Vibration monitoring as a tool for leak detection in water distribution networks

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Abstract

The control of water leaks in water distribution networks represents a critical issue for all utilities involved in drinking water supply. This paper deals with the detection of water leaks by using vibration monitoring techniques. The long-term objective is the development of a system for the automatic early detection of burst leaks in service pipes. An experimental campaign was started in order to measure vibrations transmitted through water pipes by real burst leaks occurring in an actual water supply network. The first experimental data were used for testing a prototypal algorithm for leak detection purpose, based on the calculation of the standard deviation of acceleration signals. The experimental campaign is here described and the results achieved by applying the algorithm are presented and discussed. The current algorithm exhibited satisfactory performances, with 10 of the 13 examined leaks being successfully detected.

1 Introduction

The efficiency of water distribution networks represents a major problem for all utilities involved in drinking water supply. Available statistics [1,2] show that the amount of real (physical) water losses may exceed 30% of the input volume. Real losses are given by both background leaks (very small leaks occurring at storage tanks or pipe joints and fittings) and burst leaks (resulting from pipe holes and damages). While the former ones are associated with the normal system functioning and cannot be reduced under the limit commonly known as Unavoidable Annual Real Losses, the latter ones are considered potentially recoverable losses. Hence adopting proper policies for managing burst leaks appears essential.

As for Active Leakage Control, several strategies and technologies have been proposed for achieving leak detection and location. Utilities are getting good leak detection results by adopting District Metered Areas (DMA) management [3]. An alternative and still largely adopted approach (although expensive and time consuming) is represented by periodic acoustic surveys for leak detection purpose. Indeed it is known that burst leaks generally cause water pressure fluctuations due to turbulent flow or shock waves [4], thus inducing structure-born low- or high-frequency vibro-acoustic phenomena respectively. Permanent optimized grids of noise loggers for continuously monitoring the entire water supply network may be also adopted [5], although their economic viability and leak detection effectiveness are not guaranteed [6].

Most of the methods and equipments proposed for locating leaks are based on the measurement of vibro-acoustic phenomena as well. Several studies deal with the detection of low-frequency (typically below 1 kHz) noise/vibrations by means of hydrophones/accelerometers [4–8], or with the acquisition of high-frequency acoustic signals by means of Acoustic Emission sensors, which generally operate up to 100-300 kHz [9, 10]. Other techniques, such as the exploitation of hydraulic transients [11] or non-acoustic methods and technologies were also investigated in the literature (e.g. Ground-penetrating Radar, Tracer gas technique and Magnetic fields [12, 13]). In practice leak pinpointing is performed by most utilities with common equipments based on vibro-acoustic transducers, such as listening devices (namely geophones and listening rods, whose efficiency largely depends on the operator skills) and noise correlators (which automatically pinpoint leaks by means of signal correlation techniques).

A particularly critical issue for the leakage management is represented by burst leaks occurring in service connections (i.e. small diameter pipes connecting customers to the water mains). Such leaks frequently present low rates of the leaking flow, thus being characterized by long awareness periods (namely the time from the burst occurrence to its detection), whereas large leaks are generally much more rapidly detected or reported. Consequently the total runtime (i.e. the total period to the burst repair) of these smaller bursts tends to be much longer, thus leading to higher overall losses. In addition, the increasing percentage of plastic service connections in water supply networks may further hinder the control of leaks. Indeed, problems concerning the significant damping of vibro-acoustic phenomena in plastic pipes are known [14], even if the detection of water leaks still appears achievable [6, 15].

This work deals with the use of vibration monitoring tools for the detection of burst leaks in water pipelines. In particular the study focuses on leaks occurring in service connections of the water supply network. The long-term project planned by the R&D department of the multi-utility Hera SpA (Bologna, Italy) aims at developing a device for the automatic early detection of unreported bursts occurring in the customer connection branches running from the mains to the user metering point [16]. The system is meant to be installed near the water meter and to autonomously detect and report the presence of leaks. This implies a certain detection algorithm to be run on-board. Low cost is one of the main design requirements of the final device, since a large number of devices will be needed for covering the entire network. In particular, in order to work with limited computational resources (thus lowering hardware costs), the final detection algorithm will require only simple operations to be executed. The system is expected to significantly reduce the awareness time of a large amount of water leaks, thus globally cutting the costs associated with non-revenue water.

