Applied Flow Technology

Calculating Transient Forces for Pipe Stress Analysis

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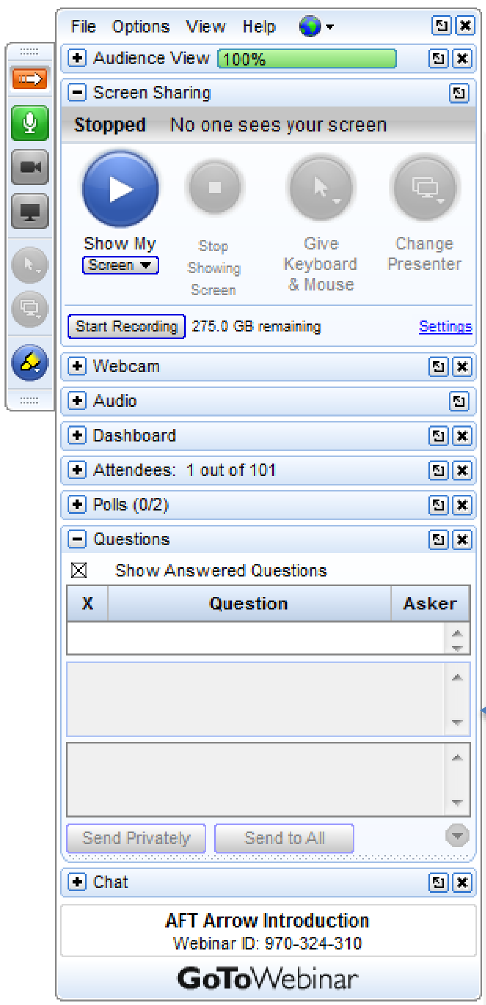
Dynamic solutions for a fluid world ™



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Attendees: 1 out of 101

AFT Arrow Introduction
Webinar ID: 970-324-310

Type your
questions

Waterhammer Causes

- Waterhammer can be caused by many events including
  - Valve closure or opening (in full or in part)
  - Pump speed change
    - Trip or startup
  - Relief valve cracking open
  - Rapid tank pressurization
  - Periodic pressure or flow conditions

Waterhammer and Force Imbalances

- Waterhammer causes transient force imbalances in piping systems
  - This is a result of fast-moving pressure waves which can create temporary force imbalances
  - Elbow pairs are especially susceptible to force imbalances due to the change in flow direction

Waterhammer Software

- Waterhammer is a sufficiently complicated process such that modeling software is usually required
- Typically the issue of primary interest to the engineering analyst is understanding transient pressure extremes
  - This allows selection of pipe strength and design for equipment protection and general safety
- *AFT Impulse*™ is a leading waterhammer software
  - *AFT Impulse* has been commercially available since 1996
  - It has been used to model thousands of piping system transients

Code Compliance

Once the overpressure is calculated, What should the designer do with this value?

The answer to this question depends on the code being used.

- *ASME Code for pressure piping B31.4. Pressure Transportation Systems for Liquid Hydrocarbons and Other Liquids.*

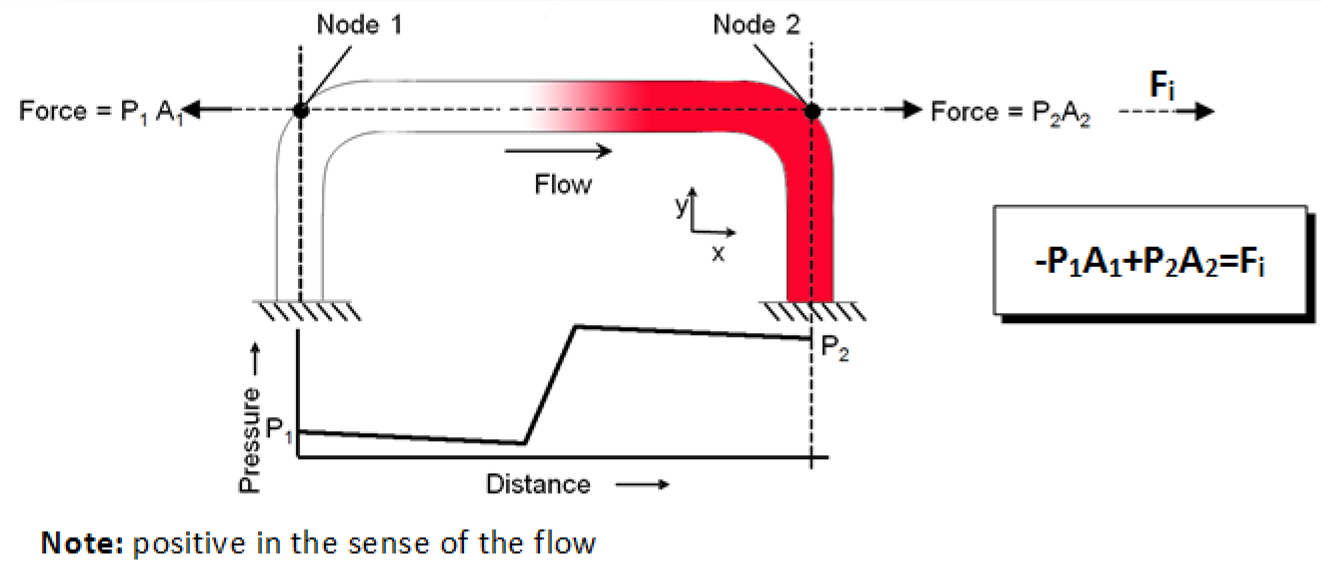
B31.4 refers directly to the maximum value of the overpressure, establishing a limit of 10% above the design pressure.

- *ASME Code for pressure piping B31.3. Process Piping*

The maximum stress produce the loads created by the surge pressure shall not exceed: 1.33 S_h (S_h=allowable stress for the operating temperature).

Traditional Force Calculation

- Traditional force calculation uses only pressure differences in the force imbalance
  - With hydro-pressure effects on pressure subtracted



$$-P_1A_1+P_2A_2=F_i$$

Note: positive in the sense of the flow

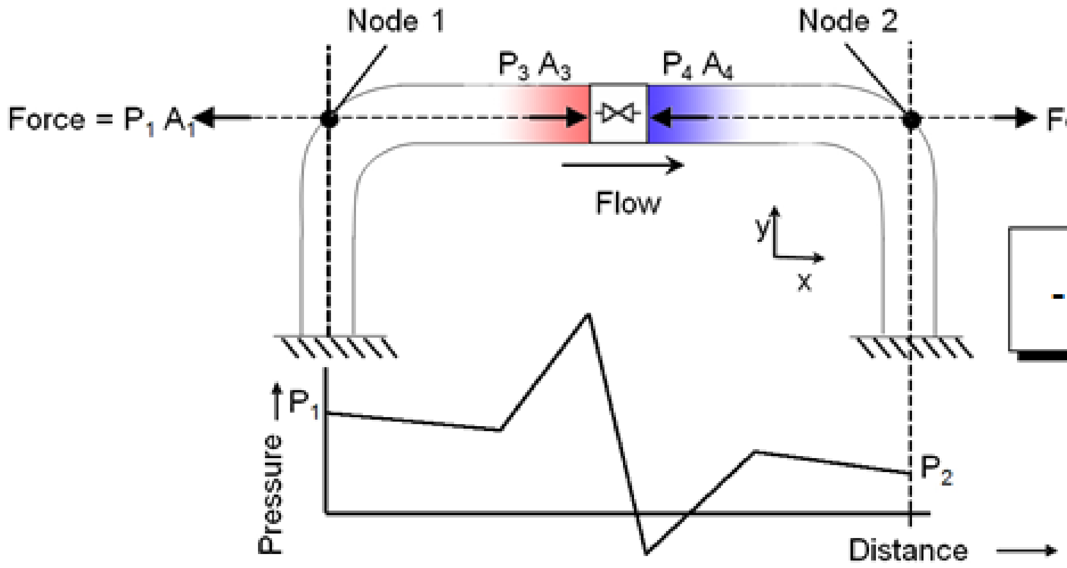
Traditional Force Calculation

- This works best when flow fully stops quickly, with no in-line components
- $dP = \rho c \Delta V$
  - Where “c” is wavespeed also known as celerity
    - Often this is referred to as “a” which is synonymous

Traditional Force Calculation

- Complexities of real systems quickly render hand-calculations useless.
  - How do pressures upstream & downstream of inline components change and add or subtract?
  - What if a valve only partially closes?
  - What about other forms of energy transmission?
    - Friction losses
    - Momentum changes
    - Area changes

