This article illustrates the performance of the portable pressure wave maker (PPWM; patent pending) device for leak detection and pipe characterization used in the water engineering laboratory of the University of Perugia, Italy. The device consists of a steel vessel filled with pressurized air and water that is connected to a test pipe by a short conduit with a connection valve at its end. By a pressure value being fixed in the PPWM that is higher than the pressure in the pipe, a pressure wave propagates in the line when the connection valve is opened. Singularities (e.g., junctions, partial blockages, and leaks) will give rise to the formation of reflected waves whose arrival time and amplitude—recorded in one or more sections of the pipe—allow their detection. Because of its modest dimensions, the PPWM can easily be carried to plants and facilities as part of a transient test-based leak-detection and system-characterization campaign. First, experimental evidence of PPWM device behavior for pipe characterization is shown. Then optimal operational conditions are determined by means of a numerical model and are tested in the laboratory. Finally, a simple formula for evaluating the generated pressure wave is given.
sections of the pipe during tests (Brunone & Ferrante, 2004).

The first approach—the inverse transient analysis (ITA)—was introduced by Liggett & Chen (1994), and is an extension of previous work by Pudar & Liggett (1992), who focused their attention on steady-state data. ITA takes pressure signals recorded in pipe systems, in which transients of known characteristics have been induced, and compares them with pressure traces generated by a numerical model simulating the same transients. With the assumption that network topology is known, leaks are modeled as nodal demands. Thus, in the ITA framework, leak location determines nodes that are nearby the actual leaks by minimizing the differences between measured and simulated pressure values. Liggett & Chen (1994) illustrated the relative superiority of transient test data compared with steady-state data because the former provide a large amount of information (relative to the requisite data) for system calibration and the exposure of leaks.

Pursuing the same route established by Liggett & Chen (1994), several researchers have proposed new approaches to maximize data utilization, exploiting all available information contained in pressure signals. Although Liggett & Chen employed the well-known Levenberg–Marquardt algorithm, other techniques have been adopted by different authors (e.g., Covas & Ramos, 2001). Genetic algorithms in a hybrid model have also performed well (Kapelan et al, 2003; Vítkovský, et al, 2000). A review of ITA techniques for leak detection can be found in Kapelan et al (2000).

The second approach, followed in this research, uses transient test information resulting from changes in pressure signals caused by singularities (e.g., junctions, partial blockages, and leaks) in the pipe system. During a transient, generated, for example, by a valve closure, such singularities create wave reflections (Swaffield & Boldy, 1993) whose characteristics enable determination of both the location and the characteristics of the singularity. Leak-detection campaigns have been based on the use of acoustic methods that must travel along the pipe being investigated. Pressure waves act in the same way, but are, of course, much quicker and more effective. Transient test techniques also allow easy surveying of nonaccessible parts of the system (e.g., submarine pipes). This approach is widely used in many fields (e.g., geophysics, radar, and fault detection) to perform system diagnoses and is also referred to as the traveling wave approach, time-domain reflectometry, or tomography. Numerous examples of system tomography are found in hydraulic and chemical engineering literature (e.g., Brunone & Ferrante, 2001; Covas et al, 2000; Brunone, 1999, 1989; Jönsson, 1999; Silva et al, 1996; Jönsson & Larson, 1992; Nicholas, 1990).

Analysis of the pressure signal can also be undertaken in the frequency domain, either via Fourier analysis (Mohapatra et al, 2006; Ferrante & Brunone, 2003; Mpesha et al, 2002, 2001; Wang et al, 2002; Souza et al, 2000) or, more effectively, with wavelet functions that...
allow the denoising of the pressure signal (Ferrante & Brunone, 2003b; Stoivanov et al, 2001).

When dealing with real pipe systems, accessing and generating transients are often challenging. In many cases, valves are installed in locations in which pressure measurements are difficult or valve response is slow, especially for valves in large-diameter pipes. Another complication is that many valves do not permit a sufficiently precise determination of pressure surges caused by the maneuver.

Thus, in many conditions introducing transients by means other than valve manipulation would be of great benefit. However, to date, a portable and easy-to-use device that does not entail overly sophisticated support instrumentation beyond that required for registering the pressure signal has not been available.

