# Numerical Comparative Modal Analysis of Connecting Rod between Fixed Crankpin and Fixed Piston Pin

**Getachew Admassie Ambaye [0000-0003-4197-0188]**

Faculty of Mechanical and Industrial Engineering, Bahir Dar Institute of Technology (BiT), Bahir Dar, Ethiopia
Getachew.Admassie@bdu.edu.et

## Abstract

Connecting rods are subjected to a tensile (inertial force), compressive (gas pressure), and bending (eccentricity) loadings. The boundary conditions used for the determination of its natural frequency depends on the loading type. For free vibration analysis, when the piston moves upward the crankpin needs to be fixed and free piston pin, while when it moves down the piston pin should be considered as a fixed and free crankpin. This paper presents a numerical (ABAQUS software) comparison of the first six dominant mode shapes and natural frequencies of the connecting rod when it is fixed at the crankpin and free at the piston pin (case 1) and fixed at the piston pin and free at the crankpin (case 2) of an optimized geometry that found from literature. The mode shapes and natural frequencies of the two cases are compared, and it shows that the natural frequency of case 2 is lower than case 1. Therefore, for design purpose, the loading frequency should be less than the natural frequency of the connecting rod when it is fixed at the piston pin.

**Keywords:** Mode shape, Natural frequency, Load frequency, Fixed crankpin, Fixed piston pin

## 1 Introduction

A connecting rod is one part of a piston engine that connects the piston to the crankshaft, and its function is to convert the reciprocating motion of the piston due to the gas power into the rotation of the crankshaft, or vice versa. The connecting rod is subjected to compressive load when the piston moves upward due to gas power during combustion, tensile forces when the piston moves downward due to inertia of the crankshaft, and shear forces due to the angle between the piston and the crankpin rotate at both ends. These loads are proportional to the angular speed of the rotation sources. The connecting rod design is complicated because it subjected to work in variably complicated conditions and the load on the rod mechanism is produced not only by pressure but also inertia [1]. It is subjected to a high compressive loads due to combustion, to high tensile loads due to inertia. A connecting rod must be capable of transmitting axial tension, axial compression, and bending stresses caused by the thrust and pull on the piston and by centrifugal force [2].

Modal analysis determines modes and which, in turn, paves a way to understand the behavior of components and structures under free vibration. There are three factors that can affect the modal analysis, which are geometry, mass, and constraints. Modes of vibration are inherent properties of a structure determined by the material properties and boundary conditions of the structure, which are defined by the mode shape and natural frequency, which cause vibrations in components. The vibration that can cause the failure of the components can be minimized by analyzing the mode shapes and frequencies and redesigning or replacing the weak components. When the load frequency is equated with the natural frequency of the component, then the resonance will occur, producing excessive vibration and eventually, this leading to destruction.

There are tremendous literatures that deals with connecting rods, specifically topology optimization and dynamic analysis using numerical and experimental methods, and some of them are reviewed as follows. Dynamic load analysis and optimization of the connecting rod were conducted by Shenoy and Fatemi [3]. The dynamics stress of the connecting rod has been analyzed extensively [4 - 6]. Mahipal et al. [7] investigated the modal analysis for maximum tensile and compressive loading conditions. Zhou et al. [8] investigated the first six mode shapes of the fixed piston pin and they concluded that the stress is mainly produced on the joint of connecting rod shell and the bottom end or the top end. Kaliappan et al. [9] analyzed the modal analysis and kinematics of connecting rod for different material. Shi and Kou [10] investigated the strength and fatigue life of connecting road by fixing the big end and applied a tensile and compressive load on the small end. Ali and Haneef [11], they conclude that contact pressure development at the interface and higher compressive stress in the bush and tensile stress development in the small end. Zhang et al. [12] Investigated that stress and modal analysis of connecting road using FE approach by fixing the small end. Roy [13] carried out research on the design analysis and optimization of various parameters of the connecting rod using CAE software and find optimal design. Finite element analysis is common for analyzing the dynamic stress, and modal analysis [14 - 17].