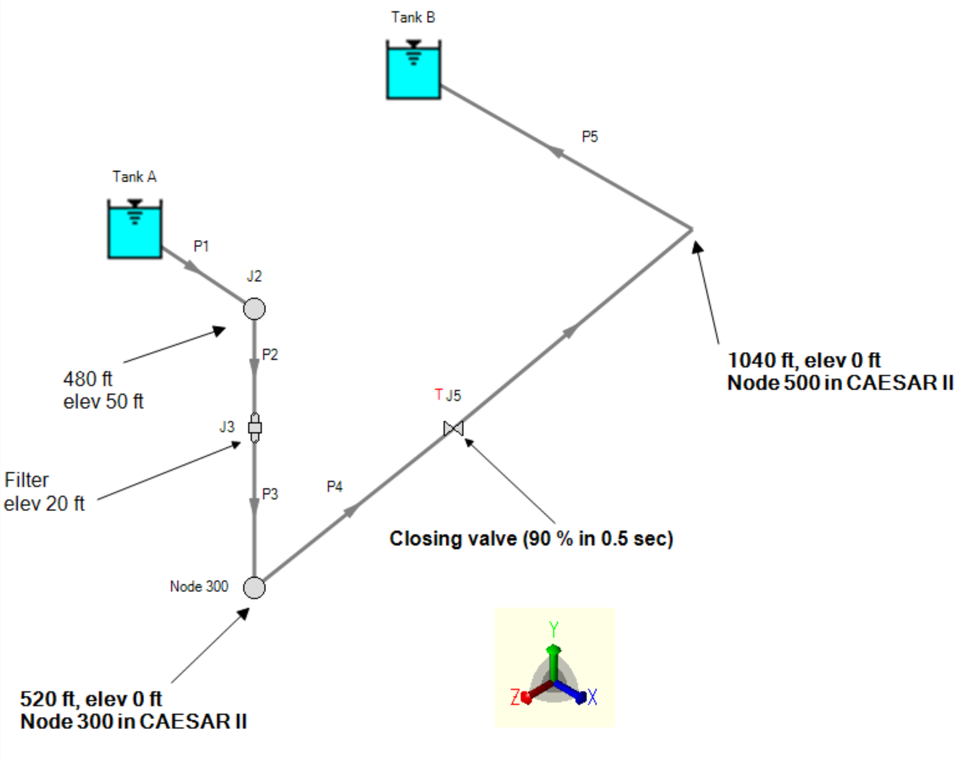
Traditional Force Calculation (4)



$$-P_1A_1+P_2A_2-P_4A_4+P_3A_3=F_i$$

Note: positive in the sense of the flow

Model Information



480 ft
elev 50 ft

Filter
elev 20 ft

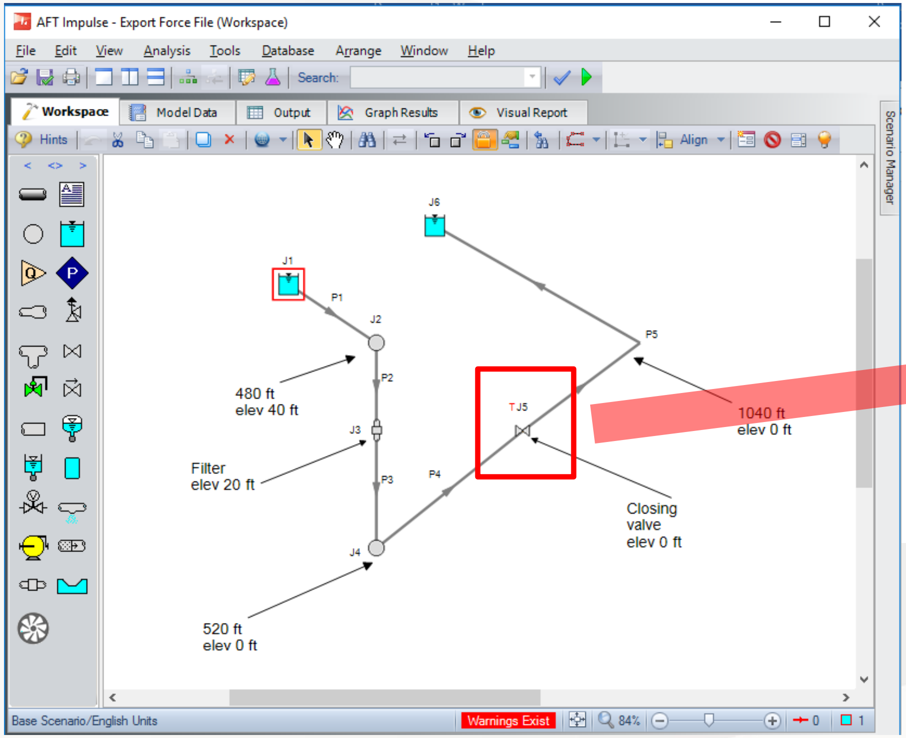
1040 ft, elev 0 ft
Node 500 in CAESAR II

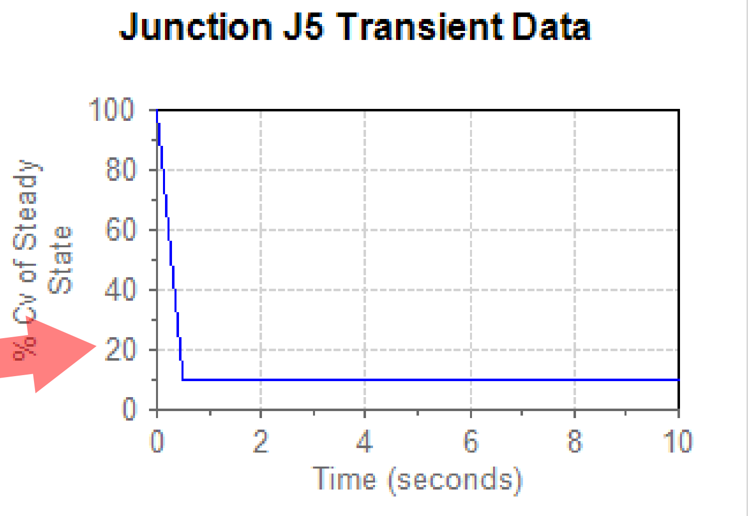
Closing valve (90 % in 0.5 sec)

520 ft, elev 0 ft
Node 300 in CAESAR II

- Liquid transferring from Tank A to Tank B. Gravity driven
- Valve closes 90% in 0.5 Sec
- Fluid Water
- Pipe 20’; sch Std; Steel
- Pressure 14.7 Psia
- Temp 60 ^{o}F

Traditional Force Calculation: Example





Traditional Force Calculation

- When a valve fully closes quickly, the magnitude of the resulting pressure rise in a liquid can be conservatively estimated using the equation:

  $F = \rho\ c\ \Delta V\ A$ (fluid density, speed of sound, change in velocity, Pipe Area)

- With our valve closing 90%, one might presume we could guess at the pressure rise using 90% of the($\rho\ c\ \Delta V\ A$) magnitude. It turns out that this is incorrect by an order of magnitude as shown in the calculations below

$C = 46{,}301$ in/sec (speed of sound in the fluid)

$\rho = 0.036\ \text{lbm/in}^3$ (fluid density)

$\Delta V = 138.3$ in/sec (change in velocity)

$g_c = 386.4\ \text{lbm*in/lbf*sec}^2$

$A = 290\ \text{in}^2$ (20” Pipe Area)

$F = 0.036*46{,}301*138.3*290*0.9/386.4 = 150{,}612.00$ lbf

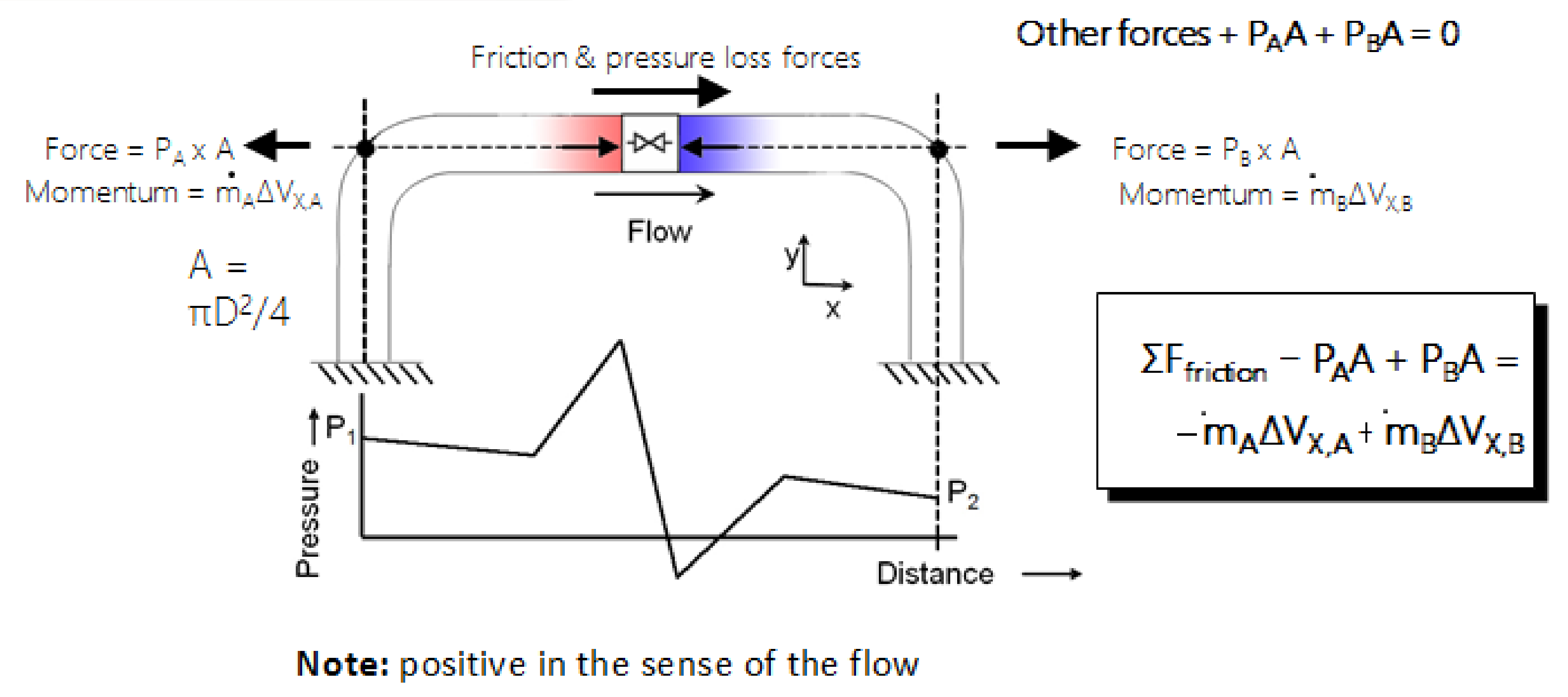
Calculated by AFT Impulse F=16,500.00 lbf <<< $F = \rho\ c\ \Delta V\ A$

Traditional Force Calculation

- Without a good ball-park pressure-rise value, our manual method is not reliable.
- How do we apply this pressure to the partially closed valve area?
- It’s at this point that, even if we understand that if we want to do a surge pressure calculation, we’ll need to rely on a computer-based transient hydraulic analysis to get reliable data.

