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Vibroacoustic measurements for detecting water leaks in buried small-diameter plastic pipes

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Abstract: Leak detection is an essential topic within the policies of water losses management in drinking water supply networks. This paper reports the results of an experimental campaign performed for assessing the sensitivity to water leaks of measurements of different vibro-acoustic phenomena. The study represents the first stage of a research aimed at developing a device for the automatic leak detection in service pipes of water distribution networks. Leaks were artificially induced on a plastic pipe (length of 28 m, diameter of 32 mm) of a buried experimental facility. Vibro-acoustic phenomena related to the leaking flow were monitored by using a hydrophone and two accelerometers. A satisfactory leak detection performance was achieved by processing the signals of both kinds of transducers.

Author keywords: Water-filled pipe; Plastic service pipe; Vibration monitoring; Leak detection.

Introduction

The efficiency of water distribution network is significantly decreased by water losses, which frequently exceed even 30% of the input volume (BDEW 2010; EPA 20102010), and in certain cases may reach much higher levels, up to 50-60% (Kanakoudis and Tsitsifli 2010 and 2014; Kanakoudis et al. 2013;), and even peak at over 70% (Kanakoudis and Muhammetoglu 2014). Since the largest part of water losses is ascribable to leaks or pipe breaks (i.e. resulting from pipe holes and damages), real losses being generally more than 50% of Non-Revenue Water (Kanakoudis and Tolikas 2001; Kanakoudis 2004), proper policies to manage such leaks are essential.

Many approaches and technologies have been proposed for achieving leak detection and location, in order to implement Active Leakage Control strategies (Hunaidi et al. 2000; Gao et al. 2005; Suzuki et al. 2005; Metje et al. 2007; Anastasopoulos et al. 2009; Fahmy and Moshelhi 2009; Bimpas et al. 2010; Ghazali et al. 2012; Cataldo et al. 2014; Yazdekhasti et al. 2016). The most widespread techniques, which are ordinarily adopted to carry on leak detection and repair programs in practice, are based on the monitoring of vibro-acoustic phenomena generated by active leaks.

Several factors are commonly considered as potential sources of leak-related noise, even if the physical mechanism of noise generation is not yet completely understood. Turbulent condition of the leaking flow is proven to be a relevant source of noise (Papastefanou et al. 2012). Some experiments suggest that the medium the water leaks into may significantly affect noise and vibration levels (Thompson et al. 2001; Vahaviolos et al. 2001). Conversely the actual influence of cavitation phenomena is a controversial issue (Anastasopoulos et al. 2009; Khulief et al. 2012; Papastefanou et al. 2012).

Nonetheless, the effects of vibro-acoustic phenomena related to water leaks and the way they propagate along pipelines are well-known. Active leaks can excite the vibrational modes characterizing fluid-filled pipes. In practical applications low-frequency modes (i.e. well below the pipe ring frequency) are mostly responsible for the observed leak noise, namely three axisymmetric waves (order n=0) and the n=1 wave, which is related to beam bending (Fuller and Fahy 1982; Muggleton et al. 2002; Gao et al. 2004). In particular, propagation of vibrational energy is mainly ascribable to the two axisymmetric waves termed s=1 and s=2 respectively (Pavic 1992; Muggleton and Brennan 2005): the former is preponderantly a fluid-borne wave; the latter mainly involves axial deformations of the pipe shell. These waves are coupled by the Poisson ratio, coupling being weak or strong depending on the characteristic of both the pipe and the surrounding medium (Muggleton et al. 2002). The monitoring of fluid pressure waves and pipe vibrations, by means of hydrophones and accelerometers respectively, is effectively adopted for detecting and pinpointing leaks.

The present research deals with the detection of leaks in plastic (namely high-density polyethylene, HDPE) small-diameter service pipes of water supply networks. It was promoted and funded by the multi-utility Hera S.p.A. (Bologna, Italy), a company that supplies about $3 \cdot 10^8$ m^3 per year of drinking water to 237 municipalities (total population of about 4 million), through a network of 35150 km of water mains. Indeed, this class of pipes represents a significant percentage of the service pipes installed in the distribution network. In particular, the multi-utility started using HDPE pipes for all the new connections about two decades ago. Moreover, since then all the leaks detected in service pipes have been repaired by completely replacing the old pipes with new HDPE ones. Although leaks in service pipes typically exhibit low flow rates, their total runtime (i.e. the total period to the burst repair) is generally longer than for large leaks. This leads to high overall losses as well (Butler 2000; EPA 2010). Consequently, they represent significant costs and require the development of proper strategies to manage pipe replacement and repair (Kanakoudis and Tolikas 2001). Indeed water losses related to service connections constitute a significant percentage of the total losses affecting the water distribution network managed by the multi-utility, as shown by the company internal reports on maintenance operations. In addition, the effectiveness of the mentioned detection techniques based on vibro-acoustic signals may result considerably reduced in case of plastic pipes (which are being recently installed in water distribution networks), due to a greater signal attenuation with respect to metal pipes (Hunaidi and Chu 1999; Hunaidi et al. 2000; Gao et al. 2004; Pal et al. 2010). Nonetheless, to the authors' best knowledge, not many studies dealt with water leaks in small-diameter pipes (most of the works being concerned with leak detection in large-diameter distribution pipes) and particularly with plastic service pipes, which are frequently characterized by a diameter smaller than 40 mm (CEN 2000). Therefore, the first objective of this work is to carry out a deeper investigation on leak detection for this kind of pipes, with main focus on longitudinal cracks, which are the most common for the network of interest. In particular, leaks are simulated through induced longitudinal cuts, whereas most of the studies simulate leaks by means of drilled holes or by opening valves (e.g. Miller et al. 1999; Yazdekhasti et al. 2016).

The second objective is to develop and test a simple and reliable algorithm for leak detection purpose by using vibro-acoustic signals. In particular the algorithm adopts a scalar detection index based on a simple statistical parameter (namely the signal standard deviation), which is computed for steady-state signals measured under the normal network operating conditions, as opposed to methods requiring induced transients or pressure increment (e.g. Anastasopoulos et al. 2009; Colombo et al. 2009). The proposed algorithm works with one single transducer, whereas many know techniques require two distinct sensors, since they are based on signal correlation (e.g. Gao et al. 2004; Yazdekhasti et al. 2016). A proper strategy is developed to overcome possible high incidence of false alerts, a known issue frequently affecting systems relying on one single sensor, such as noise loggers (Hunaidi et al. 2012; Liu et al. 2012).