The portable pressure wave maker (PPWM) device has been refined and tested in the Water Engineering Laboratory in the Department of Civil and Environmental Engineering at the University of Perugia, Italy (photo at left). The PPWM consists of a steel vessel, filled with water and air, which can be placed under pressure by means of a standard air compressor.

In practice, the PPWM and test pipe are linked by a short conduit with a small-diameter connection valve at its end. The moderate size of the valve, which can be actuated manually or electrically, not only allows the PPWM to be introduced to the pipe via a simple pressure inlet but also improves pressure signal quality. For the sake of public safety, the PPWM device must be carefully cleaned and filled with water from the test pipe when used in aqueducts.

Initially, the PPWM is brought to a higher pressure than that in the pipe. Opening of the connection valve causes a pressure wave that travels along the pipe with a velocity equal to the water hammer wave speed \( c \), detecting singularities. As demonstrated later in this article, the pressure wave amplitude generated by the PPWM can be controlled with reasonable precision, eliminating uncertainties associated with inadequate knowledge of control valve behavior. In order to avoid flow-control problems in the pipe, the diagnosis of system integrity can be simplified by considering hydrostatic conditions at the outset of the test.

The purpose of this article is

- to describe the PPWM,
- to demonstrate that the pressure signal produced by it can characterize a pipe system, and
- to provide guidelines for optimal test conditions and estimating of PPWM pressure wave amplitude.

**EXPERIMENTAL EVIDENCE OF PPWM BEHAVIOR FOR PIPE SYSTEM CHARACTERIZATION**

To evaluate PPWM performance under controlled conditions, tests were done at the Water Engineering Laboratory of the University of Perugia using the experimental setup shown in Figure 1. During tests, a high-density polyethylene pipe, with an internal diameter of 93.3 mm and supplied by a constant level reservoir, was arranged in two setups. First, a simple pipe with a length \( L \) of 352 m with the PPWM located at the pipe's end was considered. In the second configuration, a Y-system was constructed \( L_1 = 197.20 \text{ m}; L_2 = 116.78 \text{ m}; L_3 = 61.78 \text{ m} \)
with a dead end (DE) at pipe 2 and the PPWM placed at the end of pipe 3 (Figure 2). In both setups, leaks were simulated by placing orifices of different sizes and shapes in the pipe wall (see photos on pages 112 and 113). The PPWM consists of a cylindrical steel vessel with a diameter of 0.45 m and a total volume of ~0.20 m³. A ball valve connects the device to the test pipe via a flange (see photo on page 110). A piezometer is installed on the vessel to control the water level and monitor the air volume in the device.

During transient tests, pressure is measured by piezoresistive transducers with a frequency acquisition of 200 Hz. Pressure transducers are installed at the PPWM, at the supply reservoir (indicated by subscripts P and R, respectively), in the pipe close to the connection flange (section M), and at a distance of 255 m (section N).

The case of an intact (i.e., leak-free) simple pipe is considered first. In Figure 3 the pressure signals—\( h_M \) and \( h_N \), respectively—are reported for test number 1. Pressure signals are referred to the pipe axis, and time (\( t' \)) is

\[ \Delta t' = \frac{t}{H} \]

\[ \Delta = \text{pressure wave amplitude}, \]

\[ h_i = \text{pressure signals at portable pressure wave maker (P), supply reservoir (R), and pipe sections M and N} \]

Figure 3: Pressure signals at selected measurement sections for the intact simple pipe (test number 1)

\[ t' = \text{arrival time at section M of the wave reflected by the leak} \]

Figure 4: Pressure signal for the damaged simple pipe (test number 2)

\[ \text{Wave produced by: DE—dead-end section, P—portable pressure wave maker, R—supply reservoir, Y—Y-junction (first wave), } \]

\[ \text{Y''—Y-junction (second wave)} \]

Figure 5: Pressure signal for the intact Y-junction pipe-system with pressure wave arrival times (test number 3)

\[ E = \text{reduction in pressure signal} \]