Including all Inline Forces

- Including all forces including fitting pressure losses, friction & momentum improves force calculations



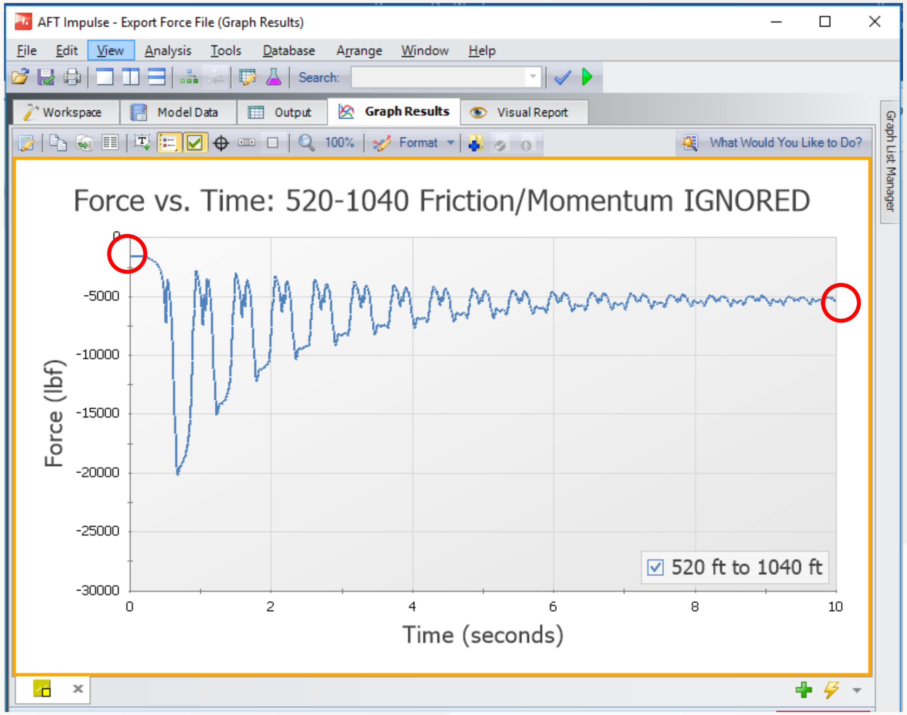
$$\text{Other forces} + P_A A + P_B A = 0$$

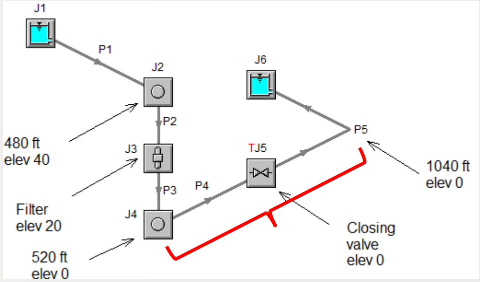
$$\Sigma F_{friction} - P_A A + P_B A = -\dot{m}_A \Delta V_{X,A} + \dot{m}_B \Delta V_{X,B}$$

Note: positive in the sense of the flow

Including all Inline Forces : Results

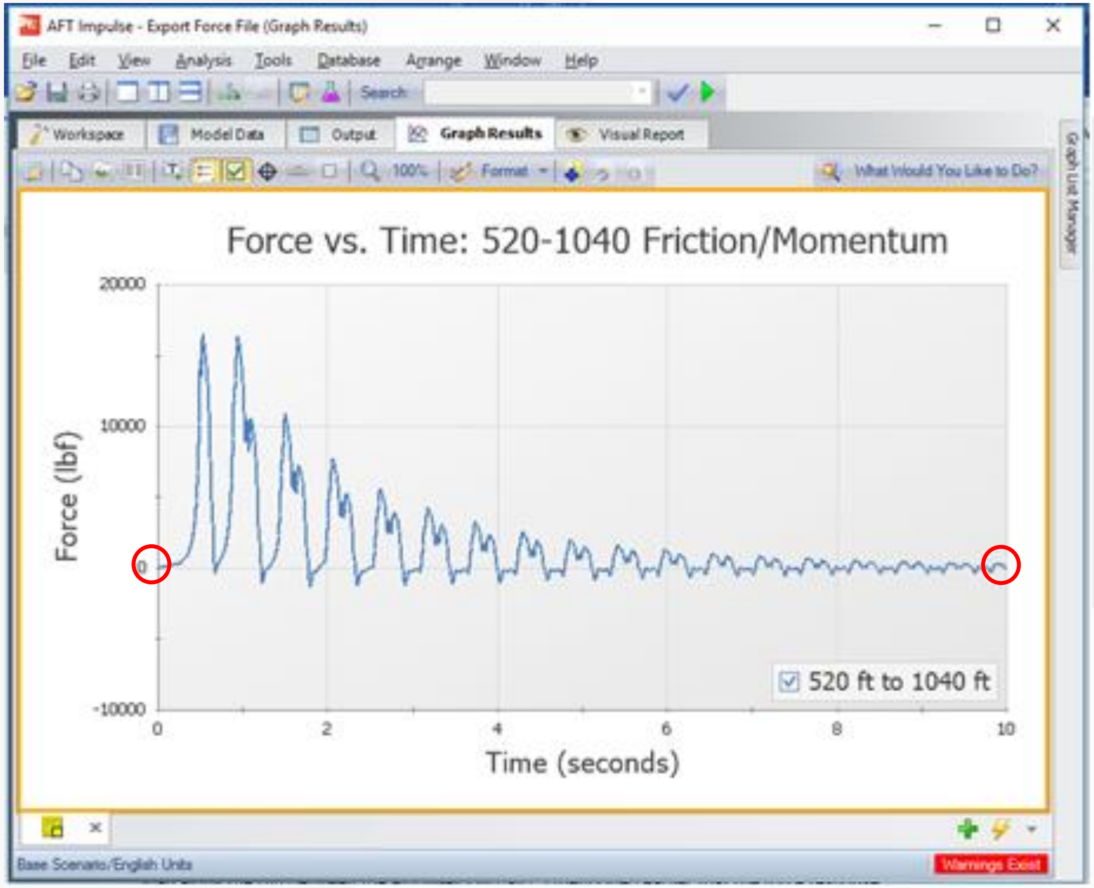
- For the initial and final steady-state conditions the force imbalance should be zero
  - Ignoring friction leads to non-zero steady-state results

