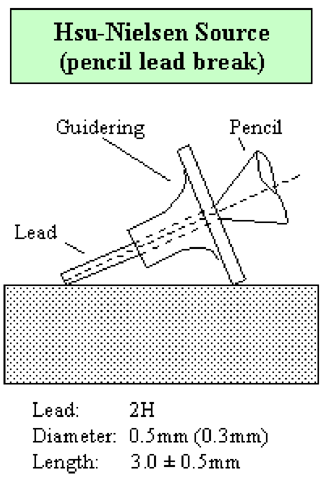
Following, trials were carried out with no damaged tubes. The way to proceed was increasing the pressure from 0 bar up to 5 bar, in steps of one bar using pressurized air (Figure 3.4). The aim was to produce the turbulence when the air flowed through the leak to pick the sound up easily.

The threshold was fixed at 34 dB (estimated value from Table 2.3), and the attempts were made with two types of sensors (VS30-V, VS375-M) this will be further explained in detail in 3.1.2. The coupling was made on the basis of the Vallen Systeme guidelines for "how to hold the sensors on place" [10]. Most universal testing machines hold specimens in a vertical position; hence comes the problem of maintaining the sensors firmly in place. They need of course a coupling substance, which is a material (usually a liquid) that facilitates the transmission of ultrasonic energy from the test specimen into the sensor [17]. Although many coupling devices are suitable for AE sensor surface contact, silicon grease is often used, which of course is excellent for contact, but makes the sensor to glide easily in vertical position of the specimen. To fix the sensor adhesive tape is wrapped around the specimen, which is efficient for many flat coupons but sometimes insufficient in other cases.

Conclusion: The results were stopped due to the great amount of events produced (remember that an event is captured when the AE sensor senses a signal over the threshold). This meant that the background noise overlapped the leak noise. Despite of having an increased the threshold level in order to avoid the background noise (threshold at 60 dB), the leak signal could not be distinguished. The trials made with tubes with no leak had the same values. The problem could be in the coupling between the pressurized air valves and the tube of the shock absorber, because it was likely that in the joint between them there would have been leaks that interfered in the measurements, therefore, the next tests were made with these valves disconnected, but in spite of this decision, after repeating the test, the background noise still overlapped with the leak noise.

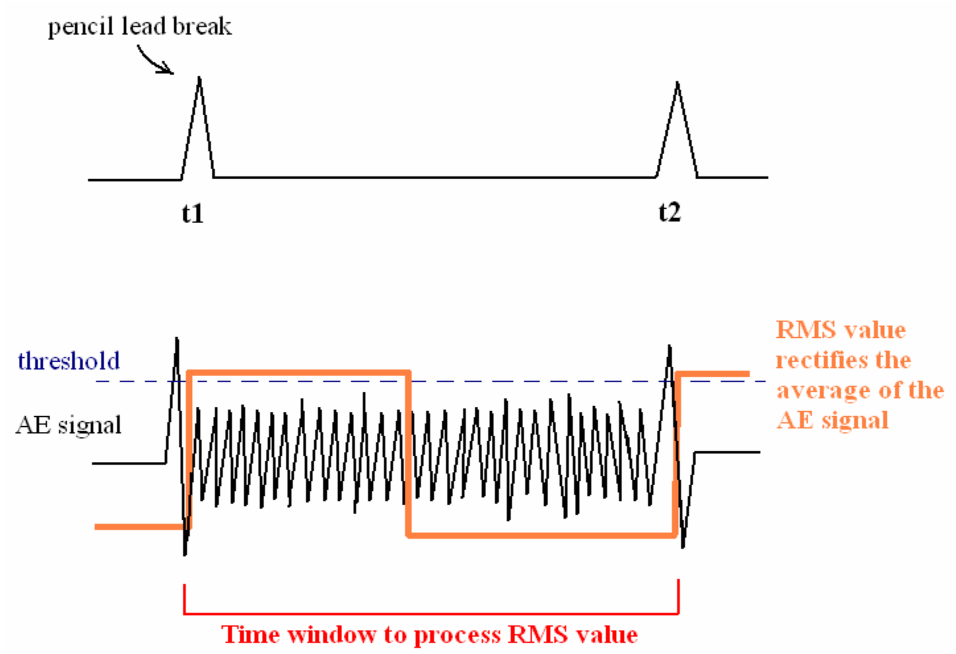
Despite these test, further improvements were looked for. Hence, attempts were made with the six-pack tubes to measure the RMS, with a pencil lead break support or Hsu-Nielsen source [5], which is an aid to simulate an acoustic emission event using the fracture of a brittle graphite lead in a suitable fitting. This test consists of breaking a 0.5 millimeter diameter pencil lead, approximately 3 mm from its tip by pressing it against the surface of the piece. This generates an intense acoustic signal, quite similar to a natural AE source that the sensors detect as a strong burst. The purpose of the test was twofold. Firstly, it ensured that the sensors were in good acoustic contact with the part being monitored. Generally, the lead breaks should register amplitudes of at least 80 dB for a reference voltage of 1 mV and a total system gain of 80 dB. Secondly, it checked the accuracy of the source location setup. This last purpose involved indirectly the determination of the actual value of the acoustic wave speed for the object being monitored.

Figure 3.5- Hsu-Nielsen source.



It was decided to use two sensors VS30-V instead of one. The threshold was fixed very high (at 70 db) to ensure no background noise and to register the lead breaks (amplitudes around 80 db). The measurements at the sensor which was in the bottom of the tube are shown in Channel 1 (RMS in µV), and the measurements from the middle of the tube are shown in Channel 2 (RMS in µV). The distance between the sensors was 17 cm. The lead broke at a distance of 8.5 cm from the sensors. The time between each broken lead was 2 minutes. The preamplifier used was the AEP4 model, which has two selectable gain settings and a wideband response from 2.5 kHz to 3 MHz.

Figure 3.6- RMS function.



In order to analyze the results, first it is necessary to explain the RMS concept. The electric signals of the sensors are processed using the Root Mean Square value, because they are often noisy and unstable, and RMS value rectifies the average of the AE signal in a certain time window, measured on a linear scale and expressed in volts, so it provides a valid and accurate signal (Figure 3.6). The RMS value (µV) of the signal between two hits (the period of time from the last threshold-crossing of a hit to the first threshold-crossing of the next hit) is continuously evaluated and stored with the next hit as result RMS. It provides information about the continuous AE signal level below the threshold [9].

Table 3.4- Two sensors measuring RMS [μV] vs. Pressure [bar] for tubes with/without leak.

	NO LEAK [μV]						LEAK [μV]					
P [bar]	**CH1**	**CH2**	**CH1**	**CH2**	**CH1**	**CH2**	**CH1**	**CH2**	**CH1**	**CH2**	**CH1**	**CH2**
0	12	11	8	7	8	7	8	8	9	7	13	14
1	12	13	8	9	21	23	9	9	8	7	11	10
2	57	63	86	88	237	257	59	56	10	8	78	66
3	100	109	282	348	439	465	171	168	12	10	231	186
4	145	162	509	673	633	646	346	345	25	22	532	409
5	189	198	1137	1057	861	760	526	518	243	262	964	810

This table can be summarized in the following two detailed graphs that show the RMS value of each tube in accordance with its pressure:

Figure 3.7- RMS [μV] vs. Pressure [bar] all tubes in channel 1.

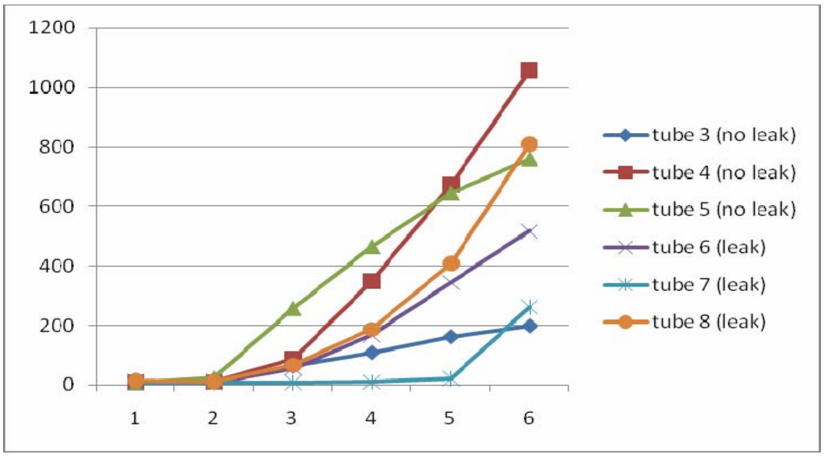
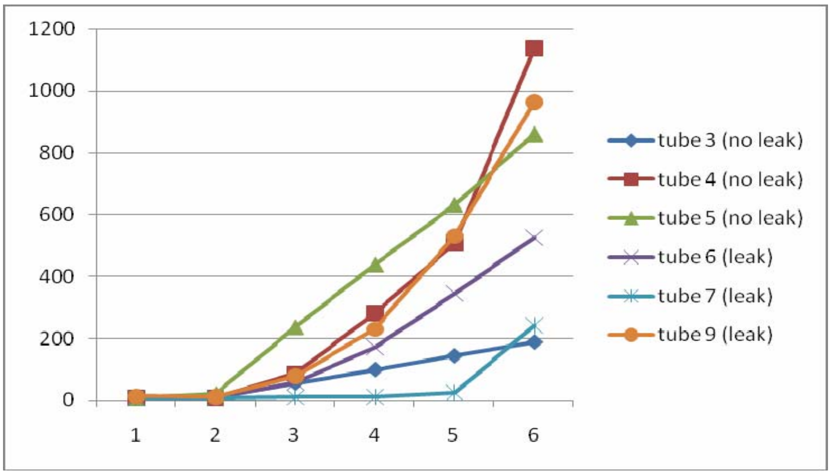


Figure 3.8- RMS [μV] vs. Pressure [bar] all tubes in channel 2.



