# FEM Based Modal and Harmonic Response Study of Stepped Shaft Having Cracks and Optimize Using ANN Method

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*Authors' contributions*

*The research work is carried out by all following authors, Selection of topic and other important information is provided by author KBW. Authors AK and SK then carried out whole research work like FEM simulation, optimization and all other works present in this research work. Paper writing is completed by author AK. All authors read and approved the final manuscript.*

*Original Research Article*

## ABSTRACT

In the present research study, modal and harmonic response analysis is performed for a stepped shaft made of SS-304 material using the FEM simulation technique. In the present study crack effect is also considered to find the role of cracks during modal analysis. Total six mode shapes are considered in this study and 500 N force is considered for harmonic response analysis. The simulation is performed using Ansys WB based APDL solver. The main outcome for this study is the critical speed of shaft for rotation from 10 RPM to 80K RPM, stress, deformation of the shaft without crack, and with crack. The selected shaft is stepped in nature, total length of shaft is 300 mm having three diameters of 20 mm, 40 mm, and 60 mm. The natural frequency for all six node shapes is from 1000 Hz to 4000 Hz having deformation from 15 mm to 30 mm approx for all combinations of crack in the shaft. After all simulation it is found that for all mode shapes, the stability and strength of the shaft are good during vibration conditions.

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## 1. INTRODUCTION

A shaft is a method for moving vitality; accordingly any sort of failure in one, for example, weakness breaks, makes genuine harm the framework. The harm may prompt plant shutdown and incredible practical misfortune. In this manner, numerous endeavors lately have been made to manage shaft break location techniques. Essentially, two methodologies can be made for nondestructive shaft break location. The first is the immediate methodology which utilizes ultrasonic, infrared radiation, or X-beam imaging. High costs of the types of gear just as the necessity of direct access to the shaft are some key downsides of direct methodologies [1-3]. The subsequent one is the backhanded methodology which for the most part appraises the split properties utilizing vibrational, and shaft regular frequencies examination or electromagnetic waves alongside a canny apparatus. In the field of non-damaging assessment (NDE), neural systems are a helpful instrument for dissecting and separating distinctive assortment of estimated amounts and signals [4-7]. Neural systems additionally have advantages of constant handling notwithstanding commotion resistance registering, and thus they are the most reasonable instruments for in-site nondestructive assessment of materials. The aim of present study is to study the role of cracks in stepped shaft for modal analysis. Different cracks locations are assumed on stepped shaft then modal and harmonic response analysis is performed for this shaft for getting the effect of cracks on the shaft. ANN method is also applied in this research work to find the optimum condition for crack location in which minimum stress formation is occurring.

## 2. MATERIALS AND METHODS

The present research work is based on the application of FEM methods for finding the role of cracks on the stepped shaft. The research methodology follow by researcher is that first the shaft is made with the help of 3 D cad software Autodesk Inventor (Version 2015) [8] for stepped shaft having different cracks at different locations. After creating the CAD file time to apply FEM methods for the present study for creating FEM simulation, Ansys 14.5 [9] is used and the reason behind to use this software is the quality for simulation analysis for this type of problems. Grid independence test is performed for the present study. Material properties for stepped shaft is collected by material manufactures and literature survey both. Two type of simulations are selected for the present study, first simulation is "MODAL ANALYSIS" and second simulation is "HARMONIC RESPONSE".

## 2.1 Shaft Geometrical Details

The dimension of shaft is show in Fig. 1, as seen in figure the shaft is in stepped nature and made of SS-304 working material. The end corners are supported by bearings. Total length of shaft is 300 mm and inner most section of shaft has 100 mm length and diameter is equal to 60 mm. Intermediate shaft has 40 mm diameter and last section has diameter of 20 mm.
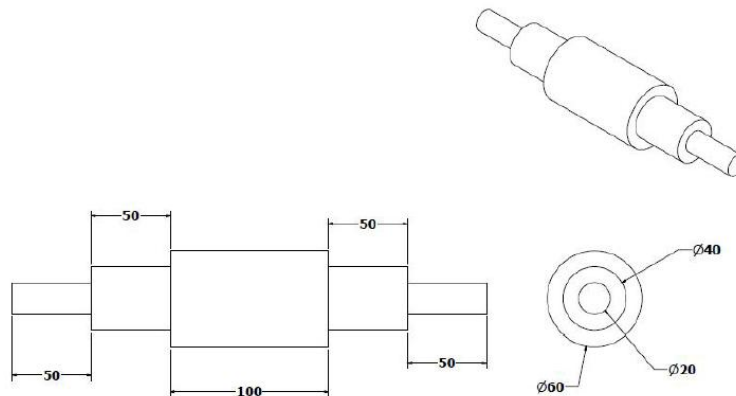


**Fig. 1. Stepped shaft dimensions used for current study**

Bearing supports are considered for the present study and load is applied on inner section of shaft during harmonic response study.

