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Design of surge tank for water supply systems using the impulse response method with the GA algorithm †

Sang-Hyun Kim*

Environmental Engineering, Pusan National University, Geumjeong-gu, Busan 609-735, Korea

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Abstract

The impact of the surge tank has been incorporated into the platform of the impulse response method. The impedance functions for pipeline systems equipped with a surge tank were also derived. Hydraulic transients could be efficiently analyzed by the developed method. The simulation of normalized pressure variation using the method of characteristics and the impulse response method shows good agreement only in the condition of an identical computational interval between pipeline elements and that of the surge tank connector. The important numerical issue, the Courant number condition, of the traditional grid-based approaches can introduce substantial difficulty for optimization of surge tank parameters. The surge tank design could be performed by incorporation of the impulse response method with the Genetic Algorithm (GA). The objective functions for the surge tank design can be made using the pressure-head response at any point along the pipeline system while considering both the security and cost of the system. Substantial flexibility in the design of surge tank parameters, such as the location in the pipeline, the length of the connector, and the diameters for the connector and the surge tank can be found during the optimization procedure.

Keywords: Pipeline systems; Surge tank; Frequency analysis; Water hammer; Evolutionary optimization

1. Introduction

Designing a surge tank for a water supply system is a practical issue in the field of fluid engineering. In order to mitigate the water hammer phenomenon in a pressurized pipeline system, hydraulic devices similar to a surge tank are frequently installed close to the end valve for the reservoir pipeline valve system. Traditionally, the method of characteristics (MOC) was widely used to simulate the transients in a pressurized pipeline system generated by valve actions [1, 2]. Hydraulic transients in water distribution systems can lead to overpressures and negative pressures, which may require excessive pipe wall thickness [1, 2]. Pipeline systems can suffer either a catastrophic failure from a surge event or fatigue failure from repeated surges. Water hammer damage can also cause leaks in the relatively weak positions where the pipeline systems meet. Water column separation can be generated from suction pressure and may result in detrimental impacts on the joint rings on numerous pipeline segments.

Surge protection devices such as a surge tank or air chambers can be designed with complete transient modeling [3]. Air chambers with throttling orifices have been modeled in conjunction with transient analysis [4]. Lee (1998) modeled the impact of air entrainment in a pipeline system equipped with an air chamber that was also simulated on the platform of transient analysis [5]. Transient analyses used in air chamber modeling are one-dimensional numerical approaches based upon grid descriptions of time and space. Surge analysis assuming small amplitude oscillations, continuity at the surge tank, and constant power to penstock provided the minimum surge tank area for stability [6-8].

However, an alternative numerical method for frequency dependent pipeline transients is the impulse response method (IRM) [9-11]. The advantage of this is that there is no restriction of the Courant number in a simulation with a substantial improvement in transient computation and calibration [12, 13].

Numerical approaches to unsteady events have integrated the impact of surge tanks or air vessels on the platform of the MOC [1, 2]. One restriction of the MOC approach is the spatial representation of hydraulic devices. The location of hydraulic devices should exactly coincide with the intersection of divided pipeline elements from the pretreatment process of numerical analysis, namely, discretization. The other limitation is time-step constraints associated with the representation of hydraulic devices for the MOC. The minimum computational time interval for a hydraulic device is generally much

† This paper was recommended for publication in revised form by Associate Editor Haecheon Choi
*Corresponding author. Tel.: +82 51 510 2479, Fax.: +82 51 514 9574
E-mail address: kimsangh@pusan.ac.kr

less than that determined from the pipeline subdivision. This demands a substantial increase in computational costs in the conventional approaches, especially for hydraulic devices with short connectors attached to long pipeline systems.

In the present study, the impulse response method is integrated with the genetic algorithm (GA) to explore the optimum solution for the design of a surge protection device in the water supply system. The solution search is based on two merits over conventional approaches. The first advantage is strongly associated with the strength of the impulse response method. Exact dimensional values and flow characteristic variables could be used in the simulation of transients over other discretization approaches. The second point is about the consideration of capital cost. Substantial capital costs have been wasted due to over-dimensional design of hydraulic devices to secure the water hammer impact. This approach will provide a method for delineating the minimum dimensions in surge tank design that provide similar surge protection impact similar to that of larger cases.

