Chapter 10
An Overview of ANSYS Harmonic Balance Method: Current Capabilities and Future Directions

Michael Kwarta

Abstract Nonlinear structural dynamics have gained increasing interest in the industry due to several key factors, including: (i) the necessity to redesign structures for greater weight efficiency, thereby reducing fuel consumption, (ii) the need for accurate prediction of the dynamics of structures oscillating at high amplitudes, and/or (iii) the importance of modeling the effects of bolted connections on a system's nonlinear response. Although nonlinear structures can be simulated using brute-force transient solvers, the computational time required is often inefficient for practical applications. The Harmonic Balance Method (HBM) has emerged as one of the most popular and effective methods for simulating the forced periodic responses of nonlinear systems. When coupled with a continuation algorithm, HBM can efficiently compute key characteristics of nonlinear systems, such as nonlinear frequency response functions and nonlinear normal modes. This work presents the current capabilities of the Ansys-HBM toolkit, which was recently incorporated into the Ansys portfolio. It discusses the physical features contributing to the nonlinear response of mechanical systems, which are supported by Ansys-HBM at the time of this publication. Additionally, features particular to HBM, such as providing initial guesses and scaling the solution vector, are described. The toolkit is evaluated using benchmark examples. Finally, the publication concludes with a discussion on future enhancements driven by industry requests that will be integrated into upcoming software releases.

Keywords Harmonic Balance Method · Nonlinear Mechanical Vibrations · Nonlinear Response Function · Benchmark Testing · Industry Applications

Introduction

Nonlinear structural dynamics have gained increasing interest in the industry due to several driving factors, including:

(i) the necessity to redesign structures for greater weight efficiency, thereby reducing fuel consumption,
(ii) the need for accurate prediction of the dynamics of structures oscillating at high amplitudes, and/or
(iii) the importance of modeling the effects of bolted connections on a system's nonlinear response.

The nonlinear characteristics of a structure can arise from local or distributed nonlinearities. Examples of the former include a bolted joint connection [1] or a small fracture in the system [2], while the latter may be exhibited by curved beams or plates due to high-amplitude oscillations [3], [4], [5], [6]. Even though the structures with nonlinear characteristics can be simulated using brute-force transient solvers, the computation time required for these simulations is often inefficient.

The Harmonic Balance Method (HBM) [7] is one of the most popular and effective techniques for simulating the forced periodic responses of nonlinear systems. When coupled with a continuation algorithm, HBM can calculate key characteristics that describe a nonlinear system, such as the nonlinear frequency response and the nonlinear normal mode [8].

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The objective of this work is to present the current capabilities of the Ansys-HBM toolkit, which was recently included in the Ansys portfolio. This paper describes the physical phenomena that cause the nonlinear response of mechanical systems supported by Ansys-HBM at the time of this publication. Furthermore, the numerical capabilities specific to HBM and supported by the software are also described.

Harmonic Balance Method Overview

The Harmonic Balance Method (HBM) is a computational technique used to analyze nonlinear dynamical systems in the frequency domain. It enables the determination of steady-state periodic responses by solving the equations of motion associated with these systems. Recently integrated into Ansys' portfolio, HBM facilitates high-accuracy and high-performance simulations.

In Ansys-HBM analysis, a model is typically divided into linear and nonlinear components. A fundamental harmonic balance equation is established and solved using the Newton-Raphson (NR) routine combined with continuation algorithms. This approach allows for the calculation of nonlinear response functions, making HBM particularly valuable for engineers and researchers working with complex mechanical systems.

At the time of this publication, HBM analysis supports specific nonlinearities, including elements modeling nonlinear stiffness, damping, and node-to-node contact elements. The linear components of the system may be reduced using component mode synthesis (CMS) to enhance efficiency. CMS techniques, such as the Craig-Bampton method [9], effectively split the structure into smaller components while maintaining their interface degrees of freedom. For a more comprehensive description of Ansys-HBM, including the derivation of the fundamental equation, convergence criteria, best practices, and step-by-step examples, please refer to the Ansys-HBM Analysis Guide [10].