The final goal of the project is the development of a system for automatic early detection of unreported burst leaks occurring in the service connections running from the water main to the users' metering points (Leoni et al. 2009). The system is required to be installed near the customer water meter and to operate at the normal functioning conditions of the network. Detecting leaks with satisfactory reliability is a primary requirement in order to avoid possible false detections, which would result in an unaffordable increment in leak management costs due to unnecessary operations of the maintenance teams. Low cost is one of the essential system requirements too, due to the planned widespread installation. Hence, very simple hardware components must be adopted in order to meet cost requirements (Martini et al. 2014). The developed algorithm is suitable to meet such requirements, as it relies on rather basic analysis techniques, thus its computational requirements being limited. The system may be integrated with the automatic meter reading (AMR) system, in order to share both the power supply and the data transmission network. Thanks to these characteristics, and since cheaper and cheaper sensors and electronics are constantly becoming available, the multi-utility estimates that monitoring service pipes may become economically convenient within the next decade.

An experimental campaign was carried out for assessing the effectiveness of measurements of different vibro-acoustic phenomena for leak detection purpose, as well as the performance of the detection algorithm based on such measurements. The experimental tests were performed on a buried test facility of the multi-utility Hera S.p.A. that simulated a typical customer connection branch of the network. Water leaks were artificially induced on a small-diameter HDPE pipe. Signals in both leaking and non-leaking conditions were measured by means of two accelerometers and a hydrophone. The leak detection performance was assessed for leaks located at different distances from the transducers. This paper describes the experimental setup, the test protocols and the techniques adopted for the analyses, and reports the most relevant results of the study.

Experimental setup and tests

The test facility used for the experiments simulates a portion of the water distribution network (Fig. 1). One polyvinyl chloride (PVC) pipe with outer diameter of 90 mm (DN 90) is used as water main. Several plastic pipes of smaller diameter (DN 32) are connected to the larger one as customers' service pipes. Two-way shut-off valves are installed at both extremities of each service pipe, inside manholes. All the pipelines are buried under about 0.5 m of soil. The rig is fed by a pressure tank which permits to regulate water pressure.

All measurements were performed on a HDPE pipe of length 28 m (the typical length of the service pipes installed in the water supply network operated by HERA S.p.A. being about 10 m). Tests were carried out on a pipe nearly three times longer than the average in order to assess the maximum range achievable for leak detection, thus possibly increasing the detection performance on standard 10 m long service pipes. The pressure was kept constant at about 3.5 bar, which is the typical functioning condition of the network.

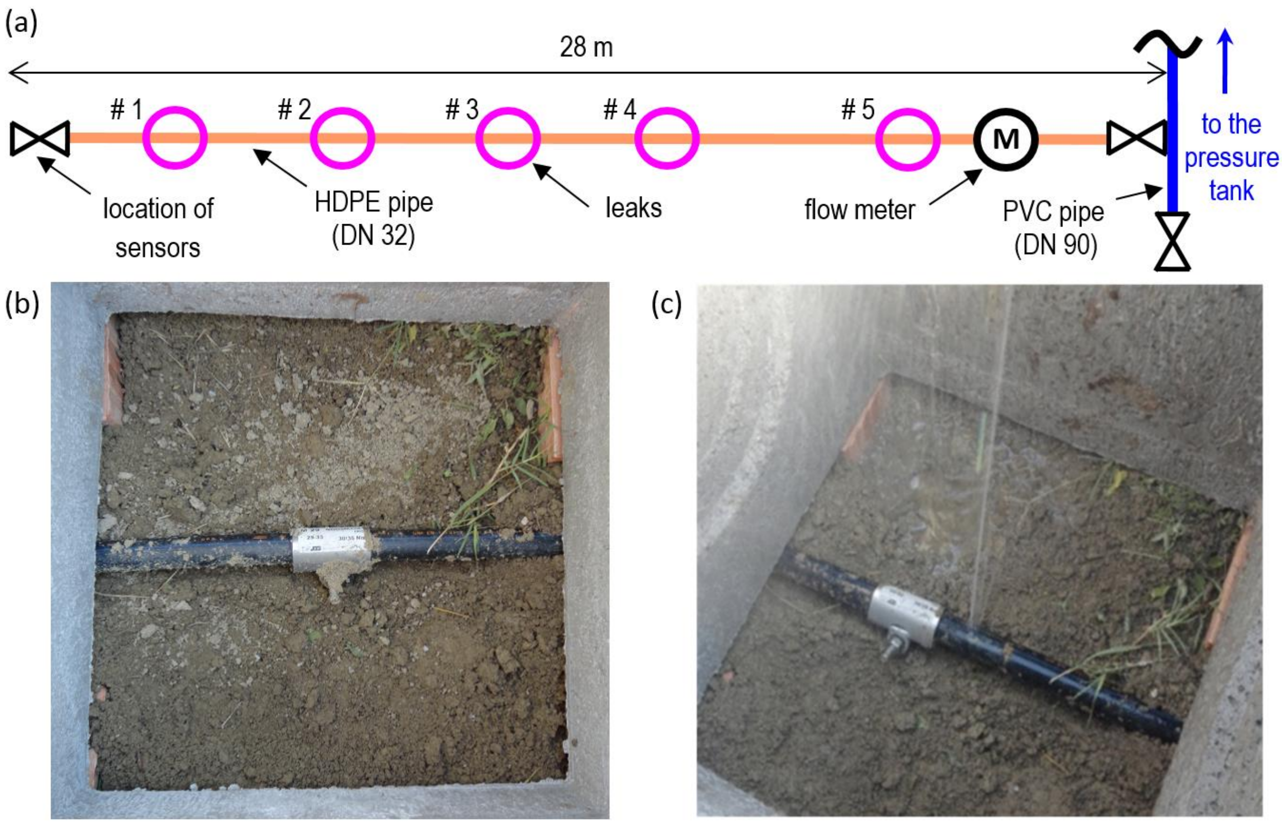

Fig.1. Experimental facility: (a) schematics of the buried pipeline, (b) a repaired leak and (c) an active leak after removing the repair clamp

Leaks were artificially generated at five different locations along the pipe (Fig. 1a), in order to study the influence on the detection performance of the distance between leaks and transducers. The distance values from the terminal valve are reported in Table 1. The induced damages were 20 mm longitudinal cuts (parallel to the pipe axis), which simulated one the most common kind of cracks characterizing burst leaks occurring in the HDPE service pipes managed by HERA S.p.A., according to its maintenance records. In particular, a 20 mm longitudinal crack is expected to generate a leaking flow of about 200 l/h in the typical network functioning conditions (as determined in preliminary experiments conducted by the multi-utility), which is the target leak rate to detect. Manholes were installed to allow the access to the leak locations. Pipe repair clamps were also installed for each leak. Such devices permitted to rapidly switch between leaking and non-leaking conditions and vice versa (Fig. 1b, c). The leaking flow was monitored by a flow meter installed at the pipe T-joint (Fig. 1a). The measured flow rates are reported in Table 1. Leak #5, larger than the other ones, had been generated for previous experimental tests and its flow rate was remarkably higher. Nonetheless, Leak #5 was taken into account as well to assess the effects of a large but relatively distant leak.