2. Transient analysis in a pipeline

The momentum and continuity equations for the transient flow in a pipeline are given as follows:

$$\frac{\partial Q}{\partial t}+gA\frac{\partial H}{\partial x}+\frac{f|Q|Q}{2DA}=0 \tag{1}$$

$$\frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}=0 \tag{2}$$

where x ,t, a, g, A, Q, H, f and D are the distance along a pipeline, time, the wave speed, the gravitational acceleration, the cross-sectional area of a pipe, the discharge of flow, the head, the Darcy-Weisbach friction factor, and the pipe diameter, respectively [1, 2].

Combining the momentum and continuity expressions to form compatibility equations along the characteristic lines defined by $dx/dt=\pm a$ and integrated from current to future time steps can be generalized as [11]:

$$\int_c^n Q|Q|dx=\left[Q_c+\varepsilon(Q_c-Q_n)\right]|Q_c|\Delta x \tag{3}$$

where ε = a weighting term for linearization, and the subscripts c and n represent the current and next time step, respectively.

Assuming a steady oscillatory flow and linearized friction, the complex head and discharge as a function of distance, x, are provided as follows [1, 2]:

$$H(x)=H_U\cosh\gamma x-Z_C Q_U\sinh\gamma x \tag{4}$$

$$Q(x)=-\frac{H_U}{Z_C}\sinh\gamma x+Q_U\cosh\gamma x \tag{5}$$

where the subscript U denotes the upstream section. The propagation constant $\gamma=\sqrt{Cs'(Ls'+R)}$, the characteristic impedance $Z_c=\gamma/Cs'$, and $s'=\sigma+i\omega$, where the capacitance (C) is gA/a^2, the inertance L is $1/gA$, the resistance (R) is fQ/gAD^2, σ is a decay factor, and ω is the frequency.

The hydraulic impedance $Z(x)$ is defined as the ratio of the complex head to the complex discharge. The impedance transfer function at the upstream end as a function of impedance at the downstream end can be expressed as follows:

$$Z_U=\frac{Z_D+Z_C\tanh\gamma l}{1+(Z_D/Z_C)\tanh\gamma l} \tag{6}$$

where l is the length of a pipeline. If the upstream impedance is determined by the constant head reservoir, then Eq. (6) can be used to configure the frequency characteristics of the system. A Fourier transform relationship can be made between the response function and the transfer function in a reservoir-pipe-valve (RPV) system. When a discharge impulse is imposed at the downstream valve of the RPV system, the pressure head response at the valve with the reservoir boundary condition of $H_u=0$, is expressed as [11]:

$$r_{Dh}(t)=\frac{1}{\pi}\mathrm{Re}[\int_0^\infty(-Z_c\tanh\gamma l)e^{i\omega t}d\omega] \tag{7}$$

where Re represents the "real part of.".

If the impedance in Eq. (7) is replaced by the ratio of a complex head of any point and discharge at the end of a pipeline system located at a downstream boundary condition, the variations in pressure can be predicted at any location within the system. Transient events can be generated through downstream valve maneuvers. Both the MOC and IRM integrate the orifice equation and utilize dimensionless valve opening to represent downstream valve conditions [2]. The MOC explicitly determines the discharge and pressure head, and is incorporated into characteristic propagation [2]. Discrete convolution with response functions such as Eq. (7) provides a time history of hydraulics in the IRM [12].

3. Representation of surge tank

A surge tank is composed of a short connector and an accumulator as shown in Fig. 1. If the lumped inertia is applied to the surge tank, the H and Q can be divided into the mean and fluctuation terms: $H=\overline{H}+h'$ and $Q=\overline{Q}+q'$.