The pressure applied to the piston and the inertial force of the flywheel and crank rod are the main sources of the loading of the connecting rod. The pressure load applied to the piston due to the combustion of the fuel may greater than the inertial force. In this case, the connecting road is subjected to a compressive load, while if the inertial force of the flywheel and crack rod is greater than the load due to the pressure of the combustion fuel, then the connecting rod is subjected to a tensile load. When the tensile load occurs in the connecting road, the crank rod pulls the piston due to an excessive amount of kinetic energy of the flywheel. Most of the analyses, including static and dynamic, have been done by fixing the crankpin and applying a compressive load at the piston pin, even though there are some literatures that done by fixing the piston pin. Therefore, this paper has compared both cases and determine the significant natural frequency and dominant modes of vibration. In addition, the effect of mesh density on the natural frequencies has been analyzed.

## 2 Modelling and boundary conditions

The connecting road is made from C70S6 with the properties shown in Table 1. The design parameters are also given in Table 2, which were obtained by Naik [18], by shape optimization and redesign. The 2D and 3D models of the connecting rod are modeled using Autodesk Inventor software based on the design parameters, as shown in Fig. 1 (a) and (b), respectively.

**Table 1.** Material and mechanical properties of the connecting rod

| Material and mechanical property | Value |
|---|---|
| Density | $7.86 \times 10^{-6}\ Kg/\text{mm}^3$ |
| Elastic modulus | $210 \times 10^3$ MPa |
| Poison ratio | 0.3 |

**Table 2.** Design parameters of the connecting rod

| Design parameter | Value (mm) |
|---|---|
| Diameter of small bore, D1 | 31 |
| Diameter of big bore, D2 | 49 |
| Distance between center of bores, L | 140 |
| Shank length, $L_{Shank}$ | 557 |
| Total width, L1 | 26 |
| Side width, L2 | 6 |
| Total thickness, T1 | 15 |
| Middle thickness, T2 | 5.5 |
| Center distance between bolts, C | 74 |
| Extended component for joining, B | 90 |
| Larger diameter of the lower jaw, D3 | 39 |

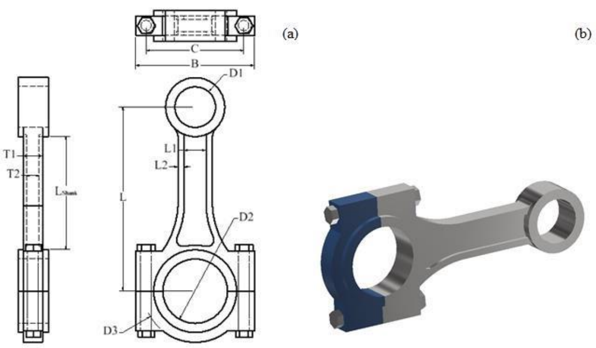

**Fig. 1.** Modeling of connecting rod: (a) 2D model with dimensions and (b) 3D model
The modal analysis comprising from two cases, the first modal analysis (case 1) is done by fixing the crankpin (RP-1) at its center and free the other end, while the second analysis (case 2) will be done by fixing the piston pin (RP-2), as shown in Fig. 2 (a). Because the modal analysis depends only on the stiffness, geometry, and boundary condition, there is no need to apply an external load.

The 3D model of the connecting road was imported to ABAQUS software and mesh using the meshing tool using C3D10 element type with 108833 number of elements, as shown in Fig. 2 (b). The mesh density for the modal analysis should not be a fine mesh, Liu et al. [19] investigated that the modal analysis with a reasonable coarse mesh will yield a correct prediction of the natural frequencies (with an approximation error of < 1%). Moreover, the mesh density does not significantly affect the modal analysis.

