Pipeline Monitoring with Vibroacoustic Sensing

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Introduction

In the framework of a research project, a proprietary vibro-acoustic system was designed for remote real-time monitoring of pipelines (Dalmazzone et al., 2010; Giunta and Bernasconi, 2013). The system consists of a discrete network of pressure and vibration sensors installed on a pipeline, at relative distances of tens of kilometers (Figure 1). The acoustic and elastic waves produced by third-party interference (TPI) and flow variations (leaks, spills, valve regulations, pig opera-tions, and so on) propagate along the pipeline and are recorded at the monitoring stations. Multichannel processing of the collected signals permits the detection, localization, and classification of the triggering event. The system was tested in single phase and multiphase transportation lines during several field campaigns (Bernasconi et al., 2012; Bernasconi et al., 2013a; Bernasconi et al., 2013b; Giunta et al, 2011a; Giunta et al., 2011b; Giunta et al., 2013).

This paper shows experimental results obtained on the following natural gas transportation infrastructures:

- Trans-Mediterranean (TransMed) pipeline: Cap-Bon (Tunisia) to Mazara del Vallo (Italy);
- Air-filled, decommissioned section of Spluga pipeline (North Italy) between Milano and Lecco;
- Centro Sviluppo Materiali (CSM) full-scale lab in Sardinia, test pipeline;
- Messina channel offshore pipelines.

The field test campaigns permitted the obtaining of:

- experimental sound propagation parameters within the fluid, in different conditions;
- environmental noise produced by flow generation and regulation equipment;
- pressure noise level produced by TPI and leak events;

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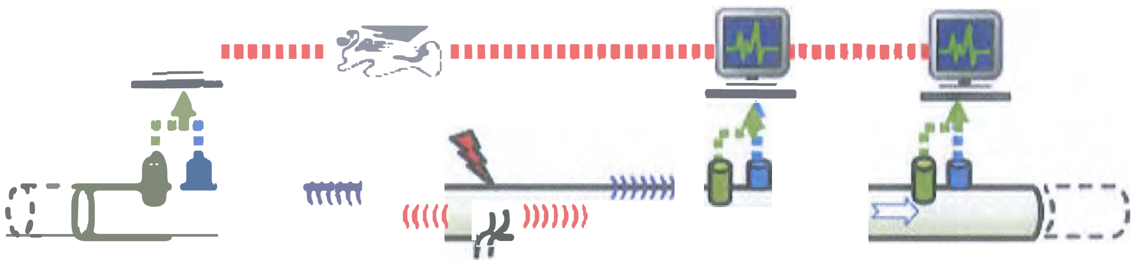


Figure 1. Conceptual scheme of the vibroacoustic monitoring system.

- vibroacoustic transients generated by travelling pigs, in low pressure and high pressure scenarios.

The experimental data were used to:

- derive and validate mathematical models of sound propagation within pipes;
- define and tune technical specifications of "ad hoc" vibroacoustic sensors;
- characterize the pipeline as an equivalent acoustic transmission channel, that is, for the long-term monitoring of pipe deformations/obstructions;
- design vibroacoustic data procedures for remote tracking of travelling pigs.

Trans-Mediterranean Pipeline: Cap Bon to Mazara del Vallo

The research and development project started with the installation of a prototypal vibroacoustic monitoring system on two 50.8 cm inner diameter lines of the TransMed pipeline, at the Mazara del Vallo terminal. During the data acquisition period, pipe maintenance and pig operations continued being carried out on both lines, in different operational conditions. An example is shown here of pig tracking, by processing the sound it produces while crossing the pipe internal welding dents.

Figure 2 shows the pressure signal when a magnetic pig was approaching Mazara del Vallo station (8 October 2009).