Application of the Taylor series expansion for the $\partial H/\partial x$, $\partial Q/\partial t$ and $fQ^2/2gDA^2$ terms and combining the lumped inertia provide the following:

$$h_U'-h_D'-fl\overline{Q}/(gDA^2)q'=l/gA\cdot dq'/dt \tag{8}$$

where h_U' is the upstream perturbation component and h_D' is the downstream perturbation component.

If $h_U'=H_U e^{i\omega t}$, $h_D'=H_D e^{i\omega t}$, and $q'=Q\,e^{i\omega t}$, then Eq. (8) can be expressed as

$$H_D = H_U - (Rl + i\omega Ll + R' Q_U e^{i\omega t}) \tag{9}$$

where $R = f\overline{Q}/gDA^2$; $R' = f/2gDA^2$ and $L = 1/gA$.

If R' is ignored, Eq. (9) can be rewritten in terms of impedance as [2]:

$$Z_D = Z_U - (R + i\omega L)l \tag{10}$$

The impulse response method also provides a more accurate representation of the surge tank as

$$Z_D = \frac{Z_U - Z_C \tanh \gamma l}{1 - Z_U / Z_C \tanh \gamma l} \tag{11}$$

The impedance transfer function can be derived for the upstream of the reservoir pipeline surge tank and pipeline valve (RPV) system, as shown in Fig. 2. The impedance upstream of the surge tank is expressed as:

$$Z_{upST} = -Z_C \tanh \gamma l_{up} \tag{12}$$

where l_{up} is the distance from the upstream reservoir to the surge tank point.

The impedance at the downstream of the surge tank position can be derived as

$$Z_{downST} = \frac{Z_{upST}}{1 - \dfrac{Z_{upST}}{Z_D}} \tag{13}$$

where Z_D is the impedance obtained from Eq. (10) or (11). Further application of Eq. (11) provides the impedance at the downstream valve position.

Therefore, when a discharge impulse is imposed at the downstream valve of the RPV system with a surge tank, the pressure head response at the valve can be expressed as

$$\mathrm{r_{DT}(t)} = \frac{1}{\pi}\mathrm{Re}[\int_0^\infty (-\mathrm{Z_{valve}})\mathrm{e}^{\mathrm{i}\omega\mathrm{t}}\mathrm{d}\omega] \tag{14}$$

The pressure head response between the valve and surge tank is

$$r_{x1h}(t) = \frac{1}{\pi}\mathrm{Re}[\int_0^\infty (Z_{valve}\cosh\gamma x_1 + Z_c \sinh\gamma x_1)\cdot e^{i\omega t} d\omega] \tag{15}$$

where x_1 is the distance from the valve to the response point and Z_{valve} is the hydraulic impedance at the valve position.

The flow response between the valve and the surge tank is

$$r_{x1q}(t) = \frac{1}{\pi}\mathrm{Re}[\int_0^\infty (\frac{Z_{valve}}{Z_c}\sinh\gamma x_1 + \cosh\gamma x_1)\cdot e^{i\omega t} d\omega]\cdot \tag{16}$$

The frequency dependent friction can be also be accounted for by replacing the propagation operator, γx, and the characteristic impedance, Z_c, with the following equations as follows [2, 15]:

$$\Gamma(s') = \frac{s'x}{a}(1 - \frac{2J_1(i\frac{D}{2}\sqrt{\frac{s'}{\nu}})}{i\frac{D}{2}\sqrt{s'\nu}J_0(i\frac{D}{2}\sqrt{\frac{s'}{\nu}})})^{-1/2} \tag{17}$$

$$Z(s) = \frac{a}{gA}(1 - \frac{2J_1(i\frac{D}{2}\sqrt{\frac{s'}{\nu}})}{i\frac{D}{2}\sqrt{\frac{s'}{\nu}}J_0(i\frac{D}{2}\sqrt{\frac{s'}{\nu}})})^{-1/2} \tag{18}$$

where J_0 and J_1 are the zero and first order first type Bessel function, respectively.

