



# A Framework for Predicting Nonlinear Frequency Response Functions of a Bolted Beam using Force-Controlled Technique in MSC NASTRAN SOL128

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## ABSTRACT

This paper investigates nonlinear dynamic behaviour in a bolted beam. Force-Controlled Technique (FCT), implemented in MSC NASTRAN SOL128, is used to predict the Nonlinear Frequency Response Functions (NLFRFs) of the beam. The predicted NLFRFs are analysed to determine softening or hardening trends resulting from the bolted joint-induced nonlinearity. The results show that the adopted FCT framework can identify amplitude-dependent changes in resonance frequency and damping, which are in line with established results reported in previous studies. This study provides a practical approach and reliable means for identifying nonlinear dynamic behaviour in bolted structures, and also supports improved modelling of bolted joint-induced nonlinearity.

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## INTRODUCTION

Mechanical joints play a crucial role in assembled and complex mechanical structures, as they form connections and interfaces between multiple structural components. Several factors must be considered when selecting mechanical joints, such as the specific range of motion required for the engineering application, load capacity, precision, and cost considerations. A number of mechanical fastening methods, such as bolts, welds, rivets, and pins, enable relative motion and transfer loads between these components to form the assembled structure [1,2]. These fastening methods ensure structural integrity, stability, component alignment, flexibility, and effective sealing in various operational conditions [3,4]. Bolted joints are a commonly used mechanical fastening method in mechanical engineering [5,6]. Due to their inherent flexibility in terms of reassembly and disassembly, these joints are a viable alternative to welded joints in mechanical structures [7].

The condition of bolted joints has a significant influence on the dynamic behaviour of bolted structures, especially when subjected to random dynamic loads over a long period of time. Bolted joints introduce additional energy dissipation, which affects the overall stiffness of the structure and, thus the damping and natural frequencies. Therefore, a comprehensive understanding of the dynamic properties of bolted structures, such as their natural frequencies and mode shapes, is essential. This understanding is crucial for maintaining structural integrity and minimising the potential for resonance-related catastrophic failures such as deformations, fractures, and damage throughout the service life. In addition, the experimental characterisation of joints plays an important role in improving the understanding of the dynamic behaviour of bolted joints.

The linear modelling method is commonly employed by engineers and researchers to predict and validate the dynamic characteristics of bolted joints. Various modelling approaches have been developed, incorporating flexible connector elements that represent the linear translational and the rotational stiffness, as well as the damping of the joints. In practice, the application of these models is usually analysed on a case-by-case basis, with validation based on natural frequencies and mode shapes.

Despite their widely use, it is important to note that these linear models have limitation when it comes to characterising dynamic behaviour at high excitation levels, where bolted structures exhibit nonlinear dynamic characteristics due to joint effects [8,9]. Such nonlinear effects can significantly alter the dynamic characteristics and result in amplitude-dependent shifts in natural frequency and damping of the vibration modes [10,11]. Consequently, linear FE models cannot accurately describe the energy dissipation, stiffness, and damping of the joint interface, which can lead to misleading results [12,13]. Incorporating nonlinear effects in the development of mathematical models for bolted structures is therefore essential for achieving reliable predictions and making informed design decisions.

The aim of this paper is to investigate nonlinear behaviour in a bolted beam. FCT, implemented using MSC NASTRAN SOL128, is used to predict NLFRFs of the beam. The predicted NLFRFs are then examined to determine whether the beam exhibits softening or hardening behaviour, in line with trends published in previous studies on nonlinearities in bolted structures.

## METHODOLOGY

### Nonlinear FE Modelling and Analysis based on FCT

The FE model used to predict the nonlinear dynamic characteristics of the bolted beam based on the FCT technique is shown in Figure 1. The excitation force is applied at the excitation point (node 18348) along the translational Z-axis. To predict the nonlinearity of the first mode, a node at each bolted joint is assigned nonlinear functions (NOLIN3 and NOLIN4) with a cubic stiffness of  $2.261 \times 10^9 \text{ N/m}^3$  in the translational Z-axis.