Figure 6: Detailed view of the pressure signal \( h_M \) and numerical model results (from Figure 3)
relative to the beginning of data acquisition. Before opening the connection valve, initial conditions (subscript 0) are hydrostatic conditions in the pipe, where \( h_{M,0}, h_{N,0}, \) and \( h_R = 21.60 \) m; and \( h_P,0 = 40.14 \) m in the PPWM, corresponding to an air volume of 0.0065 m\(^3\). Opening the valve at \( t/H_1 = 0.22 \) s, pressure difference \( h_{P,0} - h_{M,0} = 18.54 \) m produces a pressure wave with an amplitude \( h \) equal to 1.71 m that propagates along the pipe with a velocity \( a = 348.70 \) m/s. After 0.60 s and 1.01 s, the pressure wave reaches section N and the supply reservoir, respectively; after being reflected back by the constant level reservoir, it subsequently reaches sections N and M. During the observation period, no entry of air into the pipe takes place. The maneuver produced by the PPWM has the same effect as a sudden closure of an end valve, with the advantage of a controlled initial overpressure. Moreover, despite the small amplitude of the pressure wave, it allows surveillance of the pipe system.

In order to better test the reliability of the PPWM device, a damaged single pipe and a more complex intact pipe system (i.e., a Y-system) have been considered.

A circular leak with a diameter of 9.9 mm (see photo on page 113) was placed at a distance of 129.83 m from section M of the simple pipe system. Figure 4 (test number 2) portrays the arrival at \( t = 0.70 \) s in section M of the wave reflected by the leak. On the basis of such a time value \( t \) and the water hammer wave speed, within a simple time domain analysis the simulated leak is determined to be 125.98 m from the measurement section. This has an error rate of < 3% with respect to its actual position. Although the best technique for an accurate leak location is out of the scope of this article, a higher precision can be reached by analyzing the pressure signal by means of wavelet functions (Ferrante & Brunone, 2003b).

The pressure signal (Figure 5) shows the capability of locating the Y junction and the DE by means of a transient test (test number 3). In Figure 5, letter P indicates the beginning of the pressure wave generated by the PPWM, and letters Y and Y' indicate the arrival of the first and second pressure waves reflected by the Y junction, respectively. Letters DE and R indicate the arrival of the pressure waves reflected by the dead end and the supply reservoir, respectively.

Thus, on the basis of the previously mentioned experimental results, the PPWM can be properly used for the characterization of a pipe system. However during the time preceding the arrival of the first reflected wave, the gradual reduction in the pressure signal at section M occurs because of the efflux process. As an example, Figure 6 shows pressure signal \( h_M \) from Figure 3 in a larger scale. After a period of time equal to the characteristic time of the pipe \( \tau = 2L/a \), the pressure signal in the device \( h_P \) is reduced from the value of 39.89 m at the end of the maneuver to 38.74 m. This causes a reduction \( E = 0.29 \) m in the pressure signal, \( h_M \), in the same time-period. In general, for a given measurement section and pipe system, \( E \) is the difference between the value of the pressure because of the maneuver and that occurring just before the pressure wave reflected by the first singularity reaches section M (in an intact simple pipe, the...
first and only singularity—the supply reservoir—is also the farthest one). Because the proposed procedure for pipe characterization is based on the detection of discontinuities in the pressure signal, the more stable the pressure signal—i.e., the smaller the value of $E$—the more reliable the signal for detecting the reflected pressure waves. In the next section of the article, a criterion to minimize $E$ by properly arranging the PPWM device is proposed for an intact simple pipe.

**NUMERICAL MODEL FOR PPWM OPTIMAL OPERATIONAL CONDITIONS**

In order to determine optimal PPWM operational conditions, a numerical investigation is undertaken for an intact pipe in which the system of governing equations is solved using the method of characteristics (Wylie & Streeter, 1993).

With regard to node M at the connection between the PPWM and the pipe, because at any time interval ($\Delta t$) the water leaving the PPWM is replaced by air, the following continuity equation can be written:

$$\frac{U_{p,t} - U_{p,t-\Delta t}}{\Delta t} = Q_{M,t}$$

in which $U_p$ = volume of air in the PPWM; $t$ = amount of time elapsed since the beginning of the transient; and $Q$ = discharge.

The state equation for air in the PPWM describes the pressure/volume relationship:

$$h_{p,t} U_{p,t}^n = \text{constant}$$

in which $n$ is an exponent that depends on the type of thermodynamic transformation experienced by the air ($n = 1$ and 1.41 for isothermal and adiabatic transformations, respectively). Of the connection valve and the head difference between the PPWM and the pipe:

$$Q_{M,t} = \left( C_v A_v t \right) \sqrt{2g(h_{p,t} - h_{M,t})}$$

in which $g$ = acceleration due to gravity; $C_v$ = discharge coefficient of the connection valve; and $A_v$ = area of the free aperture of the connection valve.