Regarding the discretization approach, application of the momentum equation of Eq. (1) to a short connector in Fig 1 provides a relationship between the pressure heads and the external discharge for the connecting point as

$$H_J - H_S = H_S^p - H_J^p - \frac{8l_c}{\pi g D_c^2 \Delta t}Q_{ext}^p + (\frac{8l_c}{\pi g D_c^2 \Delta t} + \frac{16 f_c l_c}{\pi^2 g D_c^4}|Q_{ext}^p|)\cdot Q_{ext} \tag{19}$$

where H_J = the current pressure head of the pipeline joining point, H_S = the current pressure head at the surge tank, l_c, D_c, f_c = the length, diameter, and friction factor of the connector, respectively, and H_J^p, H_S^p, Q_{ext}^p = the pressure heads at the joining point, surge tank, and the external discharge of the previous time step, respectively, and Δt is the time interval for computation.

Integrating the characteristic equations for the external discharge for a surge tank and the continuity equation of a surge tank into the lumped inertia equation, the external discharge can be expressed as follows [16]:

$$Q_{ext} = \frac{C_c - \dfrac{\Delta t}{2A_S}Q_{ext}^P - H_J^P + \dfrac{8l_c}{g\pi D_c^2 \Delta t}Q_{ext}^P}{\dfrac{8l_c}{g\pi D_c^2 \Delta t} + \dfrac{16 f_c l_c}{g\pi^2 D_c^4}|Q_{ext}^P| + B_c + \dfrac{\Delta t}{2A_S}} \tag{20}$$

$$B_c = (\frac{1}{B_+} + \frac{1}{B_-})^{-1}, and \qquad C_c = B_c(\frac{C_+}{B_+} + \frac{C_-}{B_-})$$

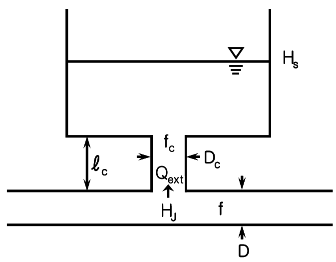

Fig. 1. A schematic for a surge tank.

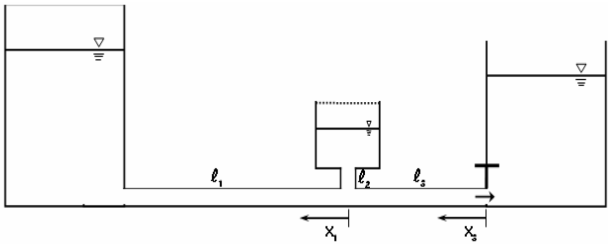

Fig. 2. Reservoir-pipeline-surge tank-pipeline-valve system.

where $C_{+-} = h \pm q(B + R|q|(1-\varepsilon))$, $B_{+-} = B \pm eR|q|$, $h, q =$ the head and discharge corresponding to the time-space coordinate of MOC, respectively, $B = a/(gA)$, $R = f \cdot \Delta x/(2gDA^2)$, and Δx = the length of a pipeline segment for discretization.

4. Integration of the impulse response method with the genetic algorithm

The optimal design of surge tank dimensions is a practical issue in the field of pipeline engineering. In this study, the scheme for searching for a solution for surge tank parameters was designed using the GA [17]. The impulse response method is integrated into the GA. The GA is a powerful search tool that utilizes evolutionary based principles to find optimal solutions [17]. As in the case of evolution, the GA starts with a population of the potential solution. A chromosome represents a possible solution to the problem. The fitness of each solution is estimated by employing an objective function. The fitness of each solution is estimated by employing an objective function. The two design criteria can be used for the derivation of the objective function. One is the function of water hammer mitigation in the design of the surge tank. The surge tank dimensions should be determined to obtain the maximum security of the pipeline. Two different goals can be explored to prevent transient impact. One is the minimization of total pressure head fluctuation at the specific point in the pipeline system.

The objective function for the minimum head variation can be expressed in terms of the pressure head time series as

$$\text{Minimize}\{\sum_{t=1}^{\text{end}}(h(t) - h_r)\} \tag{21}$$

where h (t) is the time series of the estimated pressure head and h_r is the reference pressure.

