IMPROVED METHOD OF ESTIMATING STEAM HAMMER LOADS

Proceedings of the ASME 2022
Pressure Vessels and Piping Conference
PVP2022
July 17-22, 2022, Las Vegas, Nevada, USA
PVP2022-83717

Trey W. Walters P.E.
Applied Flow Technology
Colorado Springs, Colorado, USA

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ABSTRACT

Recent research has shown that a commonly used method to estimate transient pipe forces does not reliably yield conservative predictions. As the topic of transient compressible flow is quite complex, engineers should be very cautious in applying simple algebraic formulas to estimate loads for design use. With that caution in mind, some engineers would still like to have a simple method available. This paper develops a new method that offers an improved way of estimating transient pipe loads. Comparisons are made against numerical simulations for a realistic power station piping example using real gas models for the steam properties and pipe friction. The comparisons are surprisingly good for this example. The improved method provides better estimates than methods commonly used today and is recommended as a replacement for such methods. Engineers should consider using the new, improved method as a preliminary design tool and for screening purposes. Engineers should take extra care in using the new method for detailed design purposes.

KEYWORDS

Steam hammer, piping loads, transient simulation, transient compressible flow

NOMENCLATURE

Variables and symbols

a	wave speed (ft/s / m/s)
A	cross-sectional area (ft^2 / m^2)
c	acoustic (sonic) velocity (ft/s / m/s)
D	diameter (ft / m)
F	force (lbf / kN)
L	length (ft / m)
L_{wf}	length of wave family (ft / m)
L_{shock}	length where back of wave family catches the front and forms a shock wave (ft / m) (Eq. 5)
P	pressure static (psi / kPa)
t	time (sec)
t_c	closing time of a valve (sec)
t_{shock}	time when back of wave family catches the front and forms a shock wave (sec) (Eq. 4)
V	fluid velocity (ft/s / m/s)
x	axial distance (ft / m)
γ	isentropic expansion coefficient

Subscripts

b	back (of wave)
f	front (of wave)
J	Joukowsky Equation
M	minus (direction in pipe)
source	source of transient
SS	steady-state
wf	wave family

INTRODUCTION

Walters [1] and Walters and Lang [2] showed that the Goodling Method [3-4] for estimating steam hammer loads is not reliably conservative. Walters [1] recommended that the Goodling Method should not be trusted by engineers. What then should engineers do?

A Recommendation in [1] was that "engineers should consider using a capable simulation tool to determine peak loads and load profiles." The simulation tool used in [1-2] to elucidate the Goodling Method shortcomings is a commercially available tool [5]. The advantage of such a tool is that it properly handles all important aspect of steam hammer simulation using accurate ASME Steam Tables. Further, it includes a complete force balance on the piping [6] and can therefore generate more accurate peak forces and force-time profiles. As a result, engineers will get the best answer possible while reducing uncertainty and the resulting need to overdesign.

A question arises from this line of thought. If one should not rely on the Goodling Method, are there any quick analytical short cuts that can be used to estimate steam hammer loads that provide more trustworthy predictions? This paper attempts to provide such a short cut method based on the findings in [1-2].

By necessity, engineers are pragmatic. In the Recommendations section of this paper some pragmatic advice will be given on when and when not to use the short cut method in this paper. It will be recommended to use the short cut method in this paper as a preliminary design tool and for screening purposes. Use of a "capable simulation tool" [1] is recommended to finalize design loads.

This paper relies heavily on the findings in [1-2]. One who wishes to understand the details behind this paper should consult those references. Here the relevant findings from [1-2] that explain this new method will be collected, reiterated and applied.

SUMMARY OF STEAM FLOW WAVE BEHAVIOR

Here a brief summary is given of some of the main points detailed in [1-2].

When a valve closes in a steam line (or any gas line) where there is positive forward flow, a compression wave is generated upstream of the valve. The wave travels in the opposite direction of the bulk fluid flow. When the valve closes over some finite time (as all real valves do), a *family* of compression waves is generated. For a perfect gas in frictionless, adiabatic flow, closed-form analytical relationships can be developed to predict movement and behavior of this family of waves over time and space [2]. For real systems which include real gas behavior and friction, a capable simulation tool is needed to accurately predict this [1].

Fig. 1 shows an example system from [1]. Here the steam flow is from left to right. The TSV (Turbine Stop Valve) at the right closes over some time, t_c. This generates a family of waves which moves to the left, backward into the oncoming flow of steam.