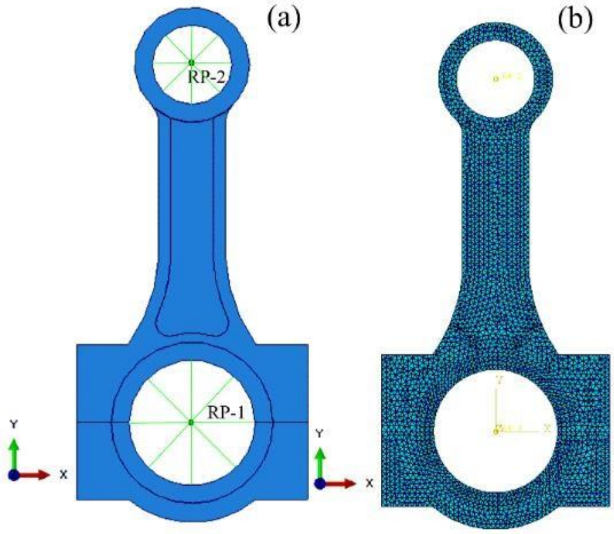


**Fig. 2.** Connecting rod model: (a) boundary condition, and (b) mesh model

## 3 Results and discussions

### 3.1 The effect of mesh density on the natural frequency

The effect of the mesh density on the modal frequency of connecting rod is analyzed for a fixed crankpin and the frequencies with mesh size are shown in Fig. 3 for the first six dominant mode shapes. The mesh size begins with the 9 mm mesh size of C3D10 element type and reduced to 2 mm by 1 mm decrements. The mesh size density slightly affects the modal frequencies. The frequency difference between lower and higher mesh density for the first three Mode orders is 1.8, 1.9, and 40 Hz respectively (Fig. 3 Mode 1 - Mode 3). The maximum frequency difference is found in third-order mode. The frequency differences for the last three modes are 27.8, 27.5, and 14.5 Hz respectively (Fig. 3 (Mode 4 – Mode 6)).

