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Effects of Crack Depth on the Mode Shapes and Natural Frequencies of Y-Junction Pipes

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ABSTRACT

Maintenance shutdowns are not affordable in process industries due to certain economic factors. Piping system in any process plant is key element and therefore must be monitored carefully to detect any damage in its initiation or early propagation stage. This research work aims to establish an effectual understanding of vibration behavior of piping structures in the process industry. Y-junction piping models having 3 cases are crack modelled, mapped mesh and analyzed in Ansys APDL®. Natural frequency data is gathered from the analysis and the data of all three cases is compared to see the effects of the crack angles on the modes and natural frequencies of the models.

1. Introduction

The piping systems in the process industry are vulnerable to the severe dynamic loads experienced in operations that include nominally random vibrations. This dynamic effect extrapolates itself if some abnormality is developed inside the operating system e.g. crack initialization in the pipe. For the accurate functioning of the process plants, cracks need to be detected primarily during crack initiation or in the early propagation stage, before ultimate failure occurs. If a crack is allowed to grow in one of the pipes without being detected, catastrophic failure could occur due to the high pressure/velocities of fluids.

2. Modal Characteristics-Based Investigations

The modal characteristics of any system comprise its natural frequencies, mode shapes, modal masses and modal damping ratios. These modal properties are highly dependent on the physical properties of the structure, which include mass, damping and stiffness. Any change in the system's physical properties ascertains a corresponding detectable change in its modal characteristics. This noticeable change in the modal properties provides the basis for the vibration-based investigations of cylindrical pipe structures. Therefore, in Phase-I of the proposed research, effect of varying fluid properties will be investigated on the natural frequencies and mode shapes of the piping structures with and without cracks.

Effective operation of the process industry is highly dependent on the integrity of the whole system. Therefore, any abnormality developed in the system should be detected timely to avoid catastrophic failure. Moreover, Maintenance shutdowns are not affordable in process industries due to certain economic factors. Piping system in any process plant is key element and therefore must be monitored carefully to detect any damage in its initiation or early propagation stage. This research work aims to establish an effectual understanding of vibration behavior of piping structures in the process industry for varying fluid and crack variables. In addition to that, the proposed research also aims to develop an effective damage detection methodology to highlight damage in dynamically vulnerable environment, which will attempt to minimize chances of sudden maintenance shutdowns of the process plants.

3. Literature Review

Understanding the effect of crack initiation and propagation on the dynamic characteristics of a system has attracted the attention of many researchers in the past [1-18]. Talking particularly about vibration behavior, Kam and LCC [I5] provide detailed information about the subject by carrying out vibration-based investigations on the turbine and compressor blades. They also considered the difference in the dynamic behavior, due to the presence of a crack in the blade, on the blade itself, on the group of blades and on the complete row of blades. In addition to that, some analytical and numerical methods have also been presented to depict the effect of the presence of a crack in a blade on the overall vibration

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response of the system. For cantilever type structures, the vibration decay time varies according to the location of the crack. Any crack near the clamped end results in a longer vibration decay time as compared to a crack developed near the free end. Therefore it is necessary to understand the effects of the presence of a crack on the dynamics of the whole system [1, 2, and 8]. Before going deep into the investigation of the crack-induced dynamics into the structure, it will be useful to address the conflicting issues related to the selection of the type of crack model for the vibration-based investigations and its modelling.

4. Modelling

Modelling was done for 3 cases as described in the table below .

