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ACCURATELY PREDICTING TRANSIENT FLUID FORCES IN PIPING SYSTEMS

Part 2: Applications

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ACCURATELY PREDICTING TRANSIENT FLUID FORCES IN PIPING SYSTEMS PART 2: APPLICATIONS

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ABSTRACT

Part 1 of this series discussed in detail how to accurately calculate the reactions induced by pressure transients that travel at acoustic velocity in either liquid or gas piping systems. Part 2 applies these methods to a variety of realistic examples to further illustrate their use and to demonstrate areas in which traditional or simplified methods may impart significant error.

Keywords: unsteady, forces, piping stress, dynamic load

1. INTRODUCTION

There are many forces that act on a piping system under transient flow, and different forces are of interest to the design engineer for different reasons.

Only some forces cause an unrestrained piping assembly to move. For example, a nozzle system will tend to move backward away from the direction of flow – a forward *reaction* force is required to prevent movement. A sudden surge in flow would increase the reaction required.

It is these reactions that this paper is focused on determining for a few common piping configurations. In some cases, like a piping bridge, there is no steady reaction required, whereas in other cases, like the above nozzle, a reaction is required for any non-zero flow, steady or transient.

The discussion here focuses on calculating and presenting these transient results, particularly the determination of an overall reaction that is required to maintain position of a piping assembly.

2. SUMMARY OF THEORY

This section is only a review of Part 1 [1]. It is not intended to be a complete derivation or explanation of the theory.

2.1 Assumptions

1. Deformation of piping is not considered – all piping is assumed to remain fully rigid under any load.

This paper compares accurate (the Acceleration Reaction Method and Component Reaction Method) and incomplete (the Endpoint Pressure Method and Improved Pressure Method) force calculation methods. Including the incomplete methods is not an indication of their validity. The authors do not recommend their use – even when the results appear to be very close to the true values. The risk of serious inaccuracies is too great to justify use of the incomplete methods.

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2. The reactions, $\vec{R}$, are the overall external forces required to prevent movement of the piping systems. They are not intended to represent reactions at a given support or point of connection.
3. Static loading due to external forces such as weight or wind is not considered. The only non-reaction external force considered on any control volume is caused by fluid pressure acting on the control surface.
4. Flow is assumed to be one-dimensional.
5. Non-piping components such as valves, pumps, screens, etc., are assumed to have negligible fluid volume.
6. Accurate transient flow values (pressure, velocity, etc.) are available

2.2 Acceleration Reaction Method

When discrete fluid transient results from a simulation are available, applying Newton's Second Law such that flow enters and leaves the system normal to the control surface results in the general Equation 1 (Equation 19 from Part 1). This equation may seem somewhat overwhelming, but it is actually a relatively simple algebraic equation. It determines the reaction $\vec{R}$ from acceleration, momentum, and pressure quantities.

$$\vec{R} \approx \sum_{m=1}^{M_{pipes}} \sum_{n=1}^{N_{nodes}} \frac{\Delta \vec{\dot{m}}}{\Delta t} \Delta x + \sum \phi \dot{m} \vec{V} - \sum \vec{F}_{applied} \qquad (1)$$

The first term is by far the most complicated – it is a summation of every M pipe in the assembly, where each pipe has N computational nodes. The nodes are Δx apart from each other, and the simulation proceeds in steps of Δt.

$\Delta\vec{\dot{m}}$ represents the change in flowrate at a calculation node between time steps. The value at a node represents the average for a particular reach of pipe. The mass flow is a vector, but it is colinear with the pipe, so no vector math is required.

The second term is a summation of momentum fluxes into ($\phi = -1$) and out of ($\phi = 1$) the control volume.

The third term is a summation of applied forces, but for the context of this paper, these applied forces are only pressure forces $P \times A$. The negative sign is important to note – the reaction opposes these applied forces.

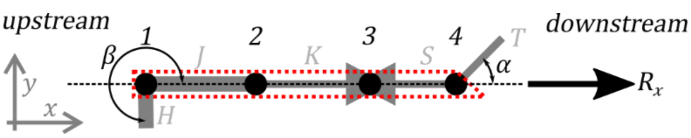

FIGURE 1: GENERAL COMPONENT REACTION

Considering Figure 1, the second and third terms of Equation 1 can be presented in a more tractable way for the reaction R_x as in Equation 2. If α or β are 90° or 270°, their respective terms go to zero. The ambient, and thus gauge, pressures can vary throughout a given system - the notation $P_{g,4}^{dn}$ refers to the static gauge pressure downstream of location 4.

$$R_x \approx + \sum_{m=1}^{M_{pipes}} \sum_{n=1}^{N_{nodes}} \frac{\Delta\vec{\dot{m}}}{\Delta t}\Delta x$$
$$+\dot{m}_4 V_{4,dn}\cos\alpha - \dot{m}_1 V_{1,up}\cos\beta$$
$$+P_{g,4}^{dn} A_{4,dn}\cos\alpha - P_{g,1}^{up} A_{1,up}\cos\beta \quad (2)$$

2.3 Component Reaction Method

This method determines a reaction for each individual component – pipes, valves, bends, etc. – in an assembly and sums them for the overall reaction.

For each non-pipe component, this includes pressure terms acting on the component as well as any terms due to change in momentum through the component.

In fact, these local reactions are determined with Newton's Second Law, just like the Acceleration Reaction Method, effectively applying Equation 2 to each individual component.

For non-pipe elements, fluid mass is assumed to be negligible. Therefore, the component reaction is composed of only the second and third terms of Equation 2.

Handling pipes is more difficult. It would be possible to simply apply Equation 2 again to the pipe, but an alternative method is to recognize that friction is the only fluid force acting on the pipe wall and sum up contributions from friction instead.

The pipe is again split into N computational nodes, each of which has independent values of *resistance* $\mathbb{R}$ and $\dot{m}$. $\mathbb{R}$ is defined as $\mathbb{R} \equiv f\Delta x/2\rho D A^2$. In some systems, $\mathbb{R}$ changes appreciably during the transient and in those cases it must be updated for each node every step. The total reaction on a pipe is then given by the summation in Equation 3.

$$R_{pipe} \approx -\sum_{0}^{N} A\mathbb{R}|\bar{\dot{m}}|\,\bar{\dot{m}} \quad (3)$$

Equation 3 considers only straight piping – it cannot be used to directly analyze elbows or complex arrangements.