Preliminary experimental tests had been performed on both a test rig and an actual service pipe of the water distribution network, by considering artificially induced leaks [17]. The investigation confirmed vibration monitoring as an effective tool for leak detection purpose, provided that no water flow induced by the customers' water consumption is present inside the monitored pipe. In such an instance, indeed, even very small values of the flow rate cause high vibration levels which cover the effects of the leak, thus making impossible the detection. The experimental data permitted to define a prototypal detection algorithm capable of automatically distinguish between leaking and non-leaking conditions [17]. The implemented algorithm uses the signal standard deviation (STD) as a metric to detect the increment of vibration levels induced by the leaking water.

A broader experimental campaign was started for collecting vibration data from real burst leaks detected and repaired in actual service pipes of the water distribution network managed by the utility. This paper describes the experimental campaign and presents the first results. In particular, the performance of the current detection algorithm is assessed and discussed. Possible signal processing techniques for enhancing the algorithm sensitivity and robustness are also investigated.

2 Materials and methods

The experimental campaign was meant for investigating vibrations generated on pipes by real burst leaks occurring in service connections. In particular, the objective was performing measurements in both leaking and non-leaking conditions for each monitored pipe, to assess the differences between the signals characterizing each condition. As a pilot study, all measurements were performed on leaks already detected or reported. Firstly, acquisitions of vibration signals were performed in leaking condition, before the repair work. Then the undamaged condition was restored and further measurements were carried out in non-leaking state. The custom acquisition devices arranged in the preliminary phase of the research [17] were adopted for the measurements. Each unit presents the following configuration. Vibrations are detected by a commercial IEPE accelerometer (sensitivity 1V/g). A signal conditioner powers the sensor and provides a signal gain of 100. The conditioned signal is acquired and recorded by a GigalogF datalogger with modified firmware (sampling frequency 3300 Hz). A battery pack powers the system, thus external power supply being not required. The measurement protocol is described hereafter.

- The maintenance team preliminarily checks the leak and installs the measuring unit near the customer's water meter (Fig. 1). The accelerometer is directly mounted on the connection pipe by means of petroleum wax. The main characteristics of the monitored leak and of the corresponding measurement setup are noted (namely the distance between the pipe damage and the transducer location, the type of customer, the specific measuring unit and a rough estimation of the flow rate).
- The measuring device automatically performs measurements during night, in order to reduce the presence of possible perturbations affecting the vibration signals. In particular, the incidence of non-zero flow rate conditions induced by customers' water consumption should result significantly limited. Sixty acquisitions per night (with duration of 10 s each) are carried out for some consecutive nights.
- The maintenance team repairs the burst by substituting the whole connection pipe, and restores the undamaged condition. During the maintenance work the sensor setup is not modified (i.e. the accelerometer is never removed from the initial measuring location).
- Acquisitions in non-leaking condition are carried out for several consecutive nights after the repair, until the unit is removed (generally after about a week). The recorded data are then extracted for the analysis. At this stage of the research both the algorithm execution and further signal processing are performed off-board.

Although measurements did not follow the natural evolution of the leak, the current procedure permitted to obtain data from real leaks occurring in different districts of the entire water distribution network managed by the utility, thus possibly taking into account most of the boundary and functioning conditions characterizing the network.

The first datasets concerning 13 different burst leaks were processed with the prototypal detection algorithm, in order to test its effectiveness. As a first step of the analysis procedure, the soundness of the recorded signals is checked for the dataset of each monitored pipe. Then the algorithm performs the following operations.

- The signal STD is computed for all collected records, thus obtaining 60 STD values for each night of measurements included in the dataset. The algorithm is directly run on the raw signals.
- A proper index characterizing each night of acquisition (hereafter referred to as *Monitoring Index*, *MI*) is determined from a subset of the corresponding STD values (Fig. 2). In particular, the *MI* of a night is defined as the average of the 10 lowest STD values of that night (Fig. 2a). Therefore the *MI* is computed by considering only an aggregate signal with duration of 100 s, with respect to the whole record of 600 s available for each night (Fig. 2b). The reduced subset should ensure that only steady state signals not affected by possible perturbations (such as water flows induced by the customers' water consumption, clearly visible in Fig. 2a) are taken into account for the analysis.
- *MIs* associated with different nights of the dataset are compared. Since the *MI* value is expected to increase due to the presence of an active leak, it can be adopted as a metric for achieving leak detection.

