Tutorial for Harmonic Analysis using CAEPIPE

The following are the Steps to perform Harmonic Analysis using CAEPIPE.

General

- A harmonic analysis is performed to determine the response of a piping system to sinusoidal loads. Harmonic forces can arise from unbalanced rotating equipment, acoustic vibrations caused by reciprocating equipment, flow impedance, and other sources. These forces can be damaging to a piping system if their frequency is close to the piping system's natural frequency, thereby introducing resonant conditions.

  It is feasible that multiple harmonic loads may be applied simultaneously at different locations of a piping system. More complex forms of vibration, such as those caused by the fluid flow, may be considered as superposition of several simple harmonics, each with its own frequency, magnitude, and phase.

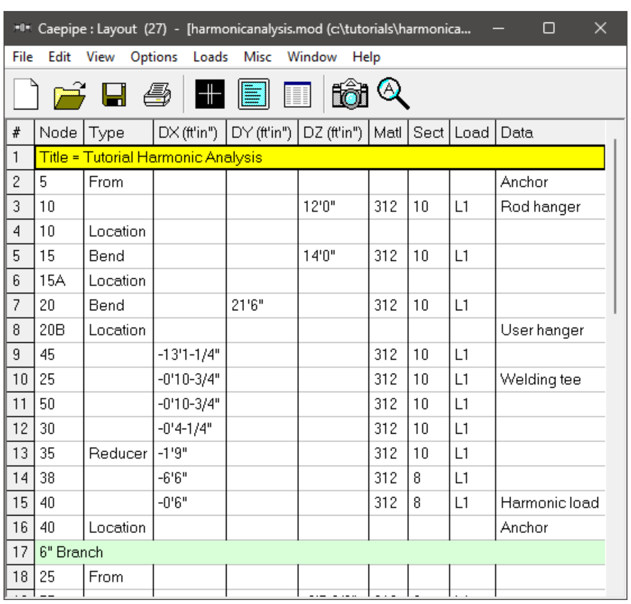
- A harmonic analysis uses the results from the modal analysis to obtain a solution. A single damping factor is used for all modes.

  First, the maximum response for each harmonic load is obtained separately. Then, the total response for multiple simultaneous harmonic loads is determined by combining the individual responses. The combination method may be specified as the Root Mean Square (RMS) or Absolute Sum. Even in the case of a system with a single harmonic load, the said combination is always carried out, so that the resulting solution becomes an "unsigned" case. For an unsigned case, the actual values for displacements, element forces and moments, etc. computed internally by CAEPIPE prior to such combination can be +ve or -ve for the dynamic event.

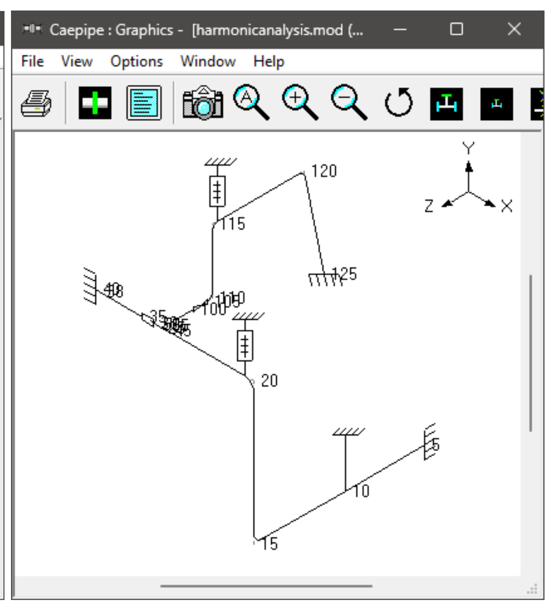
Step 1:

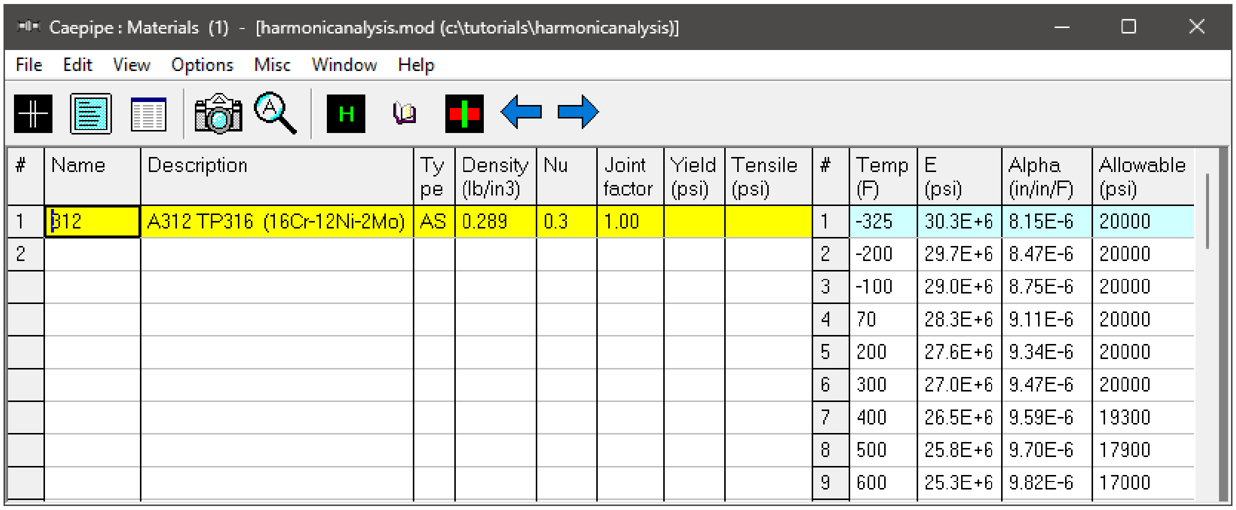
Attached is a CAEPIPE model for Harmonic Analysis. For this model, let us assume the following.