## 2.2 Shaft Materials

In the present study the shaft material is set for SS-304 and the properties of material is present in Table 1. The same properties are use in FEM simulation for both cases of modal and harmonic response analysis.

As seen in Table 1 the isotropic elasticity properties are assumed for current research study and the same is applied during FEM simulation. Because for this material linear elastic properties are used by various researchers also.

## 3. FEM MODELING STEPS

Ansys WB (Version 14.5) [08] is used in this study and the final modeling steps for this study is discuss in this section and present in Table 2 in detail.

Mesh Metric results are present in Fig. 2 for stepped shaft. Mesh metric analysis show the quality of results.

To find the best quality of mesh size grid independence test is performed for Modal analysis for mesh elements from 10,000 to 20,000 without cracked stepped shaft. After performing modal analysis for different elements, the best conversed results are got after 15000 elements for mode shape six.

## 4. MODAL AND HARMONIC RESPONSE OF SHAFT

The dynamic design and analysis were conducted for stepped shaft using ANSYS 14.5. Through modal analysis, it can acquire common frequencies, modular shapes, modular damping, modular quality, and modular solidness' of different significant segments structures. In view of these outcomes, we completed vibration investigation and inferred that the strength of ventured shaft can be ensured through maintaining a strategic distance from these frequencies or decreasing the excitation impact of these frequencies in the biggest degree. As indicated by above modular examination results, we can realize that the ventured shaft won't exposed to reverberation during working. To dissect the particular reaction impacts of ventured shaft, the symphonious reaction examination is additionally should have been directed based on modular investigation. Symphonious reaction examination of the limited component model was directed utilizing SPSS (square-root strategy) based on modular investigation.

**Table 1. Mechanical properties of SS-304**

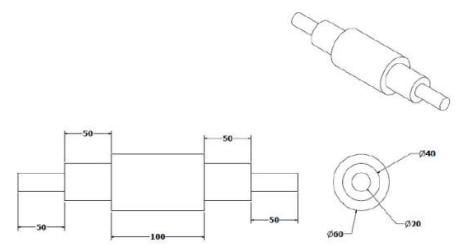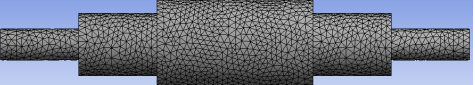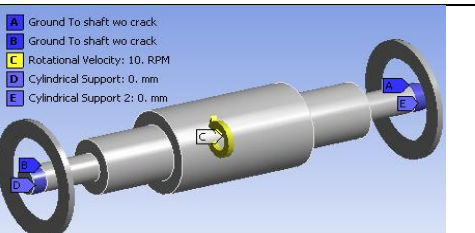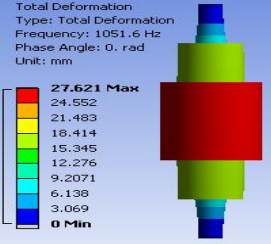| Density | 7896 | Kg/m3 |
|---|---|---|
| Young Modulus | 200 | GPa |
| Shear Modulus | 86 | GPa |
| Yield Strength | 215 | MPa |
| Tensile Ultimate Strength | 500 | MPa |
| Poisson Ratio | 0.29 | NA |
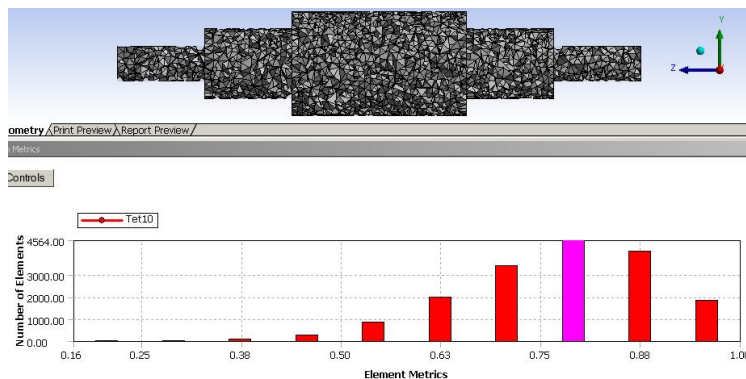