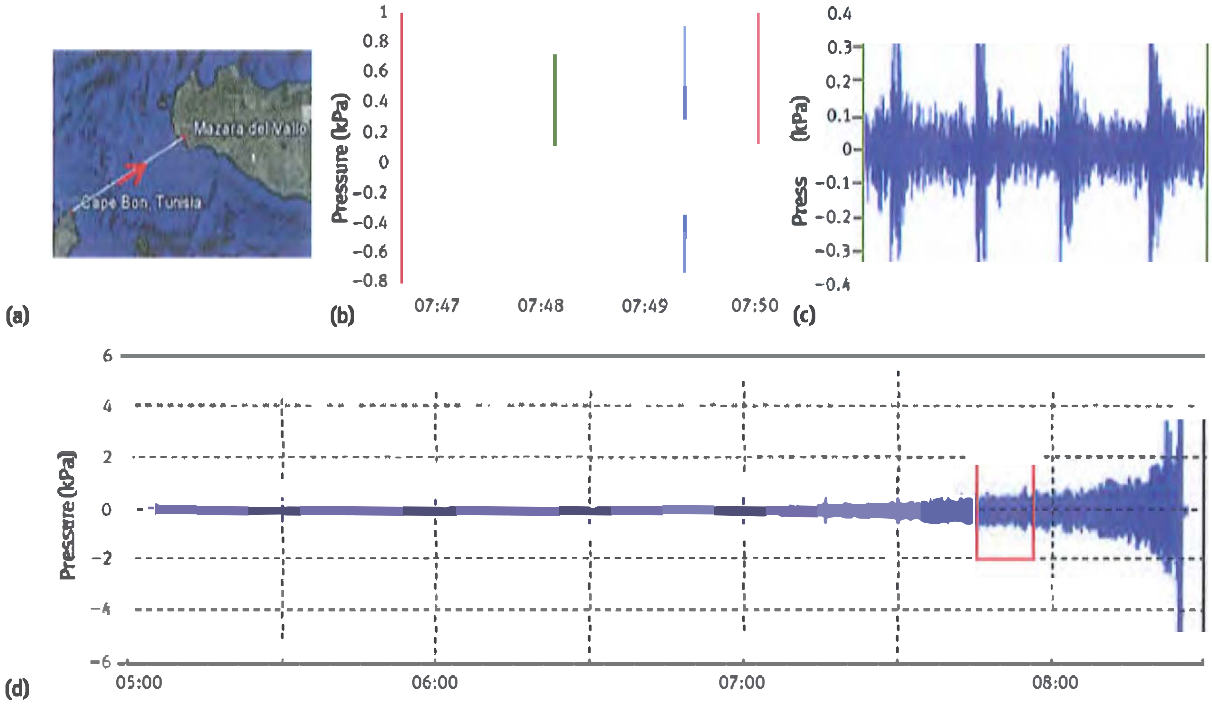


Figure 2. Pressure signal during pig operation on 50.8 cm pipe of the Trans-Mediterranean pipeline, at Mazara del Vallo terminal: (a) map; (b) minutes scale; (c) 5 s scale; and (d) hours scale.

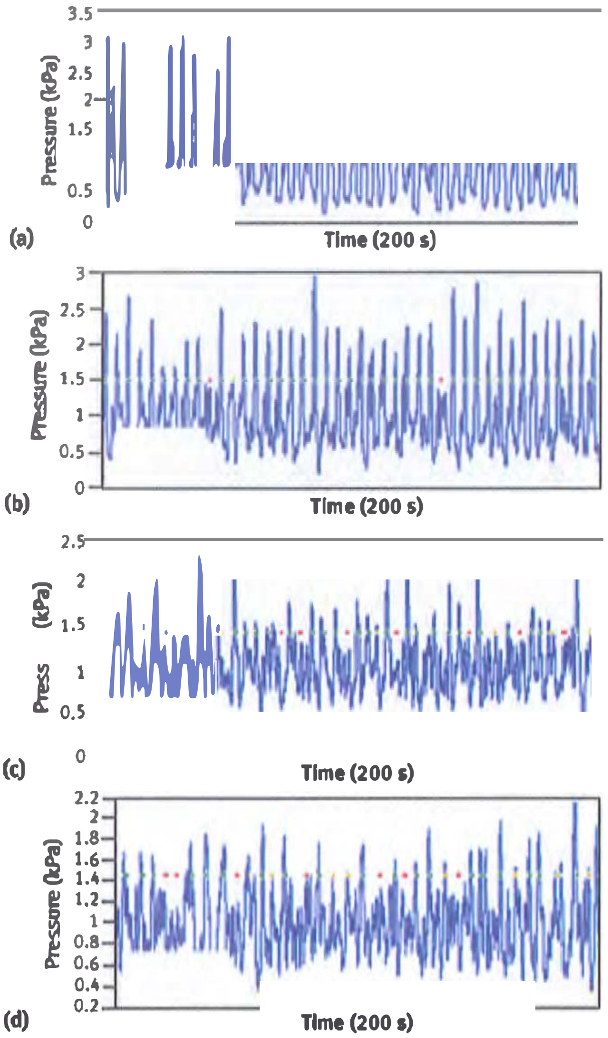


Figure 3. Pig detection with short time average to long time average data processing on pressure signal: (a) 4.5 km; (b) 9 km; (c) 20 km; and (d) 30 km.