1. Node 5 is connected to a Tank.
2. Node 40 is connected to a Pump Suction Nozzle.



#	Node	Type	DX (ft'in")	DY (ft'in")	DZ (ft'in")	Matl	Sect	Load	Data
1	Title = Tutorial Harmonic Analysis								
2	5	From							Anchor
3	10				12'0"	312	10	L1	Rod hanger
4	10	Location							
5	15	Bend			14'0"	312	10	L1	
6	15A	Location							
7	20	Bend		21'6"		312	10	L1	
8	20B	Location							User hanger
9	45		-13'1-1/4"			312	10	L1	
10	25		-0'10-3/4"			312	10	L1	Welding tee
11	50		-0'10-3/4"			312	10	L1	
12	30		-0'4-1/4"			312	10	L1	
13	35	Reducer	-1'9"			312	10	L1	
14	38		-6'6"			312	8	L1	
15	40		-0'6"			312	8	L1	Harmonic load
16	40	Location							Anchor
17	6" Branch								
18	25	From							





Caepipe : Materials (1) - [harmonicanalysis.mod (c:\tutorials\harmonicanalysis)]

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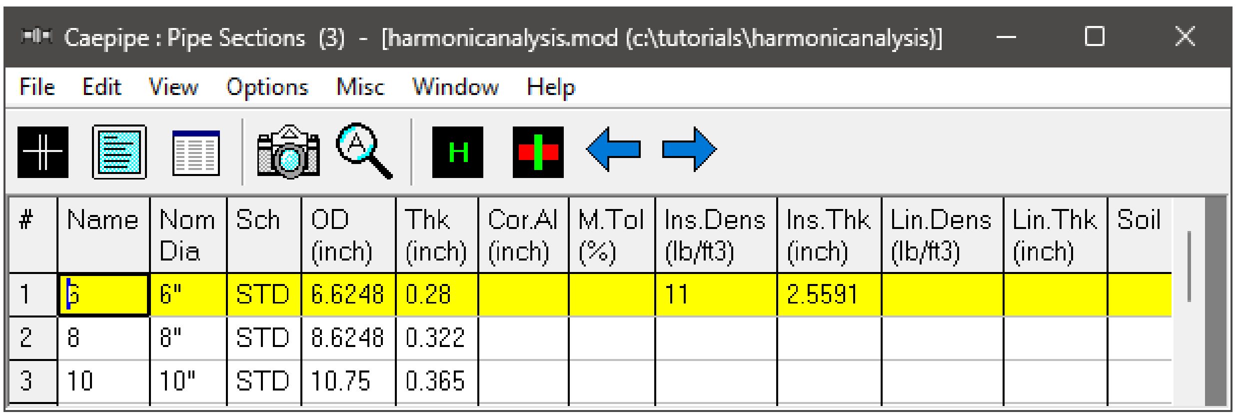
#	Name	Description	Type	Density (lb/in3)	Nu	Joint factor	Yield (psi)	Tensile (psi)
1	312	A312 TP316 (16Cr-12Ni-2Mo)	AS	0.289	0.3	1.00		
2								

#	Temp (F)	E (psi)	Alpha (in/in/F)	Allowable (psi)
1	-325	30.3E+6	8.15E-6	20000
2	-200	29.7E+6	8.47E-6	20000
3	-100	29.0E+6	8.75E-6	20000
4	70	28.3E+6	9.11E-6	20000
5	200	27.6E+6	9.34E-6	20000
6	300	27.0E+6	9.47E-6	20000
7	400	26.5E+6	9.59E-6	19300
8	500	25.8E+6	9.70E-6	17900
9	600	25.3E+6	9.82E-6	17000



Caepipe : Pipe Sections (3) - [harmonicanalysis.mod (c:\tutorials\harmonicanalysis)]