**Fig. 2. Element quality of discretized domain**

**Table 2. Modeling steps of FEM simulation**
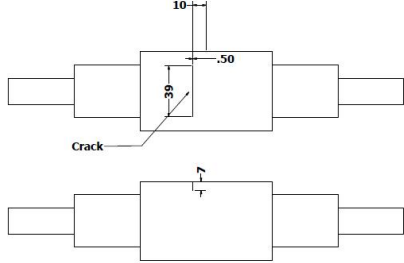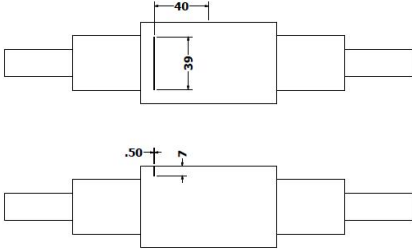
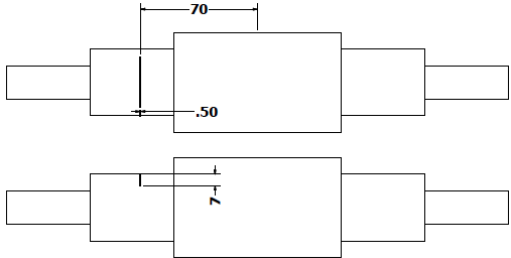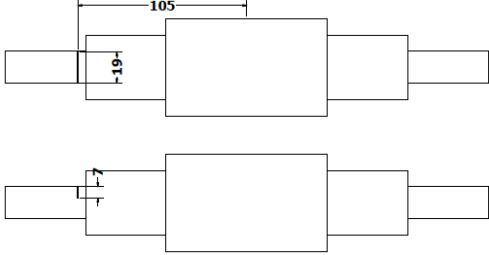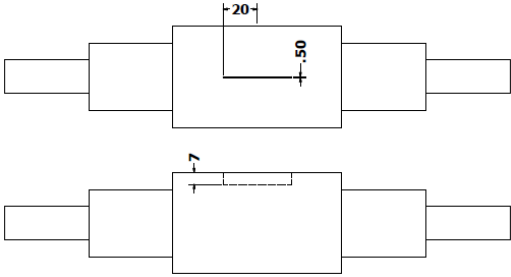| Steps | Image | Description |
|---|---|---|
| I: CAD Generation |  | Autodesk Inventor software is used for CAD file generation |
| II: Mesh Generation |  | Total Element=17010 |
| III: Material Selection | SS-304 | Properties in Table 2 |
| IV: Boundary Conditions |  A Ground To shaft wo crack / B Ground To shaft wo crack / C Rotational Velocity: 10. RPM / D Cylindrical Support: 0. mm / E Cylindrical Support 2: 0. mm | Cylindrical support present Bearing effect |
| V: Analysis Setting | Options — Max Modes to Find: 6; Limit Search to Range: No. Solver Controls — Damped: Yes; Solver Type: Program Controlled. Rotordynamics Controls — Coriolis Effect: On; Campbell Diagram: On; Number of Points: 5; Mode Reuse: Program Controlled | Rotor Dynamics is ON |
| VI: Solver | Solution Information — Solution Output: Solver Output; Newton-Raphson Residuals: 0; Update Interval: 2.5 s; Display Points: All. FE Connection Visibility — Activate Visibility: Yes; Display: All FE Connectors; Draw Connections Attached To: All Nodes; Line Color: Connection Type; Visible on Results: No; Line Thickness: Single; Display Type: Lines | APDL Solver |
| VII: Post Processing | Total Deformation / Type: Total Deformation / Frequency: 1051.6 Hz / Phase Angle: 0. rad / Unit: mm / 27.621 Max / 24.552 / 21.483 / 18.414 / 15.345 / 12.276 / 9.2071 / 6.138 / 3.069 / 0 Min | Deformation, Mode Shapes, Campbell Diagram |

## 5. CRACK DETAILS IN STEPPED SHAFT

In the present study cracks are considered as input parameter for find the role of these cracks in shaft. Although crack making in FEM modal is most complicated part but due to simplicity the simple rectangular cut is made on shaft and treated as crack for this study. The crack is 0.5 mm thick for this study. The dimensions of crack are present in Table 3.