Table 1: Cases for the analysis

Cases	*Angle between Inlets*
Case 1	30
Case 2	60
Case 3	90

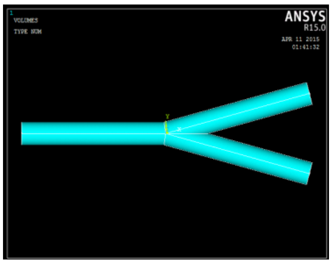


Figure 1: 30 Degree y-junction

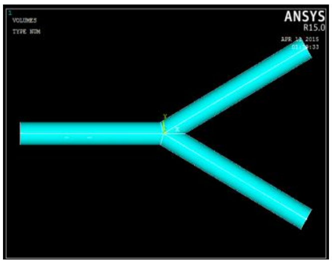


Figure 2: 60 Degree y-junction

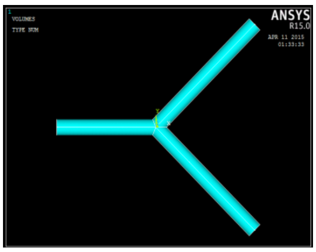


Figure 3: 90 Degree Y-junction

5. Design of Experiments

Experiments are designed to be done only on specific locations to get accurate results. Locations of all the experiments are mentioned in the table below.

Table 2: Design of experiments

Experiment No.	Case	Crack location (B/L)	Crack depth (A/D)
1.	Case 1	Location (B/L = 0.642)	0.0
2.			0.2
3.			0.4
4.			0.6
5.			0.8
6.			1.0
13.	Case 2	Location (B/L = 0.642)	0.0
14.			0.2
15.			0.4
16.			0.6
17.			0.8
18.			1.0
	Case 3	Location (B/L =0.642)	0.0
19			0.2
20			0.4
21			0.6
22			0.8
23			1.0

6. Crack Modeling

Purpose of this research is to investigate the effects of the crack on the natural frequency of the pipes. Crack free model will be taken as reference and then models with cracks will be compared from reference. Longitudinal type crack will be propagated on the junction of the pipes for the analysis.

6.1 Techniques of Crack Modelling

There are several techniques of crack modelling being taken up by the researchers, some of which are as follows:

a. Fatigue or Hair Line Crack

b. Material Removal Crack

c. Smeared Crack

d. Lumped Mass Crack

6.2 Fatigue or Hair Line Crack

Fatigue or Hair line Crack method is used here for crack modelling. In this technique, model is design in such a way that we get several volumes having their own separate nodes. These separate nodes are all merged together except for some which behave as crack during the analysis phase.

Longitudinal Crack modelling was done at several depth for the results to be compared.

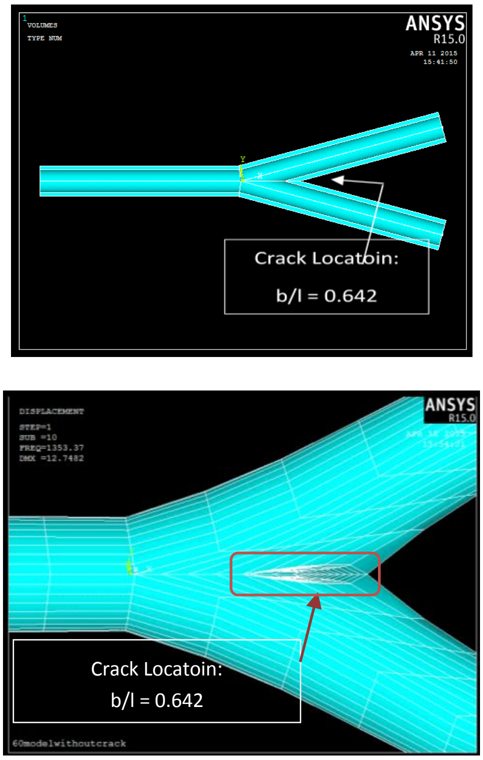


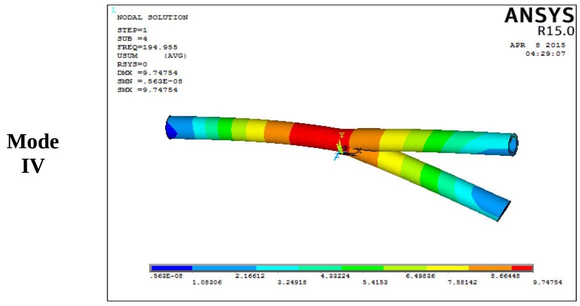
Figure 4: Crack modeling in ansys

7. Results and Discussions

Modal analysis of the pipe is done in Ansys, Apdl and mode shapes along with the data related to frequencies is gathered from there.