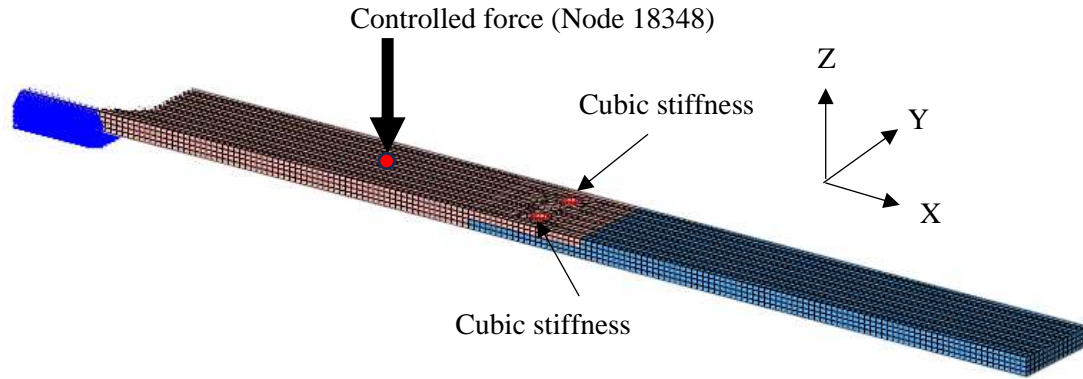


Figure 1. FE model configuration for FCT simulation.

A series of nonlinear harmonic analyses are conducted using MSC NASTRAN SOL 128 Nonlinear Harmonic Response to predict the nonlinearity of the bolted beam. The frequency range of interest is between 17.50 Hz and 20.00 Hz.

Six different forces, as listed in Table 1, are applied at the excitation point. Specifically, the lowest force applied is 0.20 N, with an increment of 0.20 for each run. Notably, the FE model excluded a force of 1.00 N, as it exhibits the same resonance frequency as 0.80 N. The highest force applied is 1.40 N.

Table 1. Force used in the FCT simulation.

Run	Force (N)
1	0.20
2	0.40
3	0.60
4	0.80
5	1.20
6	1.40

The measured damping values obtained from the FCT test, as listed in Table 2, are used to assign the damping in the FE model. It is observed that the damping value increase with the excitation force. For instance, the damping is 0.00181 N.s/m at 0.20 N, and the damping increases to 0.00215 N.s/m at 0.80 N. The damping is further increased to 0.00297 N.s/m at 1.40 N. The reduction of the measured NLFRF amplitude as the excitation force increases shows the increasing value of the damping. The detailed explanations and information on the modelling and analysis set-ups can be referred from [14].

Table 2. Damping used in the FCT simulation.

Run	Force (N)	Frequency range (Hz)	Damping (N.s/m)
1	0.20	17.50 to 20.00	0.00181
2	0.40	17.50 to 20.00	0.00192
3	0.60	17.50 to 20.00	0.00203
4	0.80	17.50 to 20.00	0.00215
5	1.20	17.50 to 20.00	0.00261
6	1.40	17.50 to 20.00	0.00297

## RESULTS AND DISCUSSION

Figure 2 shows the force spectrum at the excitation point, with the frequency range for the first mode is between 18.50 Hz and 19.50 Hz. From the figure, it is evident that the force at each excitation frequency is kept constant along the frequency range. For example, in Figure 2, the excitation force remains constant 0.40 N along the frequency range of 18.50 Hz to 19.50 Hz. The largest force remains constant at 1.40 N along the frequency range of excitation. This shows that the force excitation is constantly maintained in the nonlinear numerical analysis.