**Table 3. Crack propagation in stepped shaft**

| Crack No | Dimension | Description |
|---|---|---|
| I |  | 10 mm away from center line of shaft having 7 mm depth |
| II |  | 40 mm away from center line of shaft having 7 mm depth |
| III |  | 70 mm away from center line of shaft having 7 mm depth |
| IV |  | 105 mm away from center line of shaft having 7 mm depth |
| V |  | Crack in center section of shaft having 7 mm depth |

As seen in Table 3, four cracks are in radial direction and one crack is in axial direction. All cracks have 7 mm depth in nature.
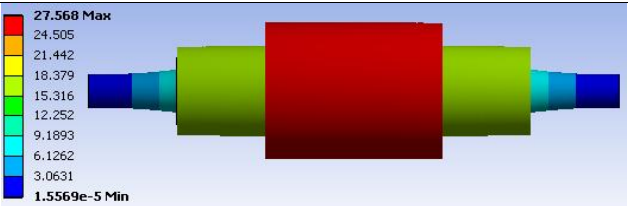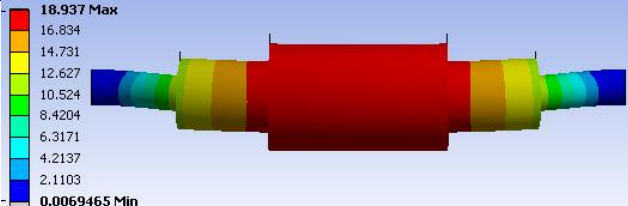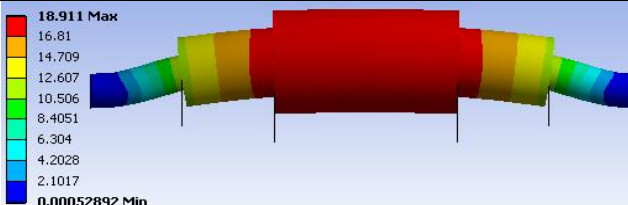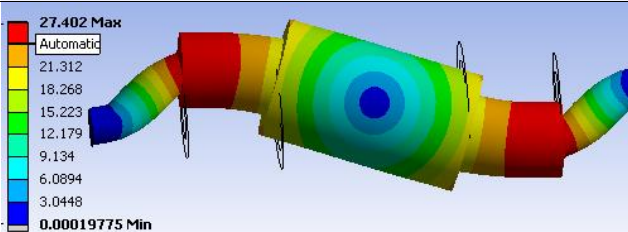
## 6. RESULTS AND DISCUSSION

The present study analyze the Modal and rotor dynamics of stepped shaft with harmonic response study for different load conditions. In the present section results are discussed for this stepped shaft. The mode shape results of shaft not having crack in it is present in Table 4 with natural frequency and maximum displacement or deformation of shaft. Total six mode shapes are considered in this study and the same is set for all combinations of cracked shaft. For avoid the repeat of results only some important results are present for cracked shaft. The stability of shaft during the maximum RPM is also present in this section for all combinations of cracked shaft. Campbell diagram is also present in this study.

As seen in Table 4, the mode shape results for stepped shaft which has no crack is present with displacement and natural frequency. The Campbell diagram for critical speed from 10 RPM to 1E+05 RPM and present in Fig. 3.

The Campbell diagram is used to find the critical speed of shaft for given rotational speed to shaft. In present figure the critical speed for three mode shapes are present in this diagram but for mode shape 4, 5 and 6 the critical speed in much higher so not present in the diagram. All mode shapes have stable rotation condition for given rotational speed to stepped shaft which has no crack on it.

Comparative analysis of stepped shaft having different cracks on it is present in Table 5, Table 6 and Table 7 for natural frequency, displacement and critical speed of shaft respectively.

**Table 4. Mode shape results for stepped shaft not have any crack**

| Mode shape | Displacement (mm) | Natural frequency |
|---|---|---|
| I |  | 1052.5 |
| II |  | 1073.7 |
| III |  | 1074.4 |
| IV |  | 2874.2 |