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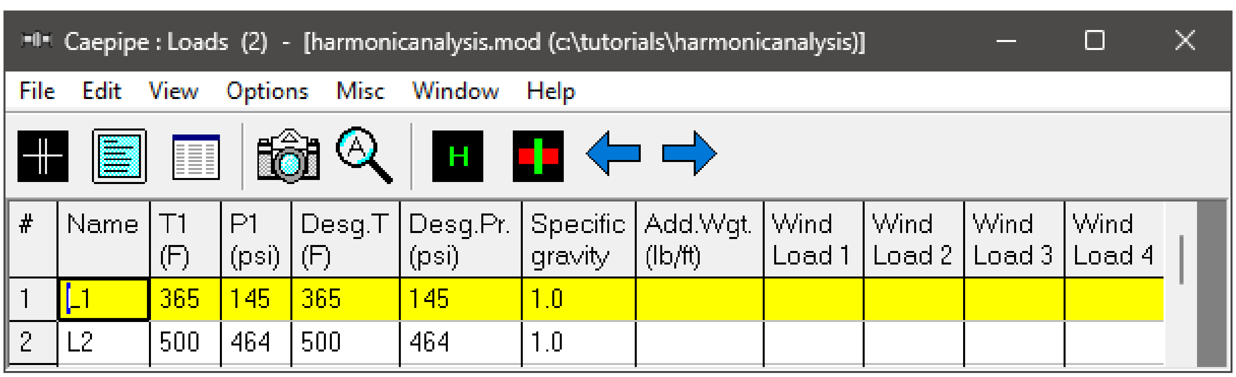
#	Name	Nom Dia	Sch	OD (inch)	Thk (inch)	Cor.Al (inch)	M.Tol (%)	Ins.Dens (lb/ft3)	Ins.Thk (inch)	Lin.Dens (lb/ft3)	Lin.Thk (inch)	Soil
1	6	6"	STD	6.6248	0.28			11	2.5591			
2	8	8"	STD	8.6248	0.322							
3	10	10"	STD	10.75	0.365							



Caepipe : Loads (2) - [harmonicanalysis.mod (c:\tutorials\harmonicanalysis)]

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#	Name	T1 (F)	P1 (psi)	Desg.T (F)	Desg.Pr. (psi)	Specific gravity	Add.Wgt. (lb/ft)	Wind Load 1	Wind Load 2	Wind Load 3	Wind Load 4
1	L1	365	145	365	145	1.0					
2	L2	500	464	500	464	1.0					

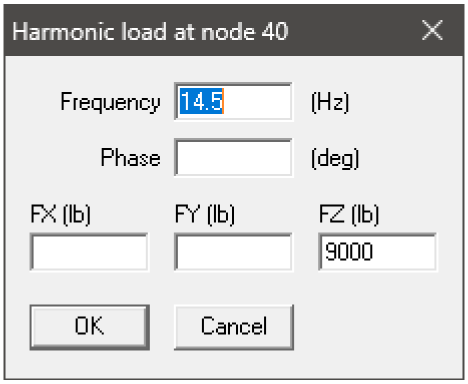
Step 2:

The harmonic load can be imposed as a Force (FX/FY/FZ) at a specified frequency and phase angle. You may be able to get more information on the harmonic loading (mass, rpm, etc.) from the manufacturer of the equipment.

For this Tutorial, the following assumptions are made.

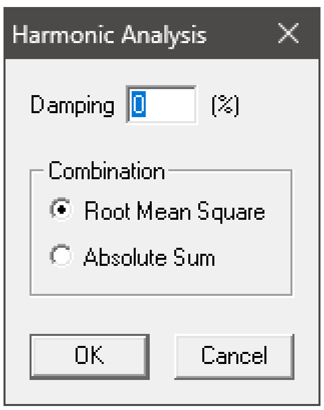
1. Frequency of the rotating equipment = 14.5 Hz.
2. Force in Global Z Direction = FZ = 9000 lb.

The above parameters are entered for analysis by creating a "Data" type called "Harmonic Load" through Layout window > Misc > Data types... at Node 40. See snap shot below for details.



Step 3:

Define “Percentage of Damping” and “Combination” method for Harmonic analysis through CAEPIPE Layout window > Loads > Harmonic…



Step 4:

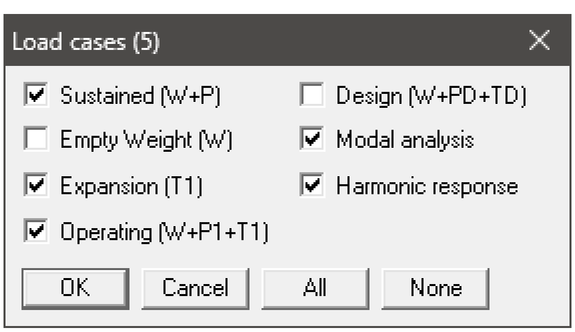
Then, include “Harmonic response” for analysis through Layout window > Loads > Load cases.