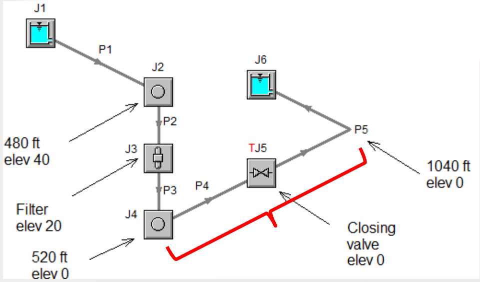




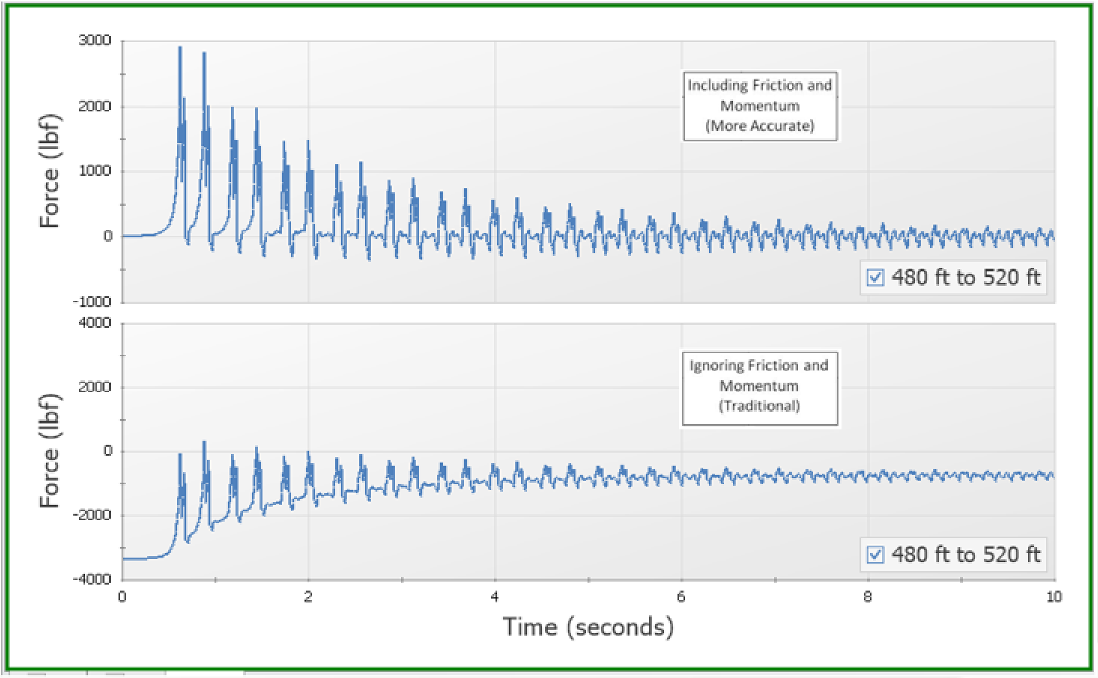
Including all inline Forces: Results

- Steady-state forces initially and finally are zero



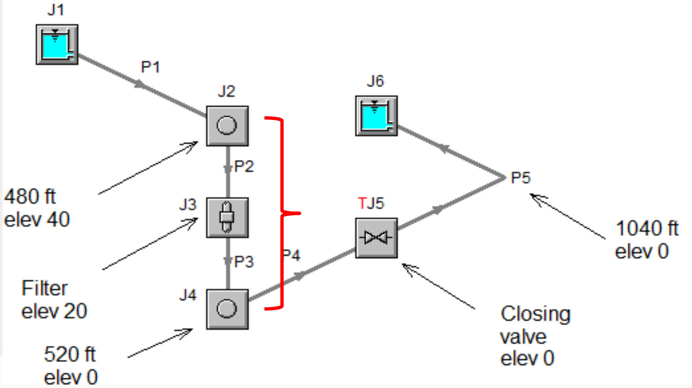


Comparing Methods at First Elbow Pair

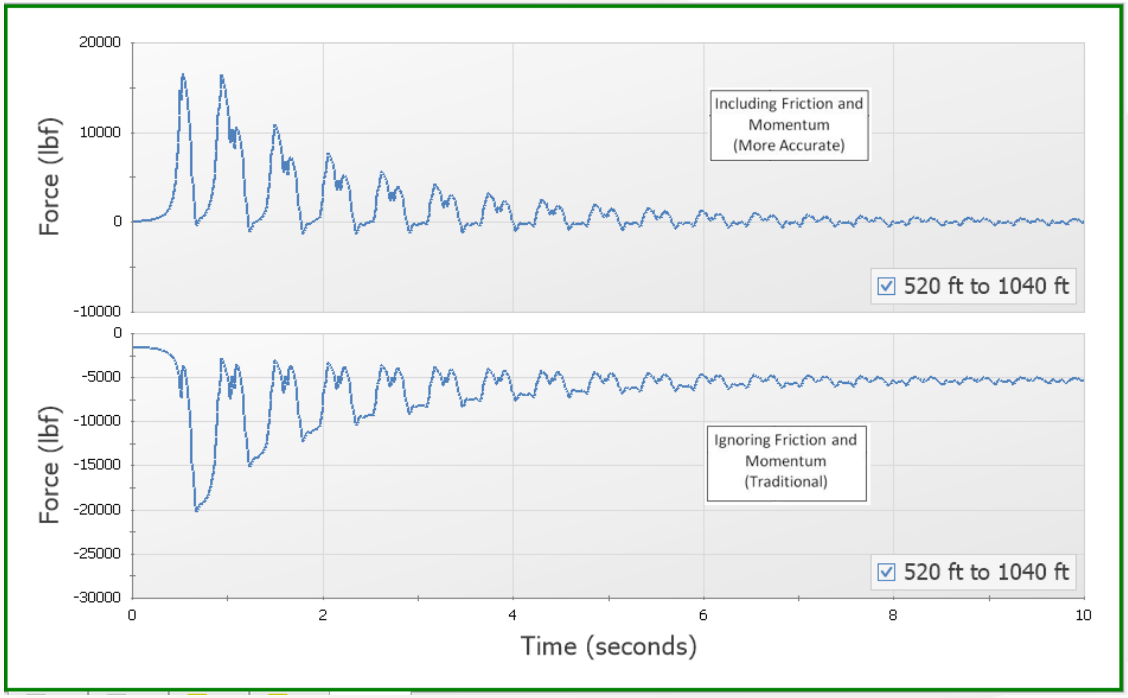


	Max (k-lbf)	Min (k-lbf)
Traditional	0.3	3.3
Friction and momentum included	2.9	0.3

Note: positive in the sense of the flow

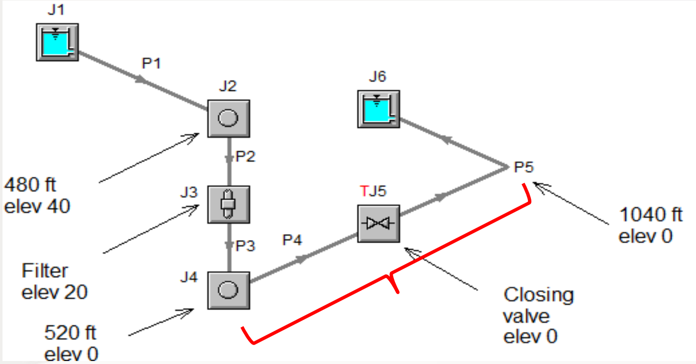


Comparing Methods at Second Elbow Pair



	Max (k-lbf)	Min (k-lbf)
Traditional	-20.0	-1.6
Friction and momentum included	16.5	1.3

Note: positive in the sense of the flow



Traditional Method Weaknesses

- The use of traditional force imbalance calculation methods can be highly inaccurate
  - Don’t know actual load magnitudes
    - Directionality of max loads can also be incorrect
  - Don’t know timing of the loads
  - Ignores some loads

3 Ways to Analyze Waterhammer with CAESAR II

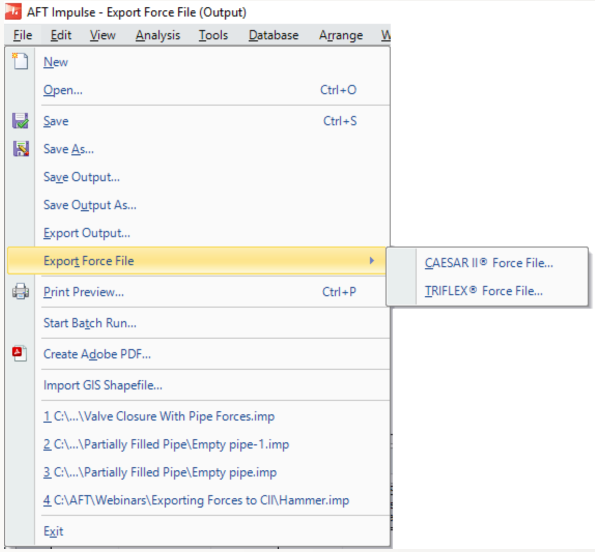
- Static Equivalent
  - Not discussed in this webinar
- Spectral Analysis
- Time-History Analysis

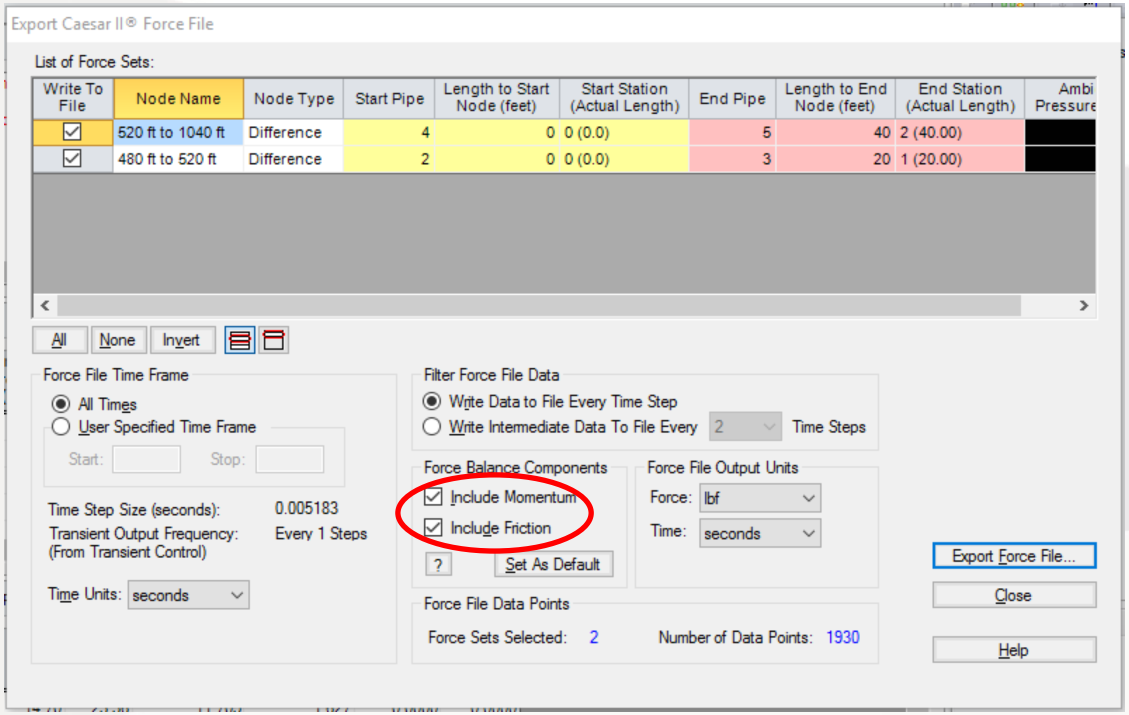
Spectral Analysis

- Static Equivalent (not discussed in this presentation)
- **Spectral Analysis**
- Time-History Analysis