The pipeline was in standard operation, at approximately 9 to 10 MPa. The sound produced by the travelling pig increased almost exponentially as it approached the receiving station; this behavior follows the wide tube approximation (Blackstock, 2000). In the zoomed windows it is possible to distinguish the wavelets generated by the pig crossing the welding dents, approximately 12 m apart from one another. There were 12 to 14 events counted per minute, corresponding to a pig velocity of 9 to 10 km/h. The velocity was very stable, at least when this event became visible, a few hours before the pig arrival.

In order to quantify the maximum detection distance, short time average to long time average (STA-LTA) data processing was performed. Figure 3 shows the result: every peak corresponds to the pig moving across a weld. By using a threshold criterion, the reliability of the events is labeled with a color scheme: green indicates correct detection, yellow is uncertain, and red is missed.

Figure 3 indicates that the pig becomes "visible" more than 30 km from the arrival.

Spluga Pipeline

Various vibroacoustic monitoring field campaigns were run on a decommissioned 60.96 cm inner diameter oil pipeline connecting North Milano to Lecco (Italy). Two sections of the pipeline were selected (Figure 4): section B, of approximately 33 km; and section A, of 3 km, submerged in Garlate Lake. Both were filled with air at 0.4 to 0.5 MPa. A network of vibroacoustic recording stations was installed along the pipeline, and controlled leak, impact, and TPI scenarios were produced.

Spilling Test

Leak tests were simulated by operating different valves along the pipeline. Short (1 s) and "long" (7 to 10 s) spilling sequences were produced. An echo detection procedure was also applied by filtering the recorded signal with a time varying matched filter. The starting matched filter was the source wavelet. Filter variations obeyed the wide tube propagation model (Blackstock, 2000).

Figure 5 shows an example of a leak test. Figure 5a shows the pressure signal recorded in V22, when producing a spill in the same position. Figure 5b shows the echo detection result: peaks correspond to replicas of the source wavelet after propagation and bounce at the pipe ends. The time axis is converted to propagation distance using the sound velocity 343 m/s. Echoes were detectable up to 150 km; then, the detection result was corrupted by noise. Zoom reveals the discrimination of very low amplitude signals, of approximately 0.2 Pa.

Impact Test

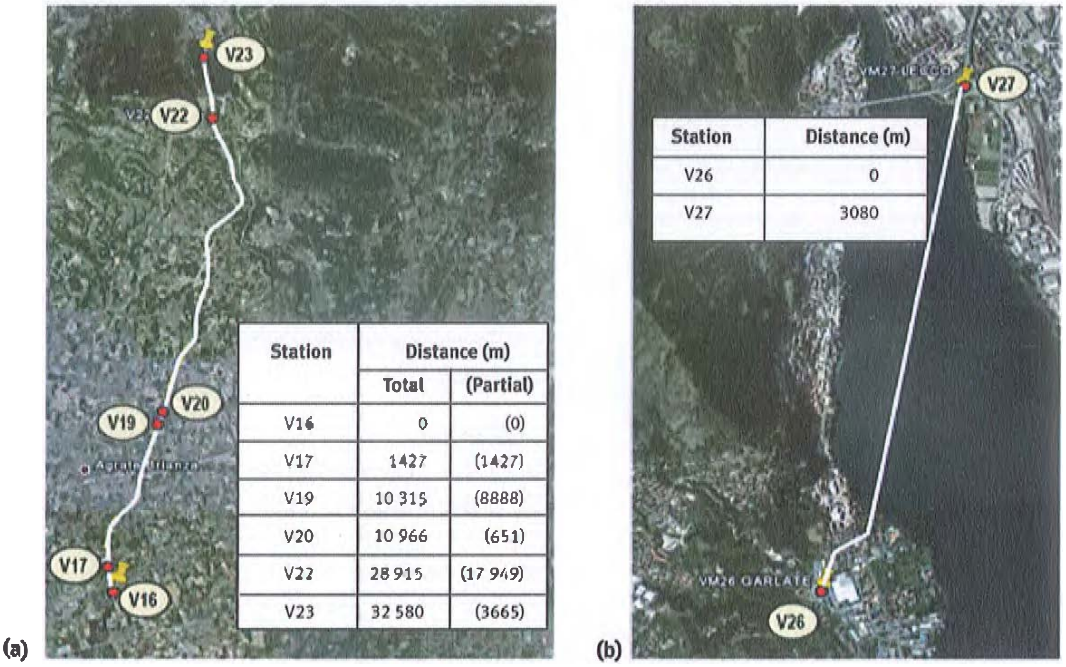
Impact tests were carried out using an oscillating pendulum mass up to 80 kg and a 5 kg hammer (Figure 6). Different impact energies, *E*, were obtained by increasing the departing distance of the pendulum ($E < 750$ J). Dynamic measurements of the pipe displacement at the hit position, by means of three component accelerometers, revealed that the energy entering the pipe was approximately two-thirds of the total one.