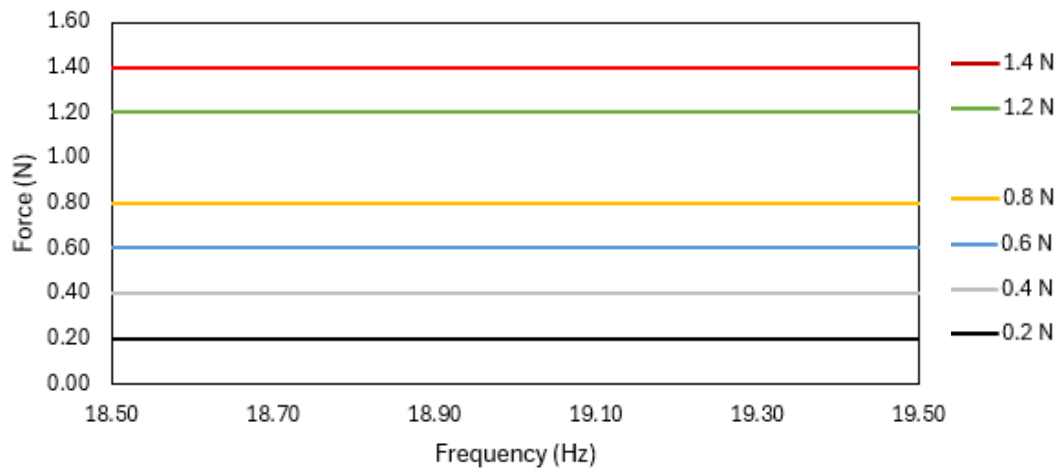


Figure 2. Force spectrum obtained from FCT simulation.

Figure 3 shows the nonlinear frequency response around the resonance frequency. Meanwhile, Table 3 lists the resonance frequencies and the amplitudes of the nonlinear frequency responses corresponding to each force. The plot shows that distortion occurs in the predicted results. The nonlinear frequency responses are bent toward left side with an increasing force, showing that softening nonlinearity is obtained from the nonlinear FE model of the bolted beam, respectively. A significant reduction in the resonance frequency is detected. For instance, the resonance frequency at 0.20 N is 19.20 Hz. The resonance frequency decreases to 18.85 Hz at 0.80 N. The resonance frequency further decreases to 18.52 Hz at the largest force of 1.40 N.

In terms of the amplitude of the nonlinear frequency responses, the amplitude increases as the force increases. As listed in Table 3, the amplitude is 0.147 mm at 0.20 N. It increases to 0.537 mm at 0.80 N and the highest peak amplitude is 0.732 mm at the maximum 1.40 N.

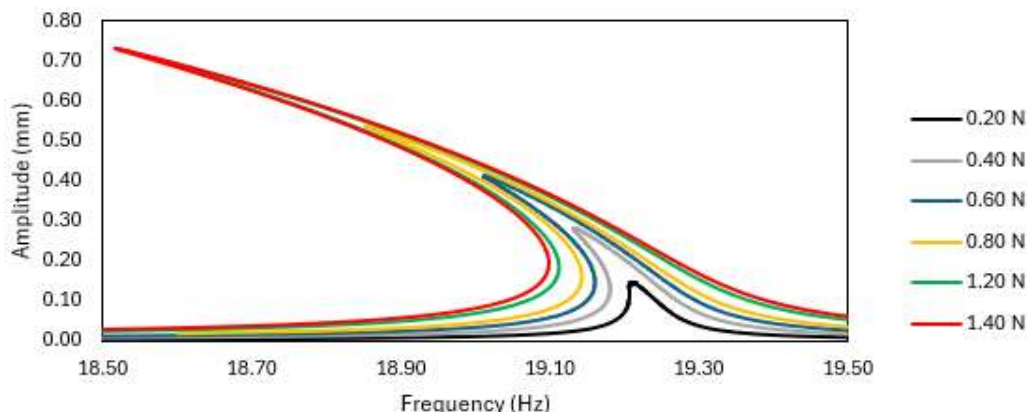


Figure 3. Nonlinear frequency response obtained from FCT simulation.

Table 3. Resonance frequencies and amplitudes extracted from the nonlinear frequency responses for each force.

Force (N)	Resonance frequency (Hz)	Amplitude (mm)
0.20	19.20	0.147
0.40	19.13	0.283
0.60	19.01	0.411
0.80	18.85	0.537
1.20	18.56	0.706
1.40	18.52	0.732

Receptance NLFRRs are used to characterise the joint nonlinearity. The predicted receptance NLFRRs at different forces are shown in Figure 4. A good prediction of the nonlinear dynamic characteristics of the bolted beam is obtained through the FE model. The resonance frequency is bent toward left as the force increases, that is based on the receptance NLFRRs. This clearly shows a softening characteristic of the dynamic response from this joined modelling, confirming consistent with established findings in the literature [15-17].