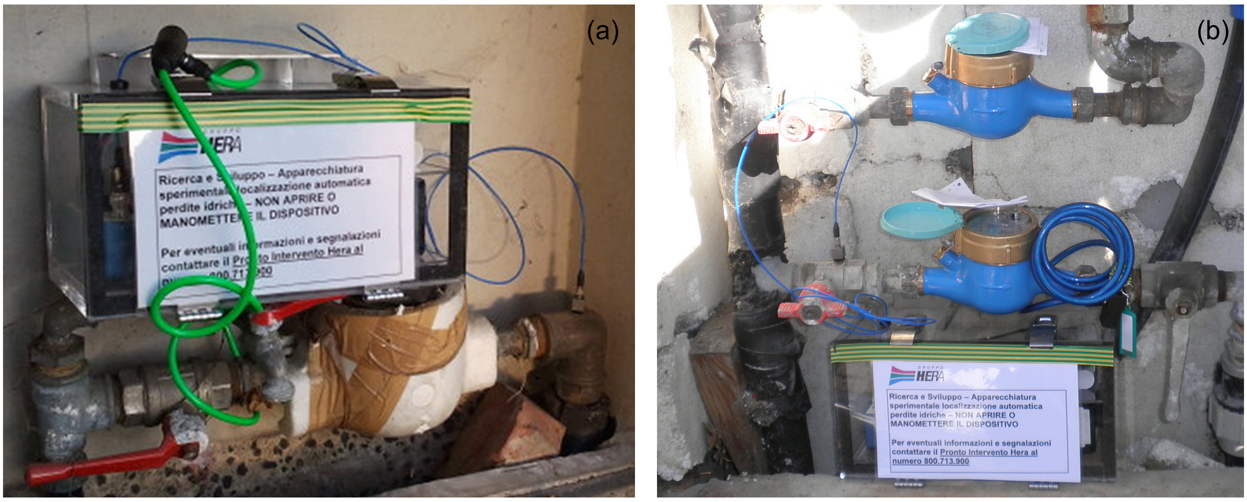

Figure 1: Pictures of the measurement setup for two monitored sites: (a) DB 1, (b) DB 2