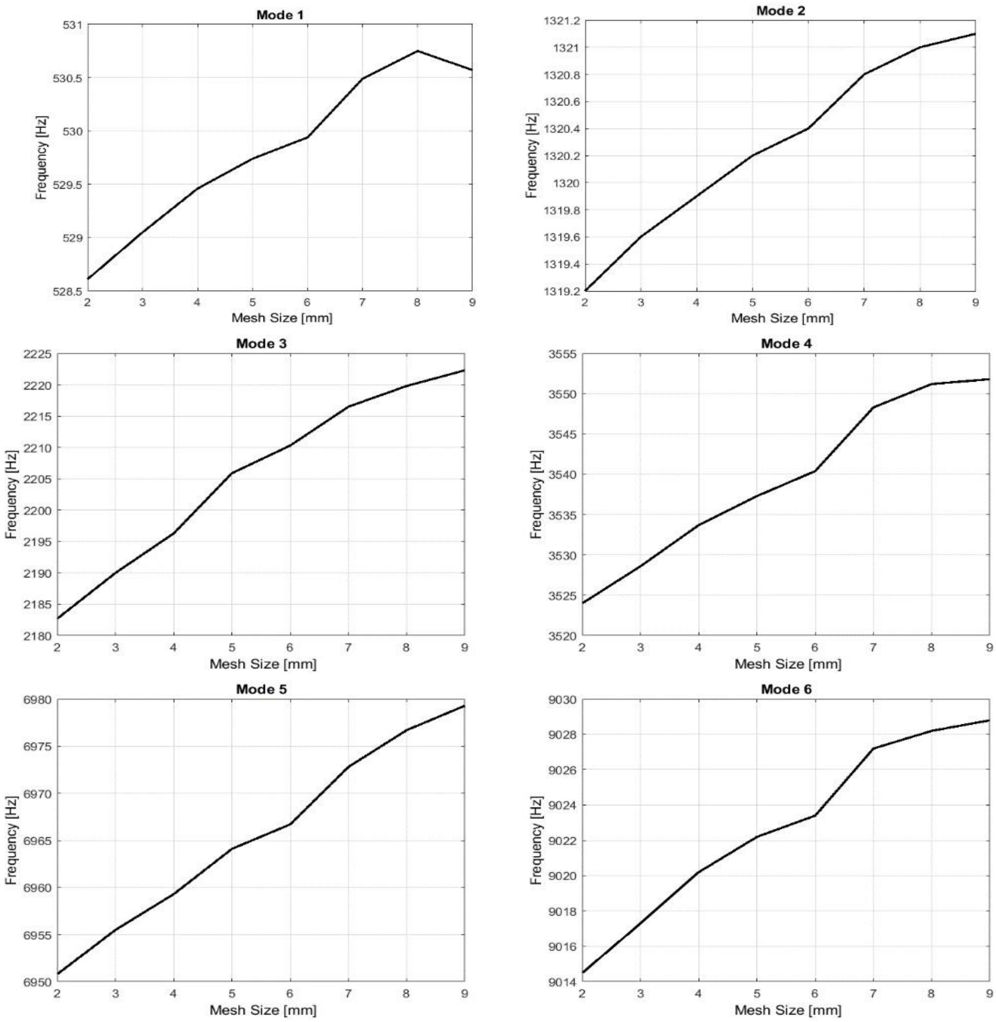


**Fig. 3.** Natural frequency versus Mesh size for the first six mode shapes with fixed crankpin

### 3.2 Mode shapes

The first six dominant mode shapes of the vibration are shown in Fig. 4 (when the connecting rod is fixed at the crankpin and free at the piston pin) and Fig. 5 (when the connecting rod is fixed at the piston pin and free at the crankpin). The first dominant mode of vibration is lateral vibration, as shown in Figs. 4 (a) and 5 (a). Transversal and torsional modes of vibration are the second and third modes of vibration. But the next two modes of vibration are the second lateral and second transversal modes of vibration, and the sixth mode of vibration is the axial vibration mode. Both cases have the same mode shape of vibration.