The Component Reaction Method captures the transient behavior as a snapshot of total forces applied at any given moment. Unlike the Acceleration Reaction Method, there are no direct temporal terms in this method. The methods disagree when the node count is low, but both methods will converge on the true reaction as the number of computational nodes increases.

2.4 Endpoint Pressure Method

A common, but incomplete, way to calculate transient forces is to multiply transient pressure results from the simulation at the endpoints of the assembly (locations 1 and 4 in Figure 1) by the local flow area and set the overall reaction equal to the difference between those local pressure forces.

$$R_x = P_{up}A_{up} - P_{dn}A_{dn} \quad (4)$$

2.5 Improved Pressure Method

The Endpoint Pressure Method has serious inaccuracies when intermediate features like a closing valve or area change exist within the assembly. Equation 4 may be improved with additional pressure terms for each component in the assembly. This approach is better, but still not fully correct.

For example, Equation 5 represents the Improved Pressure Method for Figure 1.

$$R_x = +\left(P_1 A_J - P_4 A_S\right) + \left(P_{2,dn}A_K - P_{2,up}A_J\right)$$
$$+\left(P_{3,dn}A_S - P_{3,up}A_K\right) \quad (5)$$

The Improved Pressure Method may also consider the effect of ambient pressures. For many systems, the ambient pressure can be ignored. If α and β are not 90° or 270°, or if different parts of the system experience different ambient pressures, it must be considered.

3. EXAMPLES CONSIDERED

The selected examples are intended to represent common configurations found in the field. The lack of a given configuration does not suggest that the method(s) cannot be applied to more complex arrangements.

I. *Liquid Expansion Loop* – Liquid passing through a simple expansion loop consisting of a straight run of piping terminated at both ends by right-angle bends.
II. *Liquid Expansion Loop with High Inline Static Loss* – An expansion loop with a large static loss orifice within the straight run.

III. *Liquid Nozzle* – The fluid exits the system through a reducer at one end of a straight run. The other end is terminated with a right-angle bend.

IV. *Crude Oil Pipe Rack* – Similar to Example II, except the straight run contains both a reduction in flow area and a closing valve. The flow is highly viscous and has high frictional losses.

V. *Steam Elbow Pair* – Similar to Example I, but under gas flow. Along with Example VI, represents realistic piping upstream of a steam turbine.

VI. *Steam Elbow Pair with High Inline Static Loss* – Like Example V, but with inline loss as in Example II.

3.1 Simulation Tools

Numerical results from these examples were determined using AFT Impulse and AFT xStream for liquid and gas flow, respectively. These are commercially available software tools based on the Method of Characteristics for general analysis of fluid transients in systems [2].

For the purposes of force calculation in this paper, the pressure, velocity, etc. results from these tools are considered fully accurate. Some uncertainties exist in results with any numerical simulation, which is outside the scope of this paper.

3.2 Detailed Example Data

Detailed results for all examples, as well as simulation model files, are available from [3]. These files include all flow simulation results necessary to calculate the reactions, as well as calculations of the reactions themselves.

4. EXAMPLE I – LIQUID EXPANSION LOOP

4.1 Problem Statement

The expansion loop represented in Figure 2 is simply a straight run of piping between two right-angle bends. The piping upstream and downstream of the loop (P1 and P6) are pipelines several miles/kilometers long – long enough to prevent any pressure wave reflections from interacting with the loop for a significant duration.

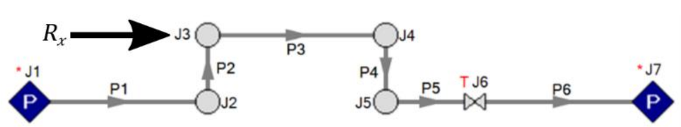

FIGURE 2: SIMPLE EXPANSION LOOP

- Reaction spans from J3 to J4, inclusive of the right-angle bends. A positive reaction is to the right.
- Computation nodes per pipe = 3 in P3 (one node at each end of P3, and one in the middle)
- Friction factors are calculated with Colebrook-White and updated during the transient
- Fluid is Water at 75°F (23.89°C)
    - Density = 62.31 lbm/ft3 (998.1 kg/m3)
    - Dynamic Viscosity = 2.215 lbm/hr-ft (0.9158 cP)
    - Adiabatic Bulk Modulus = 324,200 psi (2.235 GPa)

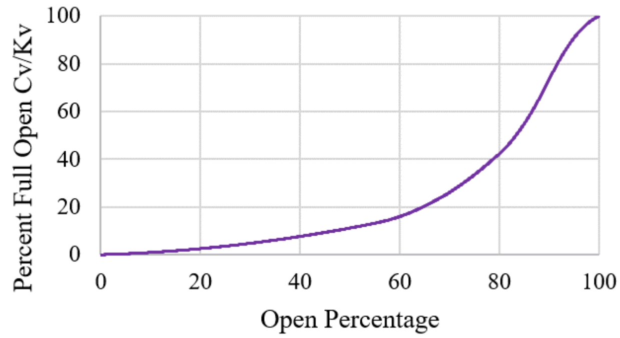

FIGURE 3: BALL VALVE CHARACTERISTICS

- Piping
    - ANSI Steel, 24” STD
    - Inner Diameter = 23.25 in (59.06 cm)
    - P2, P3, P4, P5 Length = 100 ft (30.48 m)
    - P1, P6 Length = 15+ miles (24.14+ km)
    - Absolute Roughness = 0.0018 in (0.04572 mm)
    - Calculated Wavespeed = 3883 ft/s (1184 m/s)
    - Initial Flow Velocity = 6.08 ft/s (1.85 m/s)
- Junctions
    - (all) – Elevation = 0 ft (0 m)
    - J1 – Stagnation pressure = 501 psia (3.454 MPa)
        - Note: Value is pressure 100 feet (30.48 m) upstream of J2
    - J2, J3, J4, J5 – lossless connections
    - J7 – Stagnation pressure = 500 psia (3.447 MPa)
        - Note: Value is pressure 100 feet (30.48 m) downstream of J6
    - J6 – Ball Valve
        - Fully open Cv = 94,000 (Kv = 81,300)
        - Linearly actuated closure over 30 seconds, following characteristics in Figure 3.