Figure 7 compares the pressure signal at station V20, 650 m from the hit point, for different energy impacts. Signal maximum amplitude ranges from 50 to 500 Pa, and 5 kg hammer impact energy is approximately 50 to 100 J.

Figure 8 shows an example of impact detection distance: a 5 kg hammer hit ($E < 100$ J) was produced in V26 (section A). Signal analysis and echo detection procedures revealed the hit echo reflected at the V27 pipe end, after 6160 m of propagation.

Experimental Computation of Propagation Parameters

An experimental measure of the propagation parameters can be derived by comparing successive replicas of a signal "bouncing" within the pipeline. This happened, for example, during the spill tests.



Station	Distance (m)	
	Total	(Partial)
V16	0	(0)
V17	1427	(1427)
V19	10 315	(8888)
V20	10 966	(651)
V22	28 915	(17 949)
V23	32 580	(3665)

Station	Distance (m)
V26	0
V27	3080

Figure 4. Satellite map of Spluga pipeline: (a) section B; and (b) section A. Monitoring stations are shown in red.

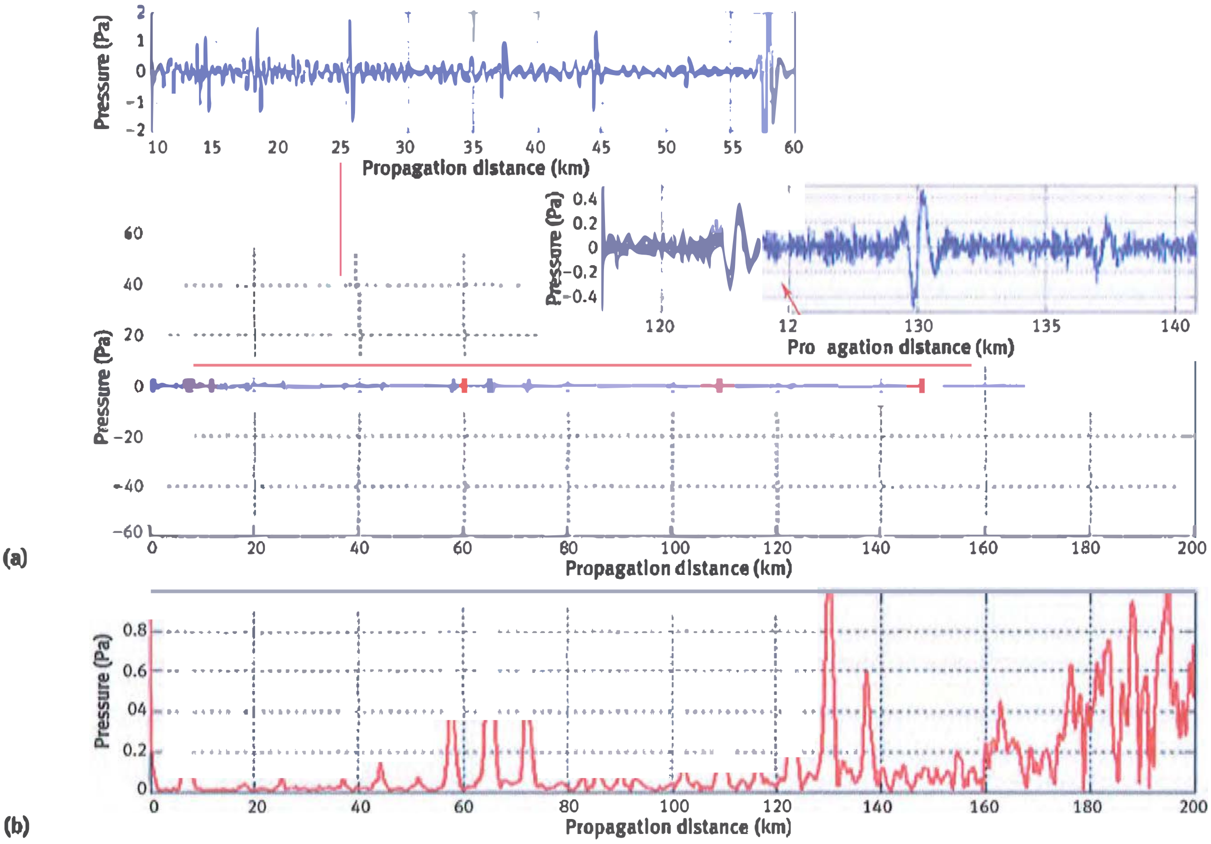


Figure 5. Example of a leak test: (a) pressure at V22, for a spill at V22, with zoom (time axis converted to propagation distance using $v = 343$ m/s); and (b) echo detection procedure. Peaks correspond to signal bouncing at the pipeline ends.