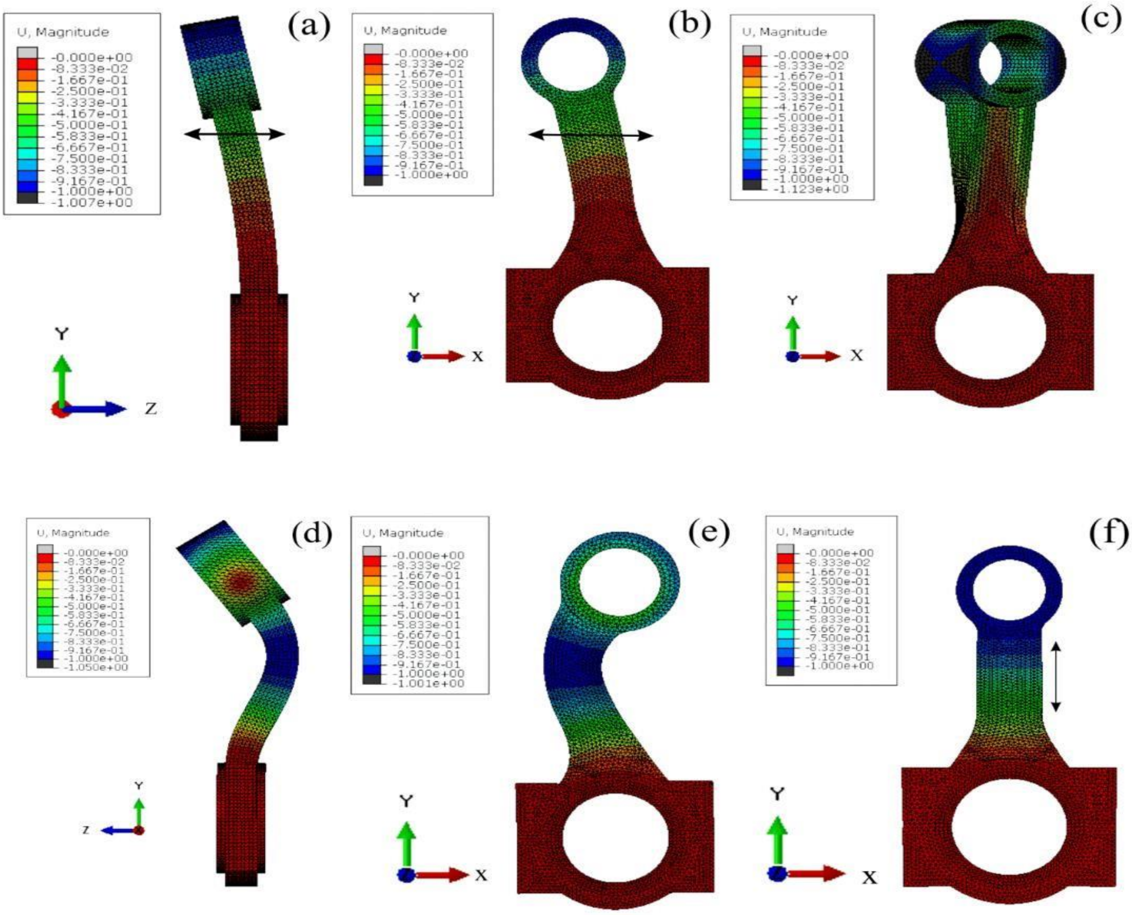


**Fig. 4.** Mode shape of the connecting rod fixed at larger diameter: (a) Mode 1, (b) Mode 2, (c) Mode 3, (d) Mode 4, (e) Mode 5, and (f) Mode 6.

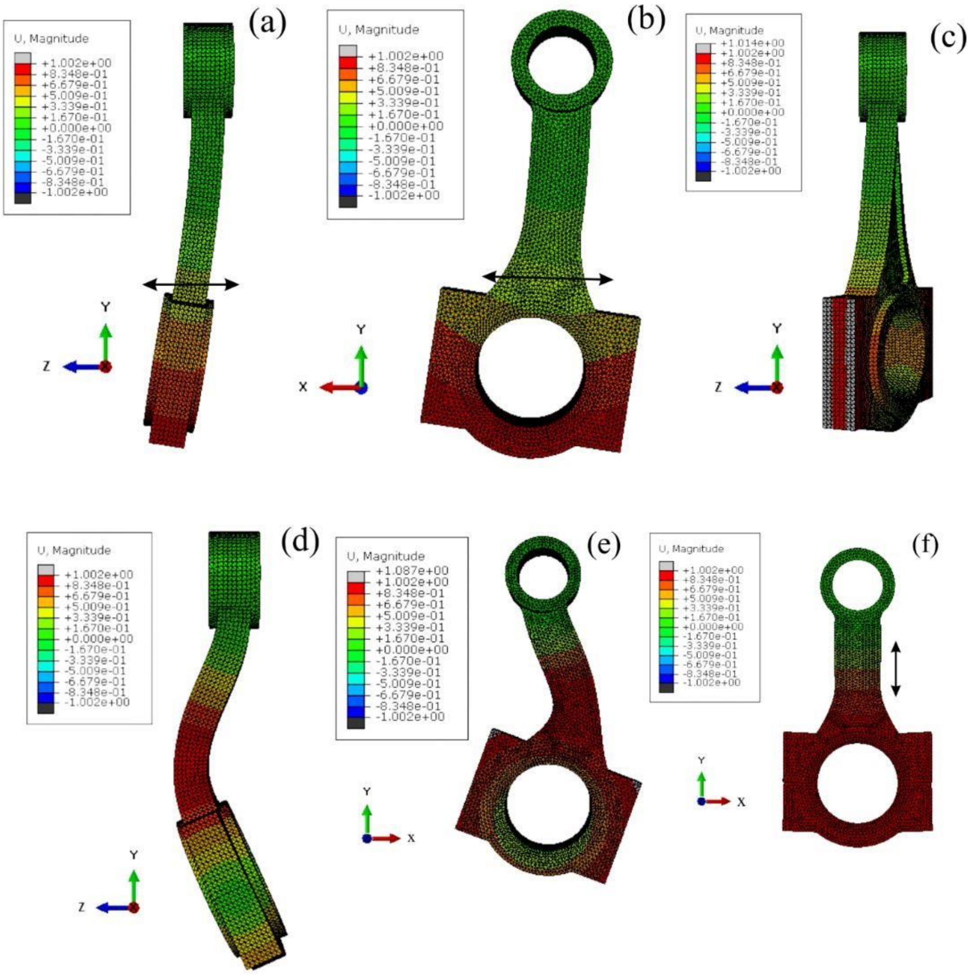


**Fig. 5.** Mode shape of the connecting rod fixed at small diameter: (a) Mode 1, (b) Mode 2, (c) Mode 3, (d) Mode 4, (e) Mode 5, and (f) Mode 6.