6

| Mode shape | Displacement (mm) | Natural frequency |
|---|---|---|
| V |  | 2876 |
| VI |  | 4080.4 |
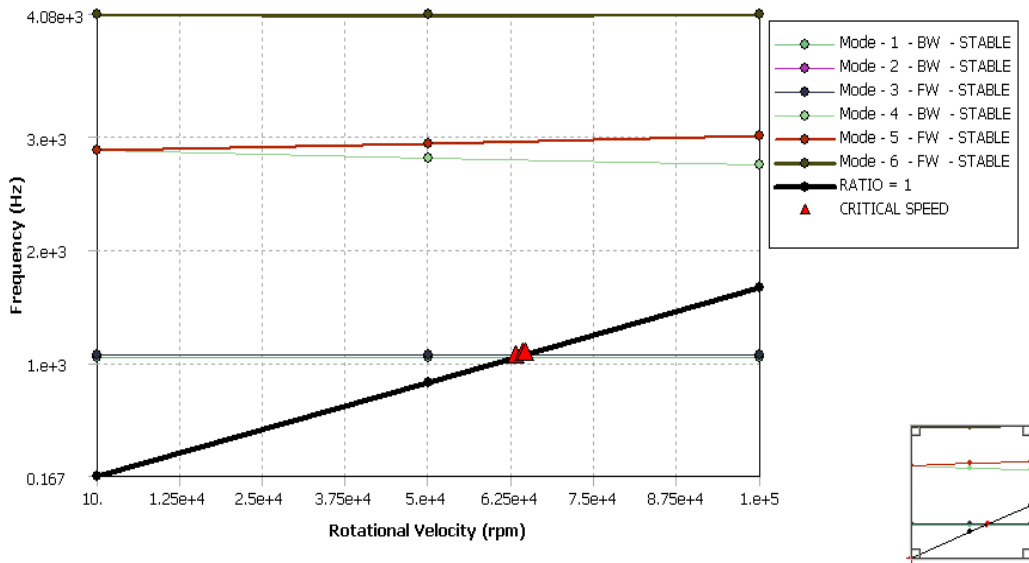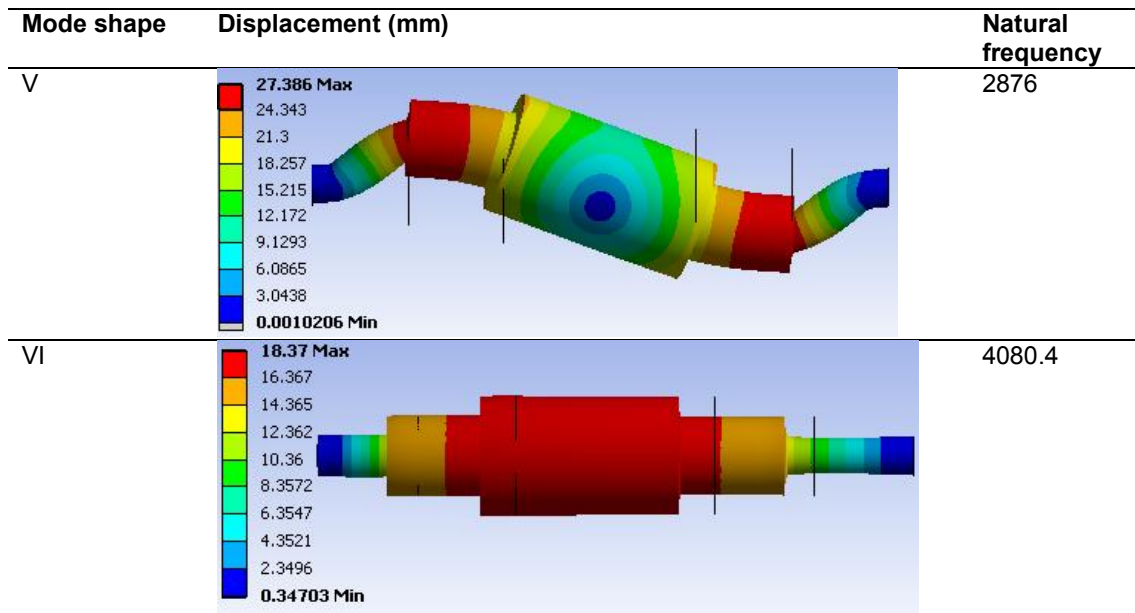


**Fig. 3. Campbell diagram for finding the critical speed of shaft**

**Table 5. Natural frequency (Hz) at different crack conditions of stepped shaft**

| Mode shape | Shaft w/o crack | Crack-I | Crack-II | Crack-III | Crack-IV | Crack-V |
|---|---|---|---|---|---|---|
| I | 1052.5 | 1052.5 | 1052.3 | 1051.2 | 1024.3 | 1051.9 |
| II | 1073.7 | 1090.7 | 1093.6 | 1083.2 | 1077.7 | 1094.0 |
| III | 1074.4 | 1094.6 | 1094.9 | 1092.8 | 1089.7 | 1094.2 |
| IV | 2874.2 | 2941.4 | 2940.8 | 2910.2 | 2817.8 | 2939.3 |
| V | 2876.0 | 2942.0 | 2943.2 | 2937.2 | 2906.5 | 2940.1 |
| VI | 4080.4 | 4105.9 | 4105.8 | 4097.0 | 4000.8 | 4104.7 |