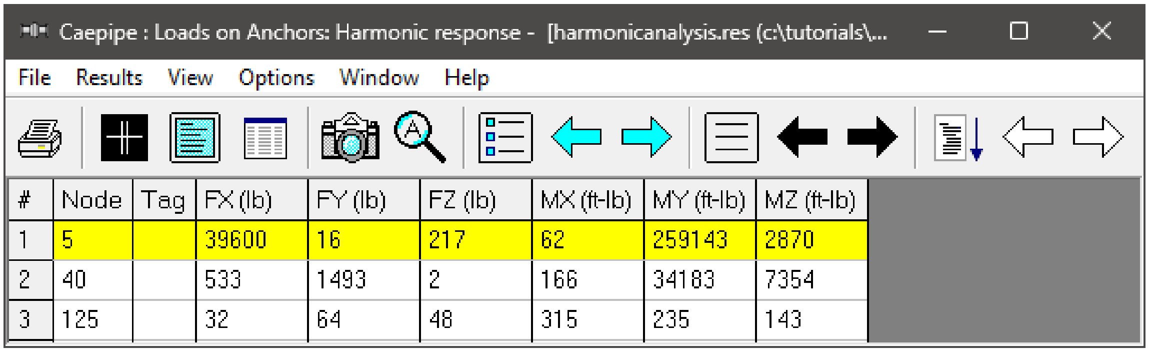
Step 5:

Save the model and perform the analysis through Layout window > File > Analyze. CAEPIPE will apply these loads to compute the response of the piping system by performing a Harmonic analysis along with other load cases defined in the piping system.

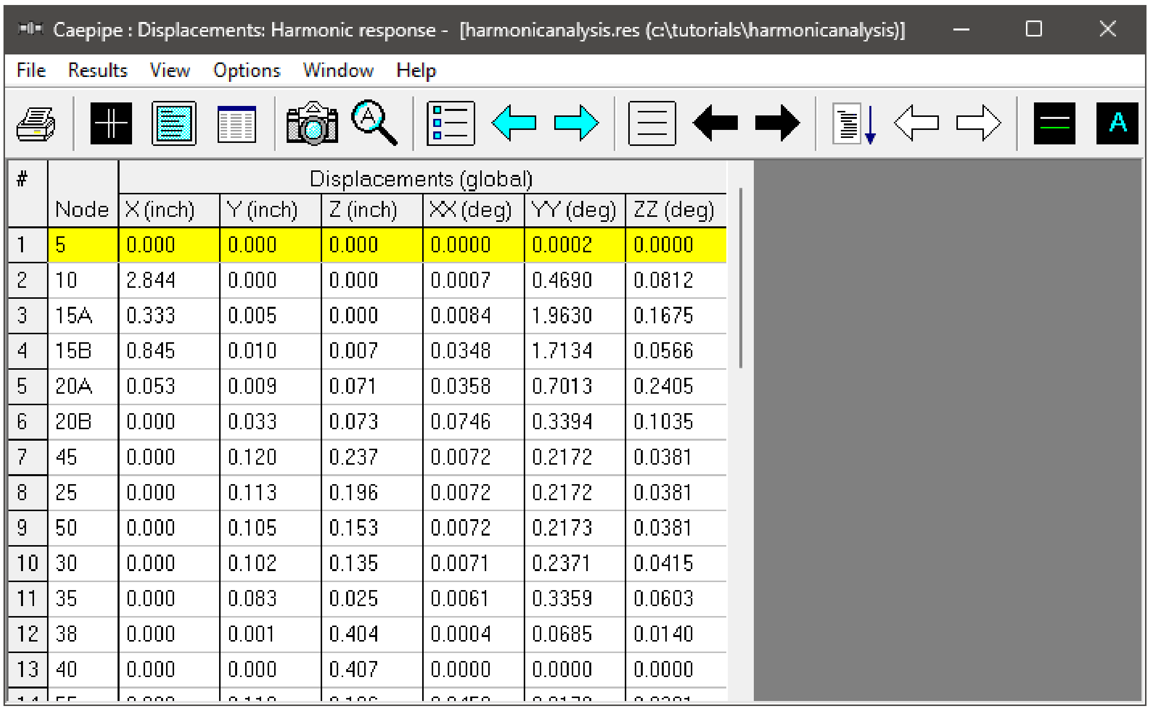
Step 6:

Upon successful analysis, CAEPIPE will now show a “Load case” with name “Harmonic response” under “Support Loads”, “Displacements”, “Element forces” and “Support load summary” results.