4.2 Discussion of General Flow Results

Due to the very long upstream and downstream pipes, no complex wave reflections happen in this case. The flow gradually comes to a halt and remains at zero velocity. Figure 4 shows the pressure delta J3 – J4 over time. There is initially a positive delta due to frictional loss, followed by a negative delta spike due to the upsurge that propagates upstream of the valve.

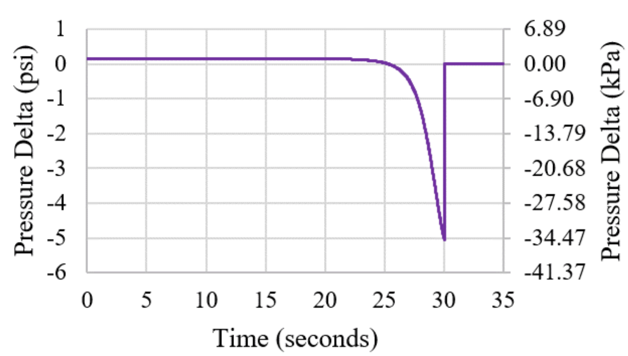

FIGURE 4: PRESSURE DELTA J3 – J4

4.3 Reaction Components

Reaction Contribution from Endpoint Pressures

Equation 4 is used to determine the reaction at any given time from the endpoint pressures alone, which results in Figure 5. This graph is nothing more than Figure 4 multiplied by the flow area.

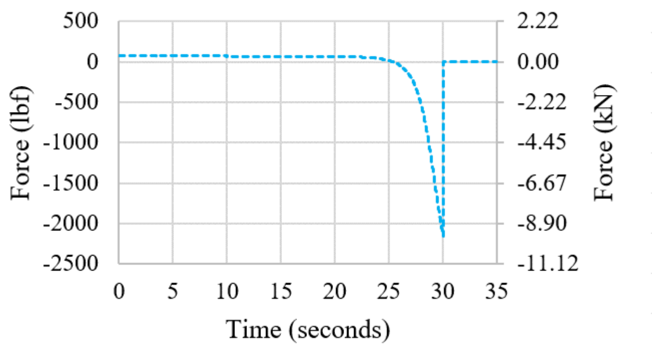

FIGURE 5: ENDPOINT PRESSURE METHOD REACTION

Reaction Contributions from Momentum Term and Pipe Friction

In Example I, this pressure completely dominates the solution. The pipe is short and the fluid of low viscosity, so frictional terms are small. The momentum terms at the inlet and outlet elbows are also small. Extrema for these terms can be found in Table 2.

Acceleration Reaction Method

The simplicity of the results for Example I make it an ideal case for explaining in detail how the Acceleration Reaction Method works. The low node count was selected intentionally to illustrate this process – more nodes are recommended in practice.

The peak force occurs just after 30 seconds. Shown in Table 1 are values for mass flow around this time.

TABLE 1: MASS FLOWS FOR ALL NODES AT TWO STEPS

	Mass Flow – lbm/s (kg/s)		
Time (sec)	***Upstream***	***Midpoint***	***Downstream***
30.005716	50.218899 (22.778909)	41.254452 (18.712705)	32.296394 (14.649398)
30.018593	41.398346 (18.777974)	32.440464 (14.714747)	23.411207 (10.619145)

To determine the reaction, Equation 2 needs to be applied to these results. The pressure and momentum terms in Equation 2 are not relevant for the reaction of interest, because the flow into and out of the reaction assembly is perpendicular to the direction of the reaction. In other words, the angles α and β in Equation 2 are both 90°, so every cosine term becomes zero. The only term left is the summation of changing mass flows, or acceleration term.

There is also only one pipe, which leaves the relatively simple Equation 6.

$$R_x \approx \sum_{n=1}^{N_{nodes}} \frac{\Delta \vec{\dot{m}}}{\Delta t} \Delta x \tag{6}$$

Because there are only 3 nodes in the system, the summation can be expanded in Equation 7.

$$R_x \approx \left(\frac{\Delta \vec{\dot{m}}}{\Delta t} \Delta x\right)_{n=1} + \left(\frac{\Delta \vec{\dot{m}}}{\Delta t} \Delta x\right)_{n=2} + \left(\frac{\Delta \vec{\dot{m}}}{\Delta t} \Delta x\right)_{n=3} \tag{7}$$

For every term, Δt is the same value, 0.01287799 seconds. Every Δx is, however, not the same – the nodal points at the upstream and downstream side only represent one half of a "reach", whereas the midpoint represents a whole reach. These values are 25 feet (7.62 m) and 50 feet (15.24 m), respectively.

The mass flow change depends on the simulation results at the particular node. Taking the upstream node as an example, the first change in mass flow shown in Table 1 is -8.820553 lbm/s (-4.000935 kg/s). Calculating the first term in Equation 7 is shown by Equation 8.

$$\left(\frac{\Delta \vec{\dot{m}}}{\Delta t} \Delta x\right)_{n=1} = \left(\frac{-8.8206 \frac{\text{lbm}}{\text{s}}}{0.01288 \text{ s}}\right) \frac{25\ ft}{32.174 \frac{lbm\ ft}{lbf\ s^2}}$$
$$= -532.21\ lbf\ (-2.3674\ kN) \tag{8}$$

Repeating this process for all three terms returns a total force value of -2132 lbf (-9.483 kN). Doing so for every time step of the simulation gives the results seen in Figure 6.