Conclusion: The obtained results ensured that the sensors were in good acoustic contact with the tubes because the lead breaks registered amplitudes of 100 dB, and the accuracy of the source location set up was checked. In air, the use of AE to measure the RMS values to detect leaks was useless, due to the lack of relationship between the damaged tubes and the good ones separately, there was no difference between them. The RMS values were not conclusive and the results were at random, because some tubes with no damage (tube 4, for instance) obtained higher RMS values than the tubes with damage (tube 6, for instance), which means that the signal between two hits was stronger in a tube without leak than in one with it. Moreover, the energy rate is proportional to the square of the RMS voltage, hence it was not possible that a tube witout leakage released more energy than a tube with a leak, because the sound amplitude in a right tube cannot be higher than in a damaged tube (see point 2.5.5).

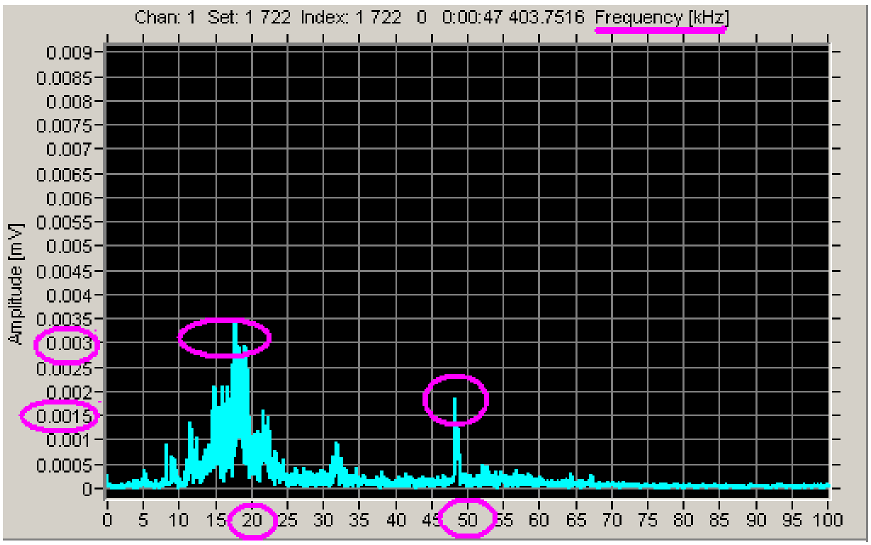
Then, the main problem was still to distinguish between the sounds from the air flowing through the leak and the environmental noise. Both of them were continuous acoustic emissions which were mixed.

Furthermore:

- Leak sound was located between 50 kHz and 55 kHz, and its amplitude changed also from 30 dB to 80 dB depending on the pressure inside the tube.

- Noise was often located between 5 kHz and 20 kHz, and its amplitude changed from 30 dB to 80 dB depending on the environment. Occasionally, in tests with tubes without leak, apart from the frequencies around 20 kHz, frequencies at 50 kHz were recorded (Figure 3.9), therefore, the conclusion that the noise is located between 5 kHz and 20 kHz was questioned.

Figure 3.9- Frequency graph for a tube without leak in which a frequency peak at 50 kHz is recorded.



3.1.2. The sensor choice

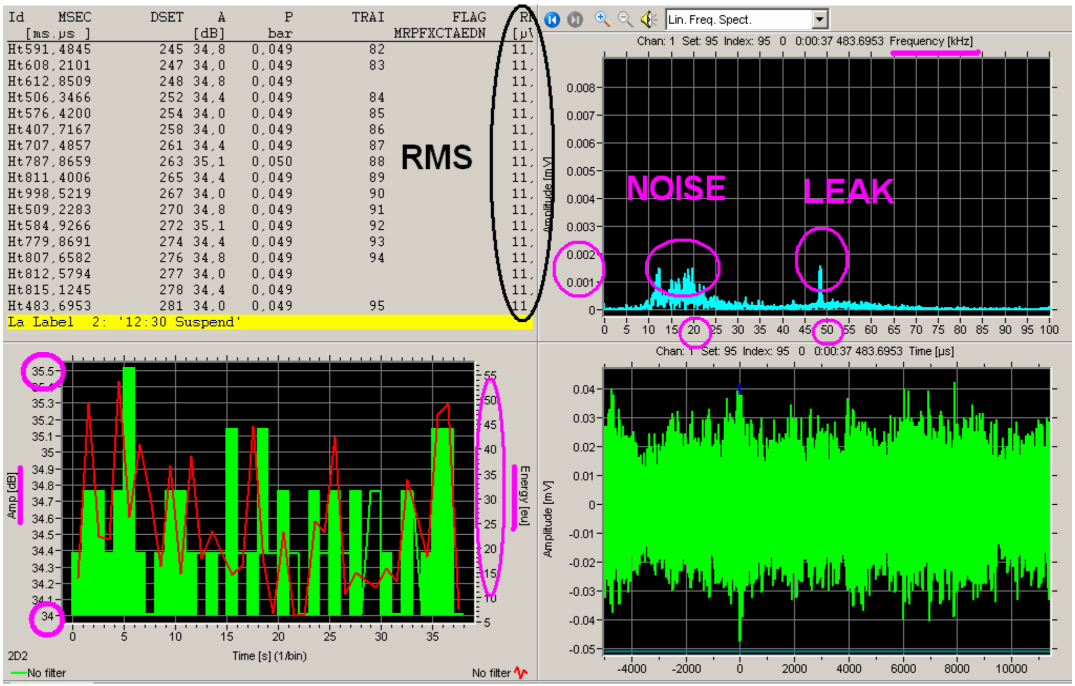
The following tests were made in order to choose the suitable sensor:

The tube (with or without leak) was pressurized up to 6 bar, and then, it was disconnected from the pumping system. The sensor (VS30-V or VS375-M) was attached to the tube side (8 cm above the weld) with the aid of the vacuum grease and a metallic coupling piece that was arc shaped. Adhesive tape was used to wrap all together. The threshold was fixed at 34 dB (first trials), and at 34.4 dB (second trials). The AE measurements were taken in the lab: a room where there were several machines working. It was noisy, although more quiet than a production environment. Therefore one needed to bear in mind that the waves recorded were also produced by environmental noise.

Following graphs show the results of using two different kinds of sensors:

- <u>Sensor VS30-V</u>

Figure 3.10- Sensor VS30-V in a tube with leak.

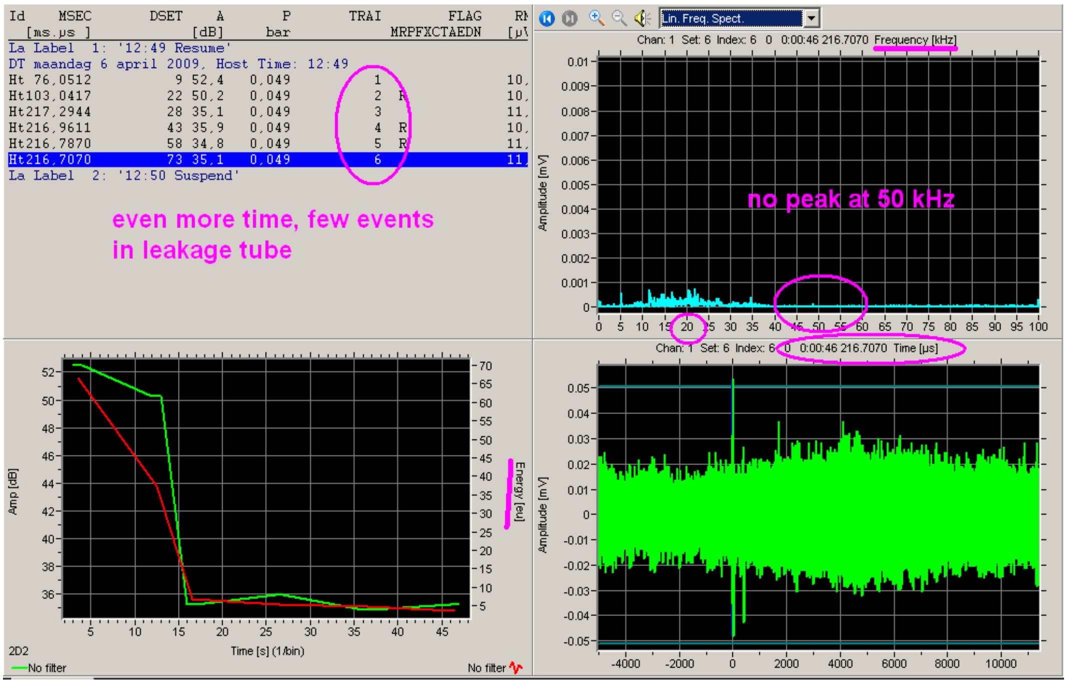


The Amplitude/Frequency graph (top right), the Amplitude and Energy/Time (bottom left), and the wave shape (bottom right) are presented in Figure 10 for a tube with leak.

First trial carried out on a tube with leak had a threshold of 34 dB. The following trial was tested at 34.4 dB in order to decrease the noise of the environment, but any important change was recorded. Top left: The RMS values were around 11 µV. Top right: The frequency range of the measured AE signals shows two clear peaks, one around 20 kHz and another at 50 kHz. The first peak was related to the background noise, and the second peak was related to the sound of the leak. Bottom left: The Energy graph shows activity up to 50 eU. The green bars reached amplitude levels between 34 - 35.5 dB. Regarding energy definition, it is possible to check that Energy and Amplitude are related, because the energy is the measure of the area under the envelope of the amplitude. Bottom right: The graph shows the continuous wave where the air flowing sound and the environment noise are mixed.

- Sensor VS375-M

Figure 3.11- Sensor VS375-M in a tube with leak.



In Figure 11 it is possible to see the Amplitude/Frequency graph (top right), the Amplitude and Energy/Time (bottom left), and the wave shape (bottom right).