Three transducers were mounted on the pipe terminal valve (Fig. 2a), to simulate the sensor setup possibly achievable in actual service pipes (where the sensors should be installed near the customer water meter, i.e. distant from the water main). Two Integrated Electronic Piezoelectric Excitation (IEPE) monoaxial accelerometers (PCB 333B55, sensitivity 1V/g) measured axial (i.e. longitudinal) and radial shell/wall vibrations respectively. A piezoelectric hydrophone (Wilcoxon Research H571LD-1A, sensitivity –187 dB, ref. 1V/μPa) monitored fluid-borne leak-related noise. The hydrophone was fastened directly to the threaded port of the terminal valve, thus preventing any water flow from exiting the valve.

Table 1. Main features of the studied water leaks

Leak	Distance [m]	Flow rate [l/h]
#1	3	200
#2	8	295
#3	13	200
#4	18	180
#5	26	4000

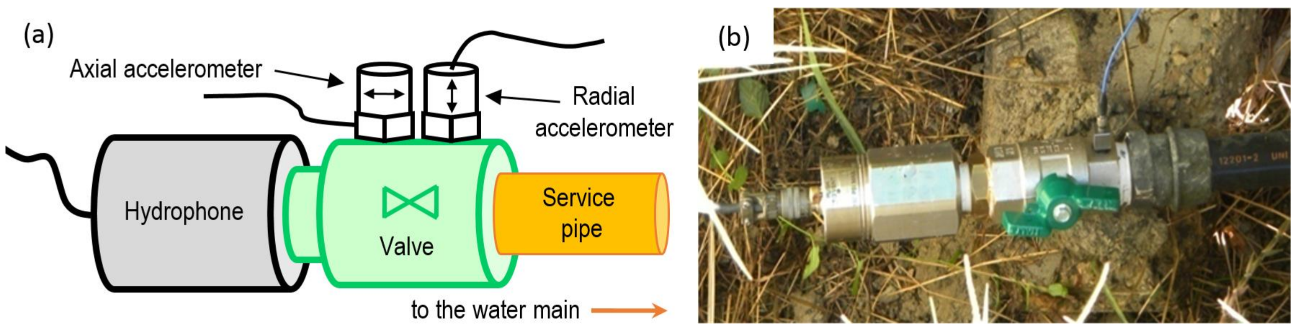

Fig. 2. Sensor setup: (a) schematics, (b) hydrophone and accelerometer close up

It is worth noting that the levels of the axial acceleration were expected to be higher than those of the radial acceleration, thus providing better detection performance. Indeed in the frequency band of interest both the s=1 and the s=2 modes normally exhibits preponderant axial displacements (Pavic 1992). However, unfavorable boundary conditions possibly found in actual pipelines may cause the monitoring of axial vibrations to be unpractical. In addition, the presence of elbow fittings between leak and transducer, while not preventing the detection (Martini et al. 2014), may alter the vibration transmission path. For all these considerations, radial vibrations of the pipe wall were investigated as well.

All the signals were simultaneously acquired by means of a LMS SCADAS Recorder SCR-01 (which also provided signal conditioning). The acquisitions were carried out by setting the sampling frequency (Fs) at 5120 Hz and the duration (Ts) at 30 s. Such parameters were determined in preliminary tests performed in the facility, which are not here reported.

Measurements were performed for both the non-leaking and the leaking conditions to assess, respectively, the environmental noise and the vibro-acoustic phenomena related to active leaks. The leaking condition was set by temporarily removing a single repair clamp (Fig. 1c), i.e. only one active leak at a time was considered. Two different cases were tested: *Case-A*, water leaking against backfill soil (such a condition was simulated by covering the leaking pipe with a plastic sack filled with soil, which could be easily installed and removed); *Case-B*, water leaking into air. Then the repair clamp was reinstalled again and measurements in non-leaking conditions were carried out. This sequence was repeated for all induced leaks. It is worth noting that during all tests the flow rate inside the pipe was entirely ascribable to the leaking flow of an active leak, in order to simulate a condition of null water consumption by the customers. Indeed the water flow induced by customers' water usage normally generates vibro-acoustic phenomena that hide the leak noise, therefore hampering leak detection. Such test condition does not reduce the reliability of the experiments since, for actual pipelines, it is possible to significantly limit the occurrence of such kind of perturbations by performing nighttime measurements (a practice commonly adopted for leak detection surveys in networks). Furthermore, measurements possibly still affected by environmental noise can be detected and removed from the acquired dataset by using proper signal processing techniques (Martini et al. 2015).

Signal processing and analysis

The analysis took into account only basic techniques, consistently with the project specifications. Indeed low cost is an essential design requirement of the final device for leak detection, since a large number of units should be installed for covering the entire network. In order to reduce the computational resources required to run a detection algorithm on-board (as the device is meant to operate autonomously), hence lowering hardware costs, only simple processing operations are allowed.

The acquired signals were processed by using a variant of the prototypal algorithm for automatic leak detection described by Martini et al. (2015). This variant was simply adapted to operate on the sets of acquisitions performed in the different test conditions of the experimental campaign (instead of working on datasets recorded in different consecutive nights). Indeed, many acquisitions were performed for each examined condition, in order to ensure repeatability of measurements, since the signals may result partially affected by environmental perturbations unrelated to the leaks (e.g. noise generated by traffic and industrial activities in the surroundings of the test facility). A very simple statistical parameter, namely the standard deviation of the raw signal (STD), is adopted to define a purpose-built parameter, referred to as *Monitoring Index* (*MI*), whose trend is monitored by the algorithm. In particular, the following operations are performed (for further details, see Martini et al. 2015):

1. The algorithm computes the STD of all the raw signals acquired for any specific dataset.
2. The *MI* value associated with the *j*-th analyzed dataset is computed as the average of the STD values of a valid (i.e. without perturbations) subset of the corresponding signals,

$$MI_j = \frac{1}{N}\sum_{k=1}^{N}\left(\sigma_{j,k}\right) \tag{1}$$

where $\sigma_{j,k}$ is the k-th element of the vector including the N lowest STD values of the j-th dataset. The experiments showed that the selection of a reduced subset of N = 10 signals permits to take into account only stationary signals, whereas those featuring anomalous transients are neglected.

3. The *MI* associated with an active leak is compared with the *MI* values characterizing the measurements in non-leaking condition. For a better reliability, *P* different datasets of measurements in non-leaking state are considered, hence obtaining a total amount of *P* different *MI* values associated with this condition. The signal levels are expected to rise when an active leak is present, with a resultant increment in the signal STD and in the corresponding *MI* value (with respect to non-leaking conditions) that allows for leak detection.
4. A further index, referred to as *Monitoring Index Efficiency* (*MIE*), is computed for assessing the algorithm efficiency in terms of sensitivity to the n-th leak, and is defined as follows:

$$MIE_n = \frac{MI_{Lk,n}}{\frac{1}{P}\sum_{i=1}^{P}\left(MI_{NL,i}\right)} \tag{2}$$

where $MI_{Lk,n}$ is the *MI* value characterizing the n-th leak and the $MI_{NL,i}$ values are the *P* different *MI* computed for the non-leaking state.