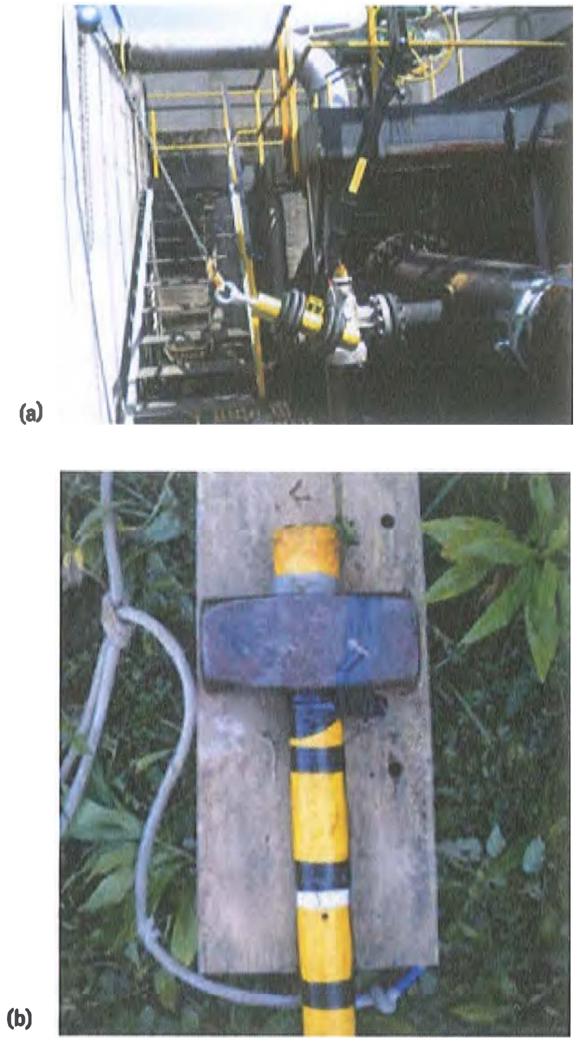


Figure 6. Impact testing: (a) 80 kg pendulum mass installed at V19 (the pipe has been protected with a metallic cover); (b) 5 kg hammer.

Figure 9 shows the experimental and the wide tube analytical attenuation factor (in dB/km). The matching is very good.

Full-scale Test Pipeline

CSM is a full-scale pipeline test site, where extreme conditions (for example, pipe failure or explosion) can be produced to study the mechanical properties of shell materials (Spinelli and Marchesani, 2004). During one of these tests it was possible to install a set of vibroacoustic monitoring stations on a 535 m long steel pipeline, 121.9 cm diameter (Figure 10a), and to produce controlled pressure waves. The pipe was filled with a Libyan-Algerian natural gas mixture with increasing pressure up to almost 13 MPa. Pressure transients were generated through gas spills and hammer strikes on the pipe shell at different gas pressure conditions.

The sound speed estimate was performed in the frequency domain by considering a single receiver and looking for the resonance frequencies, f_r. In fact, for a closed pipe of length, L, internal diameter, d, filled with a fluid with propagation velocity, c, resonance occurs at multiple frequencies (integer n).

$$f_r = \frac{nc}{2(L+0.6d)} \tag{1}$$

This behavior is in very good agreement with the theoretical speed of sound computed from the laboratory mixture composition (Figure 10b), using, for example, Groupe Européen de Recherches Gazières (GERG) models (Kunz et al., 2007).

Messina Channel Offshore Pipelines

Vibroacoustic monitoring stations were installed on two offshore natural gas transportation pipelines (15.9 km line 1 and 31.3 km line 4) crossing the Messina channel (Italy) and managed by an Italian natural gas infrastructure company (Figure 11). The objectives of the test campaign were as follows:

- measure and analyze the environmental noise in service conditions;