7.1 Comparison of Mode Shapes

Some of the Mode shapes of 30 degree junction pipe without crack are shown below.



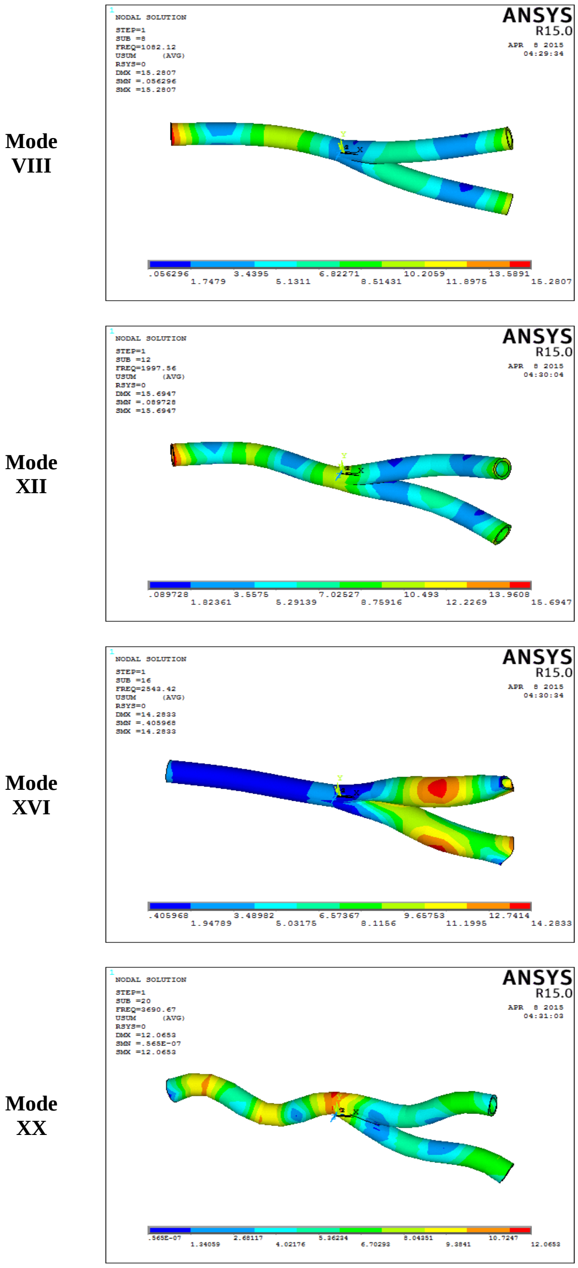
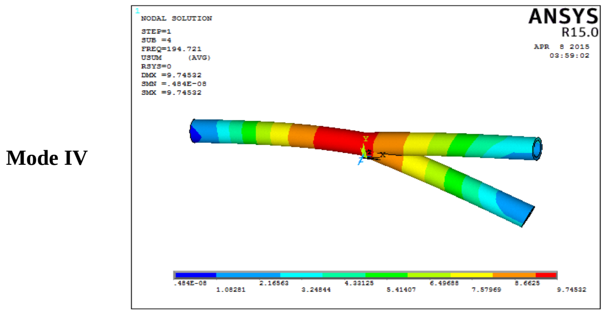
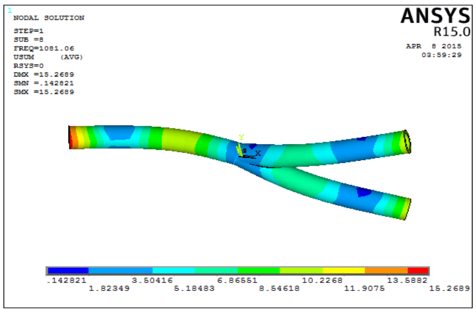