Spectral Analysis

- Generating DLF Curves from AFT Impulse




Export Caesar II® Force File

List of Force Sets:

Write To File	Node Name	Node Type	Start Pipe	Length to Start Node (feet)	Start Station (Actual Length)	End Pipe	Length to End Node (feet)	End Station (Actual Length)	Ambi Pressure
☑	520 ft to 1040 ft	Difference	4	0	0 (0.0)	5	40	2 (40.00)	
☑	480 ft to 520 ft	Difference	2	0	0 (0.0)	3	20	1 (20.00)	

Force File Time Frame
● All Times
○ User Specified Time Frame
Start: Stop:

Time Step Size (seconds): 0.005183
Transient Output Frequency: Every 1 Steps
(From Transient Control)

Time Units: seconds

Filter Force File Data
● Write Data to File Every Time Step
○ Write Intermediate Data To File Every 2 Time Steps

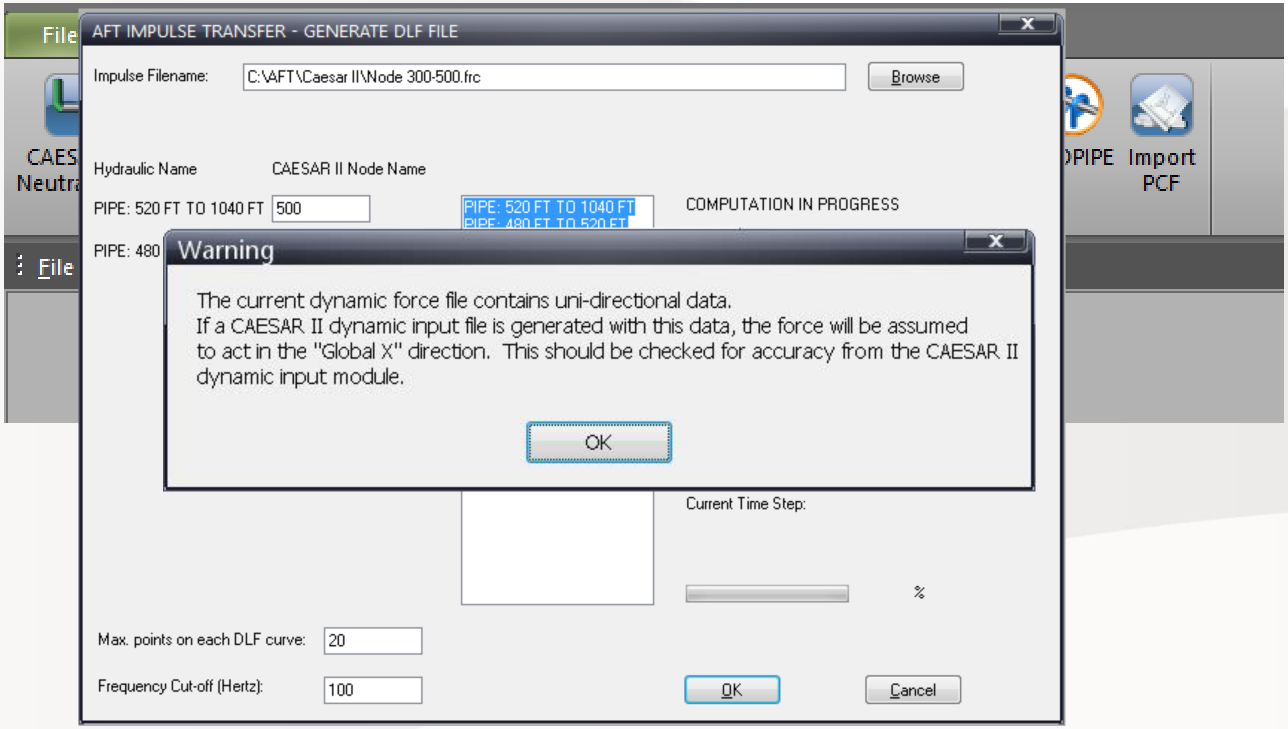
Force Balance Components
☑ Include Momentum
☑ Include Friction

Force File Output Units
Force: lbf
Time: seconds

Force File Data Points
Force Sets Selected: 2
Number of Data Points: 1930

Spectral Analysis

- Importing DLF curves into CAESAR II
- Tools > External Interfaces > AFT Impulse



AFT IMPULSE TRANSFER - GENERATE DLF FILE

Impulse Filename: C:\AFT\Caesar II\Node 300-500.frc

Hydraulic Name	CAESAR II Node Name
PIPE: 520 FT TO 1040 FT	500
PIPE: 480	

PIPE: 520 FT TO 1040 FT
PIPE: 480 FT TO 520 FT

COMPUTATION IN PROGRESS

Warning

The current dynamic force file contains uni-directional data.
If a CAESAR II dynamic input file is generated with this data, the force will be assumed to act in the "Global X" direction. This should be checked for accuracy from the CAESAR II dynamic input module.

Current Time Step:

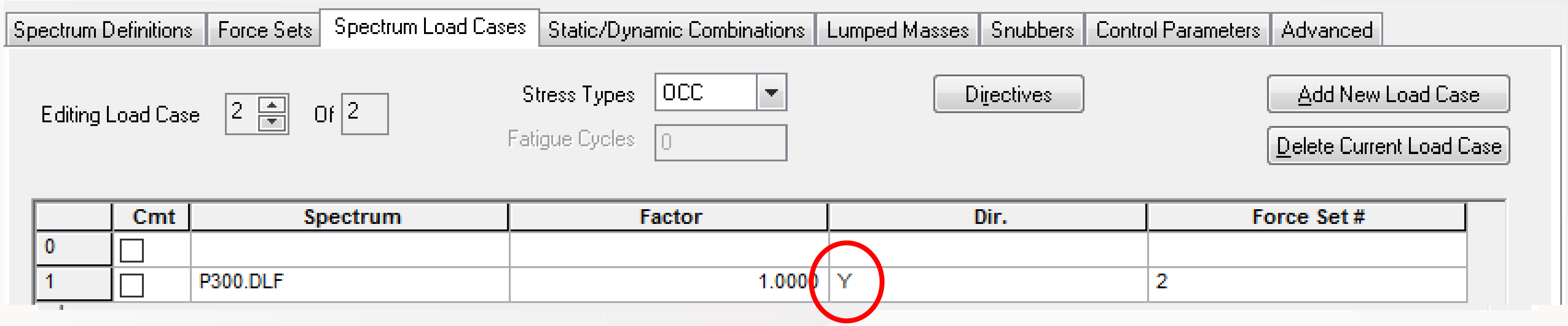
%

Max. points on each DLF curve: 20

Frequency Cut-off (Hertz): 100

Spectral Analysis

- Open Dynamic Input. Input is almost complete
- Spectrums have been defined, force set and Cases have been created
- Force direction needs to be defined in Force Sets and Load Cases.



Editing Load Case 2 Of 2

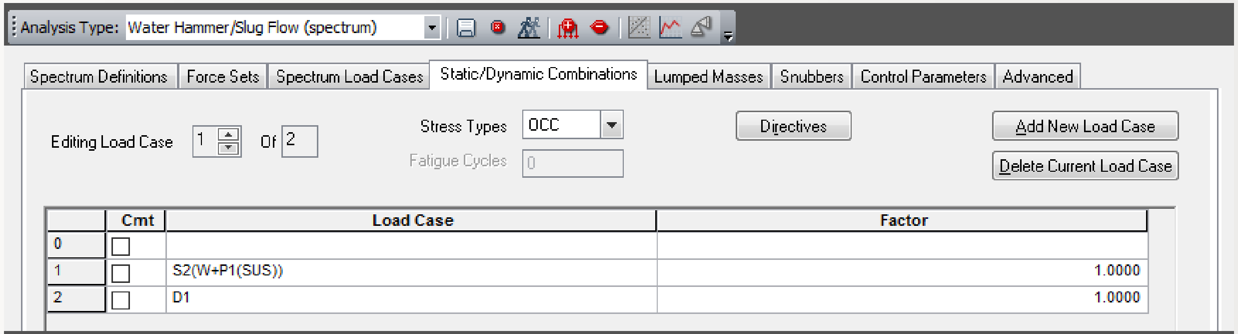
Stress Types OCC

Fatigue Cycles 0

	Cmt	Spectrum	Factor	Dir.	Force Set #
0	☐				
1	☐	P300.DLF	1.0000	Y	2

Spectral Analysis

- Static/Dynamic Combinations for Stress
- Since the forces are applied independently, two cases need to be created



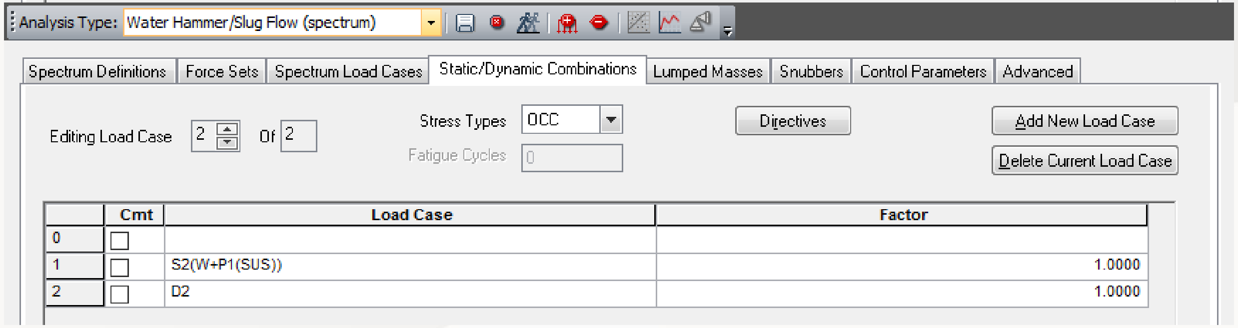
Analysis Type: Water Hammer/Slug Flow (spectrum)