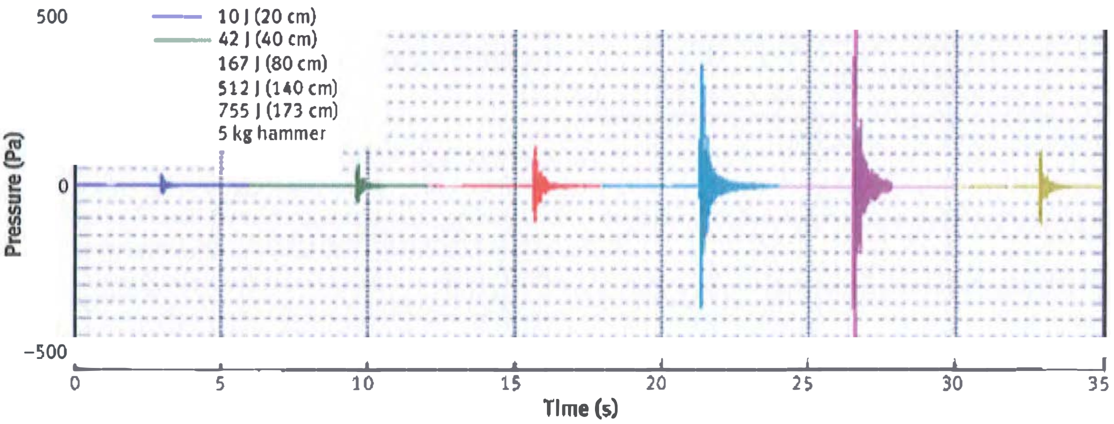


Figure 7. Pressure signal at V20, 650 m from the hit station. Impacts are on pipe protection.

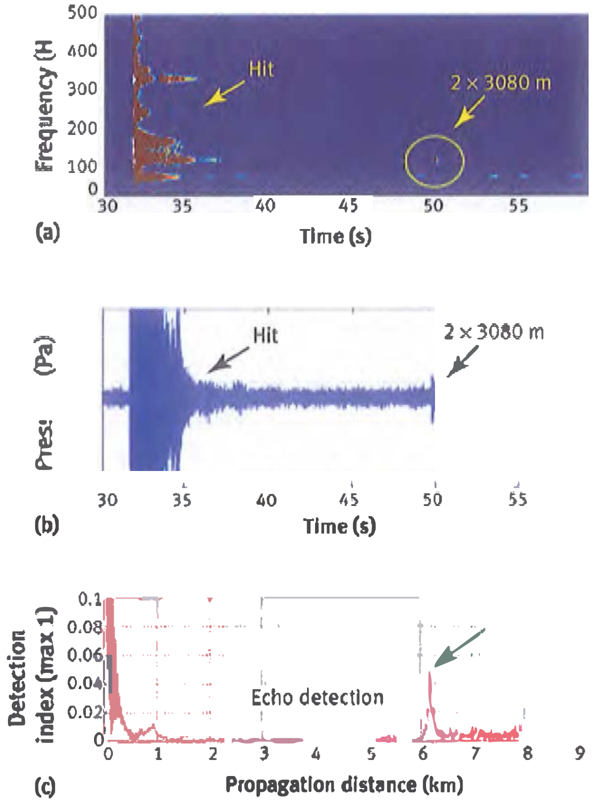


Figure 8. A 5 kg hammer impact at V26 ($E < 100$ J): (a) pressure spectrogram at V26; (b) pressure signal at V26 (middle); and (c) echo detection procedure.

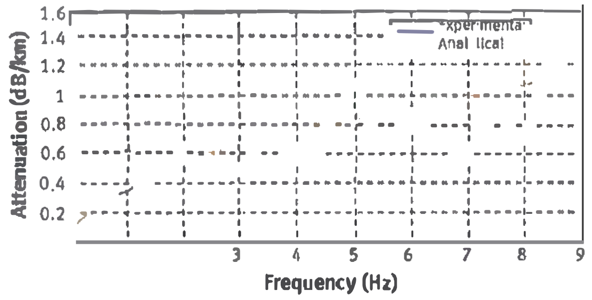


Figure 9. Attenuation factor for sound propagation.

- acquire vibroacoustic data during controlled spill and leak tests;
- design and test data processing routines for remote pig tracking;
- verify pipeline characterization with an equivalent acoustic transmission channel.

Pressure noise is continuously generated by pumps, flow regulation equipment, and local turbulence ("environmental" noise). During standard operation, absolute pressure is approximately 6 to 7 MPa at the pumping station (Messina) and 5 to 6 MPa at the receiving stations (at Favazzina and Palmi, Italy). Low pass (0.5 to 10 Hz) dynamic pressure noise is approximately 0.8 to 1.8 kPa. Pressure noise has comparable amplitude on all stations, meaning that local turbulence and flow regulations are the main sources of environmental noise. This noise is also comparable to measurements collected on the TransMed pipeline.