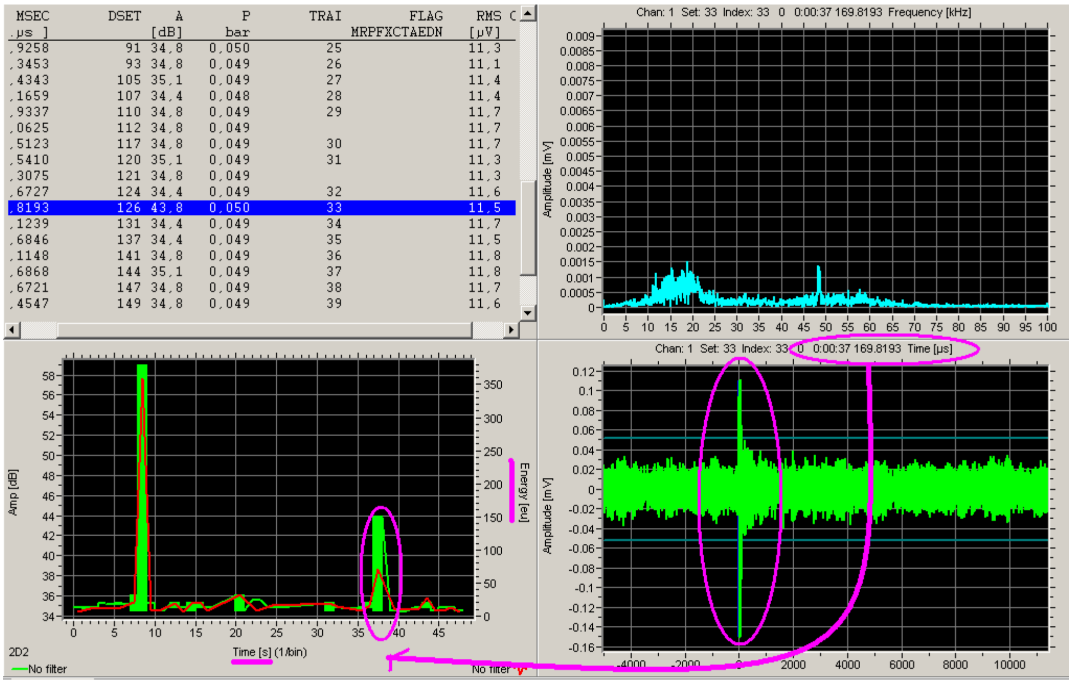
Top right: The main difference in relation with Figure 8 (VS30-V sensor) was that the peak at 50 kHz disappeared. The amplitude at 20 kHz remained at the same value. Top left: The event recording decreased considerably, what showed that this sensor was not very suitable, because the measurements were taken with the same tube under equal circumstances. Bottom right: It shows the continuous wave where the air flowing sound and the environment noise are still mixed. Bottom left: The energy is barely recorded.

Conclusions:

- According to the RMS value, at 6 bar both cases had the same values: 10-11 µV, no difference between having a leak or not.

- It was also necessary to consider the possibility of the material to crack because of the initial pressure. For instance, Figure 3.12 shows a clear burst with amplitude 44 dB, energy 150 eU and frequency 50 kHz; but this could not be identified as an AE signal of leakage because it was just released only once at 37 seconds.

Figure 3.12- Crack of the initial pressure in a tube without leak.



- The threshold was difficult to fix. If it was increased, the sensor did not measure anything, but if it was too low, the recording was saturated. The threshold depended on the surrounding environment.

- As it was said in point 3.1.1, occasionally, in tests with tubes without leak, frequencies at 50 kHz were recorded, apart from the frequencies around 20 kHz, therefore, it was not possible to ensure that the frequency of the background noise was always located around 20 kHz.

- The sensor to be used in future experiments was VS30-V (see point 2.5.2), because it measured at low frequencies, between 25-80 kHz. Sensor VS375-M which had a higher working frequency range (250-700 kHz) was not found suitable, because the leaking happened to release signals around 50 kHz and this sensor was not sensitive enough in this frequency range.

- The noise of the environment was very important when the air test was being carried out, thus, in a production environment it seemed to be impossible to do the measurements.

3.2. Trials in water (lab)

The obtained results in air were not yet very promising and conclusive. Thus, it was decided to perform the AE measurement on the pressurized tubes immersed in water and positioned on an AE sensor. The tubes for shocks absorbers were pressurized and dived into a box filled with water (Figure 3.13). This method was very similar to that used by Tenneco Europe for the detection of leaks. From that moment on, the majority of the leaks can be detected visually through the bubbles that formed. However, the objective did not consist in visually detecting such bubbles, but to do it using the sound generated by them and using the AE technique so that also an increase in the reliability of testing could be obtained.

Figure 3.13- Pressurized tubes immersed in water and positioned on the VS30-V sensor.

3.2.1. Single bubble signal

One bubble was isolated and measured with the goal of taking knowledge of how this signal was (amplitude, frequency, and wave). The tubes were not used. This one bubble signal was produced by a needle in a container filled with water. It was made in a lab environment. The threshold was fixed at 34 dB. The bubble burst reached 0.05 mV (Figure 3.14), and this peak was produced when the bubble was detached. It is likely there would have been another burst when the bubble reached the water container surface, but the figure does not show it. This latter wave propagated through a different medium (liquid instead of solid). The sound travels faster in solids than in liquids, because the internal bonds in a solid are much stronger than the bonds in a liquid [33]. The lower peaks around 20 µV are noise of the environment. The energy released by only one bubble was not worth to taking into account. The bubble frequency was 55 kHz, and the noise frequency was around 20 kHz (Figure 3.15).

Figure 3.14- Single bubble peak located at 50 µV, with noise of the environment around 20 µV.

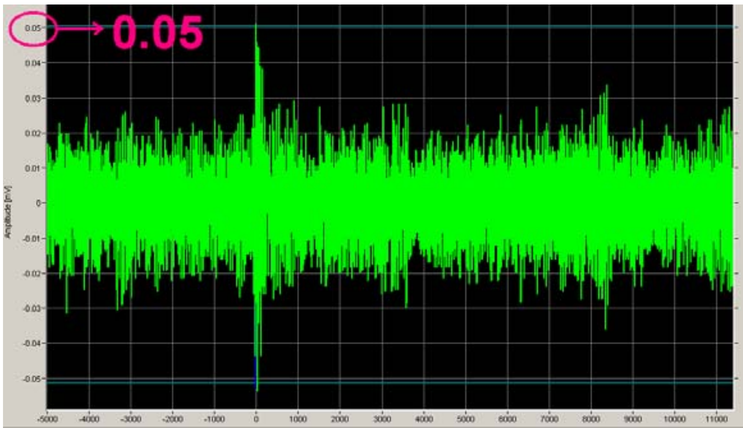
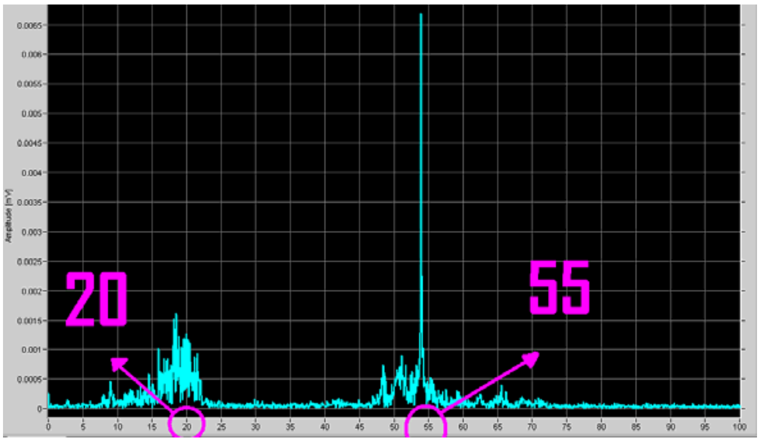


Figure 3.15- Single bubble frequency at 55 kHz, with noise frequency around 20 kHz.



3.2.2. Measuring the RMS value of the AE activity.

For these RMS value one sensor was attached to the middle of the tube and the tube was dived vertically into a box filled with water, keeping the welding part underwater. The pressure was increased from 0 to 4 bar.

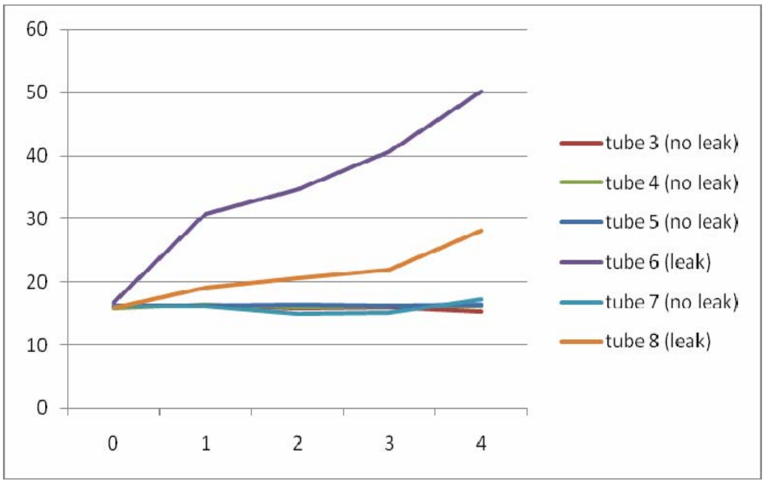
In the defective tubes after pressurizing the pressure decreased after the disconnection. So this already was one way to prove that there was a leakage, although this decrease in pressure took a long time until ithappened. Although it was decided to use the VS30-V sensor, in this first underwater test the VS375-M sensor was used too. The VS30-V sensor, which worked at low frequencies, detected the leak in two over the three failed tubes, so it was likely for the third tube the leak had closed over time due to corrosion or metal debris. The measurements with the high frequency sensor (VS375-M) only showed the leakage in one tube, which proved again the need of the low frequency (20-60 kHz) sensor in this research.