Fig. 1 is a single horizontal pipe run with the following dimensions:

- Length = 1,980 ft (604 m)
- Inner diameter = 29.25 inches (0.743 m)
- Adiabatic wall
- Seven pipe legs of 40 ft. (12.2 m) length which are bounded by elbows pairs (Fig. 1)
    - Legs 1, 4, 7, 10, 13, 16, and 19
- All other legs are 125 ft (38.1 m) except for Leg 20 which is 200 ft (61 m)

The speed of a compression wave, a, is given by the difference in the steam fluid velocity, V, and acoustic velocity, c.

$$a = V - c \tag{1}$$

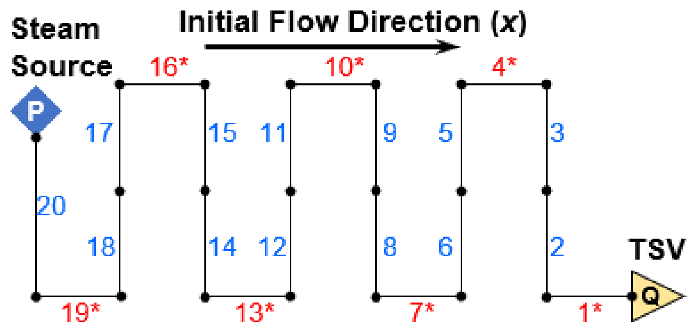

Figure 1. Schematic of example system with actual dimensions shown in the preceding bullet list for each pipe leg. Pipe legs with * symbol are those seven for which forces are calculated. Not to scale. From [1].

When there is a family of waves, there is a different wave speed at the front of the wave family than at the back. Further, the back of the wave family travels faster than the front. This is what causes the wave family to steepen as discussed in detail in [1-2].

For a perfect gas in adiabatic, frictionless flow the speed at which the back catches the front is given by (Eq. 2 in [1]):

$$\Delta a_{fb} = \left| V_{SS}\left(\frac{\gamma+1}{2}\right) \right| \tag{2}$$

Eq. 2 can also rendered in the form of Eq. 3 (Eq. 3 in [1]), which also applies to adiabatic flow of real gases with friction. Eq. 3 represents the *initial* speed of wave steepening.

$$\Delta a_{fb} = |c_b - c_{SS} + V_{SS}| \tag{3}$$

For a perfect gas in adiabatic, frictionless flow Fig. 2 can be constructed based on analytical relationships (see Fig. 6 in [2], which also has a numerical example). Some key observations can be made from Fig. 2. One can see the back of the wave family catching up with the front. Eventually it does catch the front. This will result in the wave family coalescing into a single wave (a discontinuity or shock wave). The time, t, and location, x, where this first happens is noted on Fig. 2 as t_{shock} and x_{shock}.

Walters and Lang [2] derived analytical relationships for these two parameters (Eqs. 16-17 in [2]):

$$t_{shock} = \left(1 + \left(\frac{2}{\gamma+1}\right)\left(\frac{c_{SS}}{V_{SS}} - 1\right)\right) t_c \tag{4}$$

$$L_{shock} = (c_{SS} - V_{SS})\left(1 + \left(\frac{2}{\gamma+1}\right)\left(\frac{c_{SS}}{V_{SS}} - 1\right)\right) t_c \tag{5}$$

where, in Fig. 2, $x_{shock} = L - L_{shock}$.

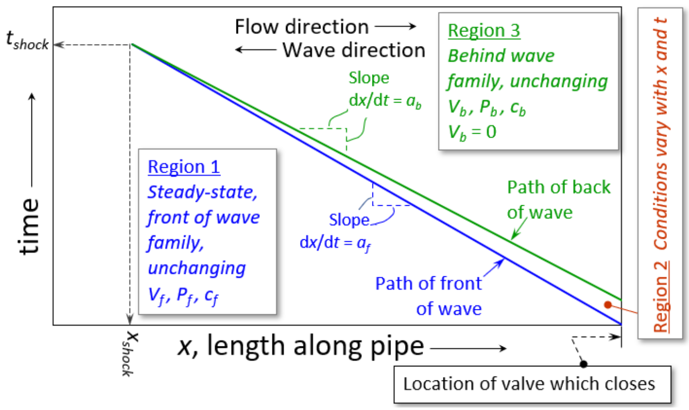

Figure 2. Paths of front and back of wave family (from right to left) in a compression wave family for perfect gas, adiabatic, frictionless flow [2].

PREDICTING TRANSIENT FORCES

The traditional method of calculating transient pipe forces is based on using only pressure forces and neglecting other terms in Newton's Second Law. Walters [1] discusses this and makes reference to the detailed discussion of a complete force balance detailed in Lang and Walters [6].