Overview of the Convergence Improvement Techniques

Achieving convergence in nonlinear analyses can sometimes be challenging. Ansys-HBM offers several techniques to improve convergence when issues arise.

Initial Guess Adjustment

When HBM analysis encounters convergence problems while calculating the first point on the nonlinear response function (RF), one effective strategy is to optimize the initial guess. By default, the nonlinear multi-harmonic solver uses zero initial condition for this calculation, which can lead to convergence failures. To mitigate this, users can provide a more informed initial guess, derived from a static analysis or a previous HBM run. This approach can significantly improve the likelihood of successful convergence.

Scaling the Solution Vector

Another technique to enhance convergence is scaling the augmented multi-harmonic solution vector. In a Newton-Raphson routine, discrepancies in the orders of magnitude among the solution vector components can lead to numerical roundoff errors, which can extend convergence times or cause failures. This is particularly relevant in scenarios where the amplitude of the forcing frequency differs significantly from the response amplitude.

To address this numerical issue, users can linearly scale each component of the solution vector by a scalar value or by values specified in a scaling vector. In many cases, applying one scaling value for displacements and another for the forcing frequency is sufficient to improve convergence rates.

Assuming the augmented multi-harmonic vector of unknowns $(\bar{u}^+)$ is expressed as shown in Eq. (1):

$$\overline{\mathbf{u}}^+ = \begin{bmatrix} \overline{\mathbf{u}} \\ \omega \end{bmatrix}, \tag{1}$$

where $\overline{\mathbf{u}}$ is the multi-harmonic solution vector and ω is the forcing frequency, Ansys-HBM allows for the scaling of selected components of this vector. The scaled vector $\overline{\mathbf{u}}^+$ can be represented as shown in Eq. (2):

$$\overline{\mathbf{u}}^+ = \begin{bmatrix} \overrightarrow{\mathbf{a}} \circ \overline{\mathbf{u}} \\ b \times \omega \end{bmatrix}, \tag{2}$$

where $\overrightarrow{\mathbf{a}}$ is a vector of the same length as $\overline{\mathbf{u}}$, and b is a scalar. This scaling approach helps stabilize the solution process and improve convergence, as illustrated in Figure 1.