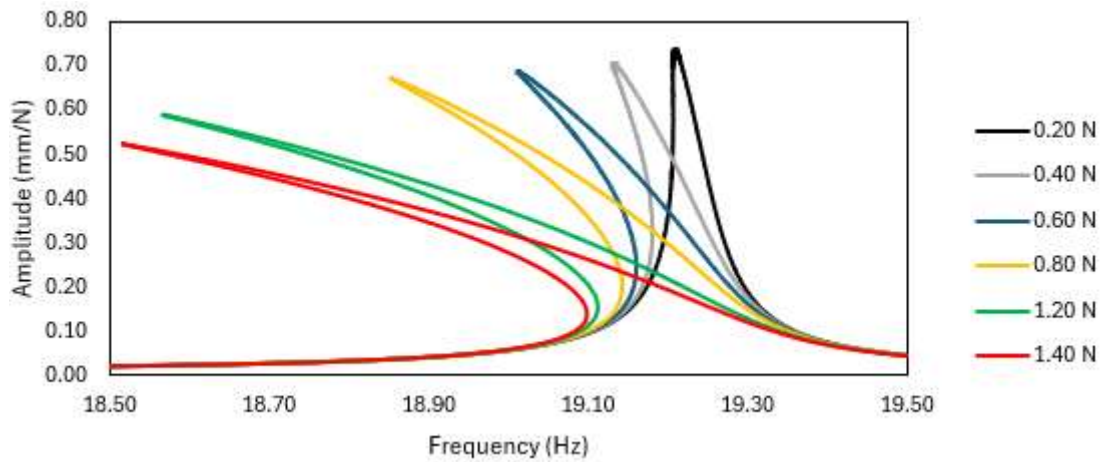


Figure 4. Receptance NLFRFs from FCT simulation.

The resonance frequency and the amplitude of the receptance NLFRFs corresponding to specific force are listed in Table 4. It is observed that the resonance frequency is 19.20 Hz at 0.20 N. The resonance frequency decreases to 18.85 Hz when the applied force is 0.80 N. The lowest resonance frequency is 18.52 Hz at 1.40 N. The amplitude of the receptance NLFRFs is also evaluated. As the magnitude of the force increases, the NLFRFs amplitude decreases. At 0.20 N, the NLFRF amplitude was 0.736 mm/N. At 0.80 N, the NLFRF amplitude slightly drops to 0.671 mm/N and decreases to 0.523 mm/N at the maximum force of 1.40 N. This indicates that the nonlinear FE modelling has resulted in the development of a good FE model to predict the joint nonlinearity.

Table 4. Resonance frequencies and amplitudes extracted from the NLFRFs at the defined force.

Force (N)	Resonance frequency (Hz)	FRF amplitude (mm/N)
0.20	19.20	0.736
0.40	19.13	0.705
0.60	19.01	0.686
0.80	18.85	0.671
1.20	18.56	0.588
1.40	18.52	0.523

Based on the obtained results, which indicate NLFRFs with softening behaviour and a reduction in NLFRFs amplitude, the developed nonlinear FE modelling and analysis using FCT has proven successful. Nonlinear functions, with the cubic stiffness of  $2.261 \times 10^9 \text{ N/m}^3$  are assigned to each bolted joint. The adoption of these functions has effectively predicted the nonlinear dynamic characteristics of the bolted beam.

## CONCLUSIONS

This paper has successfully adopted FCT implemented using MSC NASTRAN SOL128, to predict NLFRRFs of a bolted beam. The analysis showed amplitude-dependent shifts in resonance frequency and damping, confirming the presence of nonlinear behaviour in the bolted beam. Furthermore, the predicted NLFRRFs of the bolted beam showed clear softening behaviour, which is in line with established findings in the literature. These results demonstrate that the FCT implemented using MSC NASTRAN SOL128 provides a reliable means for identifying nonlinear behaviour in bolted structures and can support more accurate dynamic analysis and design of assembled components.

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