Hence, any transient force balance that only uses pressure forces is approximate. Lang and Walters [6] discuss the potential pitfalls of only using pressure forces.

With that preamble, the short cut method offered in this paper uses only pressure forces. The pressure forces themselves are approximate as the method does not account for all forces in the force balance. This is yet another reason to give strong consideration to using a capable simulation tool that accounts for a complete force balance [6].

WHAT IS RETAINED FROM THE GOODLING METHOD

Problems inherent in the Goodling Method

The Goodling Method is reviewed in [1]. There are three main problems with the Goodling Method:

1. It neglects wave steepening. In practical terms, it assumes that there is a constant "characteristic length" when in fact there isn't. See Fig. 3 (taken from Fig. 8 in [1]).
2. The characteristic length is itself miscalculated. It should be based on wave speed of the steam and not acoustic speed – see [1]. And since it changes, it is only valid at the initial stage of the transient.
3. It assumes that pressure forces are the only important forces when calculating transient pipe forces.

The calculation in [1] comparing pressure forces to a complete force balance showed that it was conservative to only use pressure forces – at least for the Example 1 in [1]. As long as engineers are looking at only straight runs of pipe with relatively small pressure drops, and <u>no static pipe fittings or valves</u> and <u>especially no transient components</u> (such as a valve which changes position), the use of pressure forces only should still be conservative. But remember that this is only an assumption at this point – based on observation of simulation results with no theoretical backing based on physics.

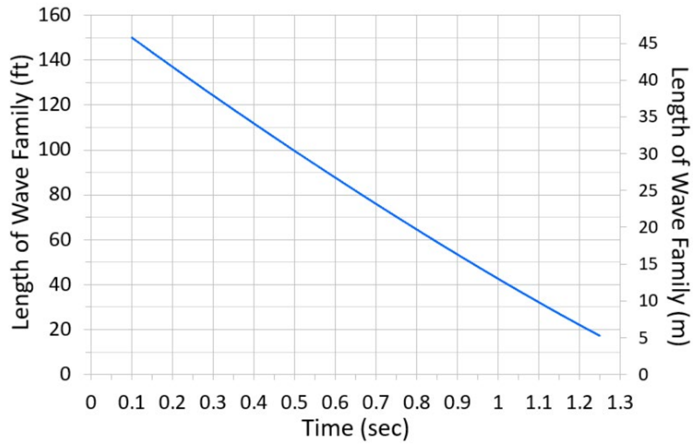

Figure 3. The length of the wave family (usually called the characteristic length) for Example 1, 200-sections case in [1]. This example uses real gas ASME Steam Tables data and pipe friction.

Steps to apply the Goodling Method [4]

1. Calculate a maximum possible transient force (this is Eq. 4 in [1]).
2. Calculate a characteristic length (Eq. 5 in [1]).
3. Use the actual length of pipe run leg to determine a maximum force for that pipe leg (Eq. 6 in [1]).
4. Create a force vs. time profile using the preceding three elements (Fig. 1 in [1] shows a typical example – see Goodling [4] for more on creating profiles using that method).

The method proposed here is intended to account for wave steepening and to predict conservative forces. Here is what is retained from Goodling:

- The general idea of characteristic length will be kept. However, it will be renamed and treated as a variable.
- Use of only pressure forces to determine forces.
- Use of the Joukowsky Equation to determine a maximum force.
- Construction of a force-time profile based on length of pipe run and wave speed.

DEVELOPMENT OF IMPROVED METHOD

The intent going forward is to construct the complete method of load estimation without need to make reference to other publications.

How fast does a wave steepen?

Another way to ask this question is, "How long does it take the back of the wave to catch the front?" Fig. 4 helps us understand this question for an example using real gas properties

(ASME Steam Tables) and pipe friction (taken from Fig. 6 in [1]).

In Fig. 4 one can see the trailing edge of the wave catching up with the front edge similar to the idealized case in Fig. 2. Eventually the back will catch the front and coalesce into a single moving shock wave.