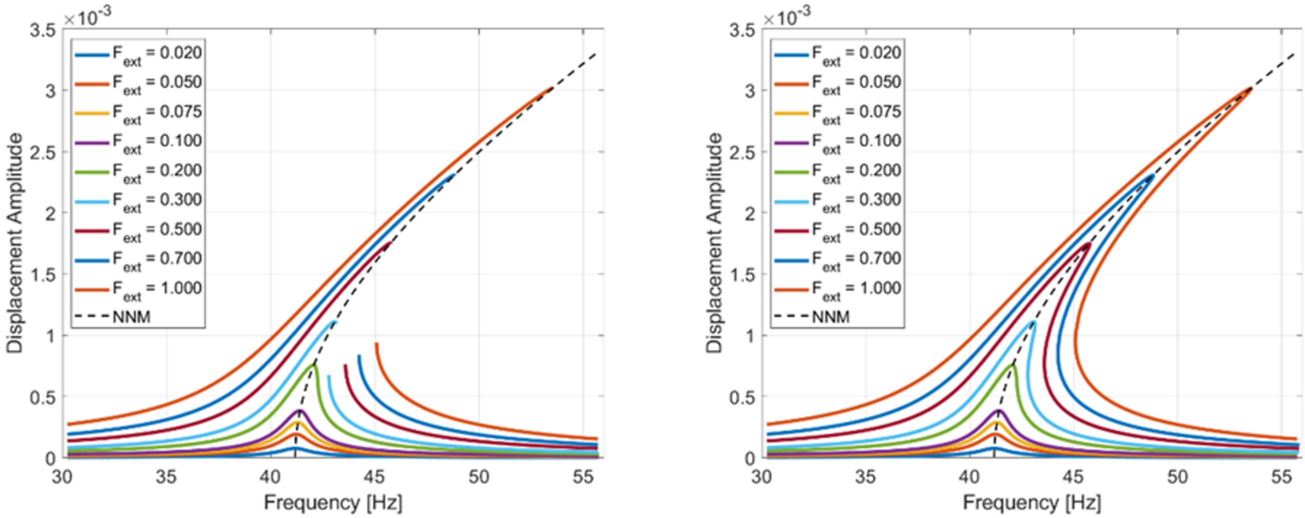

Fig. 1 Solution to a case study from [11] obtained using Ansys-HBM. In this particular study, if solution vector scaling is not applied, the algorithm struggles to achieve convergence near the boundaries between the stable and unstable regions of the nonlinear frequency response functions (chart on the left). The chart on the right shows the solution after applying solution vector scaling, which significantly improves convergence.

For more details on these techniques and their implementation, please refer to the Ansys-HBM Analysis Guide [10].

Application of the Ansys-HBM to a Benchmark Example

In this benchmark example, the Harmonic Balance Method (HBM) is applied to a Brake-Reuss cantilever beam. This structure consists of two beams featuring a frictional contact surface between them, connected by three prestressed bolted joints. A point input force is applied to one beam, while the motion of the corner of the other beam is monitored. Since this example involves a Brake-Reuss cantilever beam, one end of the assembly is fixed. The geometry of the beam in this study is similar to that described in [12]. The specific geometry, boundary conditions, and loads are illustrated in Figure 2.

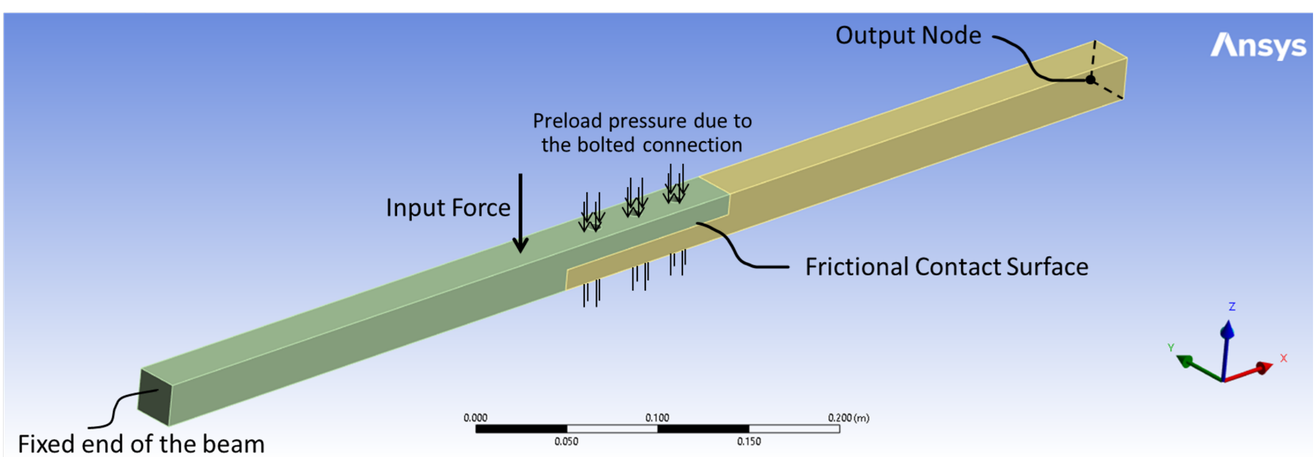

Fig. 2 Geometry, boundary conditions, and load setup for the Brake-Reuss cantilever beam model used in this benchmark example.