**Table 6. Displacement (mm) at different crack conditions of stepped shaft**

| Mode shape | Shaft w/o crack | Crack-I | Crack-II | Crack-III | Crack-IV | Crack-V |
|---|---|---|---|---|---|---|
| I | 27.56 | 27.63 | 27.59 | 27.67 | 30.01 | 27.67 |
| II | 18.93 | 19.00 | 18.96 | 18.96 | 18.93 | 18.98 |
| III | 18.91 | 19.10 | 19.02 | 19.13 | 22.76 | 19.15 |
| IV | 27.40 | 27.15 | 27.14 | 27.18 | 29.03 | 27.15 |
| V | 27.38 | 27.13 | 27.13 | 27.15 | 27.75 | 27.14 |
| VI | 18.37 | 18.39 | 18.38 | 18.43 | 19.49 | 18.38 |

**Table 7. Critical Speed (RPM) at different crack conditions of stepped shaft**

| Mode Shape | Shaft w/o crack | Crack-I | Crack-II | Crack-III | Crack-IV | Crack-V |
|---|---|---|---|---|---|---|
| I | 12631 | 12630 | 12628 | 12615 | 12292 | 12623 |
| II | 12881 | 13087 | 13120 | 12998 | 12932 | 13124 |
| III | 12897 | 13138 | 13142 | 13114 | 13077 | 13135 |
| IV | 33982 | 34769 | 34771 | 34491 | 33519 | 34744 |
| V | 35050 | 35866 | 35871 | 35712 | 35207 | 35841 |
| Stability | All modes has stable rotation of shaft for all cases | | | | | |

Harmonic response analysis is performed for one case which have crack (Design-V) for 1000 N load condition and all boundary conditions are present in Fig. 4. The frequency range for this study is select from 0 Hz to 5000 Hz as per modal analysis for natural frequency.

Stress over different frequency are show in Table 8 for this load condition. As seen in the table it is clear that by changing the frequency values the stress value gets changed which is most important part of this study, all though for all frequency the stress is in its allowable stress limit.

Total displacement for different frequency are present in Table 9 for design-V, as seen in table the displacement value is very low for 1000 N load condition for different frequency values, it means the rotation is stable for this shaft.

Frequency response for three direction for 1000 N load condition if show in Fig. 5 to Fig. 7 respectively.

**6.1 ANN Method**

In the field of shortcoming finding, numerous issues are explained through recognizable proof and arrangement apparatuses. Neural networks are incredible information investigation apparatuses in demonstrating, ID, finding, and order. Neural networks work like the human cerebrum. The principal motivation to this comparability is that a neural network obtains information through learning and the second is that a neural network's information is To create and prepare a neural network, its sources of info and yields should initially be determined. In this examination work, the initial three common frequencies of the shaft and the split particulars are picked as the neural network information sources and yields, separately. In this way a three sources of info three yields neural network would be a potential arrangement. Nonetheless, it is likewise conceivable to separate the principle neural network into three sub networks with three data sources and one yield for each. Along these lines, the three dimensional preparing issue is diminished to three one dimensional preparing issues, and consequently the network intricacy would extensively diminish. Each neural network comprises of info, yield, and concealed layers. The information layer comprises of simply the contributions to the network. At that point it is trailed by concealed layers, which comprise of any number of neurons. At long last, the network yields will be given in the yield layer.