The last equation describing the phenomenon is the compatibility equation that is valid along the negative compatibility equation:

$$h_{M,t} = C_{m,t} + B_{m,t} Q_{M,t}$$

in which $C_{m,t} = h_{M} + Q_{M,t-\Delta t} - B_{M,t} Q_{M,t}$, with $B = a/gA$ and $R_{M,t-\Delta t} = h_{M,t} - h_{M,t-\Delta t}$. $\Delta s$ being the pipe characteristic impedance and resistance coefficient, respectively; $\lambda$ and $A$ are the pipe friction factor and cross-section, respectively. Because, as it will be clarified later, the duration of the calculations is limited to $\tau$, the friction factor $\lambda$ can be evaluated according to the quasi-steady approach (Brunone et al, 1995).

For each internal node ($j$), where $M = j$ (Eq 4) the following compatibility equation that is valid along the positive characteristic line ($\Delta s/\Delta t = + a$) can be written in terms of the two unknowns, $h_j$ and $Q_j$:

$$h_{j,t} = \bar{C}_{j,t} - \bar{B}_{j,t} Q_{j,t}$$

in which $\bar{C}_{j,t} = h_{j-1} + B_{j-1,t} Q_{j-1,t}$ and $\bar{B}_{j,t} = B + R_{j,t-\Delta t}$.

Finally, other than in Eq 5 where $j = 1$, the boundary condition corresponding to the constant level supply reservoir must be considered:

$$h_R = \text{constant}$$

Testing of simulated leaks included insertion of discs in varying shapes and sizes into pipe walls. The disc used in the third test is highlighted here.
The previous equations were solved for test number 1 in which \( n = 1.41 \). The numerical and experimental results are shown in Figure 6. The numerical simulation confirms a reduction in pressure signal at section \( M \) (i.e., \( E \))—although slightly smaller than the real one (\( E = 0.26 \) m)—because of the efflux process through the connection valve.

The following numerical analysis focuses on minimizing the reduction \( E \), and in order to synthesize the results of the proposed model, the dimensionless pressure signal decay, \( \epsilon \), must be considered:

\[
\epsilon = \frac{h_{M,T} - h_{M,0}}{h_{M,0}} = \frac{E}{h_{M,0}}
\]

in which \( T \) = connection valve opening time and \( \Theta \) = observation interval. In the simple pipe the singularity is the supply reservoir located at a distance \( L \) from section \( M \). Therefore, in numerical simulations, it is assumed that \( \Theta \) coincides with \( \tau \). Such an interval is sufficient because the generated pressure wave transverses the entire system and would reveal the existence of a possible leak. In other words, the assumption \( \Theta = \tau \) requires that the signal is maintained to be as stable as possible (i.e., minimum \( \epsilon \)) and for the most unfavorable situation; i.e., a leak close to the supply reservoir. Moreover, an instantaneous opening maneuver of the connection valve has been considered. Such an assumption is realistic, as it will be shown subsequently, when a small-size valve has to be installed.

In nondimensional terms, the following functional relationship can be written:

\[
\epsilon = \epsilon (u, \zeta, \beta)
\]

in which the nondimensional quantities \( u, \zeta, \) and \( \beta \) are defined as

\[
u = \frac{U_{P,0}}{U}
\]

in which \( \nu \) is the volumetric percentage of air initially present in the vessel, where \( U = \) total volume of the device:

\[
\zeta = \frac{(C_v A_v)_{0}}{A}
\]

in which \( \zeta \) is the degree of throttling of the connection valve, and

\[
\beta = \frac{h_{P,0}}{h_{M,0}}
\]

in which \( \beta \) is the pressure ratio.

The results of the numerical investigation are reported in Figure 7. In Figure 7, parts A - C, the value of a single parameter (\( u, \zeta, \) and \( \beta \), respectively) has been varied whereas the others are assumed constant and equal to the values of test number 1 (Table 1).