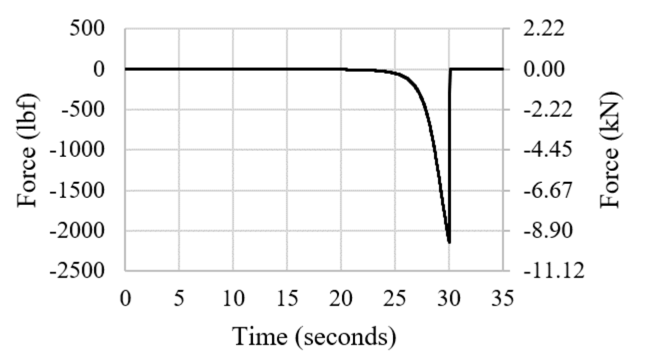

FIGURE 6: ACCELERATION REACTION METHOD

Component Reaction Method

Taking the approach of summing individual component reactions requires the relatively complicated Equation 9, even though the system is very simple.

$$\begin{aligned} R_x = &+\dot{m}_3 V_3 + P_3 A_{Pipe3} \\ &-(A\mathbb{R}|\dot{m}|\dot{m})_{up} \\ &-(A\mathbb{R}|\dot{m}|\dot{m})_{mid} \\ &-(A\mathbb{R}|\dot{m}|\dot{m})_{dn} \\ &-\dot{m}_4 V_4 - P_4 A_{Pipe3} \end{aligned} \tag{9}$$

4.4 Summary of Results

For Example I, the endpoint pressure forces dominate the solution, meaning that the simplified Endpoint Pressure Method captures the maximum and minimum forces quite well. A summary of maximum and minimum contributions and totals for each case is seen in Table 2.

Further note that the maximum/minimums of each row in Table 2 do not simply add together because peaks and valleys for each particular component reaction do not coincide in time. This is true for all Examples discussed.

TABLE 2: SUMMARY OF REACTIONS (TO NEAREST LBF/N)

Method	Maximum	Minimum
Momentum Only	2 lbf 10 N	0 lbf 0 N
Pipe Friction Only	0 lbf 0 N	-70 lbf -312 N
Endpoint Pressure	72 lbf 319 N	-2152 lbf -9.571 kN
Component Reaction	2 lbf 7 N	-2152 lbf -9.571 kN
Acceleration Reaction	2 lbf 7 N	-2148 lbf -9.556 kN

5. EXAMPLE II – LIQUID EXPANSION LOOP WITH HIGH INLINE STATIC LOSS

5.1 Problem Statement

Example II considers an expansion loop with a high loss orifice within the straight run. Unlike Example I, the system is compact and wave reflections will influence the results heavily.

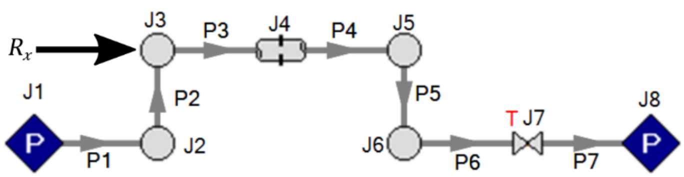

FIGURE 7: EXPANSION LOOP WITH HIGH STATIC LOSS

- Reaction spans from J3 to J5, inclusive of the right-angle bends. A positive reaction is to the right.
- Computation nodes per pipe = 50
- Friction factors are calculated with Colebrook-White and updated during the transient
- Fluid is Water with properties from Example I
- ANSI Steel, 8" STD Pipes (all)
  - Inner Diameter = 7.981 in (20.27 cm)
  - Length = 75 ft (22.86 m)
  - Absolute Roughness = 0.0018 in (0.04572 mm)
  - Calculated Wavespeed = 4389 ft/s (1338 m/s)
  - Initial Flow Velocity = 5 ft/s (1.524 m/s)
- Junctions
  - (all) – Elevation = 0 ft (0 m)
  - J1 – Stagnation pressure = 435.782 psia (3.0046 MPa)
  - J2, J3, J5, J6 – lossless connections
  - J4 – K Factor = 200
  - J8 – Stagnation pressure = 400 psia (2.7579 MPa)
  - J7 – Ball Valve
    - Fully open Cv = 10,000 (Kv = 8,640)
    - Linearly actuated closure over 1 second, starting at 0.1 seconds, following characteristics in Figure 3.

5.2 Discussion of General Flow Results

After valve closure, the flow velocity within the expansion loop will drop to zero, but it will continue falling to a negative value, nearly the same magnitude as the original positive value. This oscillation will continue until dissipated by friction.

5.3 Reaction Components

Reaction Contribution from Endpoint Pressures

Equation 4 is used to determine the reaction at any given time from the endpoint pressures alone, which results in Figure 8.

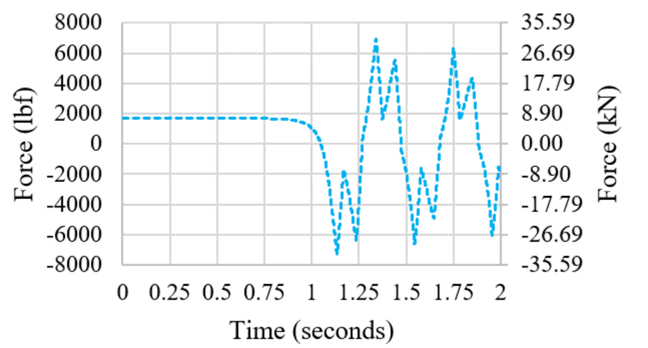

FIGURE 8: ENDPOINT PRESSURE METHOD RESULTS

Reaction Contribution from Internal Pressures

The results in Figure 8 have significant steady-state error, which can be improved by accounting for the reaction induced from pressures acting on inline components. This inline pressure reaction is calculated with a reapplication of Equation 4 on the inline orifice J4 and is charted in Figure 9. Adding the two results together generates the Improved Pressure Method results in Figure 10.