Figure 5a: Mode shapes for case-1 without crack

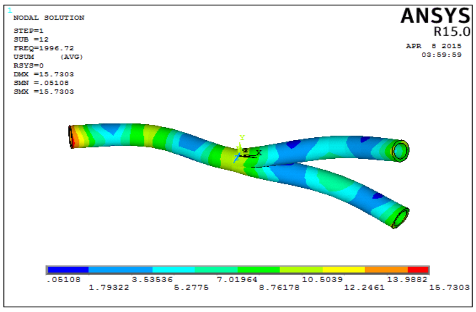
Some of the Mode shapes of 30 degree junction pipe with crack a/d = 0.2 are shown below.



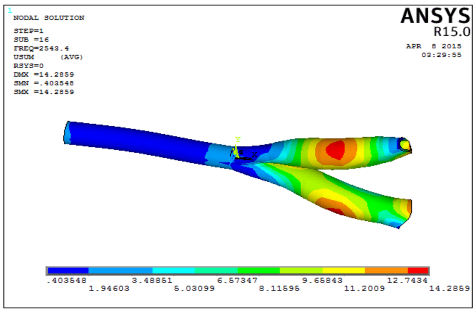
Mode VIII



Mode XII



Mode XVI



Mode XX

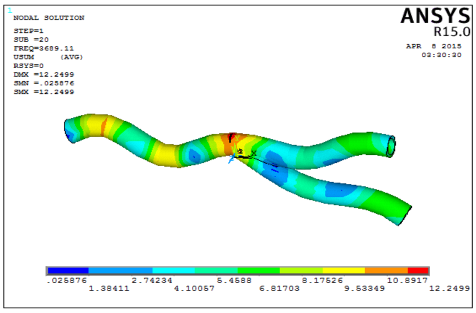
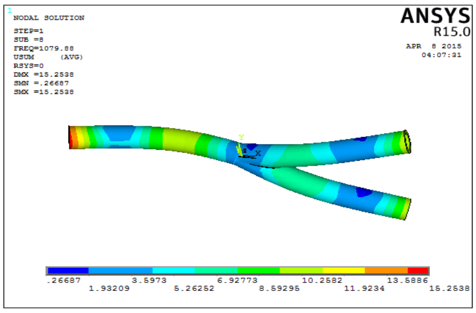
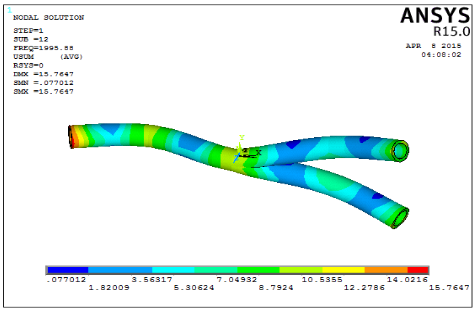


Figure 5b: Mode Shapes for Case-1 with crack depth (a/d=0.2)