Measurements were also carried out using a multimeter in order to compare them with the acquisition results of the AE system. With the aim of comparing two different situations, the test was carried in a "noisy environment", simulating the noise of a factory, and in a "quiet environment", a space in which there were no machines working. Table 3.5 shows the RMS values: AE (µV) and Multimeter (mV), in accordance with Pressure (bar):

Table 3.5- RMS [µV] and Multimeter [mV] vs. Pressure [bar] in a noisy environment

	Tube 3		Tube 4		Tube 5		Tube 6		Tube 7		Tube 8	
P [bar]	AE [µV]	M [mV]	AE [µV]	M [mV]	AE [µV]	M [mV]	AE [µV]	M [mV]	AE [µV]	M [mV]	AE [µV]	M [mV]
0	16,2	0,037	15,8	0,038	16,3	0,038	16,8	0,038	16,1	0,038	16	0,038
1	16,2	0,038	16,5	0,036	16,2	0,038	30,8	0,045	16,2	0,038	19,1	0.039
2	15,7	0,037	16	0,037	16,4	0,038	34,7	0,055	15	0,031	20,6	0.039
3	15,9	0,037	16,2	0,036	16,2	0,038	40,6	0,045	15,1	0,032	22,1	0.039
4	15,2	0,037	16,4	0,306	16,4	0,038	50,2	0,048	17,3	0,038	28,2	0.039

Figure 3.16- RMS [µV] vs. Pressure [bar] in a noisy environment.



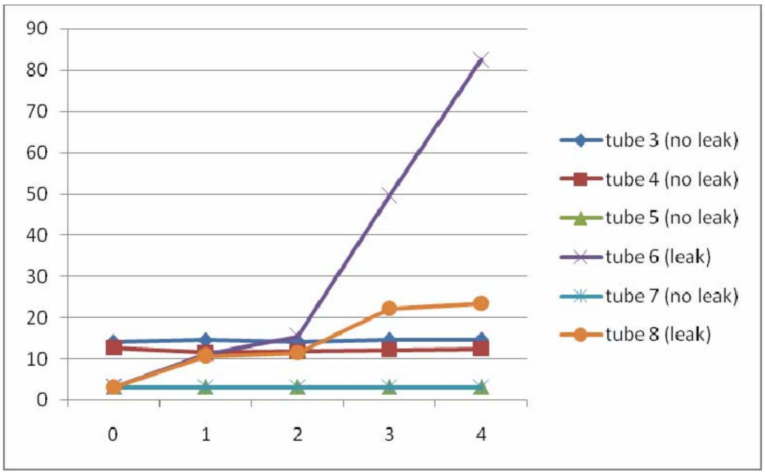
Conclusion: The results in table 3.5 were in accordance with the expected outcomes. Same RMS values (around 16 µV) could be observed for right tubes (tubes 3, 4, 5 and 7), whereas in tubes 6 and 8 were higher (from 20 to 50 µV), which means that the signal between two hits were stronger when there was a leak presented (see point 2.5.5). The RMS values can also be put on the level with the measure of the noise, because it provides information about the continuous AE signal level below the threshold. Moreover, tube 8 had a visual leak (bubbles), but they were smaller than in tube 6, because of that, their RMS values were not as high. Notice that tube 7 was supposed to be damaged at the beginning of this research (based on Tenneco Europe information), but it was finally supposed to be right due to the lack of leaks along the tests.

Table 3.6 shows the RMS values in a quiet environment: AE (µv), Multimeter (mV), in accordance with Pressure (bar):

Table 3.6- RMS [µV] vs. Pressure [bar] in a quiet environment.

	Tube 3		Tube 4		Tube 5		Tube 6		Tube 7		Tube 8	
P [bar]	AE [µV]	M [mV]	AE [µV]	M [mV]	AE [µV]	M [mV]	AE [µV]	M [mV]	AE [µV]	M [mV]	AE [µV]	M [mV]
0	14,1	0,074	12,7	0,064	3,2	0,034	3,2	0,030	3,2	0,032	3,2	0,030
1	14,5	0,067	11,5	0,057	3,2	0,034	11,2	0,068	3,2	0,038	10,8	0,048
2	14,2	0,075	11,7	0,055	3,2	0,040	15,5	0,100	3,2	0,037	11,5	0,054
3	14,6	0,074	12,2	0,064	3,2	0,037	49,6	0,115	3,2	0,037	22,3	0,064
4	14,6	0,074	12,5	0,060	3,2	0,037	82,5	0,127	3,2	0,040	23,5	0,077

Figure 3.17- RMS [µV] vs. Pressure [bar] in a quiet environment.



<u>Conclusion:</u> In spite of the fact that the test was made carefully, it was impossible to obtain RMS values around 3.2 µV in tubes 3 and 4. These tubes must have the same values than tubes 5 and 7, due to the lack of noise (no bubbles detaching through the leak and no background noise while testing). Instead of 3.2 µV, it was 12-14 µV (Table 3.6). When these RMS values were compared with the obtained results before, a drop in the values was found, (Table 3.7), except for tube 6, which was the only one that increased its value from 50.2 µV to 82.5 µV. It made

no sense, and it should be lower according to the results of the other tubes, because the drop meant that there was no noise recorded.

Table 3.7- RMS values [µV] decrease at 4 bar.

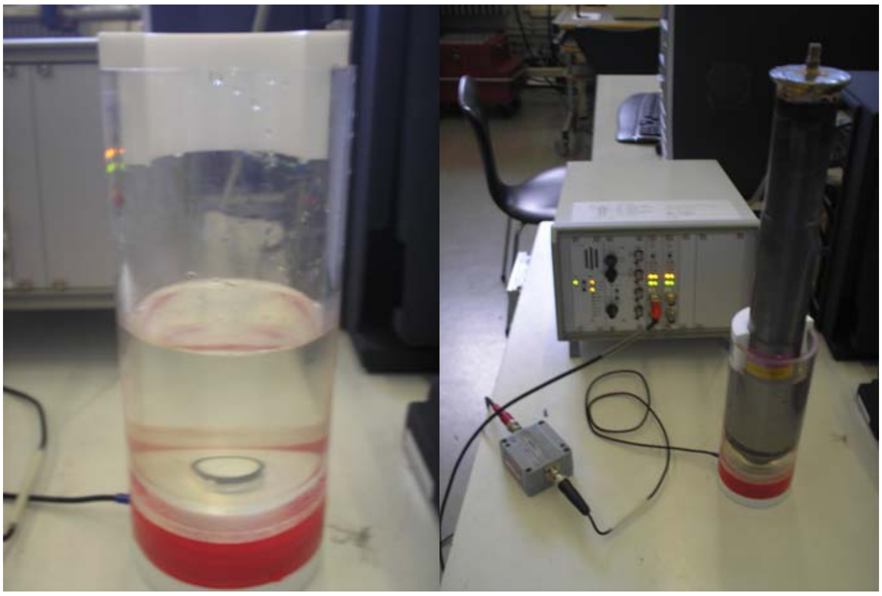
	Noisy environment	Quiet environment
Tube 5	16,4 µV	3,2 µV
Tube 7	17,2 µV	3,2 µV

Notice that with no pressure, tubes 6 and 8 got right values (3.2 µV), additionally, the sensor was not moved anytime since 0 to 4 bar, hence it proves that the sensor coupling was not blame for the wrong values. It was decided that the results were to blame on the tube support, thus the following tests were carried out with a new container.

3.2.3. Measuring the RMS value of the AE signals in a water container.

A new device was developed to be used as the water container and which supplied for the sensor a better attachment to the tube (Figure 3.18).

Figure 3.18- Water container with VS30-V sensor attached to the bottom.



The tubes for the shock absorbers were dived into the container, which allowed the tube to be fixed to the water tank vertically. Only one low frequency sensor was used (VS30-V), and it was attached to the device bottom. The pressure applied was 3 bar. The advantages of this test turned out to be the tube attachment and the fixed sensor. Several attempts were made looking for the repetition of the RMS values in a tube with leak, trying to check the feasibility of this technique:

Table 3.8- RMS values [µV] for a damage tube.

Pressure	Attempt 1	Attempt 2	Attempt 3	Attempt 4	Attempt 5
3 bar	**11,9 µV**	**18,2 µV**	**15,0 µV**	**16,0 µV**	**11,1 µV**

The mean value is 14,4 µV. The error is ± 2,3 µV. Hence the acceptable range is [12,1 – 16,7 µV].

Conclusion: The repetition assumption was not possible to ensure (Table 3.8). Therefore, the Energy was taking into consideration.

3.2.4. Measuring the Energy content of the AE signals in a water container.

Concerning the Energy, three tubes with leak were measured in the same circumstances as for RMS tests. They were dived into the water container after the pressurization to 3 bar. As it was seen in the tests carried out before, tube 7 did not show any leakage signal. Maybe because of the leak had closed itself in the meanwhile. Figures 3.19, 3.20 and 3.21 show the Energy released of each tube.

Figure 3.19- Energy released [eU] in tube 6 (leak) at 3 bar.

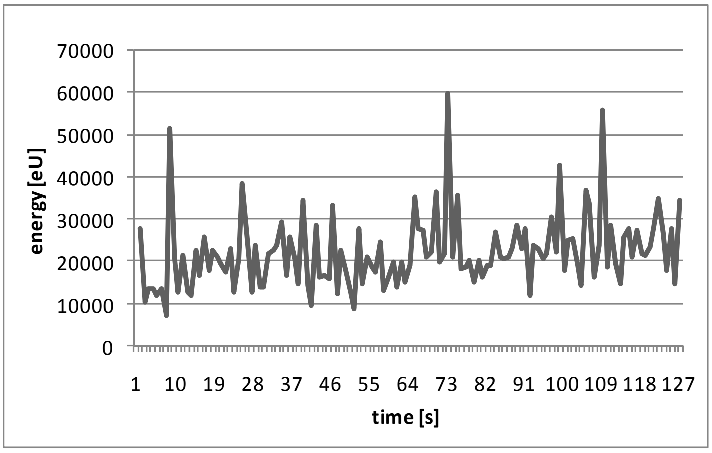
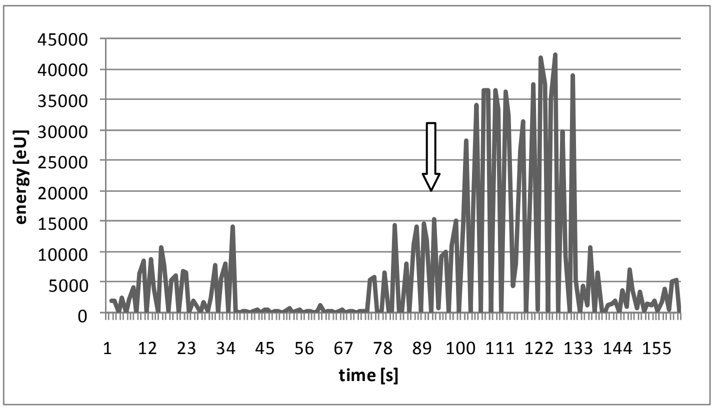


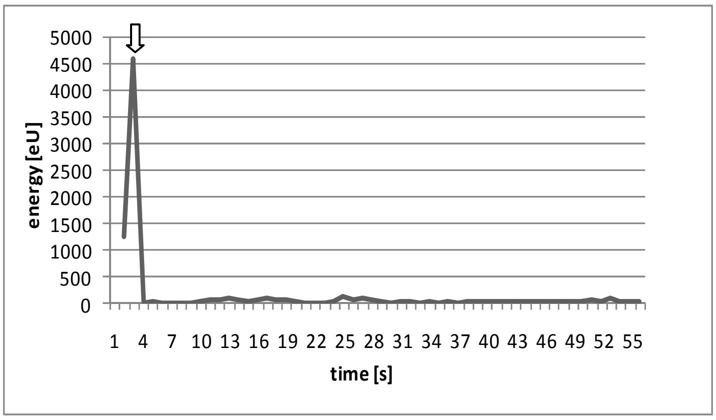
Figure 3.20- Energy released [eU] in tube 8 (leak) at 3 bar.