If the maximum overpressure or under-pressure is concerned, the objective function as the function of the computed pressure head can be expressed as

$$\text{Minimize}[\text{Max}\{|h(t) - h_r|\}] \tag{22}$$

where the notation |#| indicates the absolute value for #.

The other important surge tank design criterion is the cost of the hydraulic device. In most cases, the surge tank cost mainly

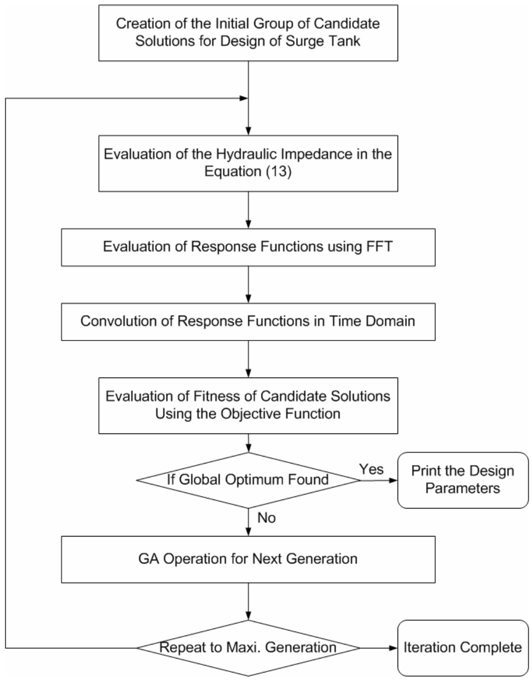

Fig. 3. Algorithm of the surge tank design and the genetic algorithm.

depends on the size of the surge tank diameter. An appropriate scaling factor is introduced to balance the objective function between the pipeline security and the design cost. In this approach, the hybrid objective function for the surge tank design is used as

$$\text{Minimize}[\{\sum_{t=1}^{\text{end}}(h(t) - h_r) + S \cdot D_S\}/2] \tag{23}$$

where S is the scaling factor determined from the optimization of Eq. (21), and D_s is the diameter of the surge tank.

Combining Eq. (22) and the cost consideration another objective function can be drived as

$$\text{Minimize}[\{\text{Max}(|h(t) - h_r|) + S \cdot D_S\}/2] \tag{24}$$

Fig. 3 shows the algorithm of the integration between the impulse response method and the GA for surge tank design.

5. Application examples

Consider a simple horizontal pipeline system equipped with a surge tank near the control valve at the downstream end of the pipeline. The water is passed from a constant head supply reservoir to another reservoir at various flow rates depending upon the differences in the pressure heads between the two reservoirs. The pipeline is 150 m in length and 0.02 m in diameter as illustrated in Fig. 2. The distance between the control valve and the surge tank is 5 m. The diameters of the surge tank and its connector are 2 m and 0.02 m, respectively. The initial flow velocity in the pipeline is 0.3 m/sec. The

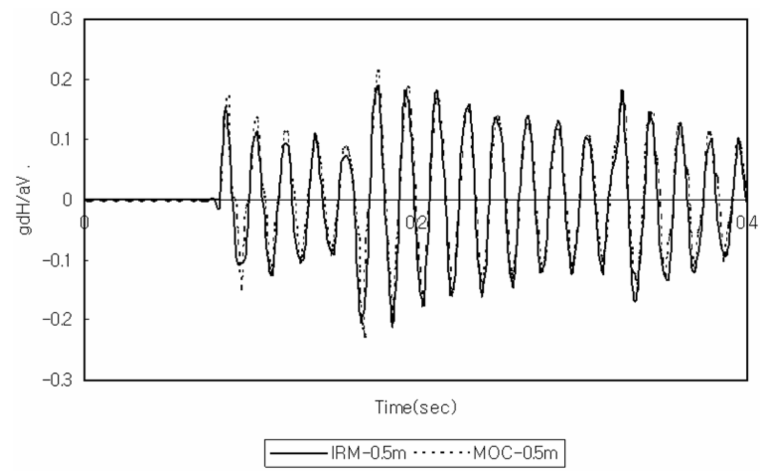

Fig. 4. The normalized pressure heads due to sudden valve closure for the pipeline equipped with surge tank connector in 0.5 m.