Editing Load Case 1 Of 2

Stress Types OCC

Fatigue Cycles 0

	Cmt	Load Case	Factor
0	☐		
1	☐	S2(W+P1(SUS))	1.0000
2	☐	D1	1.0000



Analysis Type: Water Hammer/Slug Flow (spectrum)

Editing Load Case 2 Of 2

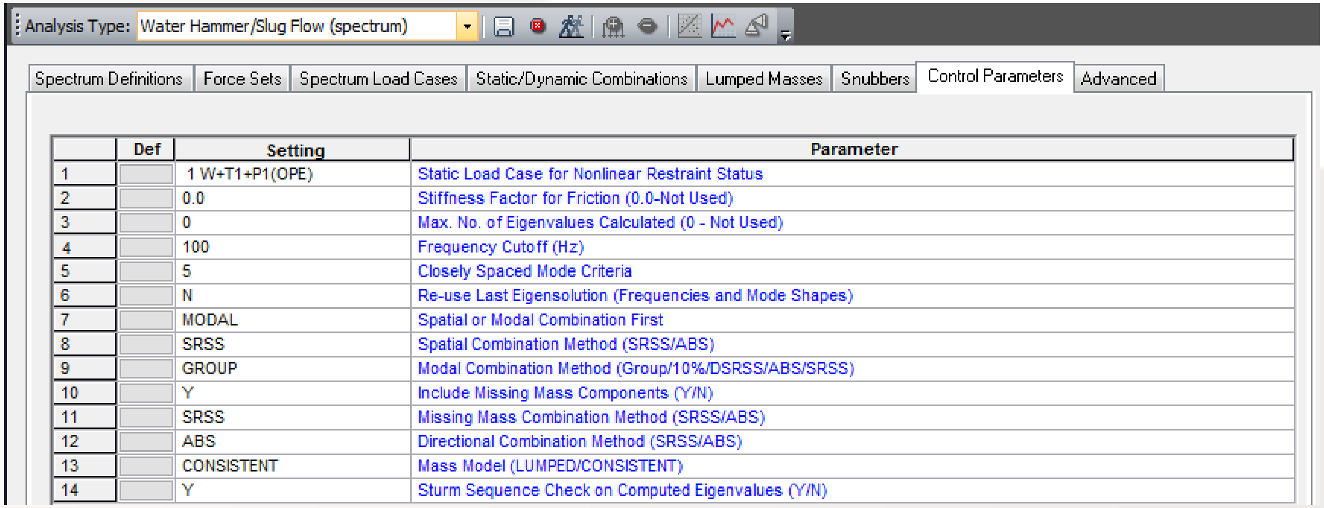
Stress Types OCC

Fatigue Cycles 0

	Cmt	Load Case	Factor
0	☐		
1	☐	S2(W+P1(SUS))	1.0000
2	☐	D2	1.0000

Spectral Analysis

- Review/Set Control Parameters



Analysis Type: Water Hammer/Slug Flow (spectrum)

	Def	Setting	Parameter
1		1 W+T1+P1(OPE)	Static Load Case for Nonlinear Restraint Status
2		0.0	Stiffness Factor for Friction (0.0-Not Used)
3		0	Max. No. of Eigenvalues Calculated (0 - Not Used)
4		100	Frequency Cutoff (Hz)
5		5	Closely Spaced Mode Criteria
6		N	Re-use Last Eigensolution (Frequencies and Mode Shapes)
7		MODAL	Spatial or Modal Combination First
8		SRSS	Spatial Combination Method (SRSS/ABS)
9		GROUP	Modal Combination Method (Group/10%/DSRSS/ABS/SRSS)
10		Y	Include Missing Mass Components (Y/N)
11		SRSS	Missing Mass Combination Method (SRSS/ABS)
12		ABS	Directional Combination Method (SRSS/ABS)
13		CONSISTENT	Mass Model (LUMPED/CONSISTENT)
14		Y	Sturm Sequence Check on Computed Eigenvalues (Y/N)

- Frequency cutoff 100 Hz, since it is a Fast Acting load.
- Run the Spectral Analysis analysis.

Spectral Analysis

- Results

Max. Displacement (Z) Case # 1	15.8 in				
Max. Displacement (Y) Case # 2	0.224 in				
Max. Stress Case # 1	37,952	lb./sq.in.	Code Stress Allowable	30989	lb./sq.in.
Max. Stress Case # 2	14,769	lb./sq.in.			

Failed by 22%

Time-History Analysis

- Static Equivalent (not shown in this presentation)
- Spectral Analysis
- **Time-History Analysis**

Time-History Analysis (1)

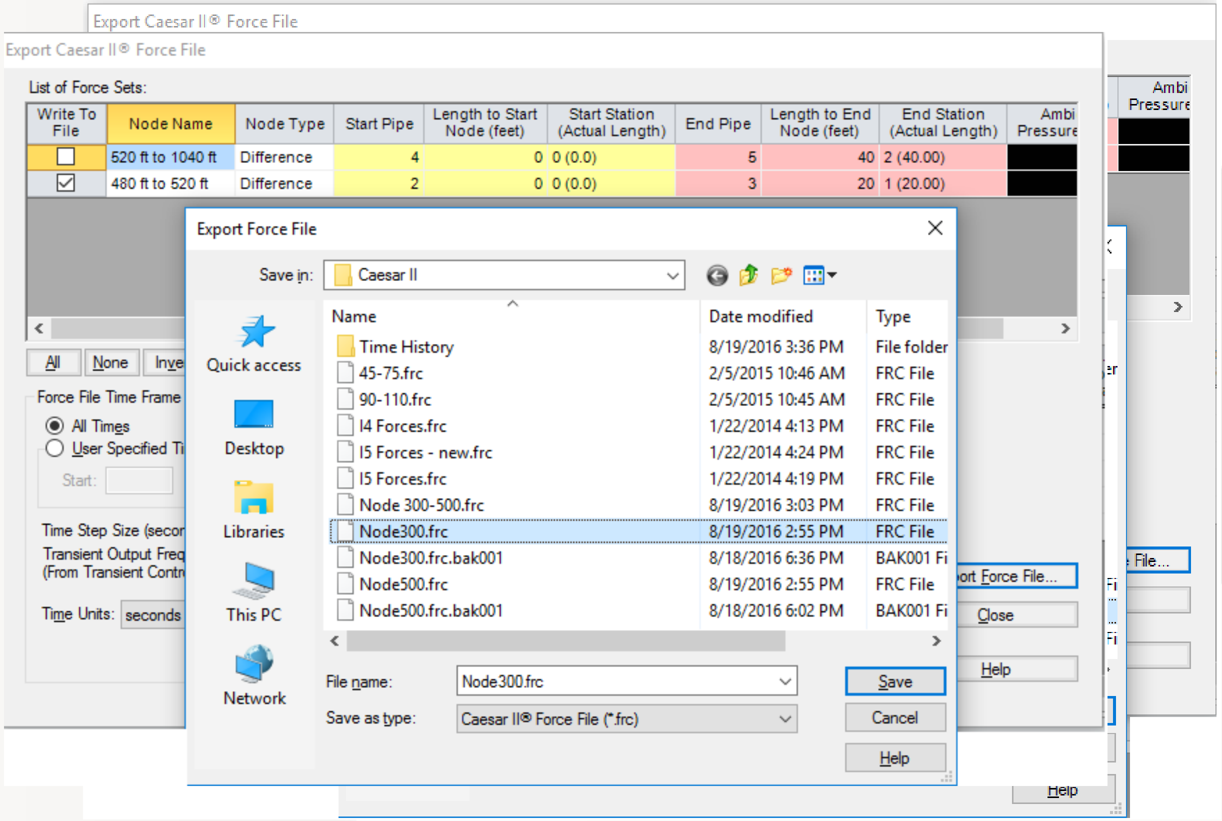
- The input required for Time-History analysis is almost exactly the same as that for Spectral analysis. Both require the same force magnitude, direction and location. Both will incorporate the same force-time data.
- The fundamental difference is that, in Time-History analysis the force-time data is applied directly to the model, and the response is evaluated at incremental steps in time through the event.
- Spectral analysis instead converts the force-time data into a maximum-response curve that is matched to the natural frequencies of the piping system.
- Unlike Spectral analysis, Time-History considers the timing of events, and considers the kinetic energy of the system in motion during the event.

Time-History Analysis (2)

- Time-History input is not automatically created for us, so we have to manually input more of the data to perform this analysis.
- Time-History requires millisecond units in the force-time input, while Spectral required seconds when importing AFT Impulse data.