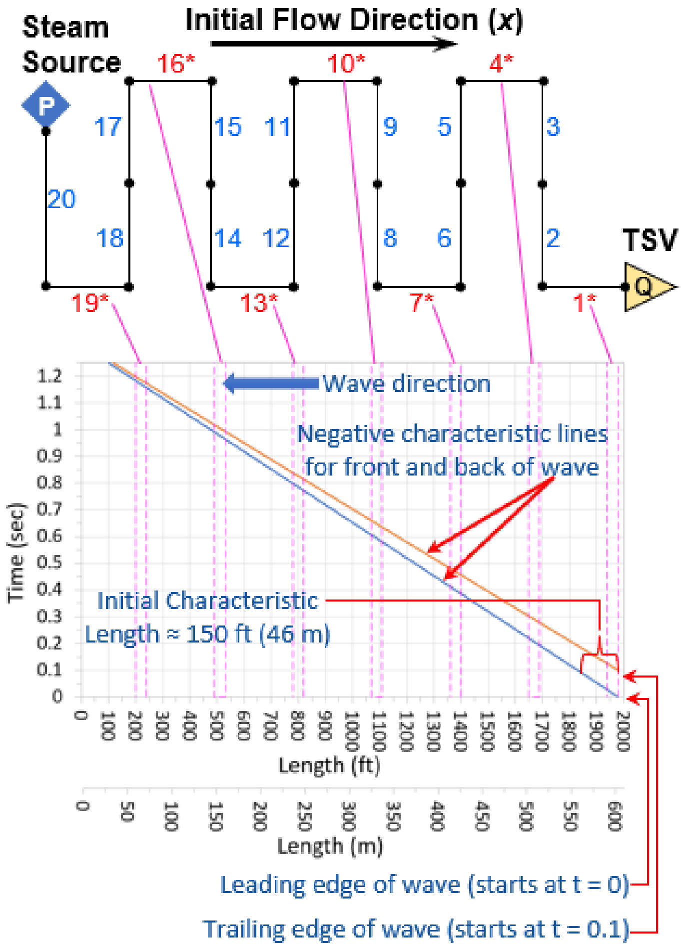

Figure 4. Positive and negative characteristic lines follow the front and back of the wave family for 200-sections Example 1 case in [1]. This example uses real gas ASME Steam Tables data and pipe friction.

What is the length of the wave family?

While the back of the wave family (in Fig. 4) has not caught up with the front, by inspection one can see that it nearly has. Fig. 3 shows the length of the wave family by subtracting the two wave positions in Fig. 4. In other words, Fig. 3 shows the length of the wave family over time. While the wave family length in Fig. 3 does not completely go to zero, it will when the back catches the front assuming the pipe is long enough.

While it has been made clear that Figs. 3 and 4 use real gas behavior and pipe friction, for the sake of interest let's assume we can use Eqs. 4-5 to predict the location and time where the back catches the front and forms a shock wave. Eqs. 4-5 are, strictly speaking, developed for a perfect gas with adiabatic, frictionless flow.

The input data to use for Eqs. 4-5 comes from Table 1 in Walters [1] and the associated discussion of the example. Tables 1 and 2 below collect data shown in [1].

Table 1. TSV steady-state conditions at valve inlet (exit of pipe at Leg 1 in Fig. 1)

Parameter	Value at TSV
D (inner)	29.25 in. (0.743 m)
A	672 in^2 (0.433 m^2)
L	1980 ft (604 m)
V	115.6 ft/s (35.3 m/s)
c	1614 ft/s (492 m/s)
$a_M = V - c$	− 1498 ft/s (− 457 m/s)
γ	1.25

Table 2. Some results using Table 1 input.

Parameter	Eq.	Calculated Result
t_{shock}	4	1.252 seconds
L_{shock}	5	1876 ft (572 m)
$x_{shock} = L - L_{shock}$	N/A	104 ft (32 m)

Looking at Fig. 4, one can see that at x = 104 ft / 32 m (the x_{shock} value from Table 2) the front and back of the wave family are very close to each other. But they have not coalesced (which is the meaning of x_{shock}). In other words, Eq. 5 *underpredicts* the actual L_{shock} value for the Fig. 4 example. This is important as it will generally result in a *conservative* maximum force prediction in the improved method.

The Goodling Method [4] uses a "characteristic length". As noted earlier, Walters [1] argues that this is not a reliable parameter and, even if it was, the Goodling Method does not calculate it correctly. As a result, a new parameter will be created here called the "wave family length", L_{wf}. This parameter is precisely what is shown in Fig. 3. Since the wave movement is a function of time and space, L_{wf} can be represented as a function of either. We will therefore create two variants of L_{wf} as follows:

$$L_{wf-t} = f(t) \tag{6a}$$

$$L_{wf-x} = f(x) \tag{6b}$$

Fig. 3 directly represents Eq. 6a. Fig. 4 indirectly represents Eq. 6b.