It is worth noting that the practical implementation of the algorithm for an actual service pipe of the network requires the definition of a proper threshold associated with the starting condition, to be initialized on the basis of measurements upon the system installation. Actual leaks are expected to start with small cracks that grow over time. In such scenario, the algorithm is expected to give a warning when the current *MI* value (evaluated every night) crosses the defined threshold. Hence, the algorithm is expected to be effective for new leaks occurring after the threshold initialization as well as for leaks existing prior to the installation that grow over time.

Further statistical parameters, namely skewness and kurtosis, were also computed for all the acquisitions and investigated as possible alternative metrics for leak detection, although other experiments had not revealed any relevant correlation with the leaking conditions (Martini at al. 2014 and 2015).

The measured signals were also investigated in the frequency domain, to possibly identify distinctive leak signatures for enhancing the algorithm effectiveness. In particular, the power spectral density (PSD) was computed and analyzed over the available frequency range, namely between 10 Hz (a high-pass filter was applied due to the frequency response limits of the hydrophone) and 2560 Hz (i.e. Fs/2).

Results and discussion

The results provided by the algorithm applied to the signals of the hydrophone and the radial accelerometer, acquired for leak #1 and *Case-A* (water leaking against soil), are shown in Fig. 3, as examples. Each bar chart reports the comparison between the *MI* value computed for the leaking condition (*Lk #1*) and those for the non-leaking acquisitions (*NL #1-4*), normalized to the highest term. The *MI* values of the non-leaking state refer to the four distinct datasets acquired after repairing leaks 1-4 respectively. The corresponding *MIE* value (which in this analysis is computed by putting at the denominator the mean of the four *MI* values in non-leaking condition) is reported in the figure right upper corner.

The *MI* values in non-leaking conditions are comparable, i.e. the background noise exhibits basically constant levels during all tests. Figure 4 reports the comparison in the time domain of two measurements concerning leak #1, in leaking and non-leaking condition respectively, for the radial accelerometer and the hydrophone. As expected, the leaking flow induces higher signal levels. This results in a remarkable increment in the *MI* of the active leak, which permits the detection. As also expected, the results observed for the three sensors are quite different, since each sensor measures a different component of the axisymmetric waves associated with the vibro-acoustic energy flow

(Pavic 1992). This behavior is consistent with the results provided by other experimental studies (e.g. Hunaidi and Chu 1999). Table 2 reports the detection results (successful or failed detection) and the corresponding *MIE* obtained by running the algorithm on the data measured with the hydrophone and both the accelerometers for all leaks in *Case*-*A*. If the leak detection is missed, the *MIE* is set to zero. The detection is considered missed as well if the *MIE* value is lower than 1.5. This specific value was arbitrarily defined to assess the algorithm performance for the measured data. It was determined on the basis of the standard deviation of the $MI_{NL,i}$ values, which was found to be about 15% of the average, i.e. the denominator of Eq. (2), for all sensors. Accordingly, the adopted threshold was considered as the minimum value to achieve leak detection with an acceptably low probability of false positives. Nonetheless, a further tuning of the threshold would be reasonably required for the final implementation of the leak detection system, depending on the desired level of reliability and tolerance for false positives to be achieved.

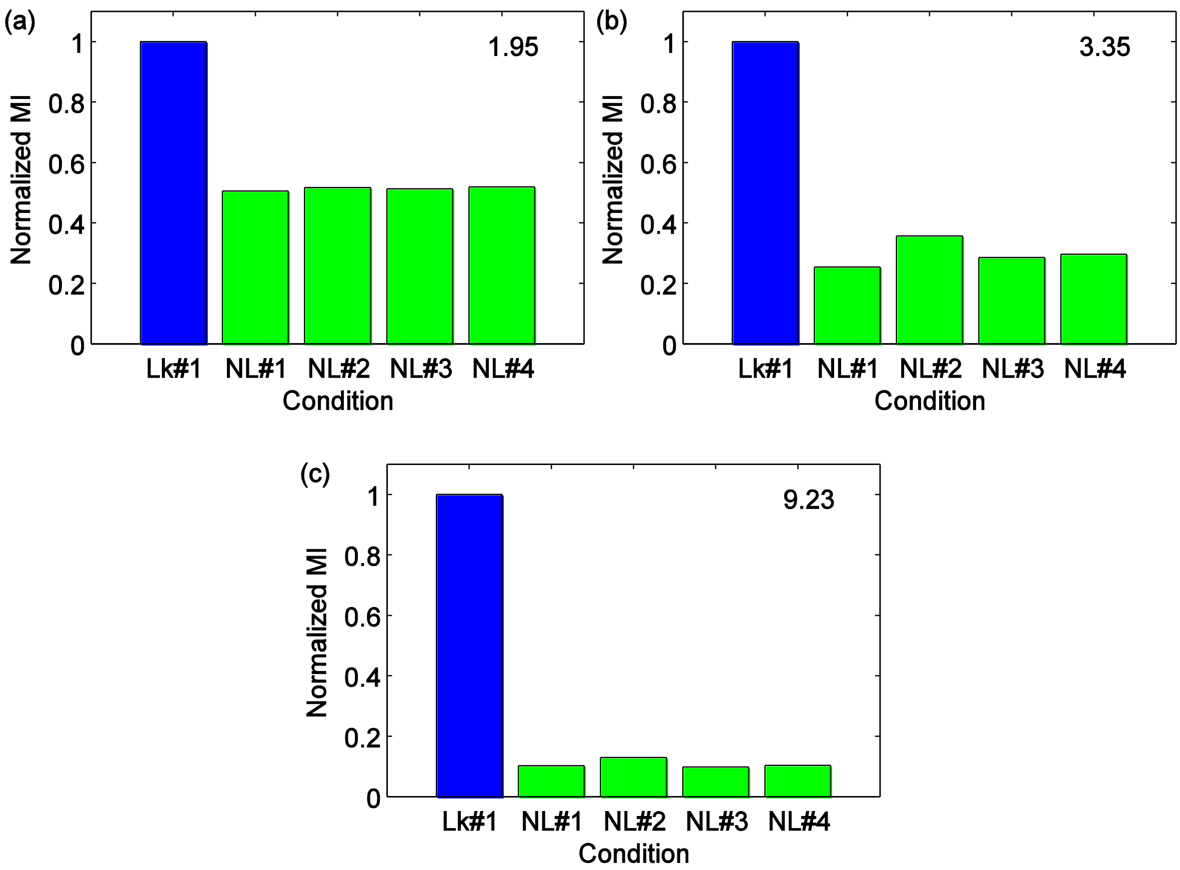

Fig. 3. *MI* computed for leak #1 in *Case*-*A* with raw signals of (a) radial accelerometer, (b) hydrophone and (c) axial accelerometer