In tube 6 the energy value ranged from 15000 to 60000 eU, and in tube 8 it ranged from 5000 to 40000 eU. Tube 6 was more stable than tube 8, which released more energy from 100 sec onwards. This could have been caused by a short diversion in the tube inclination which generated a bigger amount of bubbles.

It is also needed to take into account the size and the speed of bubble generation. When big or small bubbles are detached rapidly (depending on the applied pressure), the time between their peaks is tight, and the amplitude when the big bubbles are detached (case tube 6) is higher than when the small bubbles are released from a small leak (case tube 8).

Figure 3.21- Energy released [eU] in tube 7 (no leak) at 3 bar.



In tube 7 there was no activity, and just one peak was recorded at the beginning of the test (2 sec). It was only 4500 eU, a very low energy value in relation to the tubes with leak, which reached values between 15000-60000 eU, hence it could be a noise or a distortion produced in the lab at the beginning of the test.

Undoubtedly, in this test concerning the Energy, the difference between the damaged tubes and the right tubes was much more evident than in the RMS test, thus, the Energy seemed to be a good way to distinguish between both, therefore one more test was carried out to check the reliability from this point of view. Was the Energy a reliable source of leak detection? Looking at the Appendix (5.1, 5.2 and 5.3), Vallen Acquisition screenshots (Energy and Amplitude depending on Time), it was found out that the Energy (**red colour**) from the tubes with leak still had much more activity than those without leak. In damaged tubes the energy average was around 45000 eU, whereas in good tubes just a couple of peaks of 4000 eU were registered.

Conclusion: According to the energy graph, a significant activity was recorded when a leakage was presented, therefore, it was visually easy to make the difference between the tubes and it seemed to be a useful tool to detect if there was a leak (or not) in a tube.

3.2.5. Measuring the Frequency content of the AE signal in water container.

In order to check another characteristic of the AE signal on its discrimination power of leakage, new tests were focused on the Frequency and were carried out in the same circumstances as the RMS/Energy tests: a tube was dived into water after it was pressurized to a certain pressure.

If the threshold was not set properly and it was too low, it could not be concluded that the typical bubble release was located around 50-55 kHz in the frequency band, because the noise interfered in the test hiding the sound of the bubbles. Therefore, the frequency values were not repeated (Appendix 5.4).

However, if the threshold was set properly, the noise was still recorded, but at this level the sound of the bubbles was also recorded (Appendix 5.5). The results were more stable, and the highest peaks appeared around the same values, 20 kHz (background noise) and 50 kHz (sound of the bubbles).

<u>Conclusion:</u> According to the frequency graphs, in order to find out the frequency of the bubbles detaching from the tube, it was needed to increase the threshold up to a level for which the noise of the environment did not disturb. At this level, it was supposed that the noise coming from the environment was not recorded, but the sound of the bubbles was. In our tests, it was impossible to achieve this situation, and the noise was always recorded, although the reached level was small enough to allow the sound of the bubbles to appear. Therefore, the most difficult part was setting the threshold. Focusing on the frequency in an industrial environment seems to be impossible in order to distinguish between these two sounds, unless the tests were performed in an isolated chamber without noise. Otherwise, the machine sound can be much higher than bubbles sound, and it would be hidden.

After all those tests, it was decided to test in production environment to compare with the obtained results in lab.

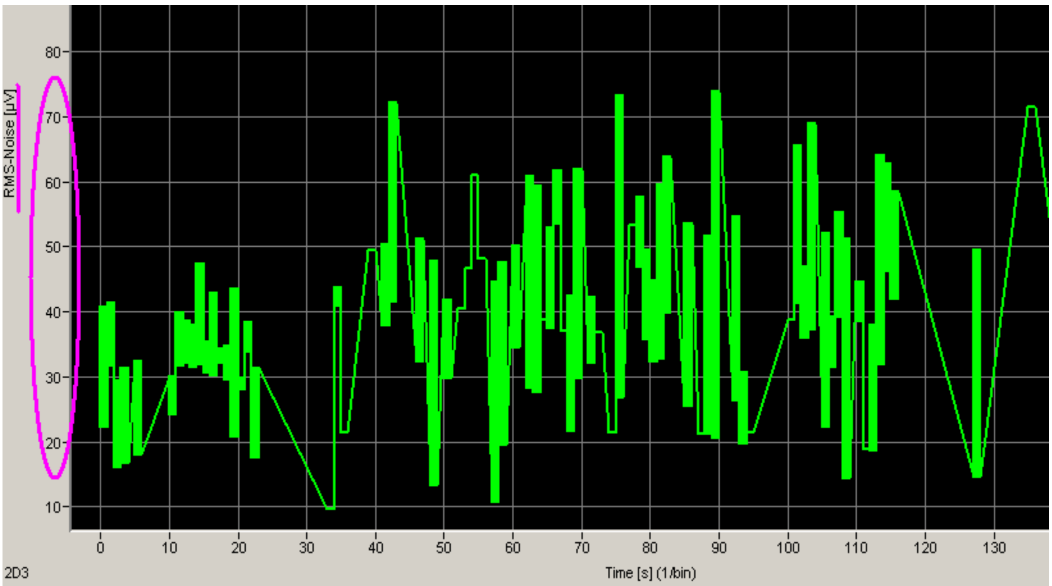
3.3. Trials in water (production environment).

3.3.1. With a prototype water container.

The procedure carried out in the industrial environment of Tenneco Europe in St. Truiden was the following. Firstly, in order to measure the noise, the container was filled with water, the AE equipment was switched on, and the sensor started to record the noise of the environment through the water (without any tube inside). In this case, the propagation medium itself was the water, because the sensor was just in contact to the liquid and there was no tube inside the container, so that the wave was transmitted through the liquid, in which the wave travelled more slowly than through the solid. After that, measurements were taken with the tube inside the container.

Figure 3.22- Machinery used for Tenneco Europe to pressurize the tubes and to dive them into the water.

Figure 3.23- RMS [µV] vs. Time [s] in production environment.



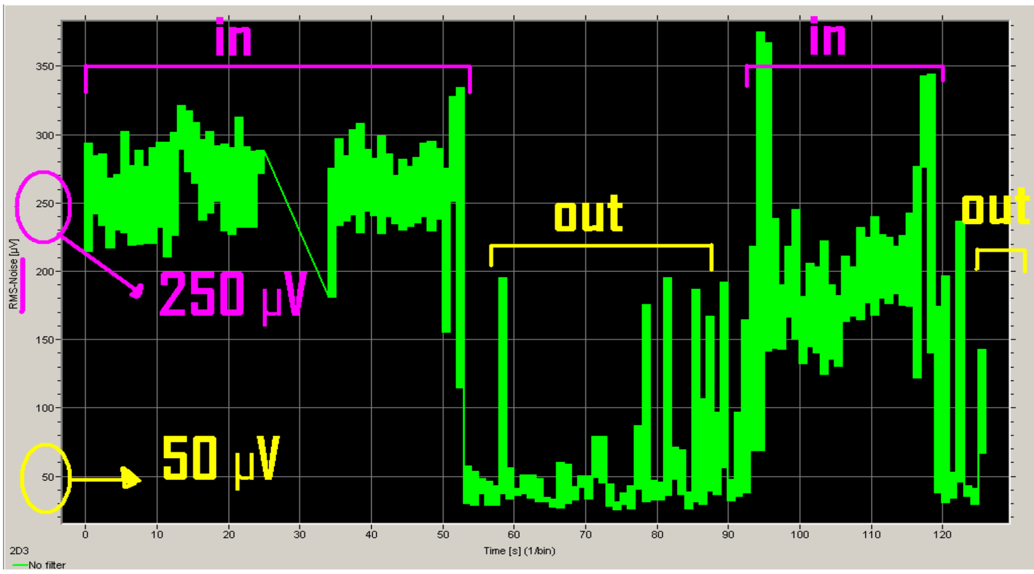
Conclusion: There were big noise levels: RMS values were between 20-70 µV (Figure 3.23). It was not possible to set the threshold. Despite it was increased, the sound of the bubbles was lower than machine noise, because as it could be seen in point 3.2.1, the amplitude of a single bubble was around 0.05 mV = 50 µV (depending on the bubble size), thus, it was visually impossible to see the difference between them. In the production environment, the main problem is the wide variety of noises produced in the factory, because mechanical noises (like hammers) or pneumatic tools (its whistles) located very close to the sensor can produce sounds of high amplitude at high frequencies, and it is not possible to distinguish them.

3.3.2. With the sensor attached to the visual leak detecting equipment of Tenneco.

Figure 3.24- Machine in charge of pressurizing and diving the tubes into water.