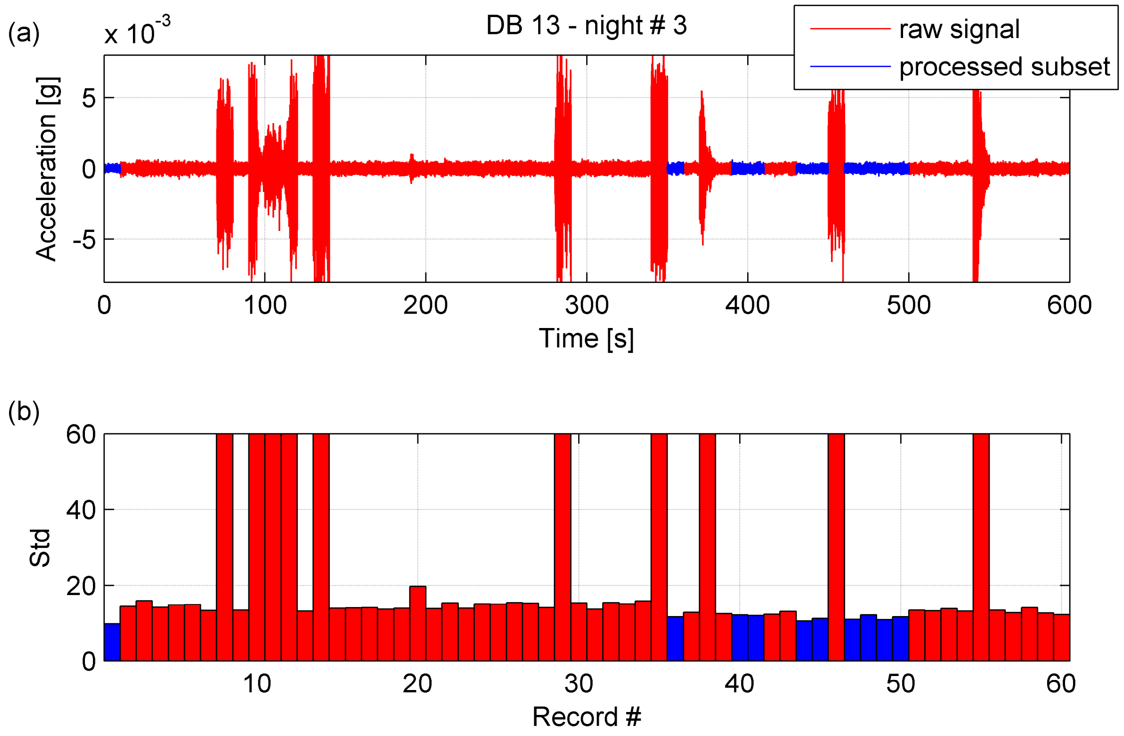

Figure 2: (a) Complete time history and (b) STD values for night #3 of dataset DB 13; the subset considered for the *MI* computation is highlighted in blue

A further index, referred to as *Monitoring Index Efficiency* (*MIE*), was computed for each dataset, in order to better evaluate the algorithm efficiency in terms of sensitivity to the leak. The *MIE* was defined as the ratio between the maximum value of the *MI* and the averaged *MIs* of the nights in non-leaking state. This definition implicitly assumes that the maximum occurs for measurements in leaking condition, i.e. that the leak is correctly detected.

Vibration data were further analyzed for investigating possible improvements to the performance of the detection algorithm. Only rather basic processing techniques were considered, in order to meet the requirements of the final leak detection system. The raw signals were processed in the time domain for the calculation of some common statistics, namely RMS value, skewness and kurtosis. Variants of the prototypal algorithm based on these metrics were tested as possible alternatives. A second analysis was performed by computing the signal power spectrum (PSD) in order to investigate the signature of water leaks in the frequency domain.

3 Results and discussion

Main information concerning the monitored burst leaks are summarized in Table 1. For each dataset, the leak flow rate (roughly estimated, by using a three-level scale, as “low”, “medium” and “high”) and the distance between the leak and the transducer are reported. The amount of nights in which acquisitions were performed, before and after the repair (leaking and non-leaking conditions respectively), is also shown. Distance values are rather uniformly distributed in the range 0-10 m, thus making this first database fairly representative of bursts possibly occurring. Almost all leaks present low flow rates. This condition is the most useful for properly verifying the algorithm, since high values would make the detection largely easier. All burst leaks are associated with high-density polyethylene (HDPE) service pipes of small diameter (DN 32).

The results obtained by processing all the datasets are summarized in Table 2. In particular the detection result (successful or missed detection), as well as an evaluation of the sensitivity to the leak (provided by the *MIE*), are reported. A value equal to 0 is assigned to the *MIE* whenever the leak is not detected. A successful detection is achieved for 10 datasets. In 2 of these cases (DB 5 and, to a certain extent, DB 13) a poor

dataset	flow rate	distance [m]	# night leak	# night no-leak
DB 1	low	1.6	2	6
DB 2	low	9.8	2	4
DB 3	medium	10	2	3
DB 4	low	2	2	5
DB 5	low	4	2	4
DB 6	low	0.5	2	5
DB 7	high	3	1	7
DB 8	low	1	4	3
DB 9	low	0.5	1	7
DB 10	low	3	1	6
DB 11	low	3.5	2	6
DB 12	medium	7	1	7
DB 13	low	6	2	4

Table 1: Main features of the performed measurements

dataset	Raw signals		Filtered signals	
	detection	*MIE*	detection	*MIE*
DB 1	yes	217.55	yes	174.95
DB 2	no	0	yes	1.72
DB 3	yes	14.34	yes	28.05
DB 4	yes	51.03	yes	38.41
DB 5	yes	2.04	yes	2.25
DB 6	yes	251.29	yes	196.53
DB 7	yes	23.79	yes	22.57
DB 8	yes	19.54	yes	29.06
DB 9	yes	412.18	yes	650.99
DB 10	no	0	yes	2.25
DB 11	no	0	yes	1.73
DB 12	yes	26.64	yes	60.83
DB 13	yes	2.42	yes	7.55

Table 2: Results of the algorithm applied to raw signals and band-pass filtered signals

performance is observed, the *MIE* having a value of about 2. In general the results are consistent with the characteristics of the leaks, i.e. the worst performances are achieved for leaks distant from the sensor and characterized by a low flow rate.