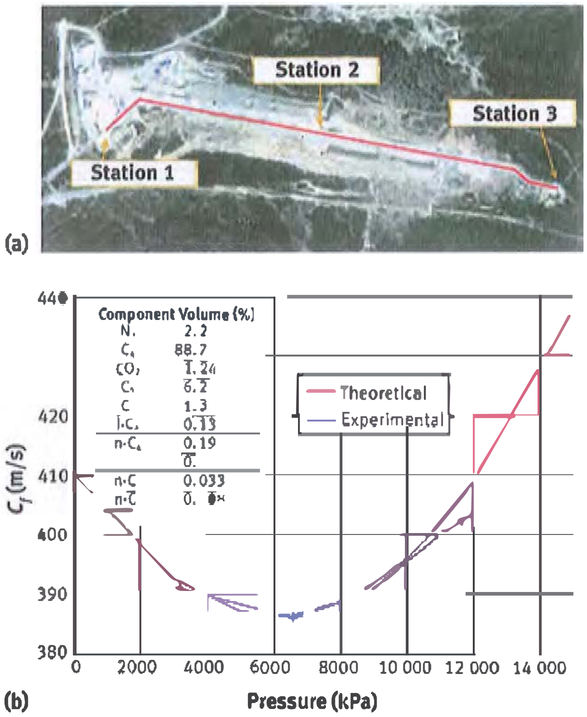


Figure 10. Centro Sviluppo Materiali pipeline: (a) full-scale test pipeline with three vibroacoustic monitoring stations; and (b) experimental and theoretical sound phase velocity in natural gas.

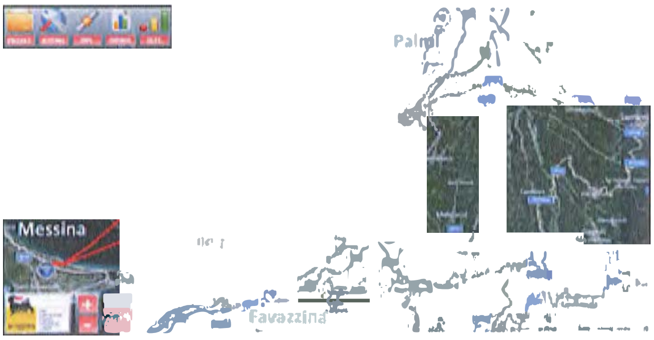


Figure 11. Line 1 (15.9 km length) and line 4 (31.3 km length) offshore natural gas transportation monitoring system display showing the map of Messina Channel.

An original description of the pipeline as an acoustic transmission channel was also proposed, parameterized by pressure sound attenuation and velocity. These parameters can

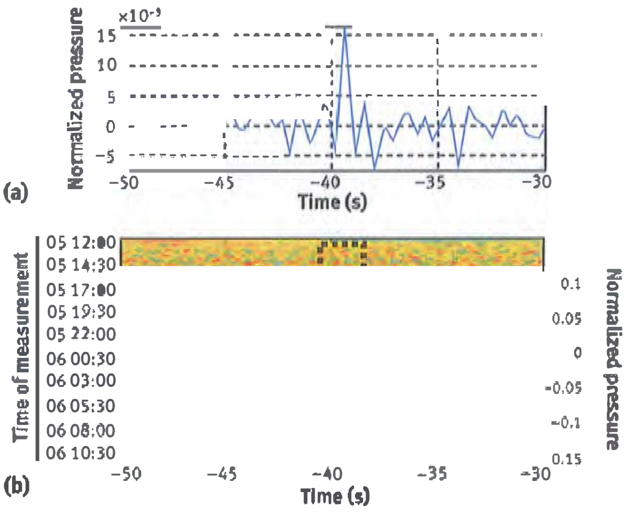


Figure 12. Cross-correlation between pressure variations at Messina and Favazzina (distance 15.9 km) from 12:00 on 5 February 2013: (a) average cross-correlation analysis; and (b) normalized cross correlation.

be continuously estimated using the "environmental" noise. Figure 12 shows, for example, the cross-correlation between the dynamic pressure signals recorded at both terminals of Line 1 (Messina to Favazzina). The pressure signal was low pass filtered below 2 Hz. There is a correlation peak at approximately −40 s, consistent with sound propagation from Messina to Favazzina at 386 m/s. Long-term monitoring (months/years) of the acoustic parameters aids the detection of slow increasing pipe obstructions and/or flow anomalies (Bernasconi et al., 2013b).

Figure 13a shows the pressure signal measured at the arriving station (Palmi) during a pig operation on Line 4. Peaks from crossing welds are clearly visible during the whole operation (Figures 13b and 13c). It is interesting to notice some stops of the pig, where welding hits disappeared (Figure 13c).