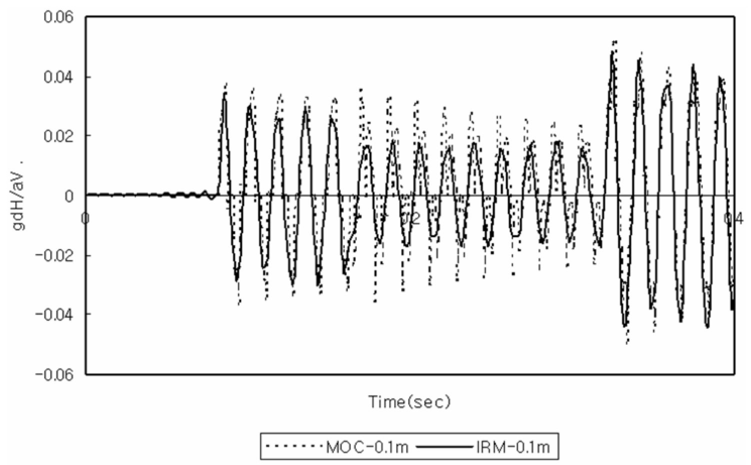

Fig. 5. The normalized pressure heads due to sudden valve closure for the pipeline equipped with surge tank connector in 0.1 m.

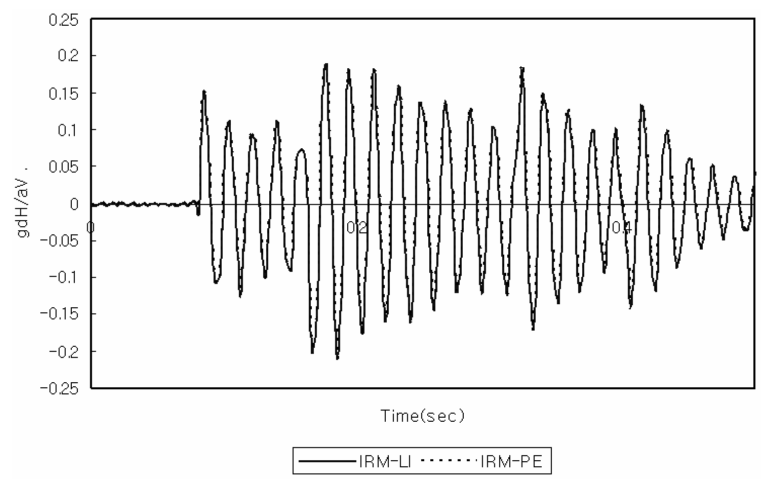

Fig. 6. The normalized pressure heads due to sudden valve closure using the lumped inertia and precise expression in surge tank representation, LI: lumped inertia; PE: precise expression.

Darcy-Weisbach friction factor of the pipeline is assumed to be 0.03, and the wave propagation speed is 1210.5 m/sec. The control valve executes a closure from a full gate opening. Water hammers are introduced from the fast and slow valve closures.

5.1 Water hammer analysis

Both the impulse response method and the method of characteristics can be applied to calculate the time series of the pressure head and discharge at any point along the pipeline. To understand the impact of the surge tank on substantial accuracy, the maximum frequency is defined as 812.28 rad/sec, which turns the computational time step into 0.00387 sec. The number of samples for fast Fourier transform is 32768. Both turbulent and laminar flow conditions are used for the simulation of the water hammer. Both fast and slow valve closures are generated as the control valve is closed in dimensionless times as 0.008 and 0.8 τ, where τ = t / (L/a); t is the closure time in seconds, L is the length of the pipeline, and a is the wave speed. The pipeline system in Fig. 2 is divided into 300 elements with a distance interval of 0.5 m, which is determined for the simulation of the water hammer events by the method of characteristics satisfying the Courant number = 1.