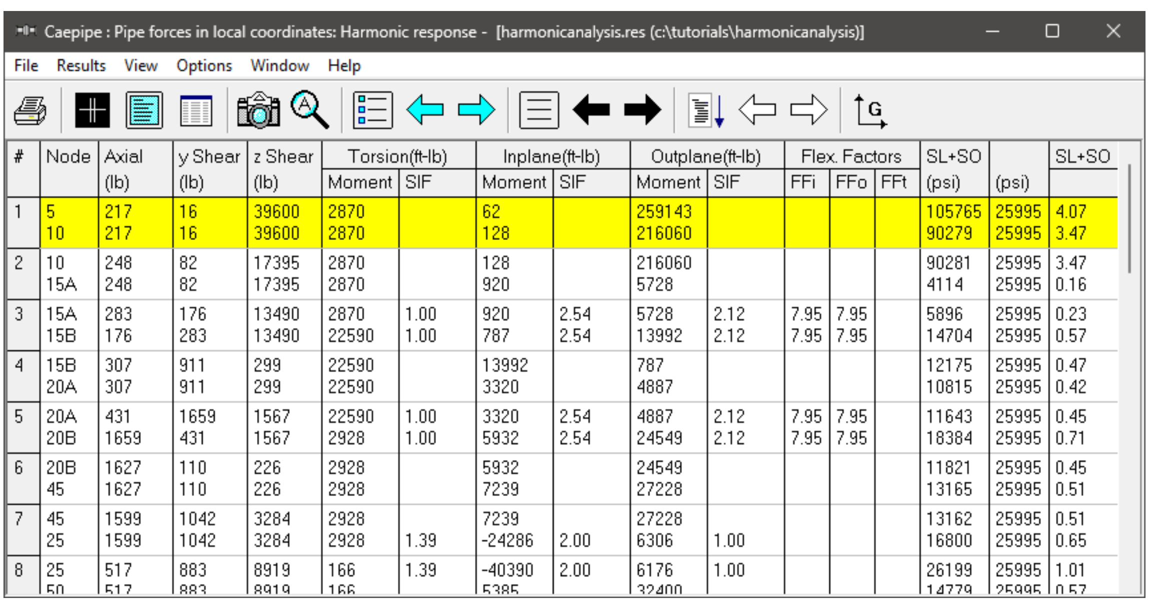




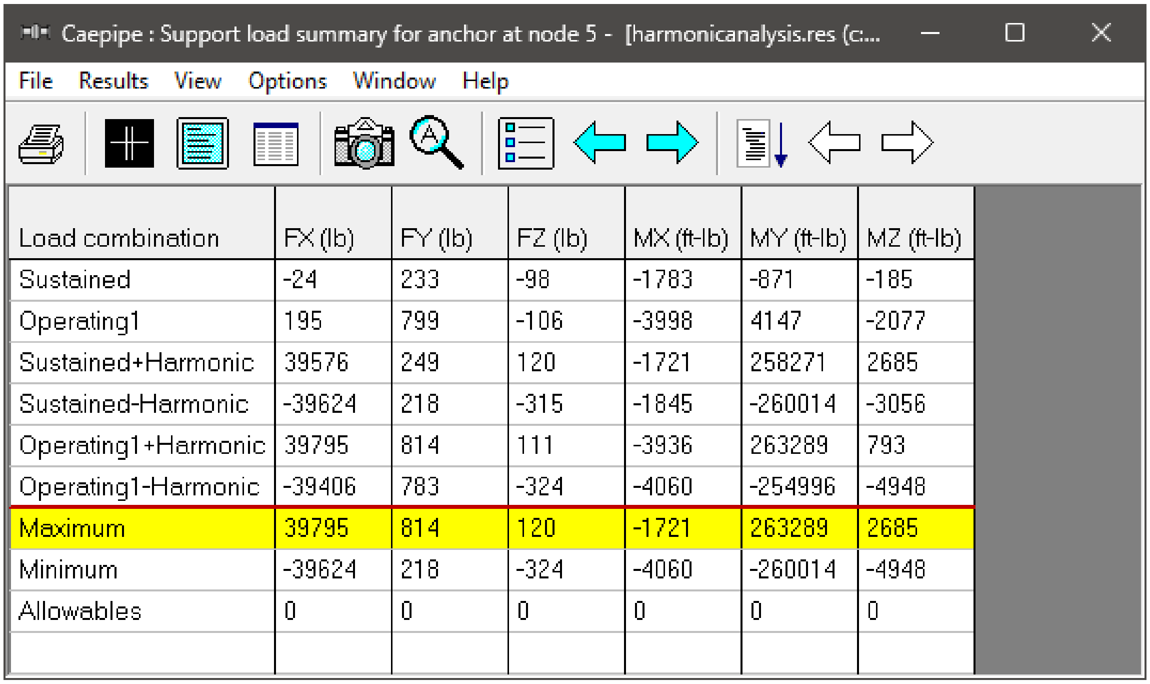
#	Node	Tag	FX (lb)	FY (lb)	FZ (lb)	MX (ft-lb)	MY (ft-lb)	MZ (ft-lb)
1	5		39600	16	217	62	259143	2870
2	40		533	1493	2	166	34183	7354
3	125		32	64	48	315	235	143