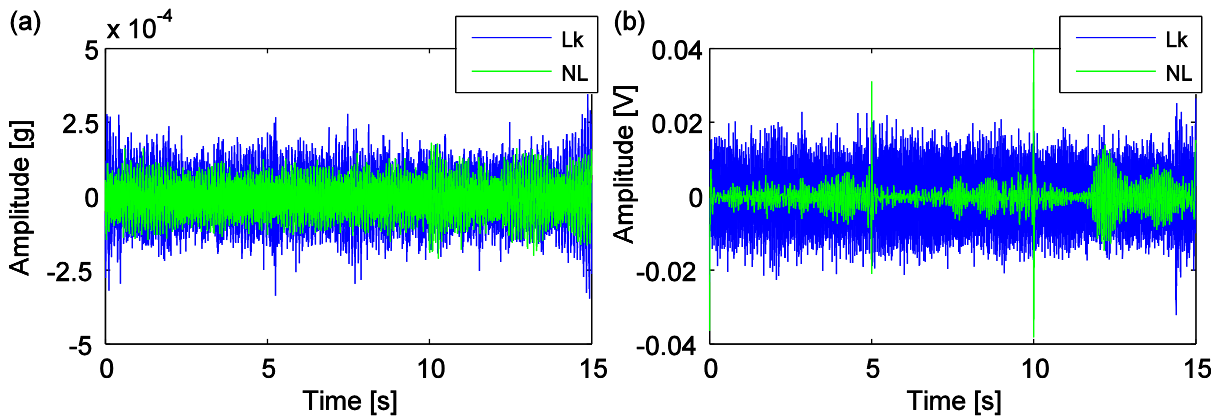

Fig. 4. Comparison between time histories measured for non-leaking condition and for leak #1 in *Case-A* by (a) radial accelerometer and (b) hydrophone

Table 2. Results of the algorithm applied to raw signals of accelerometers and hydrophone, *Case-A*

			Radial accelerometer		Axial accelerometer		Hydrophone	
Leak	Distance [m]	Flow rate [l/h]	Detection	MIE	Detection	MIE	Detection	MIE
#1	3	200	yes	1.95	yes	9.23	yes	3.35
#2	8	295	yes	1.94	yes	5.72	yes	2.95
#3	13	200	no	1.19	yes	1.52	yes	1.67
#4	18	180	no	1.05	no	0	no	0
#5	26	4000	no	1.08	no	0	yes	20.42

The performance of the algorithm based on radial accelerations is rather poor. Only the two nearest leaks are detected, and with a very low efficiency (a *MIE* lower than 2.5 being considered not completely satisfactory).

Better results are achieved with the axial accelerometer and the hydrophone, both exhibiting a similar behavior except for leak #5. Indeed such leak, which presents a high flow rate, is detected only with the hydrophone.

The analysis of the data acquired in *Case-B* (water leaking into air) reveals that the signal levels associated with active leaks are remarkably lower than in *Case-A*. The comparisons of the *MI* values computed for the signals of the hydrophone and the radial accelerometer acquired for leak #1 are reported in Fig. 5, as examples. The increment in the signal STD (with respect to the non-leaking condition) is significantly reduced. This causes the algorithm to fail the detection of almost all leaks, regardless of the considered transducer. Such a behavior is consistent with other experimental studies found in the literature (e.g. Thompson et al. 2001), which reported that water leaking against soil may appear noisier. Hence these results confirms that the medium surrounding the leaking pipe represent a chief factor for the generation of leak-related noise. However, service pipes are normally buried from their connections with the water main to the manholes where the customers' water meters are installed, thus leaks exposed to air being much less likely to occur in the system of interest. Reasonably, leaks possibly starting in the terminal unburied sections of service pipes (typically shorter than 1 m) would be extremely close to the monitoring sensors and therefore easily detected as well. Therefore, the analysis will focus on the test condition *Case-A* hereafter.

The investigation in the frequency domain takes into account the same subset of acquisitions considered for computing the *MI*. The main objective is the definition of a proper filtering technique for enhancing both the algorithm effectiveness (i.e. the number of leaks successfully detected) and efficiency (given by the *MIE* value).

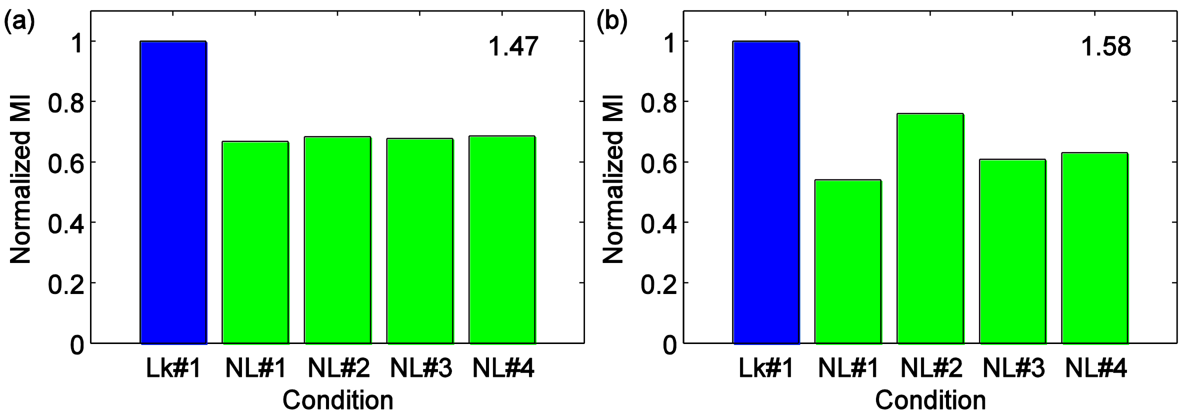

Fig. 5. *MI* computed for leak #1 in *Case-B* with raw signals of (a) radial accelerometer and (b) hydrophone