The length of surge tank connector, l_c (see Fig. 1), is specified as 0.5 m to match the identical computational grid scale between the pipeline and the surge tank component. Fig. 4 shows the normalized pressure head variations computed by the impulse response method and the method of characteristics at the upstream point 100 m from the control valve. The oscillation impact along two different pipeline segments and harmonic variation can be observed with the water hammer mitigation effect. The simulation results between the impulse response method and the method of characteristics shows good agreements in both phase and amplitude. The impulse response method provides an alternative estimation method to the traditional discretization approach for the transient mitigation impact by the surge tank [16]. However, simulations using the identical simulation condition except different lengths of the surge tank connector, l_c = 0.1 m, indicate that the reliability of the discretization-based method can be substantially degraded if the scale of the supplementary component of the surge tank does not completely satisfy the Courant number condition (see Fig. 5.). Discrepancies between the impulse response method and the method of characteristics are pronounced both in shape and harmonic responses. The modeling behaviors in Fig. 4 and Fig. 5 indicate that the impulse response method is more reliable than the method of characteristics, especially for flexible design for surge tank dimensions in conjunction with transient evaluation.

Fig. 6 compares simulations of the surge tank with the lumped inertia [2] and the precise representation proposed in Eq. (11) in this paper. Almost complete agreement between two different approaches can be found. Due to the higher accuracy of in the representation of hydraulic structure, Eq. (11) will be used for further optimization of the surge tank.

Minor oscillations in Figs. 4, 5, and 6 can be explained as the FFT cannot completely localized the abrupt signal of water hammer. Considering the accuracy of commercial pressure transducer, the scale of oscillation is negligible both for the prediction of transient and the optimization for surge tank design.

5.2 Optimization of surge tank by GA

The proposed algorithm is applied to a pipeline system equipped with a surge tank as shown in Fig. 2. The design parameters are the normalized length of the connector for the surge tank as $l_{cn} = l_c / l$, the normalized connector diameter as $D_{cn} = D_c / D$, and the normalized surge tank diameter as $D_{sn} = D_s / D$, and the normalized surge tank location as $l_{3n} = l_3 / l$, where $l = 150m$, and $D = 0.02m$ for the hypothetical example. The pressure data was computed and used for optimization at 50 m from the upstream reservoir over 10 seconds from the valve operation. This point can be feasibly adjusted depending upon the system condition. The upper searching ranges for the normalized connector length, the normalized surge tank diameter, the normalized connector diameter, and the normalized distance to the surge tank are 0.007, 250, 1 and 0.333, and those for lower limits are 0.002, 25, 0.1, and 0.013, respectively. To secure a global optimum, four different objective functions are employed and 2,500 iterations with identical GA input parameters are used [17].

Fig. 7 shows the best fitness and iterations obtained from the GA optimization of the surge tank parameters using objective functions in Eqs. (21-23), and (24). The global optimum of the best parameter can be obtained in the iteration number 1250, as illustrated in Fig. 7. Further, iteration number 1250 does not improve the fitness for four different objective functions.

The average fitness of the generation (population number = 50) indicates the overall optimization performance. Mutation and crossover activity can be observed in terms of the fluctuation in average fitness in Fig. 8. The abrupt jump in average fitness is the impact of automatic resetting in input parameters, which was introduced to improve the searching capability in a global range. Comparisons between Fig. 7 and Fig. 8 suggest that the solutions may be close to the global optimum. Table 1 presents the optimized surge tank parameters. The normalized location of the surge tank seems to be the most influential governing parameter because it reflects the harmonic and resonance impact along the system. The normalized surge

Table 1. Optimizations of the surge tank parameters .