#		Displacements (global)					
	Node	X (inch)	Y (inch)	Z (inch)	XX (deg)	YY (deg)	ZZ (deg)
1	5	0.000	0.000	0.000	0.0000	0.0002	0.0000
2	10	2.844	0.000	0.000	0.0007	0.4690	0.0812
3	15A	0.333	0.005	0.000	0.0084	1.9630	0.1675
4	15B	0.845	0.010	0.007	0.0348	1.7134	0.0566
5	20A	0.053	0.009	0.071	0.0358	0.7013	0.2405
6	20B	0.000	0.033	0.073	0.0746	0.3394	0.1035
7	45	0.000	0.120	0.237	0.0072	0.2172	0.0381
8	25	0.000	0.113	0.196	0.0072	0.2172	0.0381
9	50	0.000	0.105	0.153	0.0072	0.2173	0.0381
10	30	0.000	0.102	0.135	0.0071	0.2371	0.0415
11	35	0.000	0.083	0.025	0.0061	0.3359	0.0603
12	38	0.000	0.001	0.404	0.0004	0.0685	0.0140
13	40	0.000	0.000	0.407	0.0000	0.0000	0.0000



#	Node	Axial	y Shear	z Shear	Torsion(ft-lb)		Inplane(ft-lb)		Outplane(ft-lb)		Flex. Factors			SL+SO		SL+SO
		(lb)	(lb)	(lb)	Moment	SIF	Moment	SIF	Moment	SIF	FFi	FFo	FFt	(psi)	(psi)	
1	5 10	217 217	16 16	39600 39600	2870 2870		62 128		259143 216060					105765 90279	25995 25995	4.07 3.47
2	10 15A	248 248	82 82	17395 17395	2870 2870		128 920		216060 5728					90281 4114	25995 25995	3.47 0.16
3	15A 15B	283 176	176 283	13490 13490	2870 22590	1.00 1.00	920 787	2.54 2.54	5728 13992	2.12 2.12	7.95 7.95	7.95 7.95		5896 14704	25995 25995	0.23 0.57
4	15B 20A	307 307	911 911	299 299	22590 22590		13992 3320		787 4887					12175 10815	25995 25995	0.47 0.42
5	20A 20B	431 1659	1659 431	1567 1567	22590 2928	1.00 1.00	3320 5932	2.54 2.54	4887 24549	2.12 2.12	7.95 7.95	7.95 7.95		11643 18384	25995 25995	0.45 0.71
6	20B 45	1627 1627	110 110	226 226	2928 2928		5932 7239		24549 27228					11821 13165	25995 25995	0.45 0.51
7	45 25	1599 1599	1042 1042	3284 3284	2928 2928	 1.39	7239 -24286	 2.00	27228 6306	 1.00				13162 16800	25995 25995	0.51 0.65
8	25 50	517 517	883 883	8919 8919	166 166	1.39	-40390 5385	2.00	6176 32400	1.00				26199 14779	25995 25995	1.01 0.57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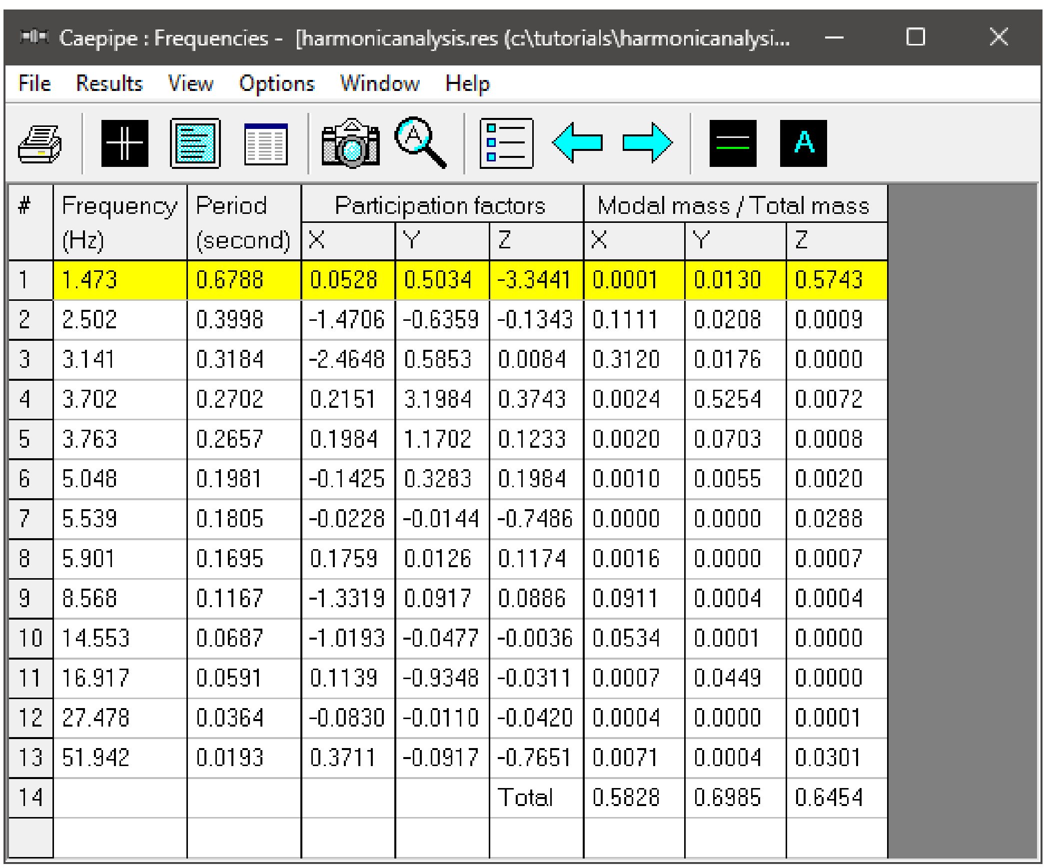
Load combination	FX (lb)	FY (lb)	FZ (lb)	MX (ft-lb)	MY (ft-lb)	MZ (ft-lb)
Sustained	-24	233	-98	-1783	-871	-185
Operating1	195	799	-106	-3998	4147	-2077
Sustained+Harmonic	39576	249	120	-1721	258271	2685
Sustained-Harmonic	-39624	218	-315	-1845	-260014	-3056
Operating1+Harmonic	39795	814	111	-3936	263289	793
Operating1-Harmonic	-39406	783	-324	-4060	-254996	-4948
Maximum	39795	814	120	-1721	263289	2685
Minimum	-39624	218	-324	-4060	-260014	-4948
Allowables	0	0	0	0	0	0