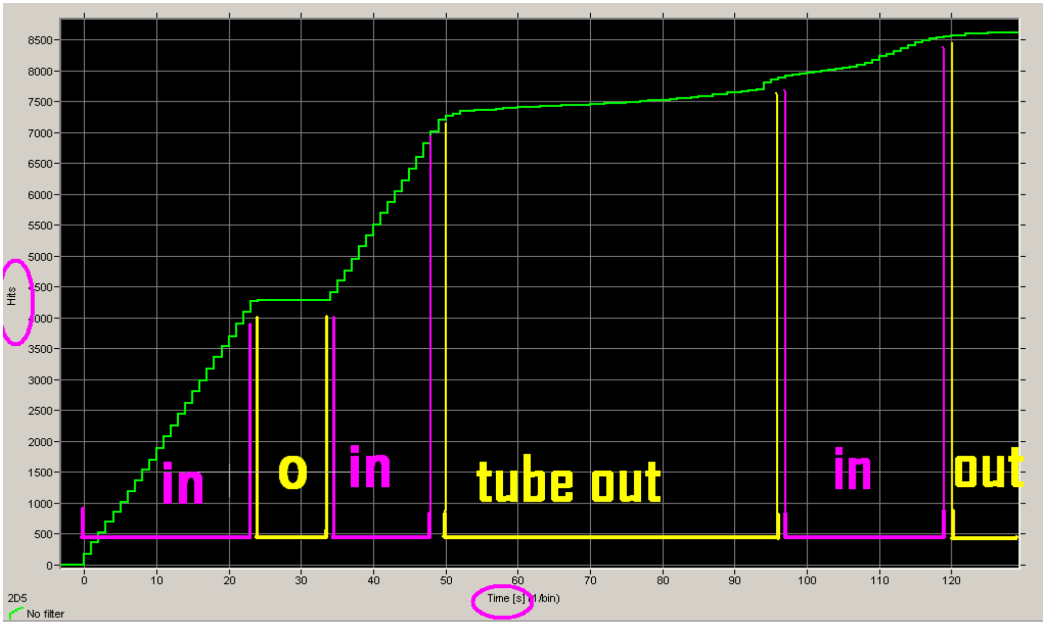
The following test was performed with the goal to monitor the sensor sensitivity in the production environment. VS30-V sensor was attached to the machine side which is in charge of pressurizing and diving the tubes into water, while it was normally working. After that, measurements were taken with a pressurized tube inside this machine. The tube had a huge leak, hence the bubbles were big enough to be recorded by the sensor (amplitudes around 250 µV). The next step was measure again taking the tube out of the machine, and compare the difference.

Figure 3.25- RMS values [µV] when the tube was in/out the machine.



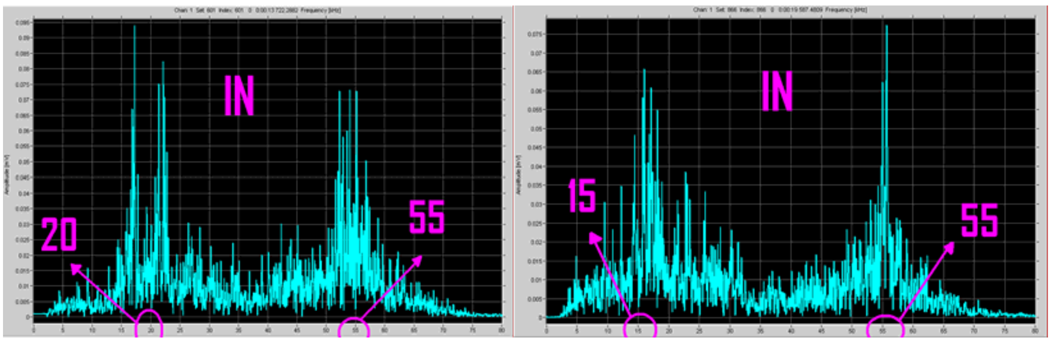
Conclusion: While the sensor was attached to the machine, the RMS was between 40-150 µV. These values were higher than the obtained with the container (see point 3.3.1), because of the fact that the machine was working while testing. The RMS values when the tube with a huge leak was inside the machine were between 150-300 µV. In case there was no tube inside the machine, there were no bubbles formation, and the RMS values decreased up to 50 µV approximately, values that made sense, because in point 3.1.1 noise was measured between 20-70 µV (Figure 3.23). It was possible to distinguish big leaks with the RMS values, although too much time was elapsed until the values became stable to make difference. Additionally, the results need to be interpreted, therefore, the industrial application is questioned.

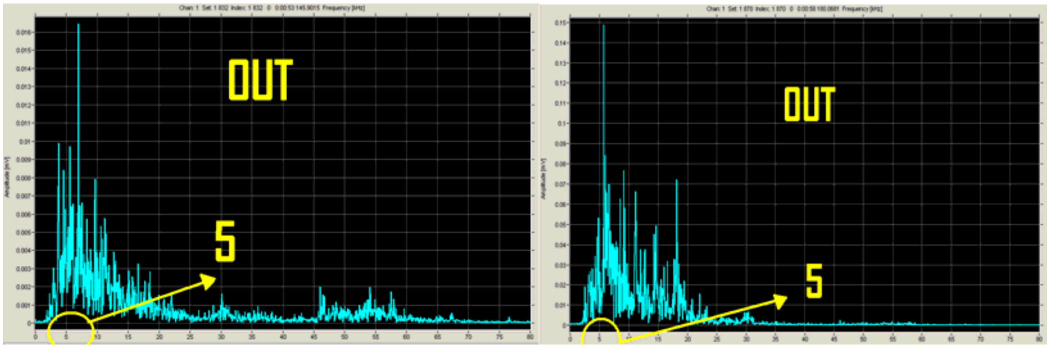
Figure 3.26- AE Hits as a function of time [s].



Conclusion: Looking at the slopes in Figure 3.26, the hits increased when the tube was inside the machine and the bubbles were detached. Therefore, the sensor feels the bubbles.

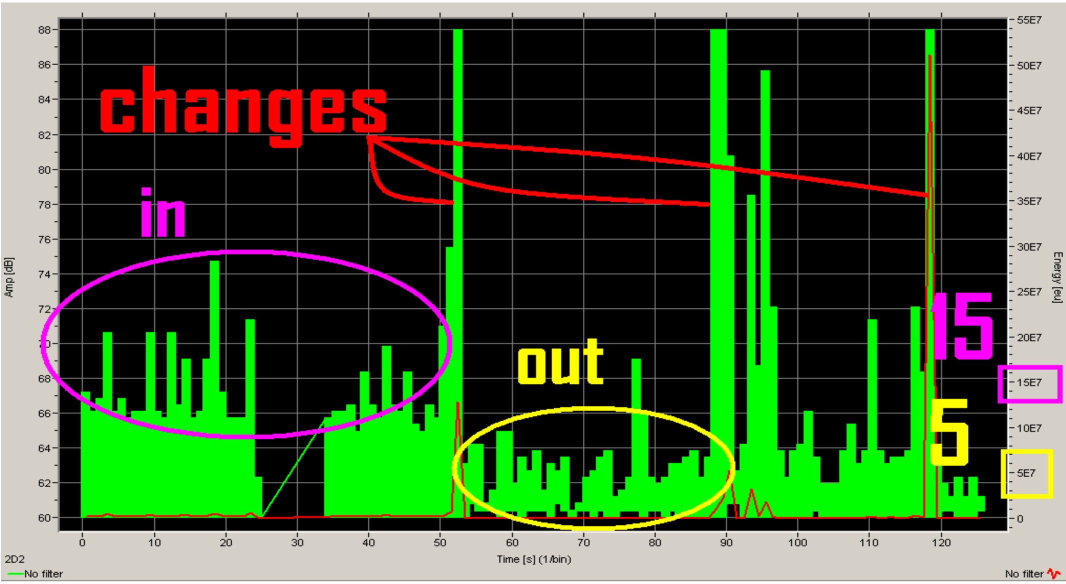
Figure 3.27- Frequency [kHz] vs. Amplitude [mV] in tests made with the tube inside/out the machine.





<u>Conclusion:</u> The bubbles can be detected visually in the Frequency/Amplitude graph. Noise was located in low frequencies, around 5 to 20 kHz, while the sound of the bubbles had higher frequencies around 50-55 kHz.

Figure 3.28- The Energy [eU] (**red line**) and the Amplitude [dB] (**green bars**) as a function of the time.



In the graph, the word "changes" means the step of taking the tube out of the machine, and vice versa.

<u>Conclusion:</u> The energy graph did not show a clear distinction. The Energy (**red line**) must show activity when the bubbles were detaching, but it did not, just in case of "changes". This analysis needs to be interpreted, thus the industrial application is questioned.

4. Modifications and alternative

Thanks to the opinion of an NDT engineer from Vallen Systeme Company with a long experience in AE, a new line of future research has been proposed.

An alternative and possibly better way could be to pressurize the tubes with water instead of air. This will result in stronger turbulences. Using this system, the sound of the leak would increase, and therefore, it would be easier to detect and distinguish it from the background noise. With the same objective of increasing the turbulence throughout the leak, the pressure should be the maximum without causing any damage to the tube.

Diving the tubes into water will not be necessary and the test would be carried out in the air. The propagation medium itself would not change because the sensor would be attached to the tube, so that the wave would be transmitted through the solid, the only thing that would change is the way the sound is generated. It is also possible then to increase the frequency range of the sensors, thus the most of the background noise would be avoided, because the sensor VS30-V is very sensitive and picks up all sounds below 100 kHz, however the exact frequency of the sound of the leaks should future be investigated.

After making contact with another expert in this field of leak detection, another alternative method was proposed to solve the leak detection problem in an industrial environment. It is based on a pressure decay method. Three possibilities are listed:

1. “Chamber” pressure variation: The tube is filled up to the test pressure after welding and is placed inside a "chamber", which surrounds it. If there is a pressure increase inside the “chamber” due to a leak in the tube, it will be measured.

2. Absolute pressure decay: The tube to be tested is filled up with air to a given test pressure. This filling phase is followed by a settling phase to stabilize the piece inner pressure. During the leak measure, the pressure drop is measured with reference to the end of the settling phase. A leak decreases the inner pressure of a piece as an inverse proportion with respect to the volume; by consequence, the higher is the volume, the more time will be needed to measure a leak. In other words, the smaller is the leak to be detected, the more time will be needed to measure a relevant drop pressure.