It is worth noticing that the diagnostic tool is not intended for leak pinpointing. Indeed, once a leak is detected in a specific connection branch, it may be straightforwardly located by using common equipment (such as correlators or listening devices), since the average length of the service pipes of the water distribution network is about 10 m.

Figure 3a shows the acceleration signals concerning two nights (immediately before and after the repair work) of the dataset DB 3, taken as an example for the cases of successful detection. The plot reports the time histories obtained by aggregating the raw signals of the 10 acquisitions with the lowest STD values, i.e.

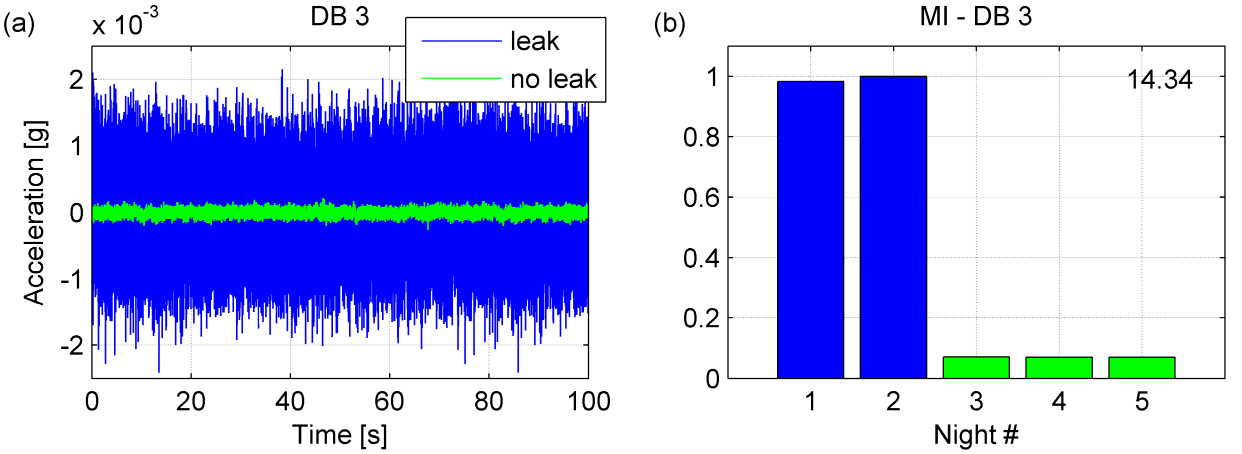

Figure 3: (a) Aggregated time histories and (b) computed *MI* values of raw signals from dataset DB 3