Step 7:

From the review of frequency results of CAEPIPE, it is noted that one of the natural frequencies of this piping system (i.e., frequency for Mode 10 shown in yellow highlight in the snap shot below) is close to the rotating equipment frequency of 14.5 Hz.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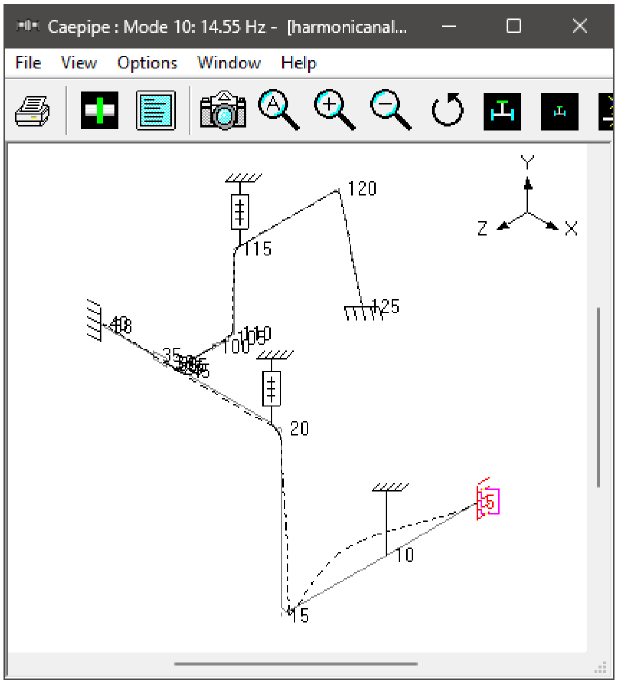
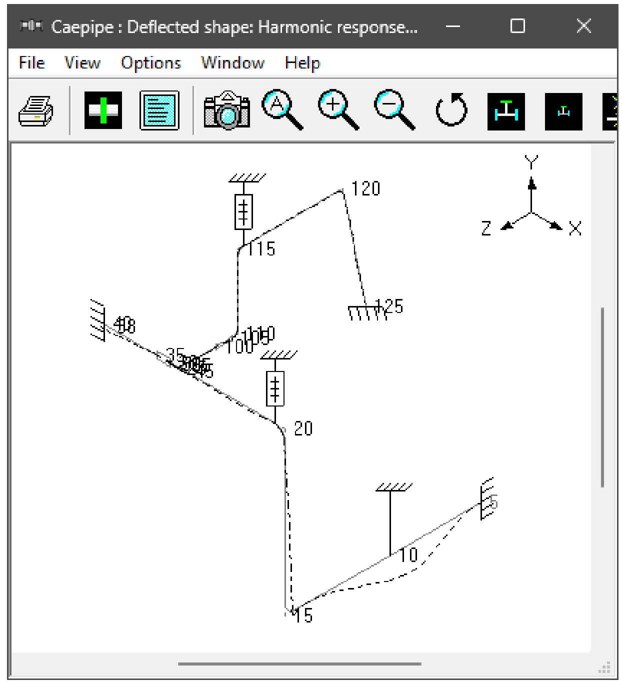
#	Frequency	Period	Participation factors			Modal mass / Total mass		
	(Hz)	(second)	X	Y	Z	X	Y	Z
1	1.473	0.6788	0.0528	0.5034	-3.3441	0.0001	0.0130	0.5743
2	2.502	0.3998	-1.4706	-0.6359	-0.1343	0.1111	0.0208	0.0009
3	3.141	0.3184	-2.4648	0.5853	0.0084	0.3120	0.0176	0.0000
4	3.702	0.2702	0.2151	3.1984	0.3743	0.0024	0.5254	0.0072
5	3.763	0.2657	0.1984	1.1702	0.1233	0.0020	0.0703	0.0008
6	5.048	0.1981	-0.1425	0.3283	0.1984	0.0010	0.0055	0.0020
7	5.539	0.1805	-0.0228	-0.0144	-0.7486	0.0000	0.0000	0.0288
8	5.901	0.1695	0.1759	0.0126	0.1174	0.0016	0.0000	0.0007
9	8.568	0.1167	-1.3319	0.0917	0.0886	0.0911	0.0004	0.0004
10	14.553	0.0687	-1.0193	-0.0477	-0.0036	0.0534	0.0001	0.0000
11	16.917	0.0591	0.1139	-0.9348	-0.0311	0.0007	0.0449	0.0000
12	27.478	0.0364	-0.0830	-0.0110	-0.0420	0.0004	0.0000	0.0001
13	51.942	0.0193	0.3711	-0.0917	-0.7651	0.0071	0.0004	0.0301
14					Total	0.5828	0.6985	0.6454