The initial value of the wave family length is determined based on Eq. 6a. It is given by the following and is analogous to (but not the same as) Goodling's characteristic length:

$$L_{wf-0} = |a_{M,SS}| t_c \tag{7}$$

where $a_{M,SS}$ is the initial wave speed at the front of the wave family and determined from steady-state conditions, $V_{SS} - c_{SS}$ (Eq. 1). It represents Region 1 in Fig. 2. See Table 1 or equivalent for values to use in Eq. 7. For real gases with friction a_M is a function of time.

Fig. 3 has the advantage of being developed from a detailed numerical simulation [1] and is thus not suitable as a short cut method. But the short cut method needs to accept and honor the behavior shown in Fig. 3. In that spirit the following approximation is proposed to define Eq. 6:

For $\Delta x_{source} > L_{wf\text{-}0}$,

$$L_{wf-x} = L_{wf-0}\left(1 - \left(\Delta x_{source} - L_{wf-0}\right)/L_{shock}\right) \tag{8a}$$

For $\Delta x_{source} <= L_{wf\text{-}0}$,

$$L_{wf-x} = L_{wf-0} \tag{8b}$$

For $t > t_c$,

$$L_{wf-t} = L_{wf-0}(1 - (t - t_c)/t_{shock}) \tag{9a}$$

For $t <= t_c$,

$$L_{wf-t} = L_{wf-0} \tag{9b}$$

where Δx_{source} in Eq. 8a-b is the distance from the source of the transient to the location of interest. In the case of Fig. 4, it would be determined as $\Delta x_{source} = L - x$ since the source of the transient is at x = 1,980 ft (604 m). Eqs. 8-9 are both equivalent ways of determining L_{wf}.

For the example at hand, Eq. 9a-b can be cross-plotted on Fig. 3 as shown in Fig. 5 below. Here you can see that Eq. 9a-b is an acceptable approximation to the Fig. 3 numerical simulation. With Eqs. 8-9 available, we are now ready to describe the improved short cut method.

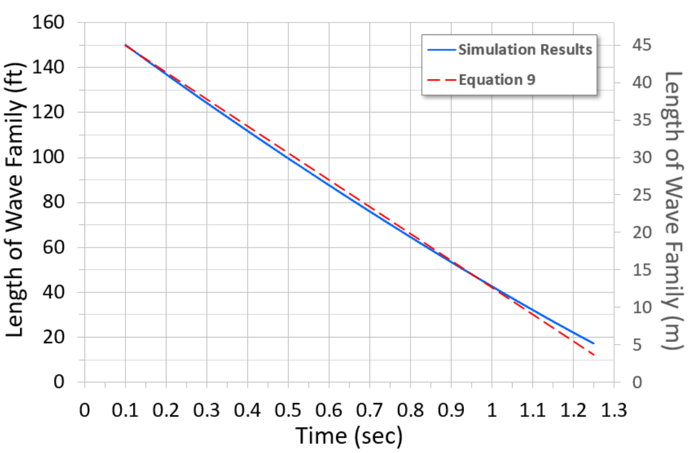

Figure 5. Length of wave family from numerical simulation [1] and from Eq. 9 approximation.

ASSUMPTIONS MADE IN IMPROVED METHOD

1. The wave speed at the front of the wave family remains constant and at the initial value, $a_{M,SS}$.
2. The maximum force can be determined using pressure forces only.
3. The maximum pressure force is obtained using the Joukowsky equation with acoustic velocity.
4. The maximum pressure force does not attenuate over time and distance.
5. The length of the wave family can be determined using Eqs. 8 or 9.
6. Constant diameter pipe with no wave reflections.
7. No fittings or diameter changes of any kind exist in the pipe run legs where forces are being calculated.
8. Only one single transient exists and there are no other transients happening during the same time in the piping that could interact with the single transient.
9. Pipe is rigidly restrained and does not move and there is no local wall deformation near shock fronts.
10. Condensation does not happen at any location or time in the pipe.

IMPROVED METHOD OF ESTIMATING TRANSIENT LOADS

Step 1

Approximate the maximum possible transient force, F_{Max}, using the Joukowsky Equation and the pipe cross-sectional area, A. This uses steady-state values at the TSV. This is the same step as used by the Goodling Method [4] except here we do not use a 1.05 multiplier for compressibility. Those accustomed to using Goodling are welcome to use the multiplier but the author does not believe it is necessary because this method better accounts for compressibility than Goodling:

$$\Delta P_J = -\rho c \Delta V \tag{10}$$

$$F_{Max} = \Delta P_J A \tag{11}$$

Step 2

Approximate the initial length of the wave family using Eqs. 1 and 7 based on steady-state values at the TSV:

$$a_{M,SS} = |V_{SS} - c_{SS}| \tag{1}$$

$$L_{wf-o} = |a_{M,SS}| t_c \tag{7}$$

Step 3

Calculate the approximate length of the wave family when it reaches the pipe run leg of interest, x_{Leg}. Use Eq. 8a-b for this and, when using an x-coordinate system like that in Fig. 1, x_{Leg} is the same thing as Δx_{source}. As the pipe run leg has a length of its own, L_{Leg}, it is recommended to use the midpoint of the pipe run leg to determine the x_{Leg} location. An example of this will be shown in the next Section.