Time-History Analysis (2)

- Generating Spectrums (They must be created separately)



List of Force Sets:

Write To File	Node Name	Node Type	Start Pipe	Length to Start Node (feet)	Start Station (Actual Length)	End Pipe	Length to End Node (feet)	End Station (Actual Length)	Ambi Pressure
☐	520 ft to 1040 ft	Difference	4	0	0 (0.0)	5	40	2 (40.00)	
☑	480 ft to 520 ft	Difference	2	0	0 (0.0)	3	20	1 (20.00)	

Force File Time Frame

● All Times
○ User Specified Ti

Start:

Time Step Size (secon

Transient Output Freq
(From Transient Contr

Time Units: seconds

Save in: Caesar II

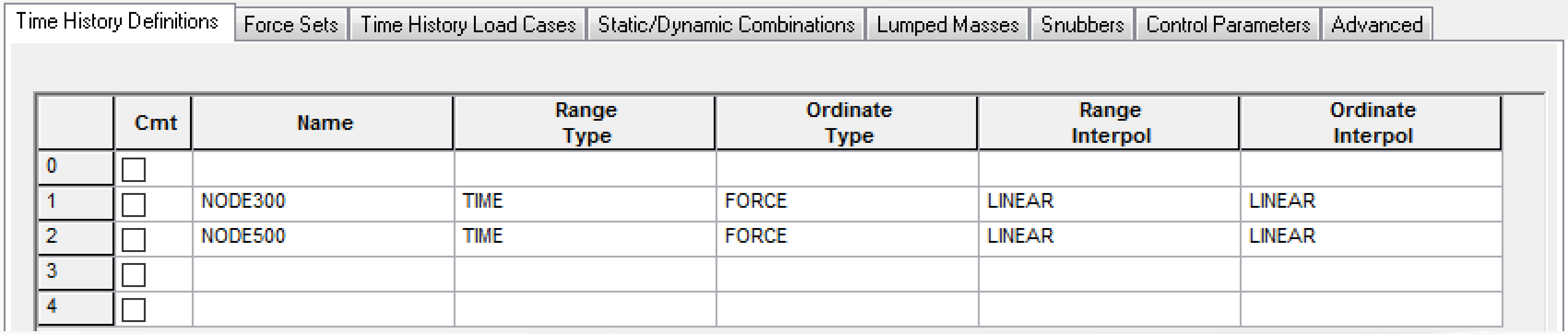
Name	Date modified	Type
Time History	8/19/2016 3:36 PM	File folder
45-75.frc	2/5/2015 10:46 AM	FRC File
90-110.frc	2/5/2015 10:45 AM	FRC File
I4 Forces.frc	1/22/2014 4:13 PM	FRC File
I5 Forces - new.frc	1/22/2014 4:24 PM	FRC File
I5 Forces.frc	1/22/2014 4:19 PM	FRC File
Node 300-500.frc	8/19/2016 3:03 PM	FRC File
Node300.frc	8/19/2016 2:55 PM	FRC File
Node300.frc.bak001	8/18/2016 6:36 PM	BAK001 Fi
Node500.frc	8/19/2016 2:55 PM	FRC File
Node500.frc.bak001	8/18/2016 6:02 PM	BAK001 Fi

File name: Node300.frc

Save as type: Caesar II® Force File (*.frc)

Time-History Analysis (3)

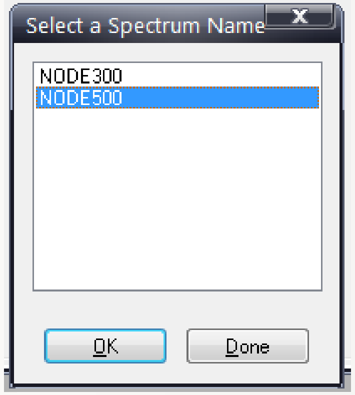
- Open CII Dynamic Input
- Add two more pulse definitions to the CAESAR II dynamic input



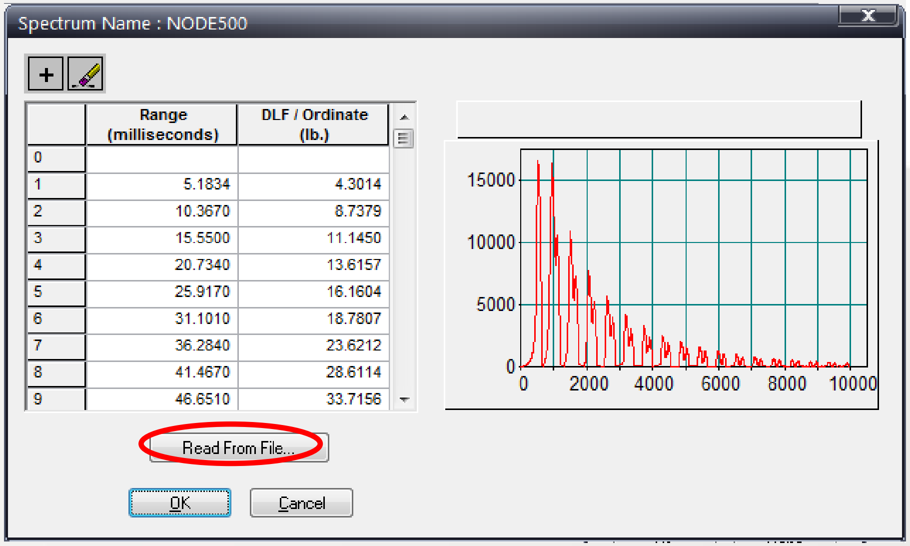
	Cmt	Name	Range Type	Ordinate Type	Range Interpol	Ordinate Interpol
0	☐					
1	☐	NODE300	TIME	FORCE	LINEAR	LINEAR
2	☐	NODE500	TIME	FORCE	LINEAR	LINEAR
3	☐					
4	☐					

Time-History Analysis (4)

- Add the data for the two new pulses


Select a Spectrum Name

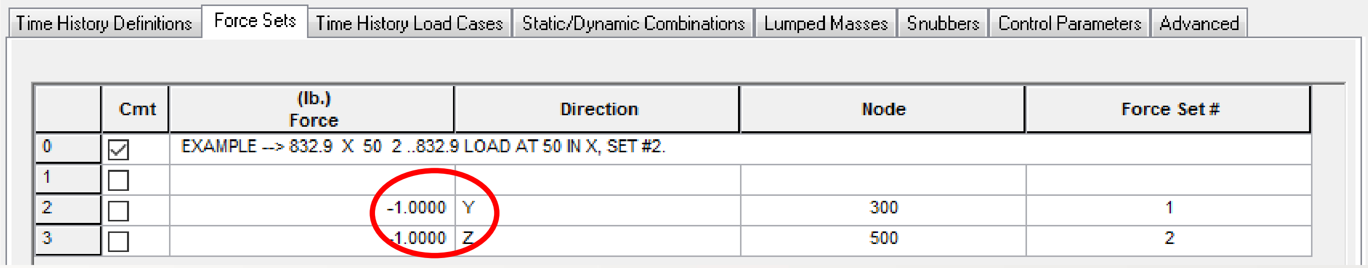
NODE300
NODE500


Spectrum Name : NODE500

	Range (milliseconds)	DLF / Ordinate (lb.)
0		
1	5.1834	4.3014
2	10.3670	8.7379
3	15.5500	11.1450
4	20.7340	13.6157
5	25.9170	16.1604
6	31.1010	18.7807
7	36.2840	23.6212
8	41.4670	28.6114
9	46.6510	33.7156

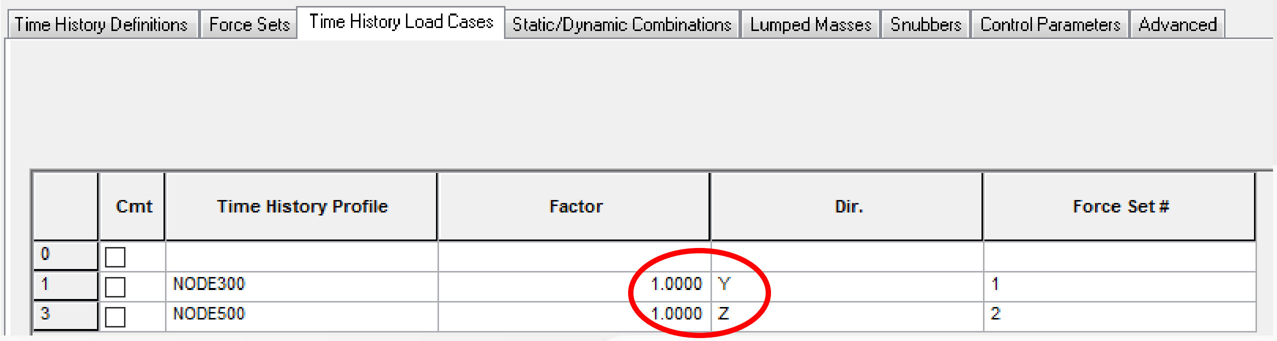
Time-History Analysis (5)

- Define the force sets: Location and direction. Magnitude is already defined when data is imported



	Cmt	(lb.) Force	Direction	Node	Force Set #
0	☑	EXAMPLE --> 832.9 X 50 2 ..832.9 LOAD AT 50 IN X, SET #2.			
1	☐				
2	☐	-1.0000	Y	300	1
3	☐	-1.0000	Z	500	2