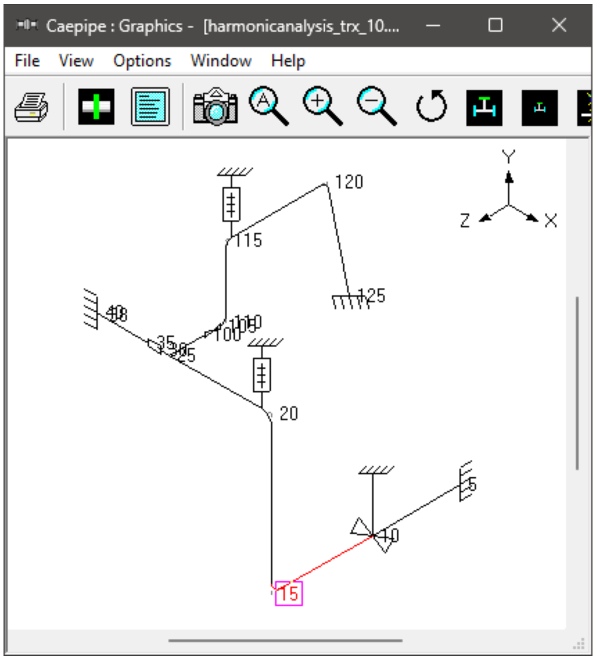
Due to closeness of Mode 10 frequency to the equipment frequency, it is observed that Mode 10 is excited on the piping system by the harmonic load, thereby creating a resonance. This can be seen graphically by plotting the mode shape corresponding to Mode 10 with frequency of “14.55 Hz” (figure shown on the left below) and the deflected shape for “harmonic response” case (figure shown on the right below). See snap shots for details.





Step 8:

In order to prevent piping failure due to resonance, it is important to suppress relevant modes by changing the stiffness of the piping system either by adding or by moving the existing piping supports. For example, for the layout shown above, a lateral restraint in X direction is added at Node 10 as the displacement in X direction is about 3” for Harmonic Response case prior to adding this X restraint. By adding this new support, the stiffness of the piping system is altered. This, in turn, removed the 10^{th} frequency with “14.55 Hz”, thereby ensuring that the natural frequency of the piping system is not close to the operating equipment frequency. See snap shots below.



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#	Frequency (Hz)	Period (second)	Participation factors			Modal mass / Total mass		
			X	Y	Z	X	Y	Z
1	1.474	0.6783	-0.0075	-0.4970	3.3457	0.0000	0.0127	0.5749
2	2.956	0.3382	-0.9955	0.9922	0.0814	0.0509	0.0506	0.0003
3	3.581	0.2792	-1.5073	-1.3860	-0.1892	0.1167	0.0987	0.0018
4	3.729	0.2682	0.0054	3.0516	0.3445	0.0000	0.4782	0.0061
5	4.705	0.2125	-1.8744	0.4453	0.0945	0.1804	0.0102	0.0005
6	5.101	0.1961	-0.4923	-0.2136	-0.1835	0.0124	0.0023	0.0017
7	5.540	0.1805	0.0155	-0.0171	-0.7481	0.0000	0.0000	0.0287
8	5.904	0.1694	-0.2497	-0.0065	-0.1154	0.0032	0.0000	0.0007
9	8.585	0.1165	-1.3138	0.0878	0.0881	0.0886	0.0004	0.0004
10	16.913	0.0591	-0.0654	0.9358	0.0313	0.0002	0.0450	0.0001
11	27.472	0.0364	-0.1185	-0.0109	-0.0420	0.0007	0.0000	0.0001
12	51.938	0.0193	0.3657	-0.0902	-0.7605	0.0069	0.0004	0.0297
13					Total	0.4601	0.6985	0.6450