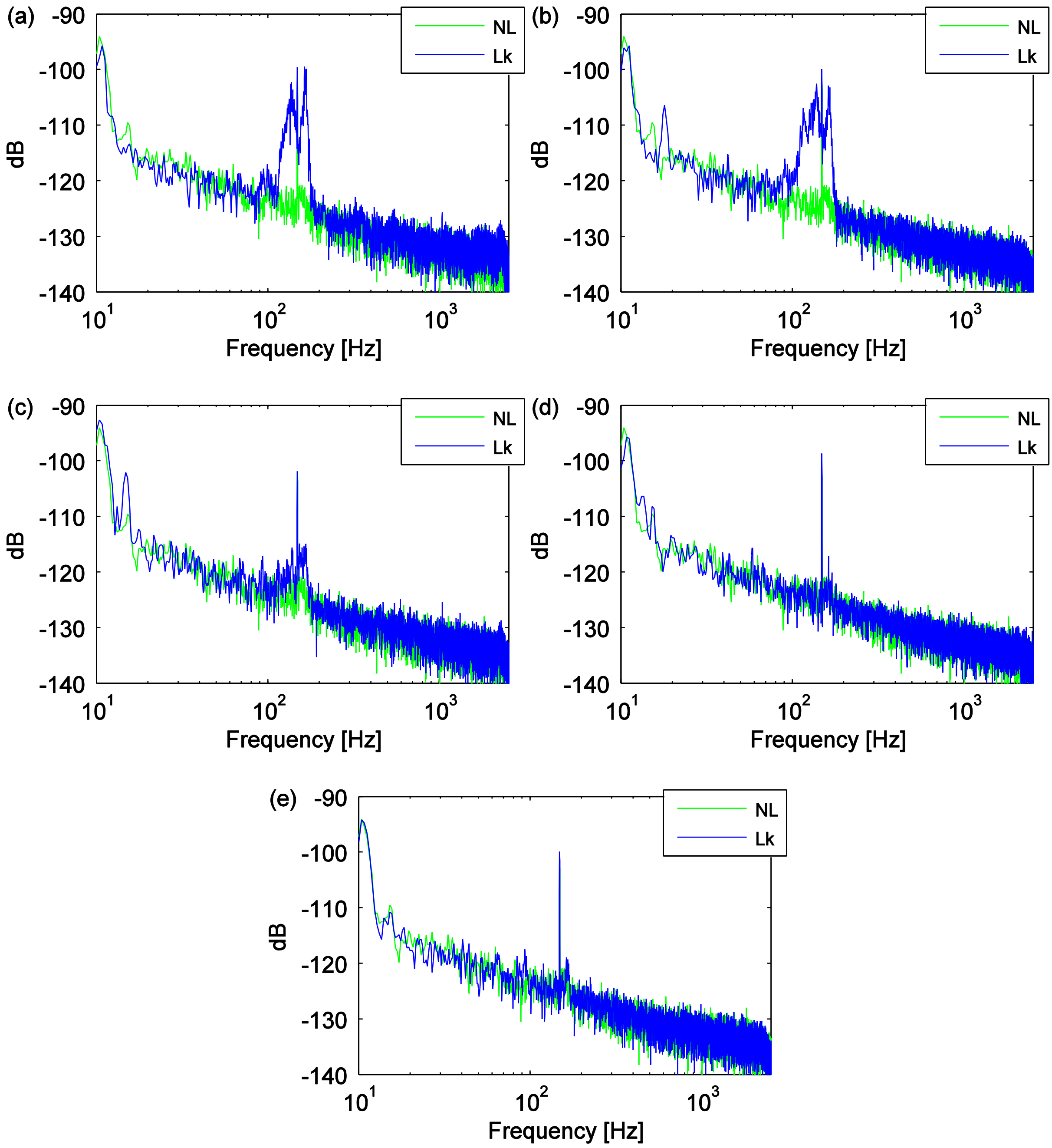

Fig. 6. Comparison of the PSDs of the radial accelerometer signals in leaking condition (Lk), for leaks (a) #1, (b) #2, (c) #3, (d) #4, (e) #5, with the PSD computed for non-leaking acquisitions (NL)

The comparison between the PSD of two signals, one concerning the leaking (Lk) and one for the non-leaking (NL) conditions of all transducers, is shown in Figs. 6-8 for all leaks. The results focus on the range up to 1200 Hz, since no significant frequency content was observed above this limit.

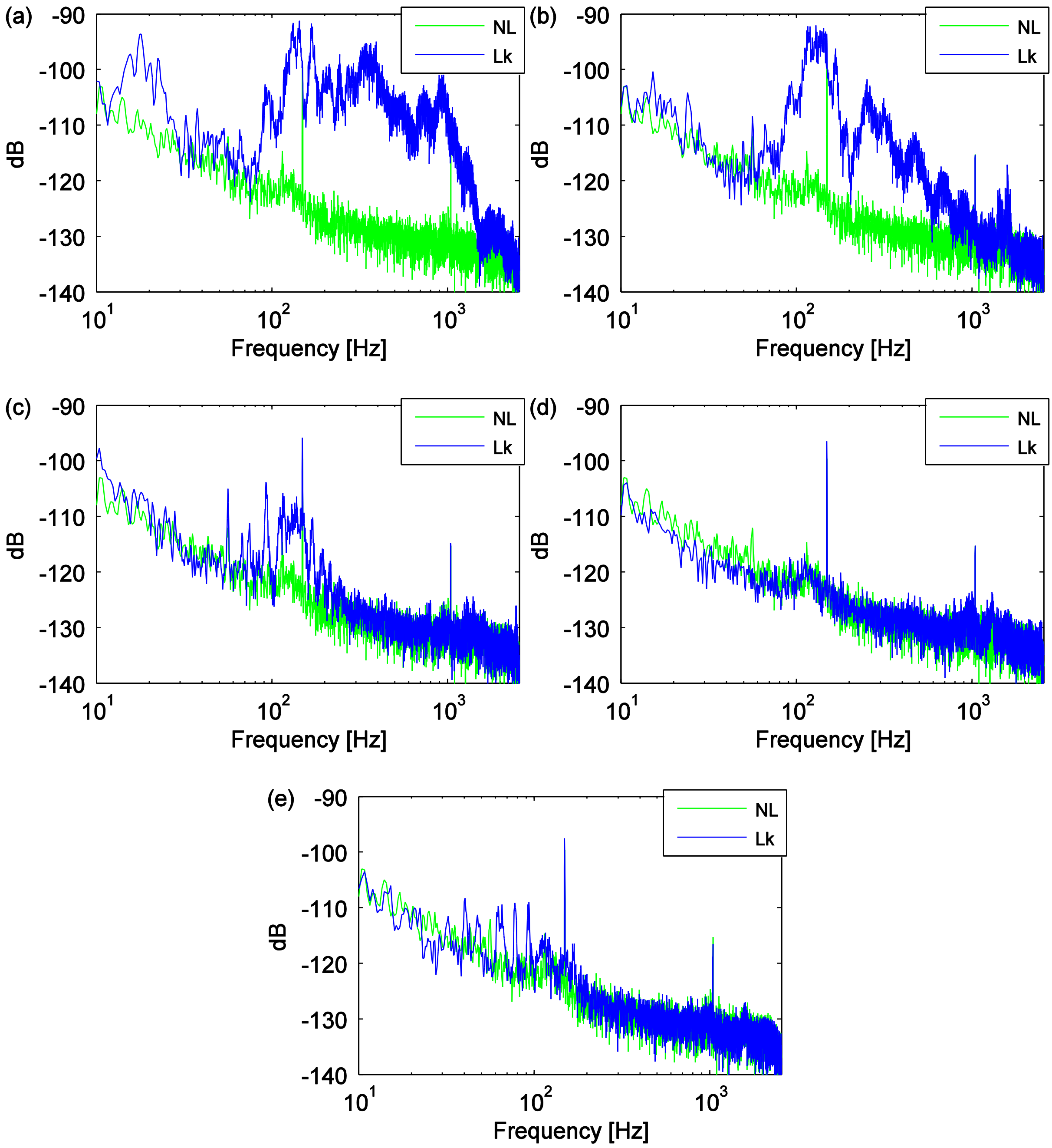

Fig. 7. Comparison of the PSDs of the axial accelerometer signals in leaking condition (Lk), for leaks (a) #1, (b) #2, (c) #3, (d) #4, (e) #5, with the PSD computed for non-leaking acquisitions (NL)

Vibrations induced by the nearest leaks to the measuring point appear clearly distinguishable from the environmental noise with all transducers. The frequency content of the radial accelerometer signal is characterized by a rather narrow bandwidth, between 100 and 200 Hz (Fig. 6). Conversely, the axial accelerometer and the hydrophone exhibit a much wider spectrum, up to 1 KHz (Figs. 7, 8). As the leak distance grows, the PSD amplitude decreases and high frequencies are damped. This phenomenon affects the signals of all transducers, but it is more evident for the accelerometers. Consequently, accelerometers appear unable to measure the vibrations related to the most distant leaks.