3. Differential pressure decay: The test is performed by comparison between a reference master piece and an object to be tested. Both objects are filled up at the same test pressure. Then the equipment waits for the settling down of the pressures and the mechanical parts. The measurement of the leak is referred to the pressure difference between the two parts. It is preferable to use as master piece

an object of the same volume and with the same features of the tested piece; moreover, it is better to use an identical piece, obviously good. In this case, the settling of the two objects will be very similar. By measuring the leak for comparison between the two parts and behaving these two in a very similar way, it will be possible to obtain a significant settling time reduction. Moreover, the use of a differential pressure sensor allows increasing the resolution of the pressure measures between the two pieces. The result is that, if a piece in test has a leak, it will be possible to measure it better and in less time [34, 35].

Table 4.1- Leak rate.

Method	**Fluid**	**Leak rate [Pa· m^3/s]**	**Test type**
absolute/differential pressure decay	Air/air	10^{-3}	Detection
"chamber" pressure variation	Ari/air	10^{-4}	Detection

These methods in production could be reliable and inexpensive, although the mayor disadvantage would be the execution time, which would take too much time. It would be increased up to 15-20 sec per tube approximately, and not 6-12 sec as the bubbles technique does.

5. General conclusions

After all the tests that were conducted, some general conclusions can be formulated over the AE technique:

The tests that were carried out with AE in air show a low reliability. The sound generated by the air going through the leak is hidden behind the existing background noise. Although it is practically impossible to set a threshold in which only the sound of the leak is registered, an adequate set up is fundamental to take down the measurements: too high of a threshold avoids capturing the background noise but at the same time it avoids measuring the sound of the leak. On the contrary, a low threshold would pick up all the existing sounds. The knowledge of the existing frequencies in which each sound is oscillating helps filter the signal using the Vallen software package.

Background noise usually oscillates at low frequencies (5 - 25 kHz), although depending on the type of noise that is produced near the sensor it can oscillate up to 50 kHz. The frequency of the air flowing through the leak is around 50 kHz, thus there is no guarantee of a complete filtration of the noise since the measured sound and the noise overlap. To detect both noise and the desired sound, a low frequency sensor (30 - 100 kHz) is the most adequate for this situation.

Despite the noise, the tests in water that were done in the laboratory using the sound of the bubbles provide results that are more promising than those done by air, however not so for those realized in a production environment which also do not provide great reliability. As an inconvenience, AE requires also a higher testing time than the visual method, since it is necessary to wait until the data is stabilized, analyzed and interpreted (Energy/RMS/hits). Thus because of this and since it appears not to be more reliable than the visual method (the leak rate does not surpass the visual method), the feasibility and the industrial application of using AE for leak detection of tubes for shock absorbers in a production environment is still questionable. The proposed changes in point 4 could help to have a better outcome for the AE technique for leak detection.

The alternative that was posed in point 4 opens a new way to the study of future research in leak detection of such tubes in the production environment. The reliability and utility of such a method in other components is already absolutely recognized, and multinationals, such as Bosch, conduct thousands of tests to check the leakproofness of the airbags that they produce in their factories.

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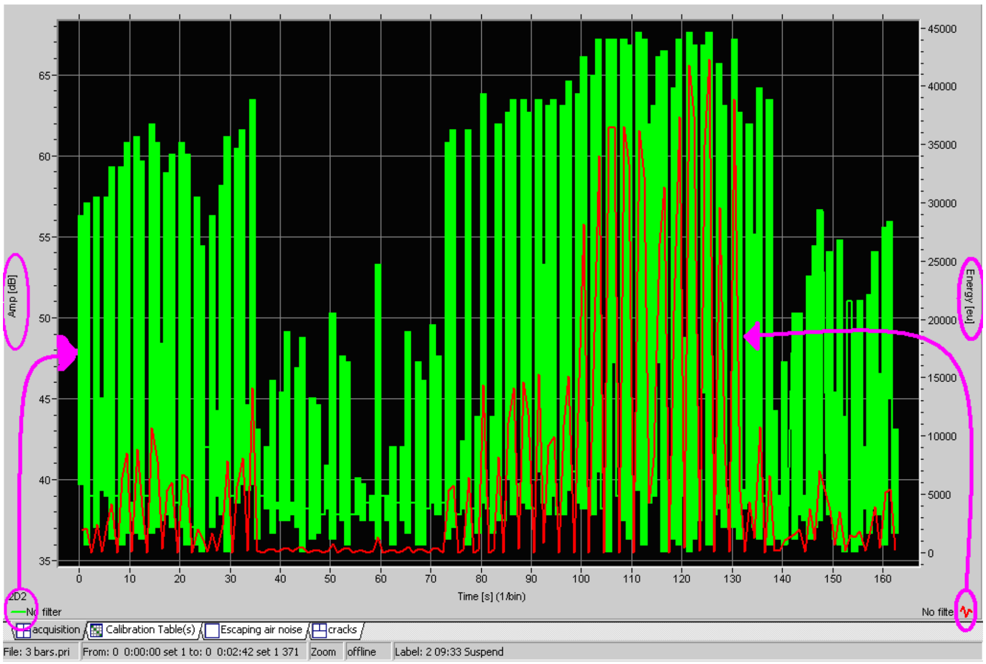
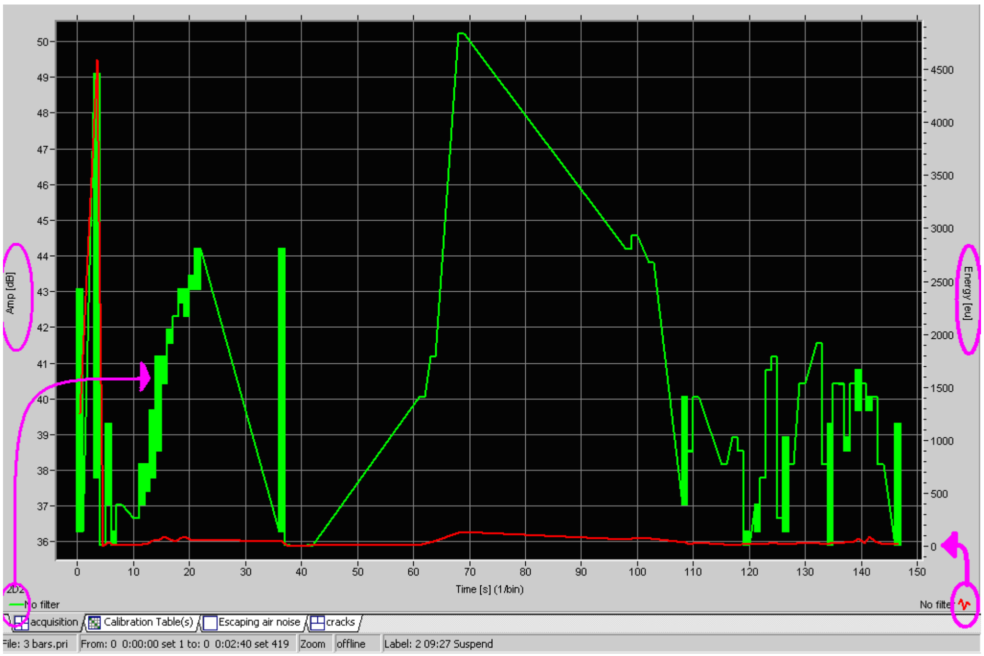
7. Appendix

7.1. The Energy (**red line**) and the Amplitude (**green bars**) as a function of the time in tube 6 (leak).

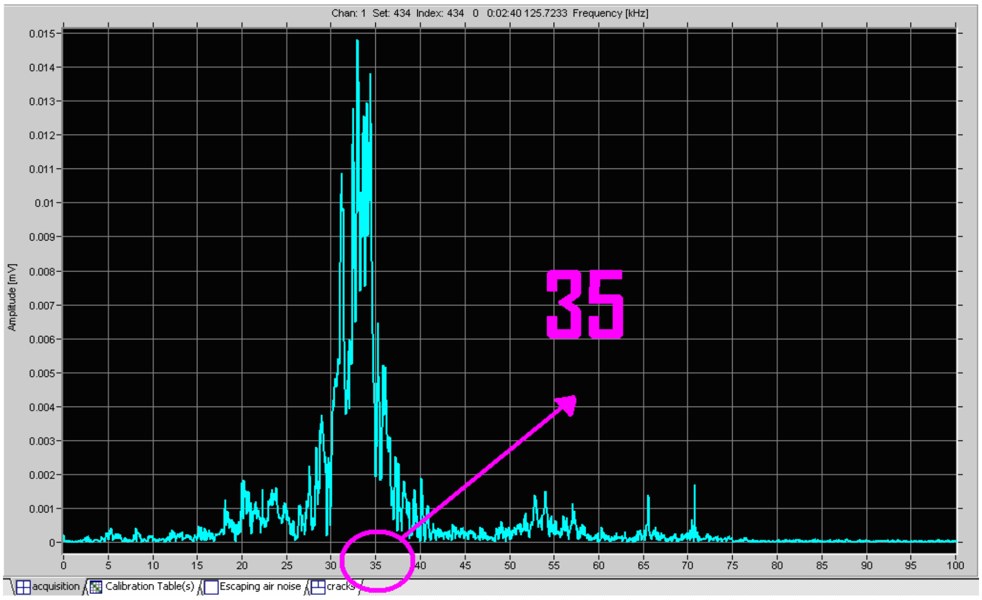
7.2. The Energy (**red line**) and the Amplitude (**green bars**) as a function of the time in tube 8 (leak).