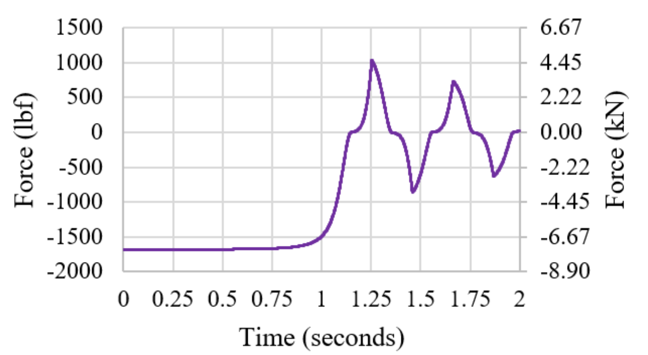

FIGURE 9: PRESSURE REACTION ON INLINE ORIFICE

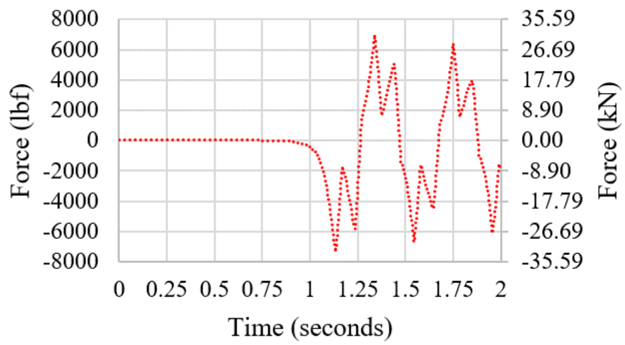

FIGURE 10: IMPROVED PRESSURE METHOD REACTION

Reaction Contributions from Momentum Term and Pipe Friction

As in Example I, there are no substantial velocity changes so these values are small as seen in Table 3.

Acceleration Reaction Method

Applying Equation 2 to this system follows the exact same process as laid out for Example I. If the results were placed on a graph such as Figure 10, the trace would be indistinguishable from the Improved Pressure Method.

5.4 Summary of Results

For Example II, the endpoint pressure forces mostly dominate the solution, meaning that the simplified Endpoint Pressure Method captures the maximum and minimum forces reasonably well.

However, the Endpoint Method has a major error for the steady-state force, which is clearly evident in Figure 9. This is mostly corrected for by including the orifice pressure reaction from Figure 10.

TABLE 3: SUMMARY OF REACTIONS (TO NEAREST LBF/N)

Method	Maximum	Minimum
Momentum Only	9 lbf 39 N	-10 lbf -45 N
Pipe Friction Only	18 lbf 80 N	-31 lbf -137 N
Orifice Pressure Only	1040 lbf 4.627 kN	-1682 lbf -7.482 kN
Endpoint Pressure	6927 lbf 30.811 kN	-7286 lbf -32.409 kN
Improved Pressure	7014 lbf 31.201 kN	-7379 lbf -32.823 kN
Component Reaction	7014 lbf 31.200 kN	-7378 lbf -32.821 kN
Acceleration Reaction	7010 lbf 31.184 kN	-7375 lbf -32.806 kN

6. EXAMPLE III – LIQUID NOZZLE

6.1 Problem Statement

This case is a high-velocity liquid jet which discharges into a pressurized container as shown in Figure 11.

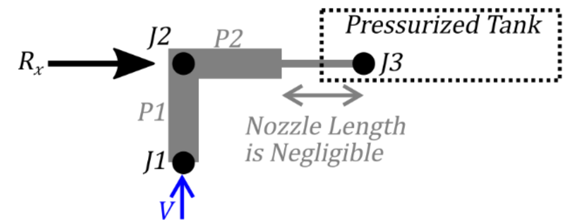

FIGURE 11: NOZZLE BACKED BY ELBOW

- Reaction spans from J2 to J3, inclusive of the nozzle and elbow
- Computation nodes per pipe = 50
- Friction factors are calculated with Colebrook-White and updated during the transient
- Fluid is Water with the same properties as Example I
- Ambient Pressure = 14.696 psi (101.325 kPa)
- ANSI Steel, 2” STD Pipes (all)
  - Inner Diameter = 2.067 in (5.250 cm)
  - Length = 50 ft (15.24 m)
  - Absolute Roughness = 0.0018 in (0.04572 mm)
  - Calculated Wavespeed = 4588 ft/s (1398 m/s)
- Junctions
  - (all) – Elevation = 0 ft (0 m)
  - J1 – Flow starts at 1 ft/s (0.3048 m/s) and ramps up linearly to 10 ft/s (3.048 m) in 0.1 seconds
  - J2 – lossless connection
  - J3 – Pressurized Tank
    - Stagnation pressure = 100 psig (689.5 kPa(g))
- Nozzle
  - Inner diameter is 0.25 in (0.635 cm)
  - Length of reduced diameter is negligible
  - Reduction in area considered lossless
  - Only the smaller diameter portion of the nozzle enters the pressurized tank (the pressure in the tank will only act on the reduced area of the nozzle exit).

6.2 Discussion of General Flow Results

The flow velocities in this case do not drop below zero but are impacted by acoustic reflections within the piping. The range of the oscillation is slightly wider than 9 to 11 ft/s (2.7 to 3.3 m/s).

6.3 Reaction Components

Reaction Contribution from Endpoint Pressures

The contribution of pressure may appear to always be the easy step in determining the reaction. However, it can quickly become complicated in situations like this one.

A simple, but incorrect, approach is to use the static pressure difference between both ends of P2 multiplied by the flow area to calculate the force with Equation 4 ($R_x = (P_{2,up} - P_{2,dn})A_2$).

Reaction Contribution from Improved Pressure Method

One problem with the Endpoint approach is that the downstream pressure does not act on the entire flow area – it acts only on the annular area ($R_x = P_{2,up}A_2 - P_{2,dn}(A_2 - A_{nozzle})$).

This is still incorrect because ambient pressure has not been considered. Unlike many systems, the ambient pressure is not balanced on all sides – it acts to the right on the full area of the elbow, but to the left only the annular area of the nozzle. A correct calculation requires the use of gauge pressures ($R_x = P_{g,2}^{up}A_2 - P_{g,2}^{dn}(A_2 - A_{nozzle})$).

The effect on the reactions is small in this case but it is important to note for completeness. The reaction calculated by the Improved Pressure Method is shown in Figure 13.

Reaction Contribution from Momentum Term

Unlike the previous examples, there are now momentum terms from both change in direction at J2 and change in velocity at J3. These are easy to calculate with the second term of Equation 2.

Calculation of these terms can be particularly confusing due to the signs involved. There is a *positive* reaction on J2 under forward flow because flow is *exiting* this particular component. This may seem to disagree with the second term of Equation 2, but that Equation is applied to the *system* and not individual components.