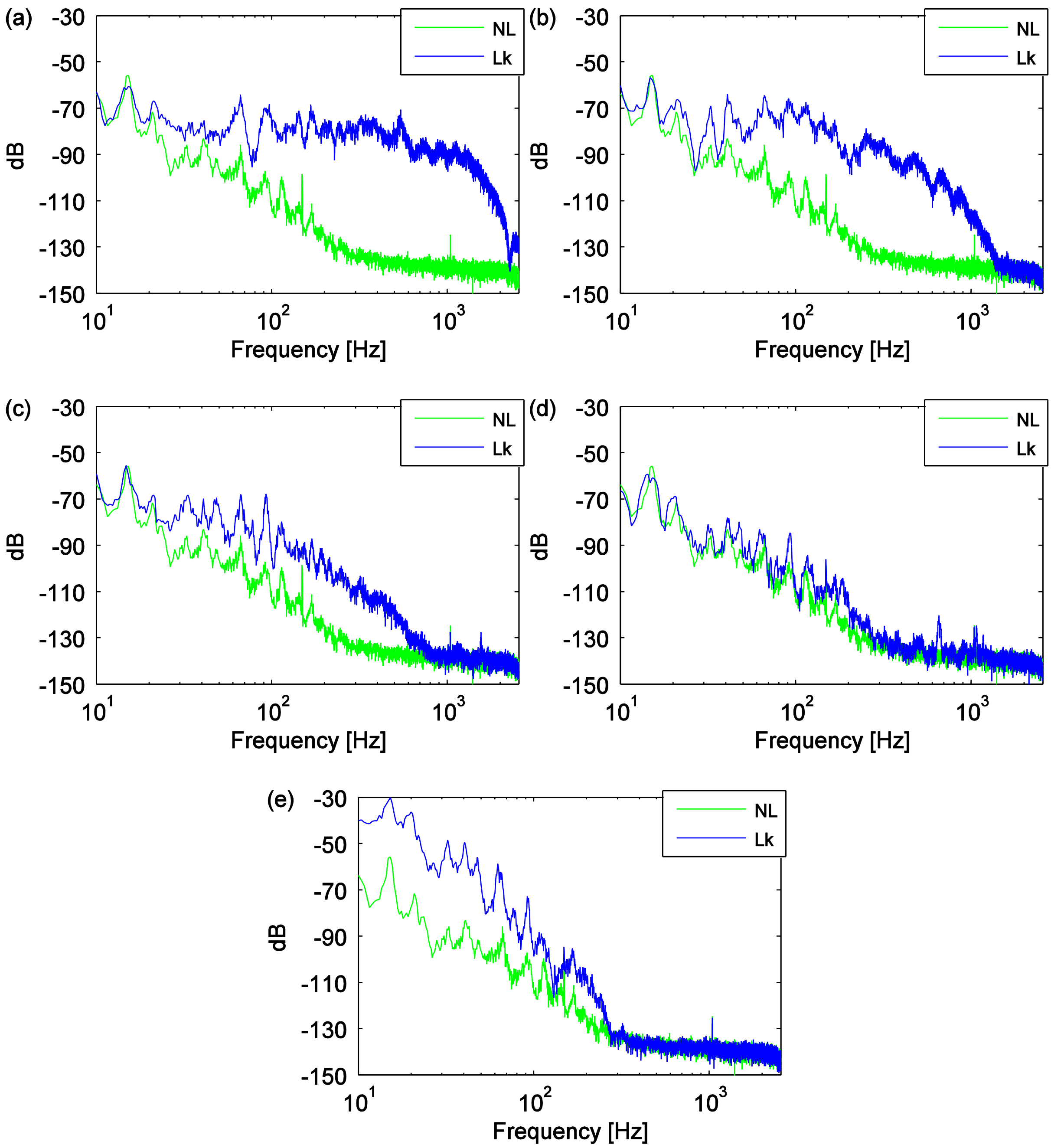

Fig. 8. Comparison of the PSDs of the hydrophone signals in leaking condition (Lk), for leaks (a) #1, (b) #2, (c) #3, (d) #4, (e) #5, with the PSD computed for non-leaking acquisitions (NL)

Spectral analysis permits to identify, for each transducer, some frequency bands in which the frequency content associated with the leaks is more evident. Different filters based on such frequency bands were tested for re-processing the measured signals before running the algorithm.

The results provided by the algorithm after applying a 100-600 Hz band-pass filter, namely a zero-phase digital Finite Impulse Response (FIR) filter, are reported in Table 3. As for the hydrophone, signal filtering permits to detect all leaks. The algorithm efficiency is remarkably enhanced for all leaks except for the most distant one. Indeed the hydrophone signals associated with leak #5 exhibit a peak of the spectrum in the band 10-60 Hz which is reasonably related to the higher leaking flow rate, since it is not observed in any other acquisition. Such frequency content is cut off by the adopted filter, thus causing the *MIE* to lower.

An improvement in the algorithm efficiency is achieved with the filtered signals of both accelerometers as well. As far as the axial accelerometer is concerned, the algorithm effectiveness is also enhanced, leak #3 being successfully detected. However, the detection of distant leaks is still missed with both accelerometers. The axisymmetric waves $s=1$ and $s=2$ (namely the fluid-borne wave and pipe vibrations respectively) would be expected to be rather strongly coupled under the boundary conditions considered in the experiment (Muggleton et al. 2002). Nonetheless only the fluid-borne wave could reach the measuring point for the most distant leaks, whereas the propagation of shell vibrations was reasonably prevented by the high attenuation of the pipe material (even if the experimental setup did not allowed to directly estimate the actual pipe damping). Further enhancements of the leak detection range seem hardly achievable for vibration measurements, since the same attenuation effects are reasonably expected to occur in buried pipe systems with similar features. However the range of effectiveness provided by the accelerometers (both the axial and the radial one) should be sufficient for the majority of the service pipes that may be found in actual networks, these typically being about 10 m long. Hence the requirements of the leak detection system to be developed by Hera S.p.A would be met.