For $x_{Leg} > L_{wf\text{-}o}$,

$$L_{wf-x} = L_{wf-0}\left(1 - \left(x_{Leg} - L_{wf-0}\right)/L_{shock}\right) \tag{8a}$$

For $x_{Leg} <= L_{wf\text{-}o}$,

$$L_{wf-x} = L_{wf-0} \tag{8b}$$

Step 4

Approximate a *maximum* force for the pipe run leg of interest using Eqs. 8a-b and 11:

For $L_{wf\text{-}x} <= L_{Leg}$,

$$F_{Leg} = F_{Max} \tag{12a}$$

For $L_{wf\text{-}x} > L_{Leg}$,

$$F_{Leg} = F_{Max}\frac{L_{Leg}}{L_{wf-x}} \tag{12b}$$

Step 5

Some analysts are interested in getting a transient forcing function on the pipe leg [4]. An improved forcing function can be obtained using Fig. 6 and Eqs. 13-14 below as approximate values. Recalling that x_{Leg} here is the pipe leg midpoint, the time when the wave first arrives at the start of the pipe run leg, t_f, is approximated by:

$$t_f = \left(x_{Leg} - \frac{L_{Leg}}{2}\right)/a_{M,SS} \tag{13}$$

The total time it takes for the wave to first enter then completely leave the pipe run leg is approximated by:

$$\Delta t_{Leg} = \left(L_{Leg} + L_{wf-x}\right)/a_{M,SS} \tag{14}$$

For those unfamiliar with the Goodling Method, Fig. 6 gives an approximate way to construct a forcing function. The shape of the forcing function depends on whether the wave family fits completely inside the pipe leg or not. If it does fit, the pipe leg will see a maximum pressure difference across the wave family. Hence, the force will be higher (Eq. 12a). If the wave family does not fit, then the pipe leg only experiences a portion of the pressure difference across the wave family. The corresponding force will thus be lower (Eq. 12b).

NUMERICAL EXAMPLE OF IMPROVED METHOD

The Improved Method will be applied to Example 1 from [1] using a minimum of 200 pipe sections. Load estimations from all seven pipe run legs will be given. Values in Tables 1-2 are used in this Example. Fig. 1 and accompanying text gives the lengths of pipe run legs. Table 3 shows results for Steps 1 and 2.

Table 4 shows the x_{Leg} locations (assumed to be midpoints), the $L_{wf\text{-}x}$ values, and peak predicted forces of Step 4. Fig. 7 shows the approximate force vs. time profiles from Step 5.

Table 5 compares peak predictions from the Improved Method and numerical simulation from [1]. Peak pressures for the first five pipe legs are surprisingly good while Legs 16 and 19 overpredict the forces in [1] by about 20%.

Fig. 8 cross-plots the Step 5 approximate profiles against the simulation results from [1]. These results show that the Improved Method does an amazingly good job on this example for Legs 1, 4, 7, 10 and 13. For Legs 16 and 19 it is conservatively higher.