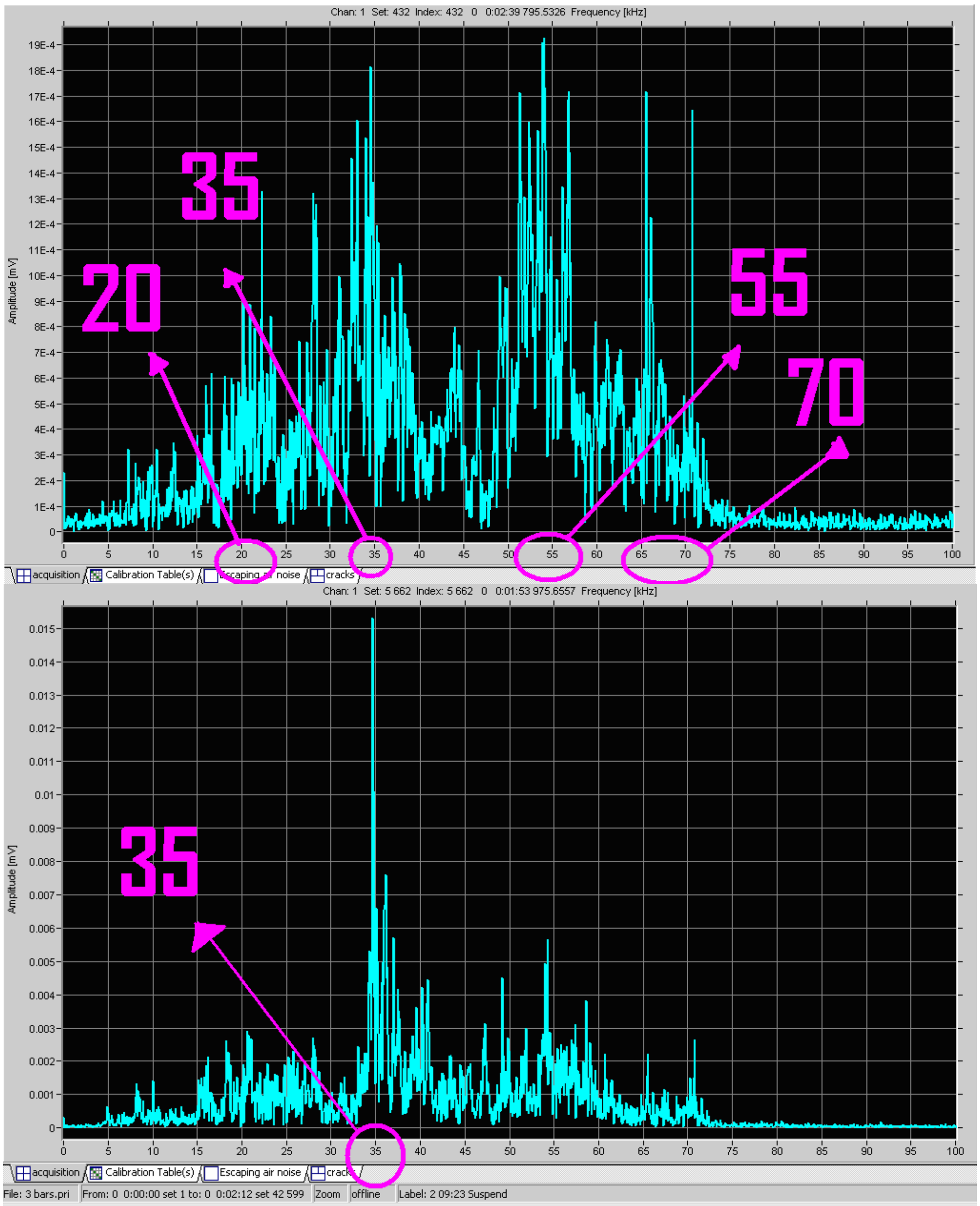


7.3. The Energy (**red line**) and the Amplitude (**green bars**) as a function of the time in tube 7 (no leak).

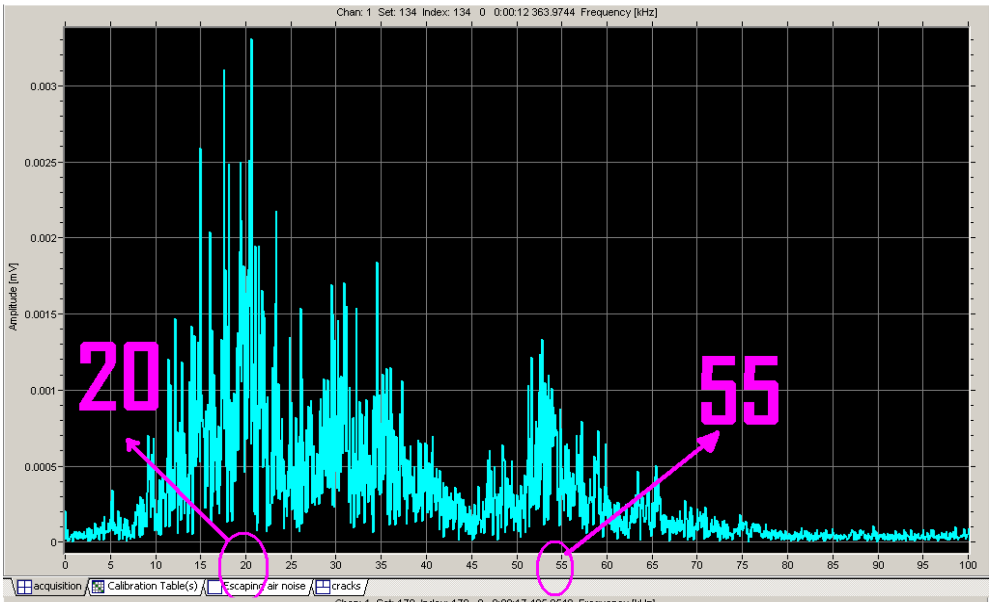


7.4. Random values in a Frequency [kHz] vs. Amplitude [mV] graph, for a tube with leak in which a low threshold level allows the noise to interfere in the signal.





7.5. Repeated values in a Frequency [kHz] vs. Amplitude [mV] graph, for a tube with leak in which a high threshold level does not allow the noise to interfere in the signal.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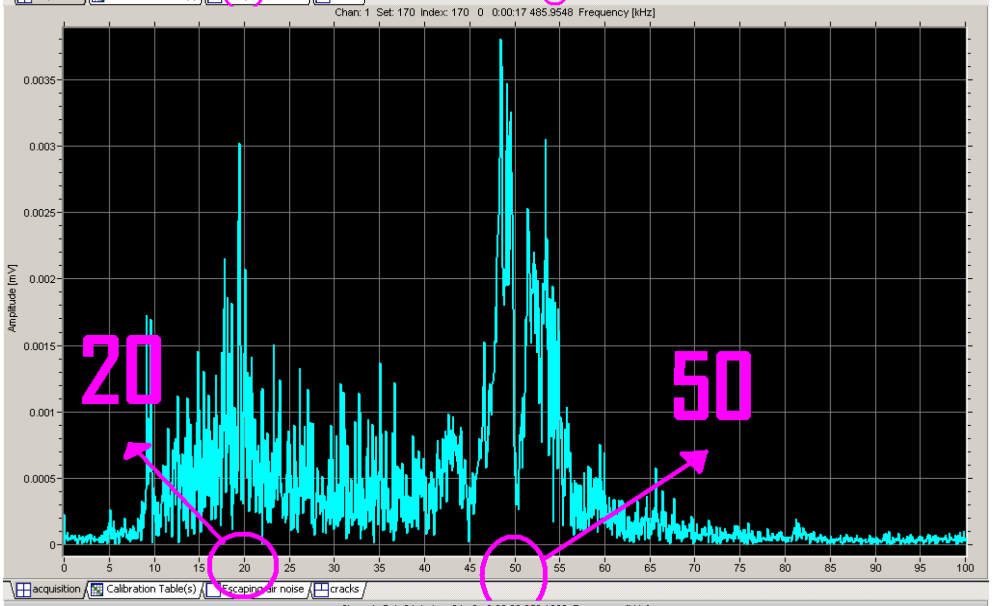
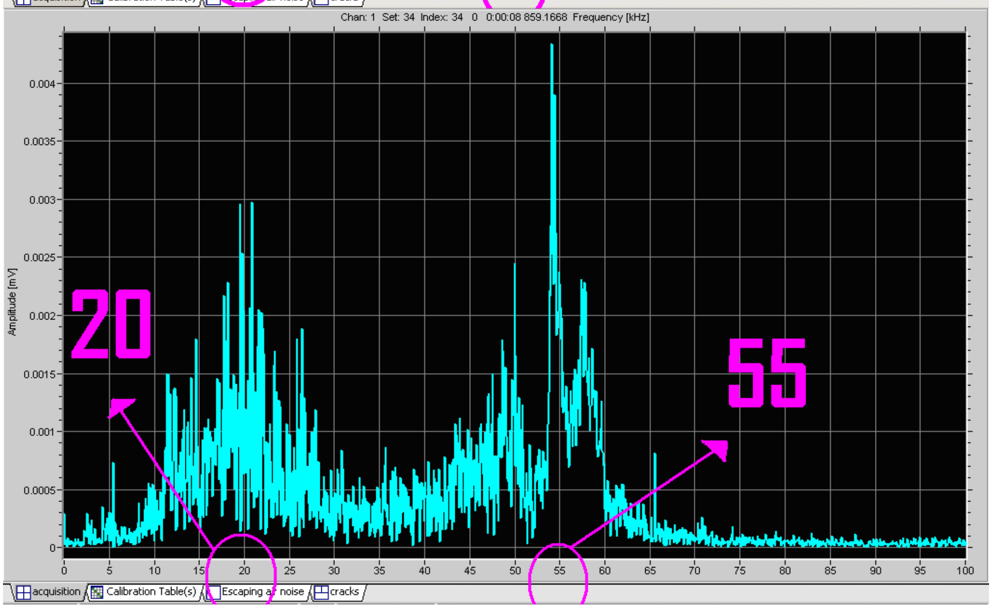
Amplitude [mV]
20
55
acquisition
Calibration Table(s)
Escaping air noise
cracks


Chan: 1 Set: 170 Index: 170 0 0:00:17 485.9548 Frequency [kHz]
Amplitude [mV]
20
50
acquisition
Calibration Table(s)
Escaping air noise
cracks


Chan: 1 Set: 34 Index: 34 0 0:00:08 859.1668 Frequency [kHz]
Amplitude [mV]
20
55
acquisition
Calibration Table(s)
Escaping air noise
cracks