Table 3. Results of the algorithm applied to band-pass filtered signals (100-600 Hz filter)

			Radial accelerometer		Axial accelerometer		Hydrophone	
Leak	Distance [m]	Flow rate [l/h]	Detection	MIE	Detection	MIE	Detection	MIE
#1	3	200	yes	2.77	yes	13.17	yes	144.60
#2	8	295	yes	2.73	yes	8.83	yes	91.85
#3	13	200	no	1.08	yes	1.70	yes	15.49
#4	18	180	no	1.11	no	1.11	yes	2.17
#5	26	4000	no	1.07	no	1.10	yes	6.24

The presented results prove signal filtering an effective strategy to enhance the performance of the prototypal leak detection algorithm for the acquisitions of both the hydrophone and the accelerometers. However, it is worth noting that the frequency content of vibro-acoustic signals associated with leaks may result partially altered in actual service pipes, due to different boundary condition. Hence a preliminary analysis of leak-related measurements performed in the actual water distribution network is advisable, in order to further refine and test both the algorithm and the filters.

As for the other investigated statistical parameters, skewness and kurtosis were computed for the complete datasets, by taking into account both the raw and the filtered signals. Figures 9 and 10 report the comparison between skewness and kurtosis, respectively, computed for the raw signals related to leak #1 and to the non-leaking acquisitions, for the radial accelerometer and the hydrophone, chosen as examples. In particular, the results concerning the ten acquisitions with the lowest STD are only shown, for a better readability. No significant correlations can be identified, either between leaking and non-leaking conditions or even between the different datasets of the non-leaking state. Similar results are obtained for all the other analyzed conditions. Hence, skewness and kurtosis are confirmed as unsuitable metrics for leak detection purpose.

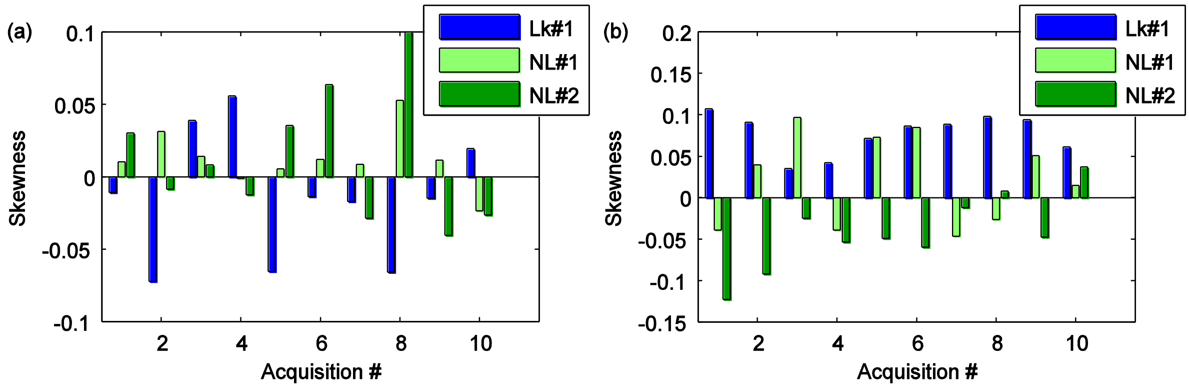

Fig. 9. Skewness associated with leak #1 (Lk#1) and 2 non-leaking datasets (NL#1 and 2), computed for the 10 raw signals with lowest STD of (a) radial accelerometer and (b) hydrophone.

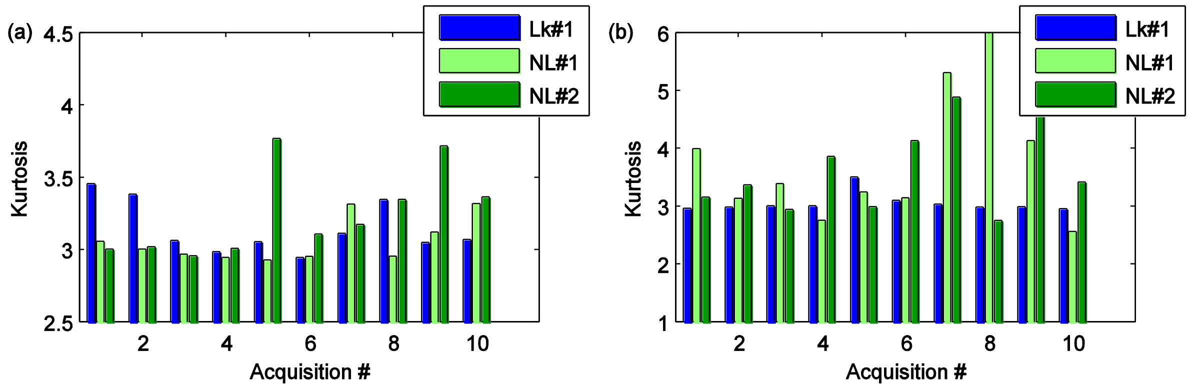

Fig. 10. Kurtosis associated with leak #1 (Lk#1) and 2 non-leaking datasets (NL#1 and 2), computed for the 10 raw signals with lowest STD of (a) radial accelerometer and (b) hydrophone.

Conclusion

Experimental tests were carried out in order to compare the effectiveness of measurements of different vibro-acoustic phenomena for detecting water leaks occurring in plastic service pipes. Leaks were artificially induced on a small-diameter polyethylene pipe. Vibro-acoustic signals related to the leaks were monitored by using a hydrophone and two accelerometers.

The most satisfactory results were provided by the hydrophone, which was able to clearly "hear" the noise generated by even the most distant leaking flows. The hydrophone measurements permitted to attain the detection of all generated leaks with excellent reliability. In addition, a simple prototypal algorithm which exploits STD of the hydrophone signals for achieving automatic leak detection was successfully tested on all leaks.

Satisfactory results were provided by the accelerometers as well. As expected, the axial accelerometer proved more sensitive to the leaks than the radial one. Measurements of the axial vibrations, processed by running the prototypal algorithm, allowed a successful detection of the three nearest leaks (one more than by using radial vibrations). None of the accelerometers permitted to detect the most distant leaks and further improvements of the detection effectiveness appear difficult to be achieved, due to high attenuation of acceleration signals in the pipe wall. Nonetheless, the accelerometers appeared suitable to be adopted for the leak detection system to be developed by Hera S.p.A. Indeed, they permitted to detect leaks over a distance range that should be adequate for most of the service pipes in the water supply network managed by the utility, in particular when proper signal filtering techniques were adopted for improving the performance of the prototypal detection algorithm. Moreover, since accelerometers are ordinarily cheaper than hydrophones, they appear economically more convenient to be adopted on a large scale.

A pilot experimental campaign on actual service pipes of the water distribution network has been started for testing a prototypal detection system based on measurements of leak-related pipe vibrations with accelerometers (Martini et al. 2015). The first results are promising and confirm both the effectiveness and the reliability of the developed system.

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