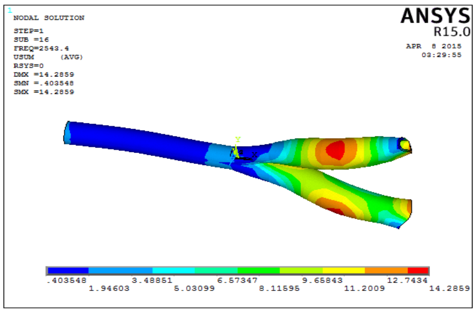
Mode VIII



Mode XII



Mode XVI



Mode XX

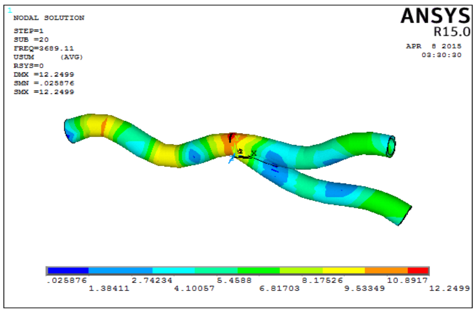
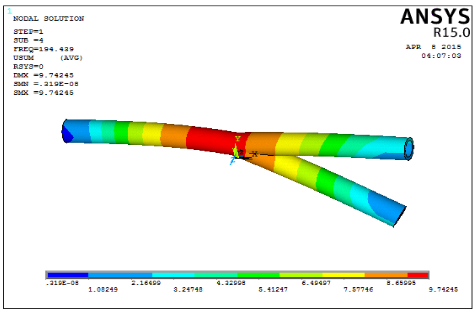


Figure 5c: Mode Shapes for Case-1 with crack depth (a/d=0.4)

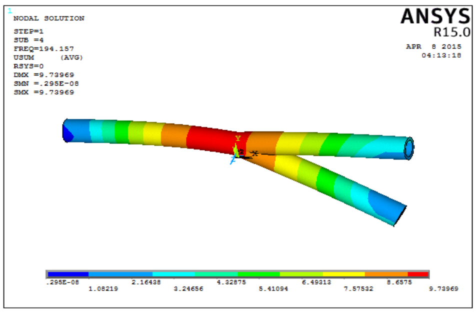
Some of the Mode shapes of 30 degree junction pipe without crack a/d = 0.4 are shown below.

Mode IV



Some of the Mode shapes of 30 degree junction pipe without crack a/d = 0.6 are shown below.

Mode IV



Mode VIII

Mode XII

Mode XVI

Mode XX

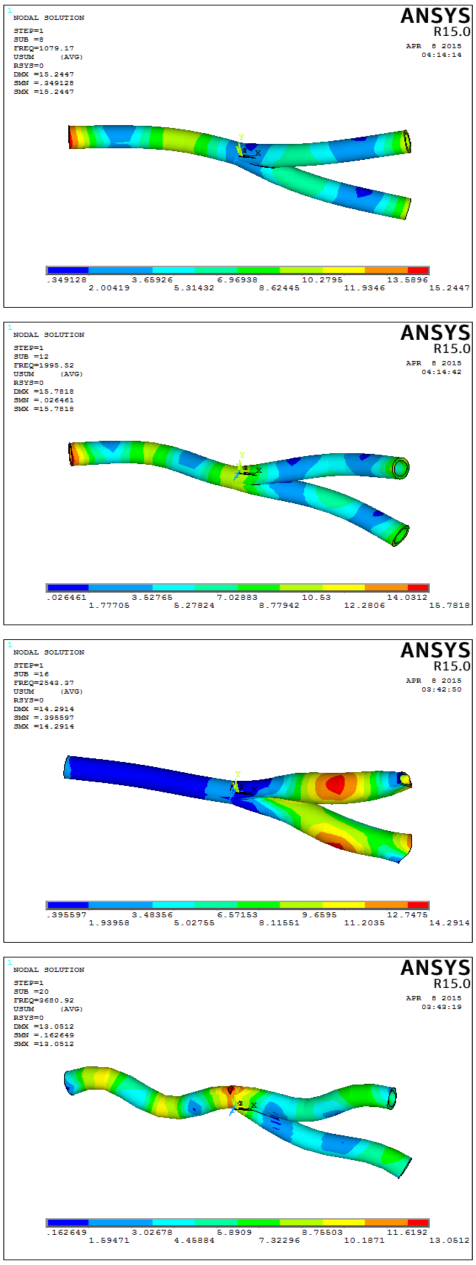
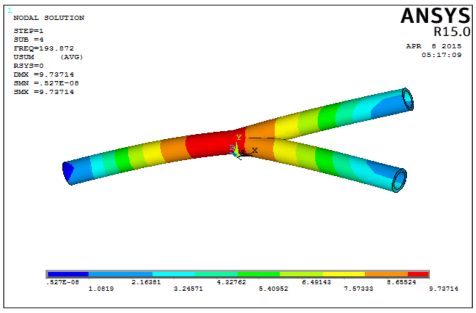


Figure 5d: Mode Shapes for Case-1 with crack depth (a/d=0.6)

Some of the Mode shapes of 30 degree junction pipe without crack a/d = 0.8 are shown below.