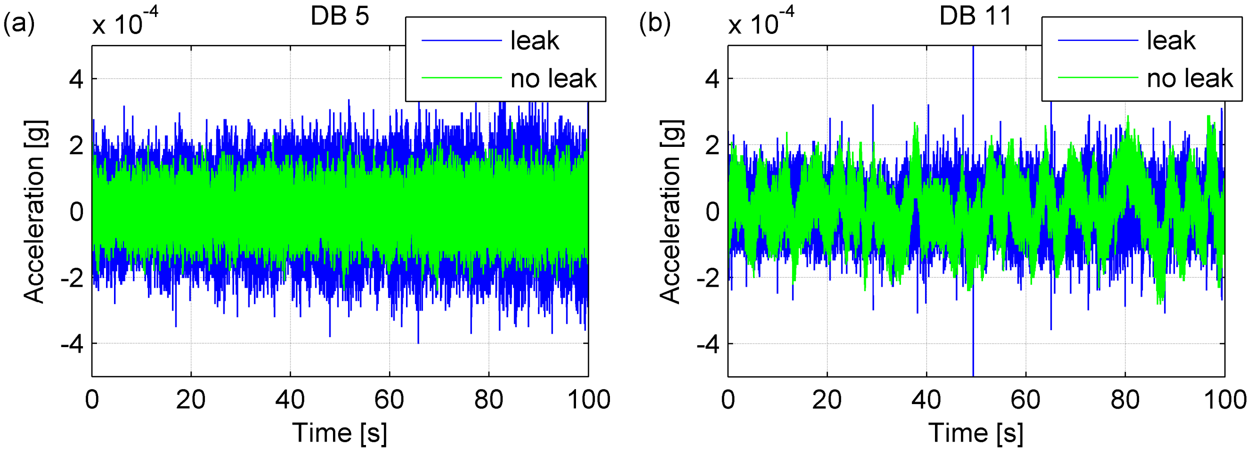

Figure 4: Aggregated time histories obtained from (a) nights #2 (leak) and #3 (no leak) of DB 5, and (b) nights #2 (leak) and #8 (no leak) of DB 11

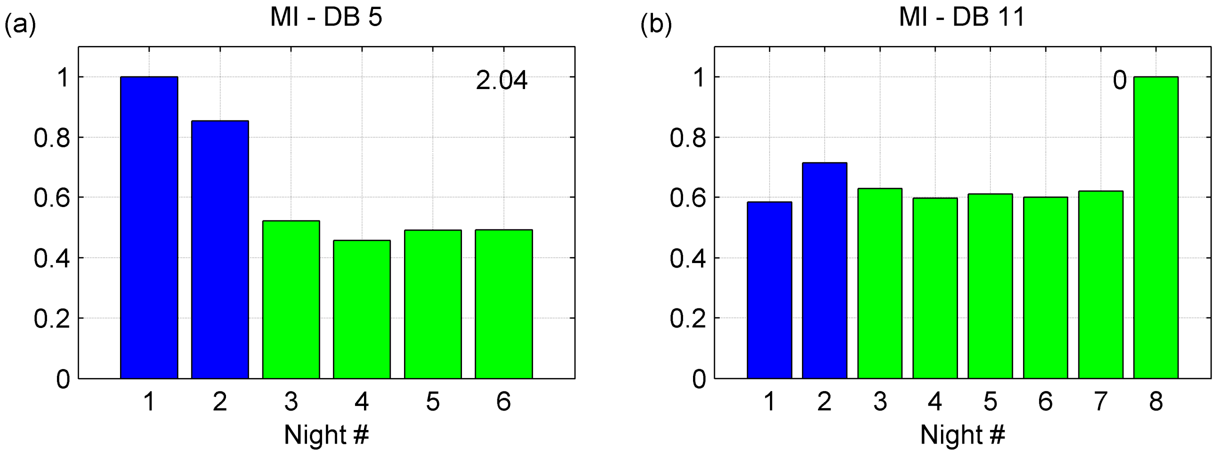

Figure 5: *MI* computed for datasets (a) DB 5 (poor performance) and (b) DB 11 (missed detection)

those ones processed by the algorithm (see Fig. 2). The *MI* values (normalized to the highest term) obtained for the dataset are shown in details in Fig. 3b. The corresponding *MIE* is reported in the upper-right corner. As predicted, a significant increment of vibration levels associated with the presence of the leak is observed (Fig 3a). The *MI* values rise correspondingly, thus permitting leak detection (Fig. 3b).

More interesting is the analysis of critical datasets. A close examination in the time domain to the five cases characterized by unsatisfactory algorithm performances reveals extremely low vibration levels. Figure

4 reports some time histories concerning two relevant cases, DB 5 and DB 11, taken as examples for the situations of poor performance and missed detection respectively. The measured accelerations never exceed amplitude of $5 \cdot 10^{-4}$ g for both leaking and non-leaking conditions. Such levels make difficult distinguishing the vibrations associated with the leak from the background noise, thus causing problems for the algorithm.