To perform the ANN in this research work language "R" is used to made the code for this task. The optimization using ANN method is performed using quasi-Newton method for this study. The neural network diagram is show in Fig. 8 in which input layer, hidden layer and output layers are clearly present.
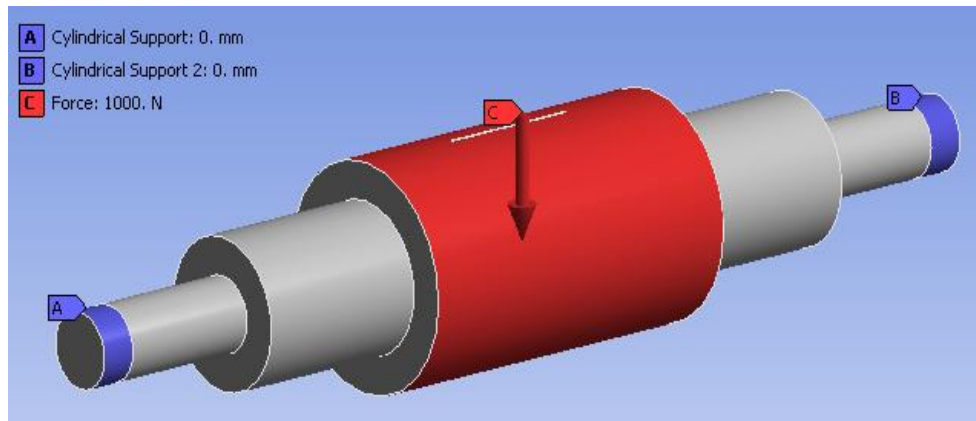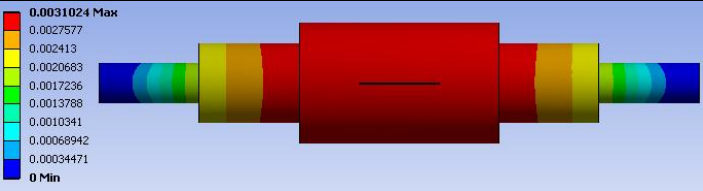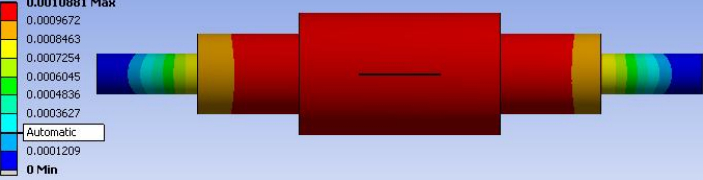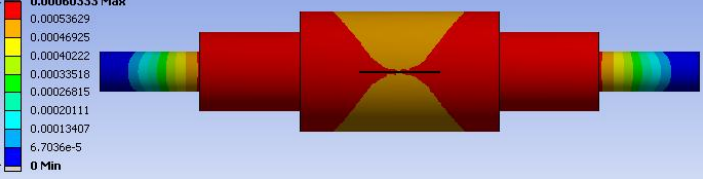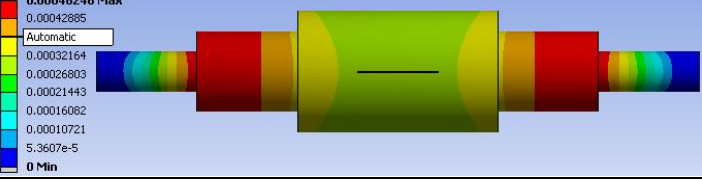
**Fig. 4. Harmonic response boundary condition**

**Table 8. Von-misses stress at different frequency for design-V**

| Frequency (Hz) | Von-misses stress | Stress (MPa) |
|---|---|---|
| 2000 |  | 11.34 |
| 3000 |  | 4.78 |
| 4000 |  | 3.33 |
| 5000 |  | 3.00 |

**Table 9. Total displacement at different Frequency for design-V**

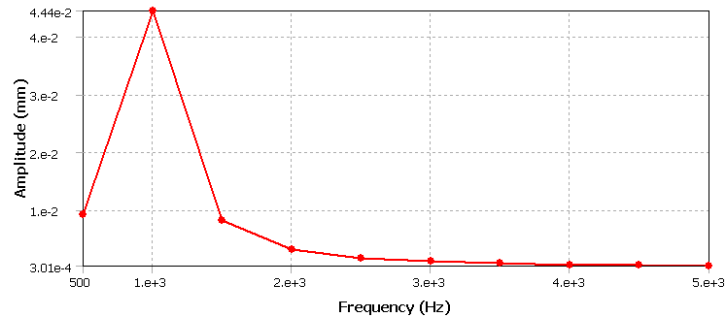| Frequency (Hz) | Total displacement | Displacement (mm) |
|---|---|---|
| 2000 |  | 0.0031 |
| 3000 |  | 0.0010 |
| 4000 |  | 0.00061 |
| 5000 |  | 0.00048 |