Mode IV



Mode VIII

Mode XII

Mode XVI

Mode XX

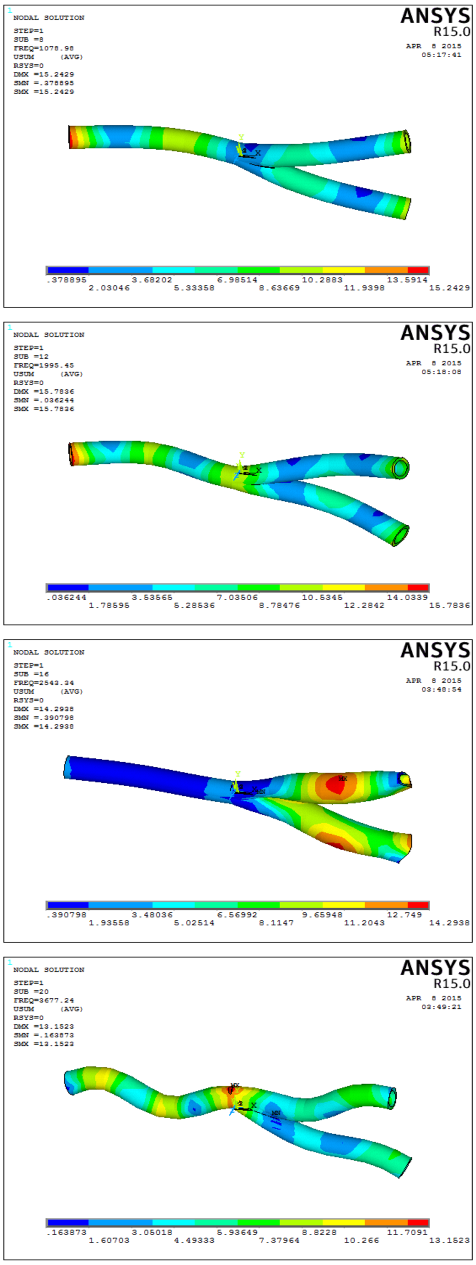
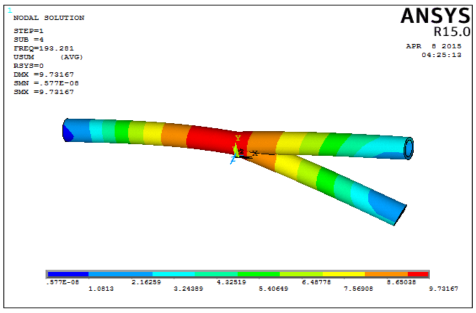


Figure 5e: Mode Shapes for Case-1 with crack depth (a/d=0.8)

Some of the Mode shapes of 30 degree junction pipe without crack a/d = 1.0 are shown below.