Contrasting the previous examples, the contribution to force from this term is substantial at high flows, as seen in Figure 12.

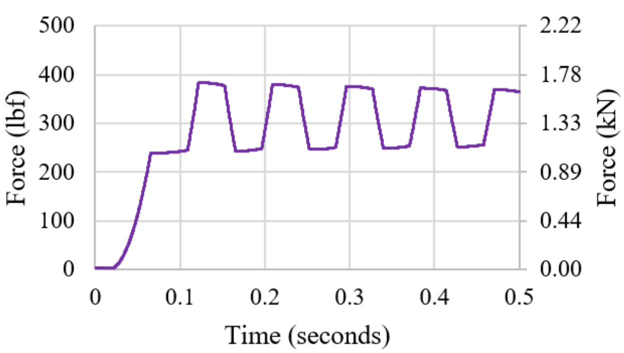

FIGURE 12: CONTRIBUTION FROM MOMENTUM

Acceleration Reaction Method

Because the outlet to the system is not perpendicular to the reaction direction, Equation 2 does not simplify to only the first term. The inlet terms still cancel, but the full contribution from pressure and momentum are felt at the outlet, as shown in Equation 10.

$$R_x \approx + \sum_{m=1}^{M_{pipes}} \sum_{n=1}^{N_{nodes}} \frac{\Delta \vec{\dot{m}}}{\Delta t}\Delta x + \left[\dot{m}V + P_{gauge}A\right]_{Nozzle} \quad (10)$$

The transient results of the method are shown in Figure 13 in comparison with the Improved Pressure Method.

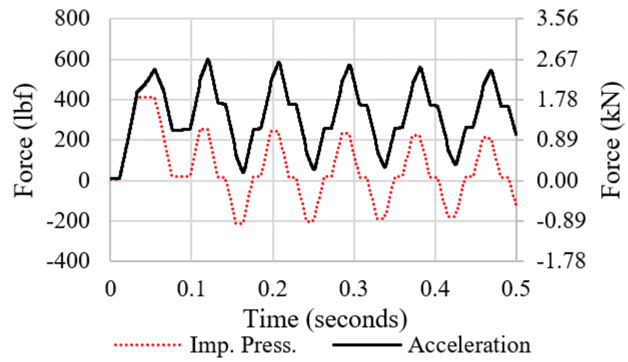

FIGURE 13: ACCELERATION REACTION AND IMPROVED PRESSURE METHODS

6.4 Summary of Results

This example is not dominated by one component force – both pressure and momentum contribute large portions of the overall reaction.

Neglecting the momentum term here would both significantly underestimate the maximum force and appear to show an average loading near zero, where the true reaction is a positive value for the entire transient.

TABLE 4: SUMMARY OF REACTIONS (TO NEAREST LBF/N)

Method	Maximum	Minimum
Momentum Only	384 lbf 1.706 kN	3 lbf 14 N
Pipe Friction Only	0 lbf -1 N	-17 lbf -74 N
Endpoint Pressure	409 lbf 1.820 kN	-218 lbf -969 N
Improved Pressure	414 lbf 1.841 kN	-213 lbf -947 N
Component Reaction	599 lbf 2.662 kN	8 lbf 36 N
Acceleration Reaction	599 lbf 2.666 kN	8 lbf 36 N

7. EXAMPLE IV – CRUDE OIL PIPE RACK

7.1 Problem Statement

Crude oil is transferred within a tank farm. A relatively long straight length of piping bounded by right-angle bends in a pipe rack contains a valve that beings closing but is halted before complete closure. A reduction in flow area also exists within the straight run.

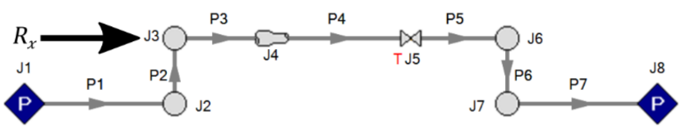

FIGURE 14: CRUDE OIL PIPING ASSEMBLY

- Reaction spans from J3 to J6, inclusive of the right-angle bends. A positive reaction is to the right.
- Computation nodes per pipe = 51 in shortest pipe
- Friction factors are calculated with Colebrook-White and updated during the transient
- Fluid is Crude Oil
  - Density = 53.56 lbm/ft3 (857.9 kg/m3)
  - Dynamic Viscosity = 18.41 lbm/hr-ft (7.610 cP)
  - Adiabatic Bulk Modulus = 205,200 psi (1.415 GPa)
- Piping
  - P1 – P3; ANSI Steel, 8” STD
  - P1 – P3; Inner Diameter = 7.981 in (20.27 cm)
  - P1 – P3; Wavespeed = 3914 ft/s (1193 m/s)
  - P4 – P7; ANSI Steel, 6” STD
  - P4 – P7; Inner Diameter = 6.065 in (15.41 cm)
  - P4 – P7; Wavespeed = 3945 ft/s (1202 m/s)
  - P1, P7 Length = 2000 ft (609.6 m)
  - P2, P6 Length = 100 ft (30.48 m)
  - P3, P5 Length = 200 ft (60.96 m)
  - P4 Length = 300 ft (91.44 m)
  - Absolute Roughness = 0.0018 in (0.04572 mm)
  - Initial Flow Velocity P1-3 = 11.5 ft/s (3.51 m/s); P4-7 = 19.9 ft/s (6.07 m/s)
- Junctions
  - (all) – Elevation = 0 ft (0 m)
  - J1 – Stagnation pressure = 380 psig (2.620 MPa(g))
  - J4 – Lossless area reduction
  - J2, J3, J6, J7 – lossless connections
  - J8 – Stagnation pressure = 100 psig (689.5 kPa(g))
  - J5 – Ball Valve
    - Fully open Cv = 10,000 (Kv = 8640)
    - Linearly actuated from 100% to 10% open over 3 seconds, following characteristics in Figure 3

7.2 Discussion of General Flow Results

The valve J5 does not close completely, which means that the flow does not come to a complete halt. The velocity at the valve begins at approximately 20 ft/s (6.1 m/s) and is reduced to approximately 13.5 ft/s (4.1 m/s) by the partial closure.