The *MI* values computed for the examined datasets are shown in details in Fig. 5. As for DB 5 (Fig. 5a), the *MIs* associated with the two nights in leaking conditions are higher than the other, thus allowing to detect the leak, though with little sensitivity. However on night #2 a decrement of *MI* value is observed, whereas an opposite behaviour would be expected. This feature contributes to lower the detection effectiveness. Results are significantly worse for dataset DB 11, where the *MI* value obtained for the last day (Fig. 5b) dominates the other values (which are all comparable), thus preventing the leak from being detected.

The signal PSDs are shown in Fig. 6 for the datasets DB 5 and DB 11. The spectral analysis reveals that signals recorded in non-leaking conditions are generally dominated by components at low frequencies (below 150 Hz). Conversely, the presence of the leak induces vibrations in a wider frequency band. As expected, due to the variability of boundary conditions associated with the tested sites, the monitored leaks do not exhibit identical signatures in the frequency domain. However some frequency bands common to all signals associated with leaks can be identified. Such bands can be exploited for the definition of proper band-pass filters to process the signals before running the algorithm. Different filters were successfully tested. The results provided by the algorithm after the application of a 200-600 Hz band-pass filter are shown in Fig. 7 for the two datasets DB 5 and DB 11. For both cases an appreciable increment of the algorithm performance is observed. In particular, in the latter dataset the highest MI value is now exhibited for the night preceding the repair (night #2), whereas the last night of measurements is no more affected by any anomaly, thus allowing for the possible detection of the leak, though with a low efficiency.