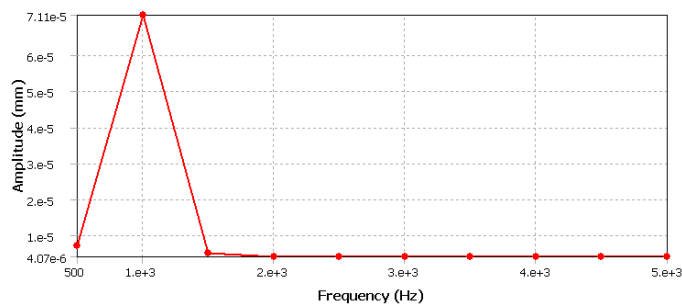**Fig. 5. Displacement amplitude in x-direction for different frequency values**



**Fig. 6. Displacement amplitude in y-direction for different frequency values**
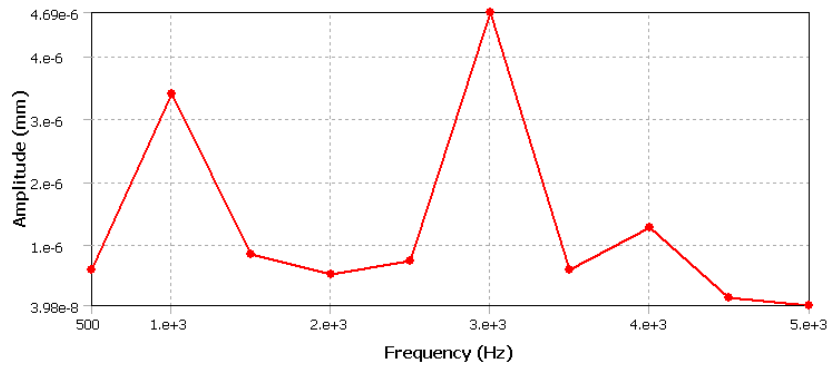
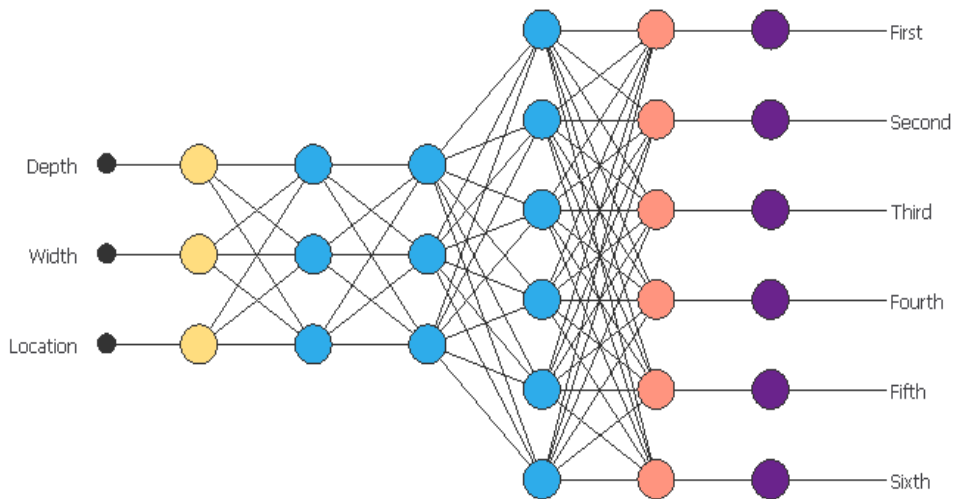**Fig. 7. Displacement amplitude in z-direction for different frequency values**



**Fig. 8. Neural network graph for vibration analysis of stepped shaft**

**Table 10. Optimal solution of NF for stepped shaft using ANN**

| Depth | Width | Location | I | II | III | IV | V | VI |
|-------|-------|----------|---------|---------|------|---------|---------|---------|
| 9 | 0.6 | 60 | 1049.19 | 1088.50 | 1121 | 2917.51 | 2949.94 | 4126.54 |

After performing the ANN optimization analysis the best optimum outcome from ANN method is present Table 10.

## 7. CONCLUSION AND FUTURE SCOPE

Stepped shaft is used to modal and harmonic analysis for different crack conditions using FEM method and the main conclusions are following:

I. On the basis of modal analysis, for stepped shaft, the maximum deflection and natural frequencies are calculated for six mode shapes which help to avoid week working conditions of shaft due to resonance.

II. Critical speed analysis and Campbell diagram show the stability for all design cases of crack for different rotation speed direction.

III. Harmonic response analysis is performed by Modal analysis and it is found that Von-misses stress and deformation analysis is very less for 1000 N load condition for this stepped shaft.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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