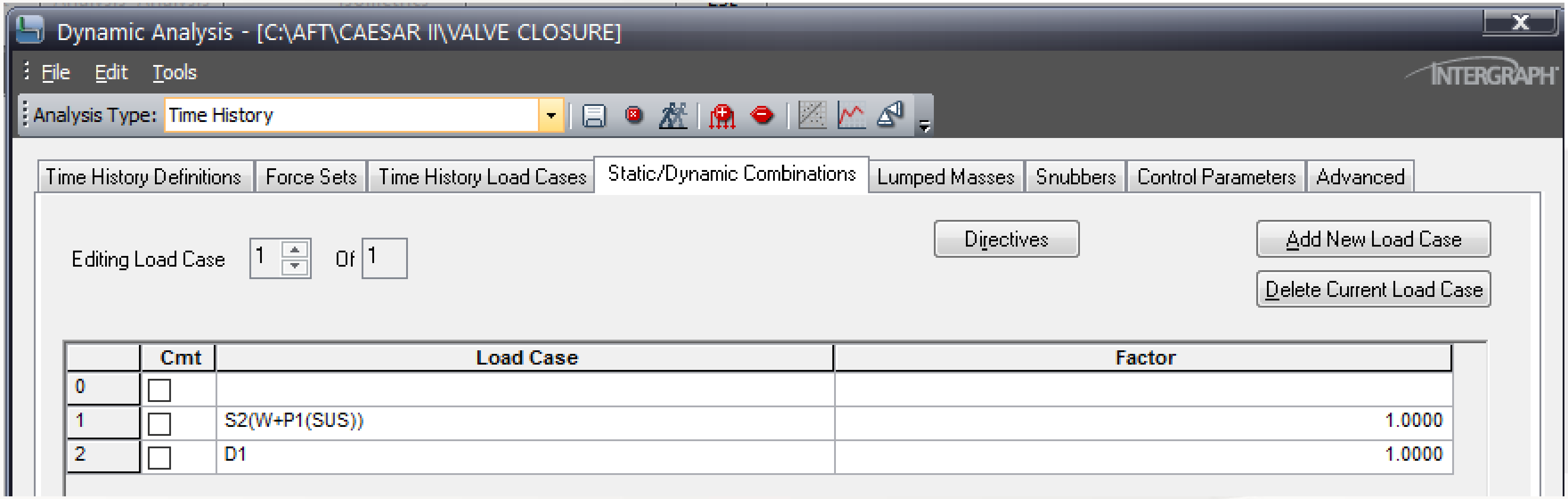
- Create the time-history load case.



	Cmt	Time History Profile	Factor	Dir.	Force Set #
0	☐				
1	☐	NODE300	1.0000	Y	1
3	☐	NODE500	1.0000	Z	2

Time-History Analysis (6)

- Create the Static/Dynamic Combination.



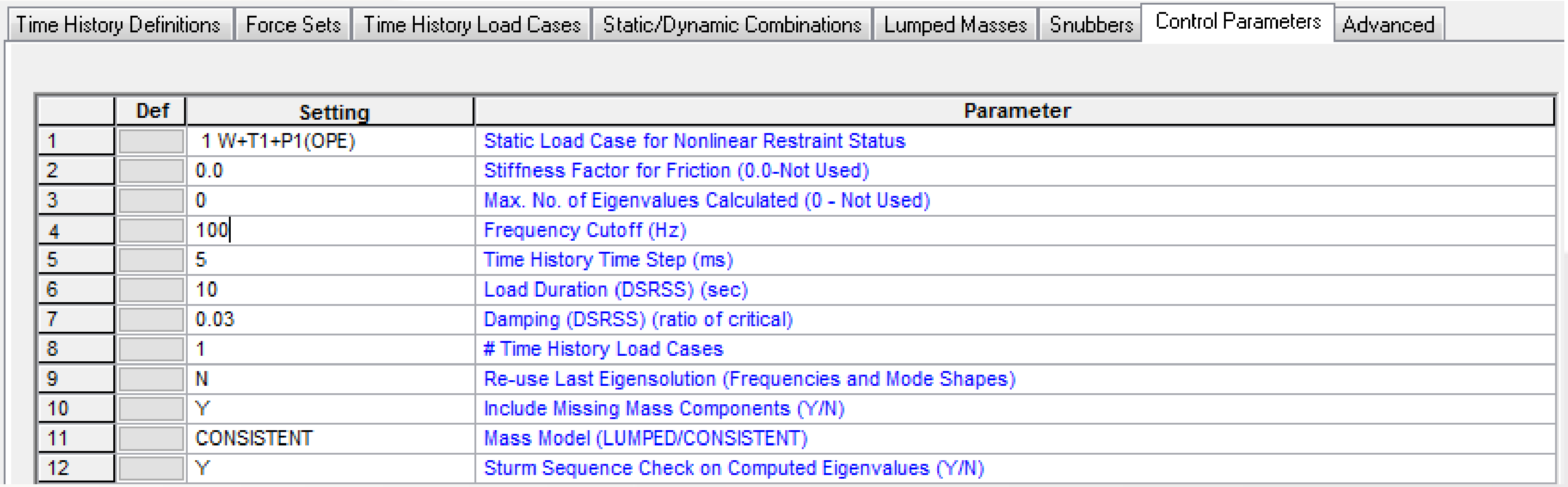
Analysis Type: Time History

Editing Load Case 1 Of 1

	Cmt	Load Case	Factor
0	☐		
1	☐	S2(W+P1(SUS))	1.0000
2	☐	D1	1.0000

Time-History Analysis (7)

- Update Control Parameters dialog



	Def	Setting	Parameter
1		1 W+T1+P1(OPE)	Static Load Case for Nonlinear Restraint Status
2		0.0	Stiffness Factor for Friction (0.0-Not Used)
3		0	Max. No. of Eigenvalues Calculated (0 - Not Used)
4		100	Frequency Cutoff (Hz)
5		5	Time History Time Step (ms)
6		10	Load Duration (DSRSS) (sec)
7		0.03	Damping (DSRSS) (ratio of critical)
8		1	# Time History Load Cases
9		N	Re-use Last Eigensolution (Frequencies and Mode Shapes)
10		Y	Include Missing Mass Components (Y/N)
11		CONSISTENT	Mass Model (LUMPED/CONSISTENT)
12		Y	Sturm Sequence Check on Computed Eigenvalues (Y/N)

- Frequency cutoff 100 Hz, since it is a Fast Acting load.
- Time step (5 ms) and duration (10 sec), were taken from AFT Impulse.
- Run the time-history analysis.

Time-History Analysis (8)

- Results

Max. Displacement (Z)	10.0 in				
Max. Displacement (Y)	0.3 in				
Max. Stress	36,806	lb./sq.in.	Code Stress Allowable	30989	lb./sq.in.

Failed by 18%

Solutions

How Do We Prevent This Failure?

1. Slow the closing of the valve to a minimum of 1 Sec.

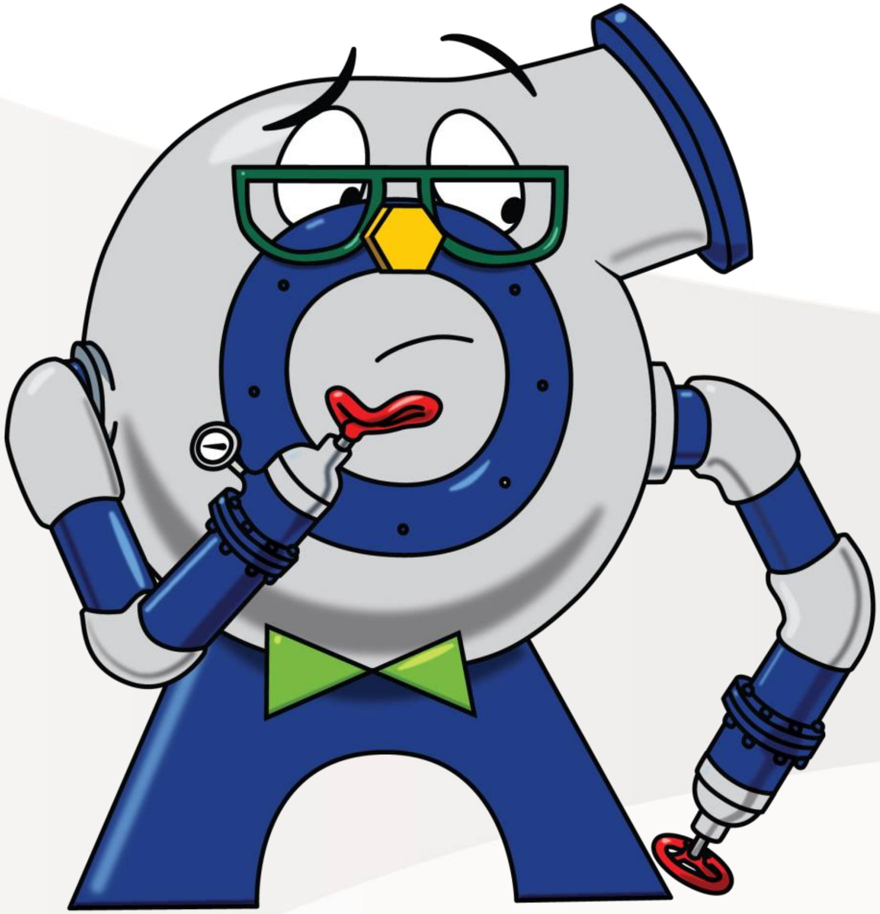
Max. Displacement (Z)	7.98 in				
Max. Displacement (Y)	0.25 in				
Max. Stress	30,022	lb./sq.in.	Code Stress Allowable	30989	lb./sq.in.

2. Add an axial restraint in the run 520-1040 to absorb the load.
    1. The equivalent load is on the order of 13,472 lb, a restraint could be expensive.
    2. Better ideas is to try to lower the magnitude of the load (if possible).

Conclusions

- It is important to model waterhammer events for proper system design and operation
- *AFT Impulse* can generate transient forces which can be easily imported into CAESAR II, for either Spectrum or History analysis.
- Traditional force estimation techniques which rely on pressure differences can be highly inaccurate
- Manual method ($F = \rho c \Delta V A$), can be too conservative specially with partially closing valve events.
- Partial closure of the valve can also cause failure if not done properly
- Spectral analysis can be conservative compared to History analysis

Q/A



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