Figure 7, part A, shows how enlarging the initial volume percentage of air, \( u \), increases the stability of the pressure signal, i.e., the decay of \( \epsilon \) diminishes. One limitation to reducing \( u \) is to avoid the air intrusion into the pipe during the interval \( \Theta \). However, as seen in Figure 7, part A, with \( u = 20\% \), the decay assumes an acceptable value, with little likelihood of air intrusion.

The same effect is seen with reduced throttling of the connection valve, \( \zeta \), as seen in Figure 7, part B. Decreasing the product \( C_v A_v \) reduces the flow entering the pipe and, as a result, the pressure signal remains more stable. The desirable reduction in the product \( C_v A_v \) is within the range of commercially available valves and should prevent air entry into the pipe.

With regard to the dependence on the pressure ratio, it can be observed that according to results in Figure 7, part A (i.e., for the relationship between \( h_{R} \) and \( U_P \)) the larger \( h_{R} \) is with respect to \( h_{M,0} \), the larger \( \epsilon \) is (Figure 7, part C). Such an aspect is of particular importance for real pipe systems. It implies that a good quality pressure sig-
nal can be obtained with a small difference between \( h_{P,0} \) and \( h_{M,0} \) and when a small pressure wave is produced by the PPWM.

On the basis of such results and for a given pipe system to be characterized (i.e., for given \( h_{M,0}, \alpha \) and \( A \)), the PPWM can be set up to obtain a good quality pressure signal by properly adjusting the initial values of \( C_v A_v, U_P \) and \( h_P \). The conclusions are also valid with an isothermal expansion of air in the PPWM (\( n = 1 \)).

Results of the proposed numerical model have gone through laboratory testing in which the parameters \( u, \zeta \), and \( \beta \) have been varied. In Table 1, as an example, the results of some laboratory tests are reported as well as those given by the numerical model (indicated by subscripts e and n, respectively). Experimental results confirm the numerical model (Table 1).

Although the maximum entity of the pressure wave would be given by \( h_{P,0} - h_{M,0} \) in the case of no energy dissipation in the efflux process through the connection valve, a more reliable value can be determined analytically. Specifically, if an instantaneous maneuver is considered and, within optimal test conditions, it is assumed \( h_{P,T} = h_{P,0} \), by combining Eqs 3 and 4 the following can be written:

\[
\delta = \frac{\bar{a}^2}{\Delta_0 g} \frac{2\delta}{\bar{a}^2 \zeta^2} \left[ 1 + \frac{2\delta_0}{\bar{a}^2 \zeta^2} - 1 \right] \tag{8}
\]

in which \( \delta \) = relative pressure wave amplitude (\( \Delta/\Delta_0 \)), \( \bar{a}^* \) = nondimensional wave speed (\( a/\bar{a} \), with \( \bar{a} = \sqrt{K/\rho} \)), \( K \) = fluid bulk modulus of elasticity, and \( \rho \) = fluid density. Thus it is possible to obtain the maximum amplitude of the pressure wave generated by the PPWM by means of Eq 8, for a given test pipe, within optimal test conditions. The dependence of \( \delta \) on \( \bar{a}^* \) and \( \zeta \) is shown in Figure 8; such curves have been obtained by considering the values of \( \Delta_0 \) and \( U_{P,0} \) from tests 1 and 4. The smaller \( \zeta \), the better the quality of the pressure signal and the smaller \( \delta \); further, the smaller the pipe stiffness (i.e., \( a \)) and the larger the pipe area, the smaller \( \delta \) (Figure 8).

CONCLUSIONS

The PPWM is easily transported and used in leak detection and pipe characterization studies that are based on the execution of transient tests. An important property of the PPWM is that transient tests can be completed without a suitable maneuver valve in the pipe system.

The performance of the PPWM is demonstrated through experimental tests carried out at the Water Engineering Laboratory of the University of Perugia, Italy. Particularly, results of laboratory tests show the possibility of detecting singularities present in a pipe system using pressure waves of limited amplitude (i.e., a few meters of water column). A model to define the optimal test conditions is illustrated, and a simple relationship is proposed for evaluating the pressure wave produced by the PPWM.

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![Figure 8](image_url)

**Figure 8** Relative pressure wave amplitude as a function of the connection valve throttling degree and nondimensional wave speed.
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