Conclusion

A proprietary vibroacoustic monitoring system was used to characterize and study sound pressure transmission in gas transportation pipelines during in-service conditions. Experimental data were used to tune and validate physical models of vibroacoustic data generation and propagation, as well as to design advanced procedures of real-time pipeline monitoring. The main results are as follows:

- Sound propagation in gas filled pipelines obeys the rigid pipe assumption and wide tube approximation.
- Environmental noise is on the order of 1 to 10 kPa in the low frequency band (<10 Hz). It is produced by flow generation and regulation equipment, as well as by local turbulence. Adaptive noise reduction requires very accurate design of sensors positioning and knowledge of the pipe system layout.
- Pressure noise level produced by TPI and leak events is on the order of 0.1 to 2 kPa at the source location. Medium-high energy impacts ($E > 500$ to 1000 J) could be detected in the 50 to 300 Hz bandwidth at a distance up to 10 km. Spills and leaks are low pass signals (<10 Hz); efficient reduction of environmental noise is fundamental for their remote detection.
- Travelling pigs generate vibroacoustic transients when they cross pipeline internal welding dents. This signal, on the order of 1 to 5 kPa, could be effectively processed to track the position of the pig and its velocity from a distance of several tens of kilometers.

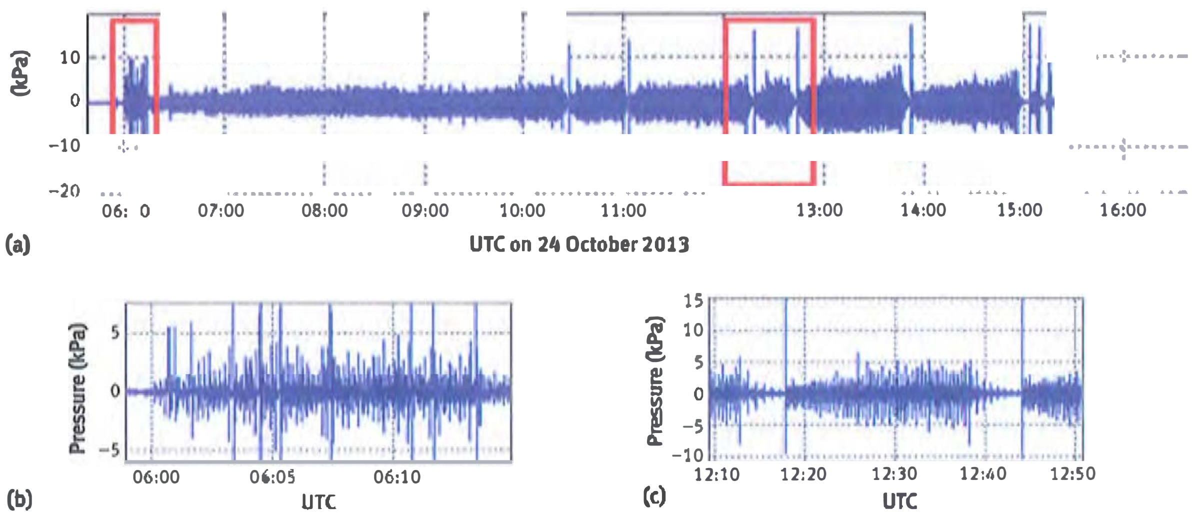


Figure 13. Palmi station: (a) pressure signal during pig operation on line 4; (b) zoom from 6:00; and (c) zoom from 12:10. UTC = coordinated universal time.

- Pipeline terminals are sources of environmental pressure transients (pumps, flow regulation equipment, bending, and so on) that propagate in both directions along the conduit. It is then possible, by cross-correlation analysis between the vibroacoustic data collected at the terminals, to obtain an equivalent acoustic transmission channel of the pipeline. Long-term monitoring (months, years) of the acoustic channel parameters can aid the detection of pipe deformations or obstructions and of anomalies or failures of the flow regulation equipment.
- Leak detection procedures could benefit of a joint analysis of pressure transients phenomena and mass/volume imbalance, to exploit the complementary nature of the two approaches and to increase the reliability of the interpretation.

ACKNOWLEDGMENTS

The research and development project has been promoted and supported by Eni, S.p.A., and it has delivered a proprietary vibroacoustic technology for remote real-time monitoring of pipelines (e-vpms). The authors are grateful to TMPC, Snam Rete Gas, and CSM for essential technical and logistical assistance on pipeline test sites, and to Aresys and Solgeo, partners of the project team.

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