7.3 Reaction Components

Reaction Contribution from Endpoint Pressure and Improved Pressure Methods

Like Example II, applying the Endpoint Pressure Method and Improved Pressure Method show dramatically different results, as shown by Figure 15. Unlike Example II, both methods are far from correct.

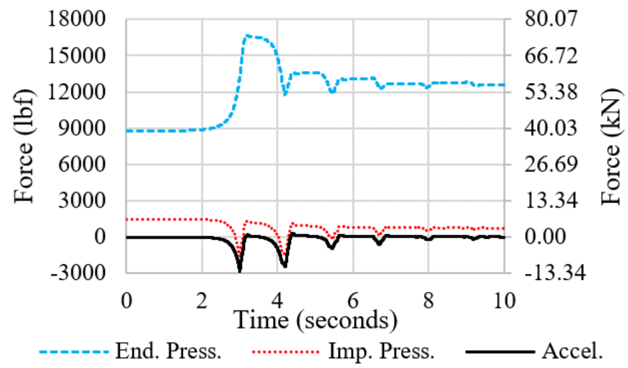

FIGURE 15: ENDPOINT PRESSURE, IMPROVED PRESSURE, AND ACCELERATION REACTION METHODS

Reaction Contribution from Momentum Term

While a change in area does exist at J4, making the momentum larger than Examples I or II, the magnitude of the momentum term for Example IV is still small (see Table 5).

Reaction Contribution from Pipe Friction

Unlike all previous examples, the high viscosity and long piping length result in much higher forces due to friction in pipes. Figure 16 shows the frictional contribution, and Table 5 shows that the maximum friction magnitude is about half of the maximum reaction magnitude.

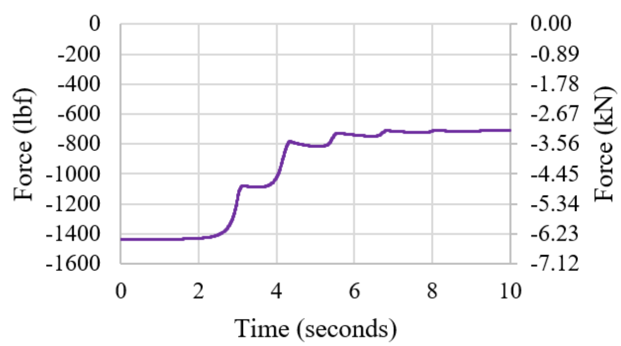

FIGURE 16: REACTION DUE TO PIPE FRICTION

Acceleration Reaction Method

As in all previous examples, the Acceleration Reaction Method and Component Reaction Method agree strongly with one another. Magnitudes from these methods are seen in Table 5 along with other component magnitudes.

7.4 Summary of Results

TABLE 5: SUMMARY OF REACTIONS (TO NEAREST LBF/N)

Method	Maximum	Minimum
Momentum Only	5 lbf 23 N	-9 lbf 39 N
Pipe Friction Only	-709 lbf -3.152 kN	-1436 lbf -6.389 kN
Endpoint Pressure	16649 lbf 74.059 kN	8753 lbf 38.936 kN
Improved Pressure	1493 lbf 6.641 kN	-1648 lbf -7.331 kN
Component Reaction	328 lbf 1.460 kN	-2851 lbf -12.681 kN
Acceleration Reaction	327 lbf 1.456 kN	-2851 lbf -12.671 kN

8. EXAMPLE V – STEAM ELBOW PAIR

8.1 Problem Statement

The example shown in Figure 17 represents a large diameter steam piping system supplying a steam turbine. All data, including discussion of the flow behavior, is available in [4].

The Turbine Stop Valve (TSV) closes in 100 ms and sends a *pressure wave family* – a collection of related pressure waves generated over time – towards the steam source.

The inner pipe diameter is 29.25 in. (74.295 cm), and the total length is 1,980 ft (603.5 m). The horizontal pipes in Figure 17, including pipe 13, are 40 ft (12.19 m) long, and the vertical pipes are 125 ft (38.1 m) long, except for the pipe at the steam source which is 200 ft (60.96 m) long.

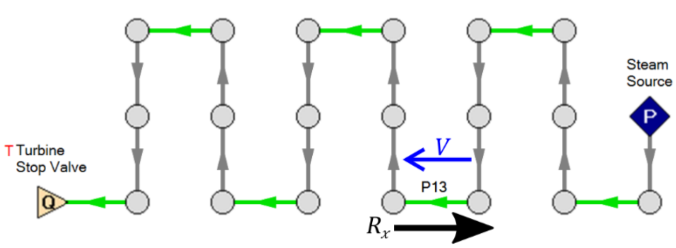

FIGURE 17: SCHEMATIC FROM REFERENCE [4]

8.2 Discussion of General Flow Results

The mass flow for all nodes in pipe 13 is seen in Figure 18. Note the comparatively smooth behavior from the compressible dynamics – an effect that can potentially mislead an analyst into assuming the forces are not significant.

The flow does not fall to zero because there is a large zone of gas in the piping downstream of pipe 13 that continues to be compressed after the wave passes. The wave will eventually reflect off of the steam source and the flow direction will reverse, and the flow will oscillate in direction until dissipated by friction.

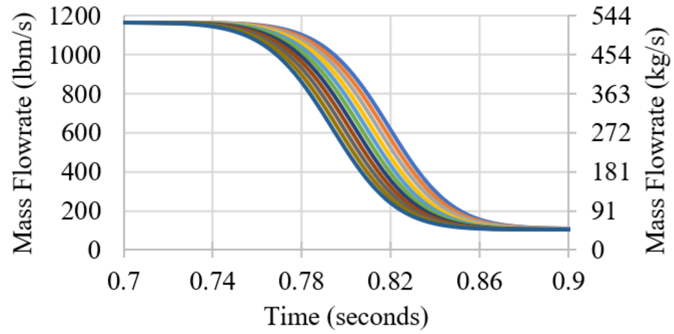

FIGURE 18: MASS FLOWS AT ALL NODES IN PIPE 13 – NODES CLOSEST TO TURBINE STOP VALVE DECREASE FIRST

8.3 Example Calculation

To show a simple calculation of the peak force, this system was analyzed with 10 computing sections (11 nodes) rather than the 200 in [4].