Parameter / Objective functions & fitness	Normalized distance to surge tank l_{3n}	Normalized connector diameter D_{cn}	Normalized surge tank diameter D_{sn}	Normalized connector length l_{cn}
Eq. (21) 14.62	0.165	0.28	64	0.0021
Eq. (22) 9.8	0.171	0.49	130	0.0028
Eq. (23) 9.8	0.165	0.26	26	0.002
Eq. (24) 7.7	0.177	0.59	27	0.0021

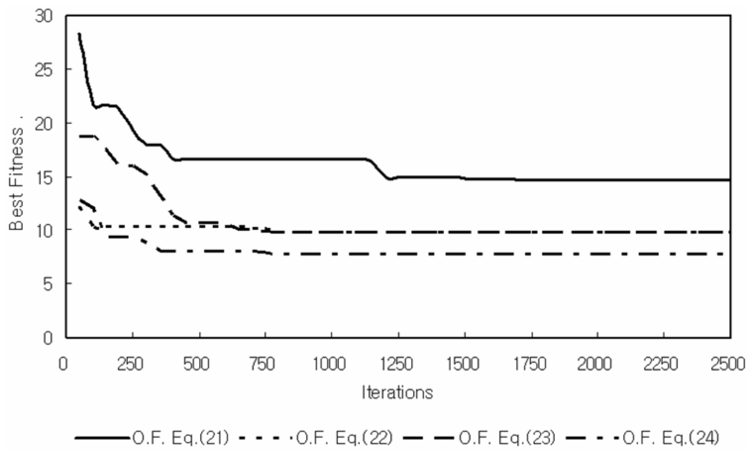

Fig. 7. Best fitness and iterations of best parameters for four objective functions.

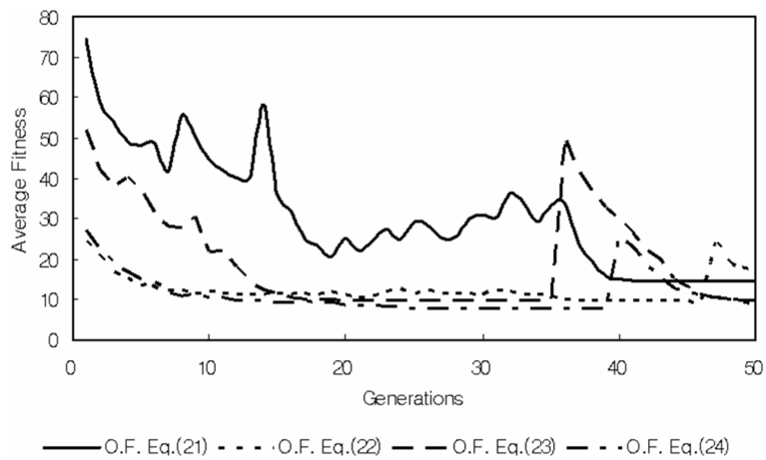

Fig. 8. Average fitness and generations for four objective functions.

tank diameter shows sensitive optimization results considering the difference in counting the cost functions. The normalized connect diameter is somewhat affected by both from the security and cost functions. The normalized connector length was found to be converged into the lowest range of optimization practice. Optimization results using Eqs. (21) and (22) addressed the security of pipeline but those for Eq. (23) and (24) further considered the cost of system. The size of surge tank is greatly reduced for Eqs. (23) and (24).

6. Conclusions

An innovative method for the design of surge tank was developed and applied to the pipeline systems equipped with a surge tank. The pressure head or discharge responses are derived at any point of the pipeline system, including the impact of the surge mitigation. The numerical difficulty of the grid-based approach can be ignored in the impulse response method. The accurate representation of the surge tank provides transient simulation that is identical to the lumped inertia approach. The genetic algorithm was incorporated in the impulse response method to optimize the location and dimensional parameters of the surge tank. The searching potential associated with the optimization of the surge tank location and connector length is apparently more improved compared to the other approaches due to the absence of the Courant number limitation. The experimental verification of the surge tank design through the impulse response method could be a future research objective.

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Sanhyun Kim received his Ph.D. degree in Civil and Environmental Engineering from Purdue University, West Lafayette, IN USA in 1996. He is currently a professor in the Department of Environmental Engineering in Pusan National University, Busan South Korea. Dr. Kim's research interests are theoretical and experimental study of pipeline hydraulics and water quality dynamics, and surface and subsurface hillslope hydrological processes in unsaturated zone.