Mode IV



Mode VIII

Mode XII

Mode XVI

Mode XX

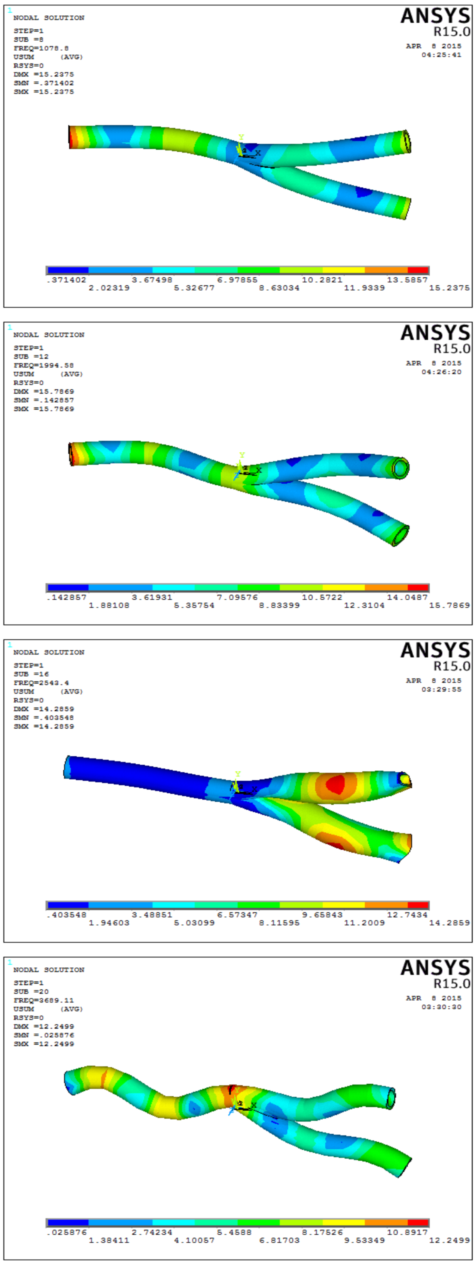


Figure 5f: Mode shapes for case-1 with crack depth (a/d=1)

It can be seen after through comparison that crack propagation does not affect the mode shapes of the pipe junction. Mode 4, mode 8, mode 12, mode 16 and mode 20 can be viewed and compared in fig 5-a to fig 5-f for consistency of mode shapes.

7.2 Comparison of Natural Frequencies

Natural frequencies of 30 degree pipe junction under a longitudinal crack at various crack depths can be seen in Table 3.

Natural frequencies of 60 degree pipe junction under a longitudinal crack at various crack depths can be seen in Table 4. It can be observed that the frequencies decrease with the increase in crack depth. Moreover, the frequencies increase with higher mode shape.

Natural frequencies of 90 degree pipe junction under a longitudinal crack at various crack depths can be seen in Table 5. It can be observed that the frequencies decrease with the increase in crack depth. Moreover, the frequencies increase with higher mode shape.

Table 3: Comparison of natural frequencies case-1

Mode No.	Crak Depth (a/d)					
	0	0.2	0.4	0.6	0.8	1
1	9.49E-03	9.87E-03	8.73E-03	8.44E-03	9.11E-03	7.75E-03
2	1.35E-02	1.06E-02	1.00E-02	9.70E-03	1.81E-02	1.20E-02
3	2.49E-02	3.50E-02	3.53E-02	2.95E-02	2.96E-02	3.10E-02
4	194.95	194.72	194.44	194.16	193.87	193.28
5	313.55	311.59	310.11	309	307.91	305.55
6	407.57	407.54	407.5	407.47	407.44	407.42
7	728.12	727.35	726.61	726.03	725.58	724.94
8	1082.1	1081.1	1079.9	1079.2	1079	1078.8
9	1138.2	1137.8	1137.2	1136.8	1136.4	1135.5
10	1390.4	1386	1369.7	1359.8	1355.1	1353.4
11	1408.9	1390.3	1390.1	1389.8	1389.5	1388.6
12	1997.6	1996.7	1995.9	1995.5	1995.5	1994.6
13	2186.5	2179.9	2174.7	2170.8	2167.1	2158.6
14	2442.1	2439	2423.5	2401.3	2394.9	2389.4
15	2508.3	2491.7	2454.9	2449.4	2449	2446
16	2543.4	2507.3	2506.4	2505.8	2505.4	2504.9
17	2845.2	2838.7	2834.6	2832	2829.5	2822.9
18	3083.2	3068	3051.4	3036.1	3020.9	2993.7
19	3115.3	3114.3	3113.4	3113	3112.9	3112.7
20	3690.7	3670.1	3624.8	3594.5	3576.6	3565.7

8. Conclusion

After thorough investigation it can be seen that the longitudinal crack does not affect the mode shapes of the pipes however natural frequencies other than the first three (Because of very low number/Value) of the pipe junction decreases with the increase in crack depth which means if the crack propagates the natural frequencies of the pipes will decrease and this phenomenon can be used during condition monitoring of the structure to track any crack propagationthat can help to prevent damage of the pipes at early stage by detection of cracks. This decrease in natural frequency due to crack propagation/increase will always happen, no matter what the junction angle is. Moreover, the natural frequencies are increasing towards higher mode shapes.