Table 6 shows how to use the Acceleration Reaction Method (Equation 2) for a particular time step near the maximum reaction. The calculation is for pipe 13 in Figure 17.

Dividing pipe 13 into 10 sections results in a Δx equal to 4 ft (1.219 m). End computing stations, denoted with *, contain only half of this distance. The simulation time step was 1.659 ms.

TABLE 6: DEMONSTRATION OF ACCELERATION REACTION METHOD CALCULATION FOR COMPRESSIBLE FLOW

Comp. Station	Mass Flowrate at Computing Times (sec)		Eq. 2	Eq. 4
	$\dot{m}$ at t = 0.806261 (lb_m/s)/(kg/s)	$\dot{m}$ at t = 0.807920 (lb_m/s)/(kg/s)	$\Delta\dot{m}\frac{\Delta x}{\Delta t}$ (lb_f)/(kN)	Endpoint pressures at t = 0.807920 seconds (psia)/(kPa)
0*	851.2 / 386.1	825.4 / 374.4	968 / 4.3	1013.2 / 6985.7
1	810.6 / 367.7	783.2 / 355.2	2055 / 9.1	
2	767.6 / 348.2	738.9 / 335.1	2152 / 9.6	
3	722.7 / 327.8	693. / 314.4	2222 / 9.9	
4	676.5 / 306.8	646.3 / 293.2	2262 / 10.1	
5	629.6 / 285.6	599.3 / 271.8	2270 / 10.1	
6	582.6 / 264.3	552.7 / 250.7	2246 / 10.0	
7	536.4 / 243.3	507.2 / 230.	2189 / 9.7	
8	491.4 / 222.9	463.3 / 210.2	2104 / 9.4	
9	448.3 / 203.3	421.7 / 191.3	1995 / 8.9	
10*	407.5 / 184.8	382.6 / 173.5	933 / 4.2	1047.2 / 7220.4
TOTAL Acceleration Reaction Method			**21396 / 95.2**	
Endpoint Pressure Method (ΔPA)				**22877 lbf 101.76 kN**

8.4 Reaction

The reaction methodology is identical for gas and liquid flows – several approaches are available. Figure 19 shows the force vs. time profile for two methods.

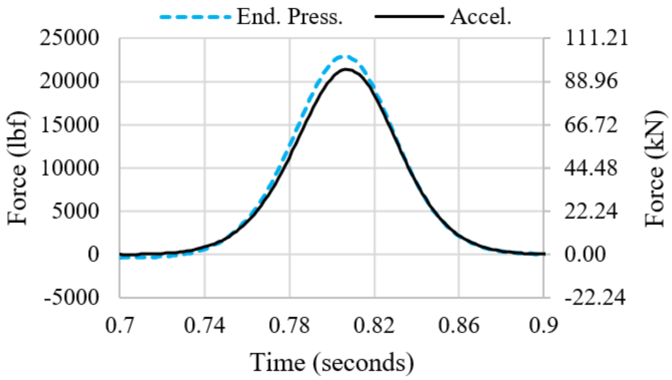

FIGURE 19: ACCELERATION REACTION AND ENDPOINT PRESSURE METHODS

9. EXAMPLE VI – STEAM ELBOW PAIR WITH HIGH INLINE STATIC LOSS

9.1 Problem Statement

This case is nearly identical to Example V, with only one difference – an orifice with a K factor of 12 is located at the midpoint of pipe 13, as shown in Figure 20.

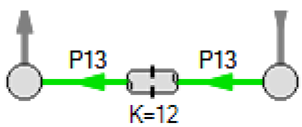

FIGURE 20: PIPE 13 MODIFICATION FROM FIGURE 17

9.2 Reaction

Figure 21 shows the reaction vs. time profile for three methods. Here it is clear that the Endpoint Pressure Method Equation 4 gives wildly incorrect maximum forces and general force vs. time profile.

The Improved Pressure Method (Equation 5) gives results not much different than the Acceleration Reaction Method. While this may suggest that the Improved Pressure Method is a good substitute for the Acceleration Reaction Method, some models are not configured like Figure 20 which has a point loss, and thus pressure reaction, at the orifice. Rather, loss factors are sometimes distributed within the pipe as an effective increase in friction. This approach would yield results similar to the Endpoint Pressure Method.

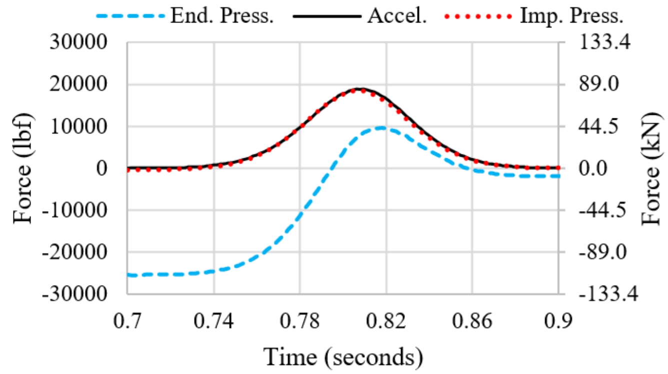

FIGURE 21: ACCELERATION REACTION, ENDPOINT PRESSURE, AND IMPROVED PRESSURE METHODS

10. CONCLUSION

Calculating transient forces on a piping assembly may at first glance appear to be a straightforward task. However, the complexities of control volume definition, accurate bookkeeping of signs, and challenging determination of some transient terms creates complication.

This complication leads some engineers to use methods such as the Endpoint Pressure Method as an attempt to streamline the problem. Unfortunately, this method is incomplete, and in some cases dramatically misestimates the force values.

Determining the true forces may be accomplished by careful application of Newton's Second Law. The authors strongly recommend the use of the Acceleration Reaction Method described herein, even for simple systems. Without taking the time to make this calculation, the engineer can never be sure if the force values from an incomplete method are valid.

ACKNOWLEDGEMENTS

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