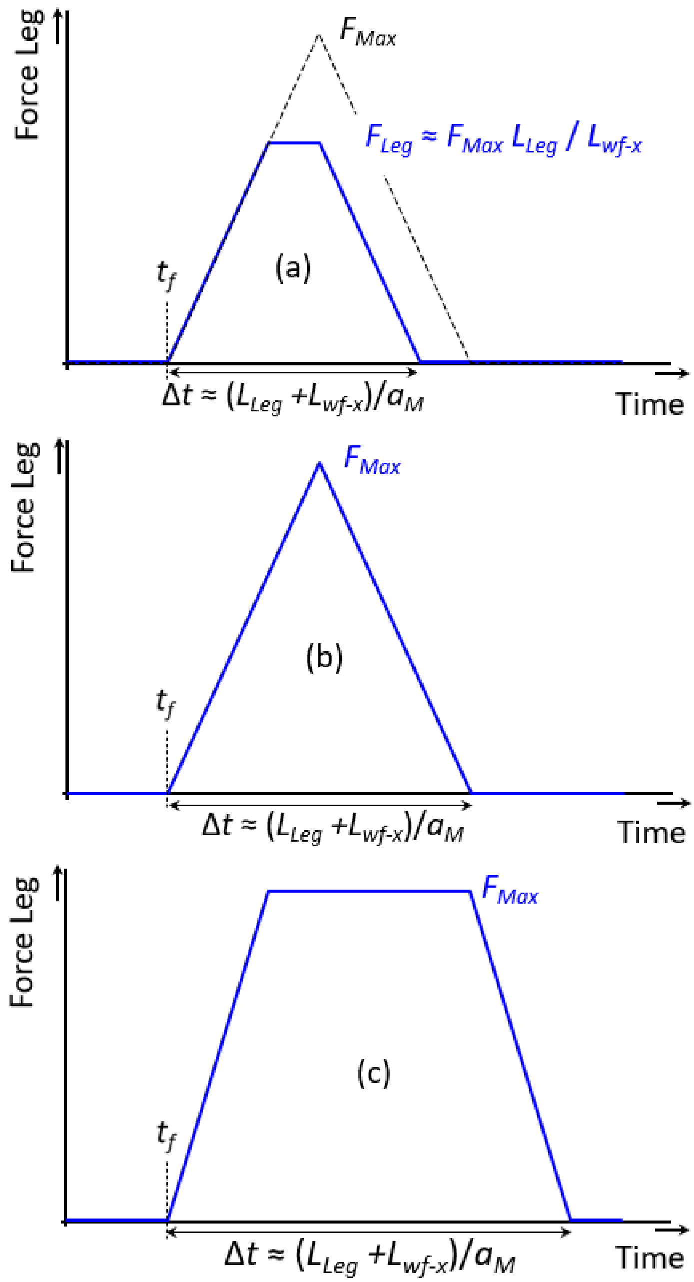

Figure 6. Force-time profile for wave moving past a pipe run length for (a) $L_{Leg} < L_{wf\text{-}x}$, (b) $L_{Leg} = L_{wf\text{-}x}$, (c) $L_{Leg} > L_{wf\text{-}x}$. The approximate time at which the wave arrives at the pipe run is given by $t_f = (x_{Leg} - 0.5L_{Leg}) / a_M$

Table 3. Improved Method Steps 1-2 intermediate results

Parameter	Eq.	Calculated Result
ΔP_J	10	86.9 psid (599 kPa)
$L_{wf\text{-}0}$	7	149.8 ft (45.7 m)
F_{max}	4	61,288 lbf (272.6 kN)

Table 4. Improved Method Steps 3-4 results

Leg #	x_{Leg}	$L_{wf\text{-}x}$	Peak Force	
	Fig. 1	Eq. 8	Eq. 12	
	ft / m	ft / m	lbf	kN
1	20 / 6	150 / 45.7	15,582	69.3
4	310 / 95	137 / 41.8	17,036	75.8
7	600 / 183	114 / 34.7	20,500	91.2
10	890 / 271	91 / 27.7	25,733	114.5
13	1180 / 360	68 / 20.6	34,553	153.7
16	1470 / 448	44 / 13.5	52,573	233.8
19	1760 / 537	21 / 6.5	58,369	259.6

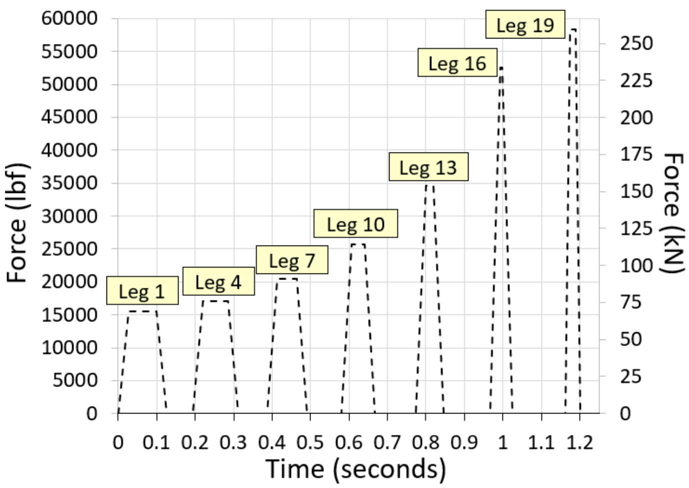

Figure 7. Force vs. time profiles for Example showing approximate Improved Method transient curves.