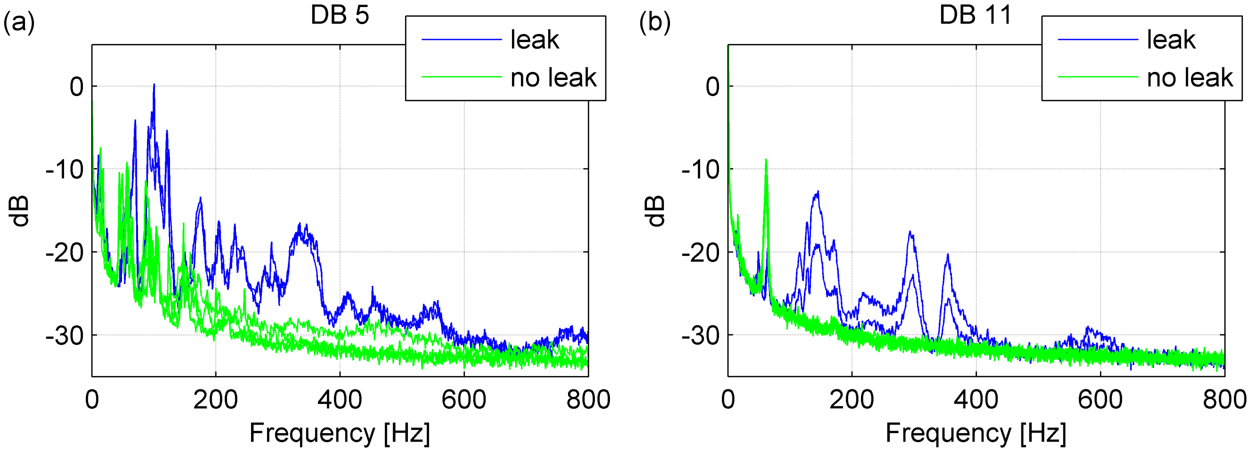

Figure 6: PSD of aggregated signals from datasets (a) DB 5, (b) DB 11

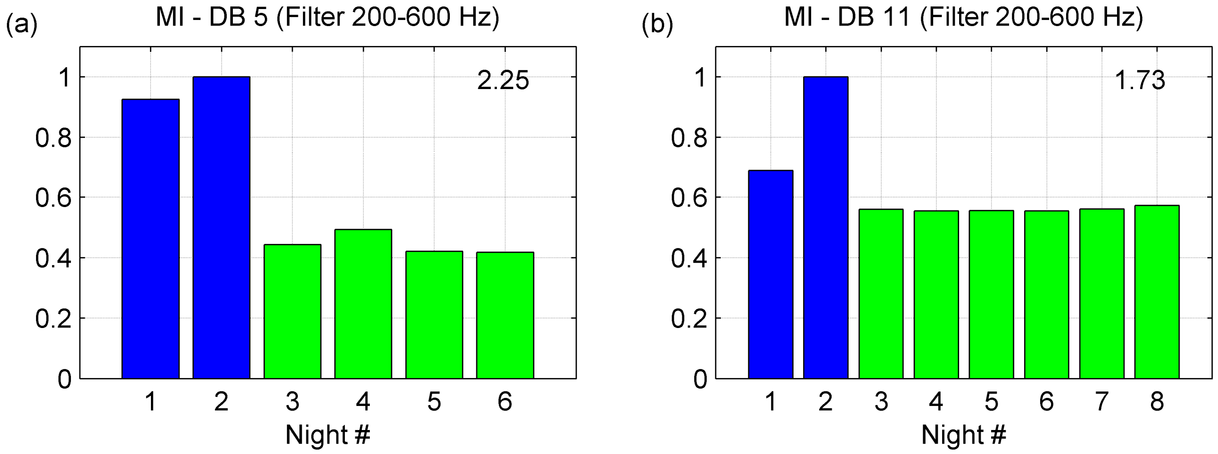

Figure 7: *MI* computed by the algorithm for filtered signals of datasets (a) DB 5, (b) DB 11

The results obtained with the same filter for the whole database are summarized in Table 2. The algorithm performs remarkably better, since all leaks are detected. In particular, improvements are observed for all datasets previously characterized by poor performances, and all the other cases still presents satisfactory results. Actually for some datasets a low efficiency is still experienced, as shown by the low *MIE* values, thus the algorithm requiring to be further refined. However these results prove band-pass filtering as a potentially profitable solution for enhancing the algorithm, since its detection performance may be improved with a moderate increment of its complexity.

It is worth noticing that the vibration signals analyzed in this paper are characterized by frequency values higher than those reported in the literature for burst leaks occurring in plastic pipes, typically below 200 Hz [8, 15, 18]. Reasonably the different behaviour is ascribable to the small dimensions of pipes monitored in this study, while in the other works larger and longer pipes were generally considered.

The investigation of the other statistics provided unsatisfactory results, which therefore are not reported. In particular no appreciable correlation between the presence of the leak and the trend of neither skewness nor kurtosis were revealed. Hence the algorithm variants based on such statistics did not prove effective for detecting the leak.

Conversely the results obtained by using the RMS value were comparable to those provided by the STD-based algorithm. Indeed, for signals characterized by a null mean value, STD and RMS values coincide. However it is worth noticing that the measuring setup may introduce a signal bias. Obviously even small signal offsets may significantly alter the algorithm performance whenever vibration levels are small. This behaviour has been indeed experienced with some acquisitions of the database. Possible offsets may be easily removed by filtering the continuous component of the signal. However the use of STD appears more profitable since it permits to directly operate on the raw signal without any additional processing.

4 Conclusions

This paper presented a study concerning the detection of burst leaks in water pipes by means of vibration monitoring. An experimental campaign was started for measuring vibration signals associated with real leaks occurring in actual service pipes of a water distribution network. The effectiveness of a prototypal algorithm for leak detection purpose was verified with the first acquisitions performed within the campaign. The algorithm is based on the simple standard deviation computed on raw signals, thus being very simple to be implemented in practice and requiring very limited computational resources to be executed. The tests provided satisfactory results, thus proving the algorithm as an effective tool for detecting leaks. Hence the implemented algorithm appeared worthy to be further investigated and developed.

Signal filtering was successfully tested as a possible solution for incrementing both the algorithm robustness and sensitivity to leaks. The use of proper band-pass filters appeared a viable strategy for enhancing the algorithm detection performance with a limited increment of its complexity.

In the future steps of the research the experimental campaign will be continued for collecting a statistically representative database. The algorithm will be tested on the enlarged database in order to enhance the algorithm detection performance, by further refining the algorithm steps and possibly optimizing the band-pass filter.

In addition, the use of detection strategies based on acoustic measurements as possible alternatives to vibration monitoring will be investigated as well. In particular, further experimental tests involving both hydrophones and Acoustic Emission sensors will be carried out for assessing, respectively, low- and high-frequency phenomena associated with burst leaks in plastic service pipes, and their possible exploitation for leak detection purpose.

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