In both cases, the transversal vibration mode is the dominant mode shape, followed by the transversal vibration mode, followed by the torsional. For design purposes, at least the first 3 modes of vibration need to be considered, this is because the rest mode of vibration has at least high natural frequencies, and the load frequencies might not have equal with these frequencies.

### 3.3 Natural frequencies for tensile and compressive load

The natural frequency of the connecting rod shows limited free vibration up to which its vibration will not produce severe destruction, but when the loading the vibration gets closer to the natural frequency of the connecting rod then, resonance will occur. This can produce the destruction of the connecting road as well as the components that connect with is such as the piston and crank rod. The natural frequency of the connecting rod when it is fixed at the crankpin and fixed at the piston pin verses with the mode shape is shown in Fig. 6.

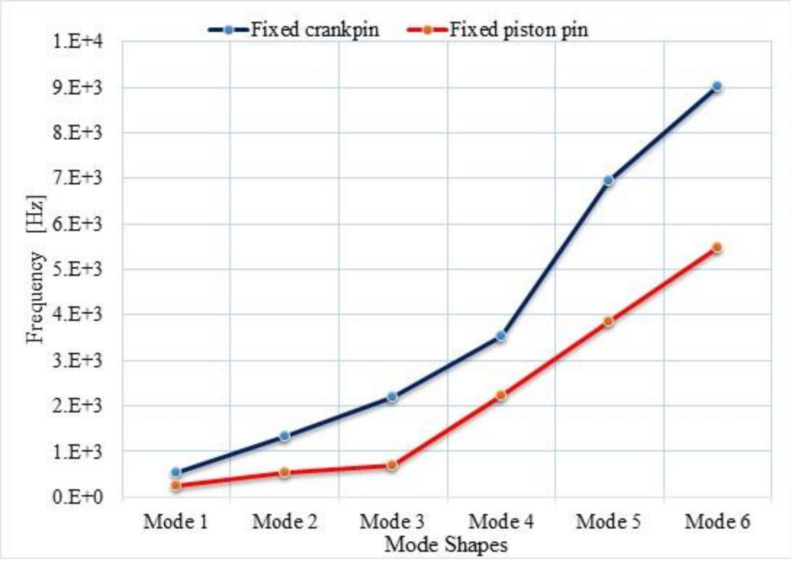


**Fig. 6.** Frequency-versus mode shapes.

The natural frequency versus mode of vibration are shown. Fig. 6. The natural frequency of the connecting rod when it is fixed at the piston pin and free at the crankpin is less than when it is fixed at the crank pin. This indicates that the loading frequency, which means the number of cycles of the piston movement pre-unit time, should be less than the natural frequency of the connecting rod when it is fixed at the piston pin. In this case, the loading frequency of the connecting rod should be less than 247.39 Hz.

## 4 Conclusions

In this paper, the modal analysis of the connecting rod for two cases which are, fixed the crankpin and free piston pin (case 1) and fixed the piston pin and free the crankpin (case 2) presented. The first six dominated mode shapes and corresponding frequencies were obtained from the modal analysis, and the simulation results led to draw the following conclusions and recommendations.

- The natural frequency of the fixed smallest diameter (piston pin) is lower than the fixed crankpin. Therefore, during the forced vibration analysis the natural frequency of the fixed piston pin should be considered, because it's the worst case as compared to the fixed crankpin. The load frequency of the connecting rod should be less than the natural frequency of the connecting rod when it is fixed at its piston pin.
- The natural frequency difference between case 1 and case 2 increases as the order of the mode increases. In addition, the mesh grid does not significantly affect the natural frequency.

- The primary vibration mode of the connecting rod is the lateral vibration, and the second and third modes of vibration are transversal and torsional vibrations.

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