Figure 3 presents sample results obtained using the Ansys-HBM. The graph displays frequency responses (FRs) acquired near the second nonlinear bending mode of the cantilever beam, computed for various input force magnitudes. Notably, the

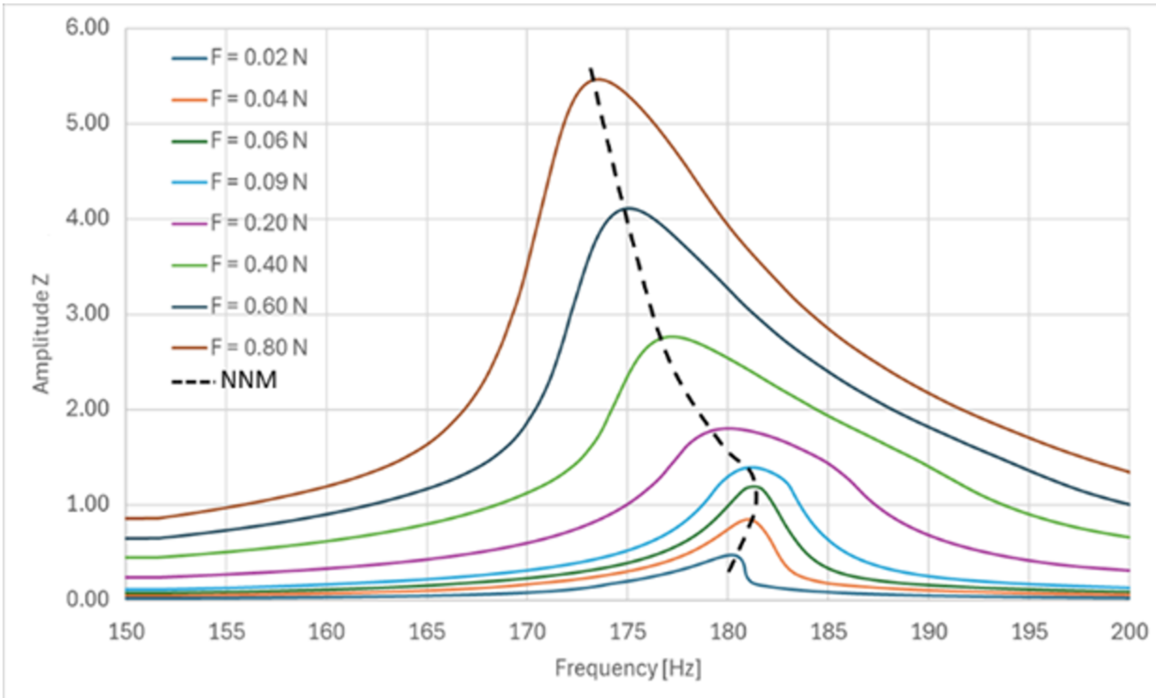

Fig. 3 Frequency response (FR) curves for the Brake-Reuss cantilever beam near the second nonlinear bending mode, obtained for various input force magnitudes. The nonlinear normal mode (NNM) curve illustrates the amplitude-dependent natural frequency and its stiffening-softening characteristic.

plot reveals that the nonlinear natural frequency, represented by the nonlinear normal mode (NNM) curve, is amplitude-dependent and exhibits a stiffening-softening characteristic.

Conclusions

This work has presented an overview of the ANSYS Harmonic Balance Method (HBM) and its capabilities for simulating nonlinear oscillating mechanical systems. The application of ANSYS-HBM to the Brake-Reuss cantilever beam example demonstrated its effectiveness in capturing amplitude-dependent nonlinear response functions. The results show that the implemented method can accurately represent nonlinearities in systems featuring bolted joints and contact surfaces. Moreover, this work discussed various techniques for improving convergence in HBM analyses, such as optimizing initial guesses and scaling the solution vector. These strategies enhance the reliability and efficiency of simulations, addressing common challenges encountered in nonlinear analyses. Future work will focus on further refining this method, exploring additional types of nonlinearities, and applying HBM to more complex systems.

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