Table 5. Results Comparison for Example using Improved Method and Numerical Simulation from [1, Table 4]

Leg #	Peak Force on Pipe Leg in *x* Direction			
	Improved Method		Simulation [1]	
	lbf	kN	lbf	kN
1	15,582	69.3	14,610	65.0
4	17,036	75.8	16,985	75.6
7	20,500	91.2	20,361	90.6
10	25,733	114.5	25,469	113.3
13	34,553	153.7	33,823	150.5
16	52,573	233.8	44,019	195.9
19	58,369	259.6	47,699	212.2

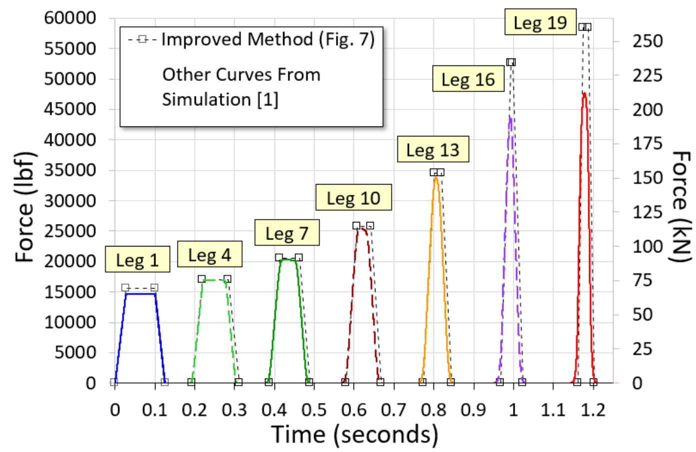

Figure 8. Force vs. time for Example showing cross-plot of Improved Method and simulation results from [1].

A CRITIQUE OF IMPROVED METHOD

Transient compressible flow is a complicated subject. Indeed, until recently there were virtually no quality commercial tools capable of simulating this while also being pragmatic for engineering design use. Expecting that simple, algebraic relationships for the Improved Method are adequate for high pressure steam systems in expensive power stations carries risk, especially when there are commercial tools available.

For example, while the Improved Method is not necessarily excessively conservative in the Example shown in the paper, it may be excessively conservative in Example 3 in Walters [1]. That example has increased flow by 20% for a hypothetical power uprate. That example shows there is no guarantee that forces will always increase as one moves farther from the source of the transient.

In addition, various TSV closure profiles may exist which have a longer closing time and/or are non-linear. It is not known how the Improved Method will work on such systems.

Whereas it has been shown in this paper that the Improved Method does a surprisingly good job of predicting transient forces in the Example problem, it does make a number of assumptions which are listed in an earlier section of this paper.

One assumption is that the initial steam wave speed remains constant (Assumption #1). Fig. 7 in Walters [1] shows that it does change with time (albeit by only about 1% in the provided example).

A second general assumption (Assumptions #2 and #3) is that one can use only pressure forces to obtain peak forces. Using only pressure forces and ignoring other parameters in Newton's Second Law will not always be conservative. Lang and Walters [6] show that a complete force balance is more accurate and reliable than use of only pressure forces.

A third assumption relates to fittings (Assumption #7). If there are any fittings in the pipe run leg, diameter changes, wave reflection points, and even transient events from something like a closing valve in a pipe run, the Improved Method will likely not be accurate and maybe not even conservative.

RECOMMENDATIONS

1. Existing systems designed using the Goodling Method should be re-evaluated for maximum pipe loads for safety reasons. Strengthened pipe supports should be added where deemed necessary.

2. Engineers should consider using a capable simulation tool to determine peak loads and load profiles. This will yield the most accurate predictions, handle wave reflections should they occur, identify undesirable transient condensation and will not add unnecessary conservatism.
3. The Improved Method in this paper offers more reliable force estimates than Goodling. The Improved Method is recommended as a screening tool and at the preliminary design stage. For example, it can be applied to existing designs in power stations to show which systems should be evaluated for strengthened supports.

CONCLUSIONS

An Improved Method of estimating steam hammer loads is detailed. To be used, it requires only a quality steady-state solution. Comparisons against simulation results show surprisingly good agreement. The Improved Method offers significant advantages over the Goodling Method and should be considered by the engineering community as a replacement for Goodling.

The method makes many assumptions and may be best used as a screening tool or for preliminary design purposes. Many existing pipe systems in operating power stations have been designed using the Goodling Method which has been shown to be potentially unconservative. This Improved Method can help evaluate which of these pipe systems should be re-evaluated for safety reasons.

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