It is concluded that, with the decrease in material due to crack propagation there will be no effect on mode shapes, however the natural frequencies will always decrease.

Table 4: Natural Frequencies for Case-2 against various crack depths

Mode No.	Crack Depth (a/d)					
	0	0.2	0.4	0.6	0.8	1
1	0.0085396	7.73E-03	7.92E-03	1.15E-02	8.00E-03	8.45E-03
2	0.0088036	1.12E-02	1.26E-02	1.48E-02	8.65E-03	1.07E-02
3	0.032321	2.75E-02	2.81E-02	2.21E-02	3.24E-02	3.13E-02
4	176.5	176.2	175.89	175.65	175.47	175.2
5	189.49	189.36	189.18	189	188.81	188.55
6	377.7	377.65	377.58	377.53	377.48	377.45
7	633.53	633.45	633.33	633.2	633.04	632.84
8	844.36	844.26	844.16	844.08	844.01	843.96
9	964.28	954.35	946.26	941.7	939.7	938.9
10	1010.3	1010.2	1010.2	1010.2	1010.2	1010.1
11	1129.3	1129	1128.6	1128.1	1127.7	1127
12	1752.6	1746.7	1741.5	1739.3	1738.9	1737.8
13	1963	1960.8	1958.5	1956.9	1955.8	1954.2
14	2084	2075.6	2068.8	2066.4	2066.1	2062.6
15	2217.2	2206.2	2197.9	2192.9	2190	2188.7
16	2241.3	2240.5	2239.4	2238	2236.6	2234.6
17	2512.7	2507.8	2502.9	2499	2495.7	2492
18	2626.5	2617.4	2610.3	2606.1	2603.6	2602.7
19	2681.3	2679.8	2677.5	2674.9	2672.2	2668.2
20	2863.3	2861.8	2860.4	2859.5	2859	2858.6

Table 5: Natural Frequencies for Case-3 under various crack depths

Mode No.	Crack Depth (a/d)					
	0	0.2	0.4	0.6	0.8	1
1	0.012785	0.011099	0.012669	0.012487	0.0092025	0.0095517
2	0.013656	0.012225	0.016009	0.013787	0.010329	0.013253
3	0.029145	0.033942	0.026877	0.036924	0.031442	0.02923
4	106.86	106.82	106.78	106.74	106.73	106.72
5	164.16	164.09	164.01	163.92	163.84	163.77
6	317.9	317.86	317.8	317.73	317.67	317.64
7	488.56	488.56	488.56	488.55	488.53	488.52
8	580.17	580.17	580.16	580.14	580.13	580.11
9	745.29	740.94	736.84	733.86	732.4	732.5
10	871.87	871.71	871.56	871.41	871.35	871.38
11	961.21	961.01	960.71	960.4	960.14	959.85
12	1265	1262.2	1260	1258.4	1258.2	1258.2
13	1554.2	1545.7	1538	1532.1	1529.4	1530
14	1710.2	1709.9	1709.5	1709.3	1709.1	1709.1
15	1718.7	1718.7	1718.6	1718.5	1718.4	1718.1
16	1750.5	1748.8	1746.8	1744.9	1743.3	1741.8
17	1788.3	1787.7	1787.3	1787.1	1787	1786.3
18	2191.7	2191.1	2190.6	2190.3	2190	2189.8
19	2448.2	2447.6	2446.8	2445.6	2444.3	2442.8
20	2488.4	2486.6	2484.9	2483.5	2483.2	2483.7

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