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Dynamic simulation and performance evaluation of vibratory bowl feeders integrated with paddle shaft mechanisms

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ABSTRACT

Vibratory bowl feeders play a crucial role in automated manufacturing by efficiently orienting and transporting parts. This study investigates the performance of a vibratory bowl feeder through both experimental and simulation-based analysis. The system's efficiency was evaluated at different frequencies ranging from 47 Hz to 79.75 Hz, comparing actual and simulated results for parts per minute and time required to process 200 parts. The findings reveal discrepancies between actual and simulated outputs, with the actual parts per minute ranging from 30 to 160, while simulation results varied from 40 to 200. Similarly, the time for processing 200 parts decreased from 15.3 minutes at 47 Hz to 2.2 minutes at 79.75 Hz, whereas the simulated time ranged from 7.8 to 1.0 minutes. Dynamic simulation and FEA-based performance analysis were conducted to optimize the shaft design of a double shaft paddle mixer, enhancing durability and efficiency in industrial mixing applications. The study highlights the potential of advanced simulation tools in optimizing vibratory feeder performance, enabling real-time adjustments for improved efficiency. Future enhancements include the integration of machine learning and control adaptability to refine operational accuracy and adaptability.

Keywords: vibratory bowl feeder, automation, assembly, sorting, orientation, material handling, dynamic simulation.

INTRODUCTION

Automation plays a crucial role in optimizing manufacturing and assembly operations in the modern industrial sector. Effective material handling and component feeding systems contribute to higher production rates, reduced reliance on manual labor, and enhanced product uniformity. Among various automation solutions, vibratory bowl feeders are instrumental in precisely feeding and orienting small mechanical components, such as nuts and bolts, ensuring smooth integration into automated assembly lines. Manufacturers often face challenges in efficiently handling and feeding small components in automated systems. The key issues include high costs associated with multiple feeder systems, frequent jamming, and misalignment due to improper part orientation, excessive noise and vibration-induced wear, irregular feed rates leading to production slowdowns, and limited flexibility in accommodating different component shapes and sizes. Addressing these challenges necessitates the development of a versatile and optimized vibratory bowl feeder that enhances precision, minimizes operational expenses, and reduces downtime. A vibratory bowl feeder uses controlled vibrations to move components along a spiral track, systematically aligning and feeding them into an assembly system. These feeders are extensively utilized in the automotive, electronics, pharmaceutical, and aerospace industries, where precision and reliability are paramount. Their capacity to process large volumes of small parts with minimal human intervention makes them indispensable for improving production efficiency and maintaining quality control. Despite their advantages, conventional vibratory bowl feeders suffer from part misalignment, inconsistent feed rates, excessive noise, energy inefficiency, and maintenance challenges. Additionally, most feeders are designed for specific components, limiting their adaptability and increasing costs when multiple part types need to be handled. This research aims to design, develop, and experimentally analyze a vibratory bowl feeder specifically for nuts and bolts, focusing on enhancing efficiency, reliability, and flexibility to address these limitations.

Vibratory bowl feeders come in various types, each with unique advantages and limitations. Straight Wall Bowl (Figure 1) Feeders are simple, easy to maintain, and ideal for uniform components like screws and nuts but unsuitable for irregular shapes. Conical Bowl Feeders (Figure 2) features a spiral track for feeding different-sized parts, offering versatility but requiring more maintenance. Stepped Bowl Feeders (Figure 3) have multiple levels to sort and separate components efficiently, though they are more complex to set up and maintain.

A vibratory bowl feeder is an essential automation device designed to efficiently transport, sort, and orient small components for seamless integration into production lines. It operates using controlled vibrations that guide bulk materials along a spiral track, ensuring that each part reaches the next stage in the correct orientation. These feeders play a crucial role in industrial automation, enabling high-speed and precise feeding of components such as screws, nuts, bolts, and electronic parts. Known for their durability, efficiency, and versatility, vibratory bowl feeders help streamline manufacturing processes by reducing manual handling, minimizing errors, and improving overall productivity. They are widely used in automotive, electronics, pharmaceutical, packaging, and aerospace industries, where consistent part orientation is critical for smooth assembly operations. Additionally, these feeders can be customized to handle different materials, sizes, and shapes, making them a reliable and cost-effective solution for bulk material handling and sorting applications.

Figure 1. Straight wall bowl feeder

Figure 2. Conical bowl feeder

Figure 3. Stepped bowl feeders

The study utilized finite element simulation with modal analysis in ANSYS Workbench to determine the fundamental frequencies and validate the design parameters of vibratory bowl feeders. Experimental verification confirmed that the simulation model effectively predicts structural characteristics before manufacturing [1]. An approximate model for predicting part behavior in a vibratory bowl feeder by analyzing dynamic, geometric, and electromagnetic parameters. Numerical solutions and dynamic simulations were used to evaluate performance, making the procedure accessible for practical applications [2]. The study develops a simplified dynamic model for vibratory bowl feeders, leveraging the symmetrical spring arrangement to determine the system's stiffness matrix. The analysis shows that the bowl follows elliptical vibrations, and resonance conditions are identified, while the "slip-stick" motion for part movement is deemed unlikely [3]. They examine the dynamics of a vibratory bowl feeder for automatic assembly, presenting a geometric model and force analysis that leads to a comprehensive dynamic model. By equating the feeder to a three-legged parallel mechanism, the research derives motion equations using Newtonian and Lagrangian methods, with simulations validating the model's accuracy [4].

Vibratory bowl feeders are widely used in industrial automation for feeding and orienting parts, traditionally utilizing electromagnets as actuators. However noise, non-linear motion, and passive characteristics persist, leading to research on alternative technologies. Studies by Boothroyd and others have explored feeder mechanisms and orientation devices. At the same time, recent advancements propose piezoelectric actuators, offering faster response, wider frequency bandwidth, and precise control, improving feeding efficiency over conventional electromagnet-based systems [5]. An approximate method for calculating the natural frequency of vibratory feeders, addressing the complexity of spring deformation in bowl-type systems. The research establishes relationships between spring constants and settings, derives frequency equations for different feeder types, and validates theoretical findings through experimental analysis [6]. The design of industrial parts feeders is traditionally a time-consuming trial-and-error process, even for single-part orientation. This study explores the use of dynamic simulation to accelerate feeder design, providing probabilistic analyses of vibratory feeding behavior and comparing simulated experiments with real industrial bowl feeder tests, demonstrating strong correlations between the results [7].

Vibratory bowl feeders are widely used in modern production for handling lightweight and small discrete parts, with numerical models applied to optimize their design. However, discrepancies between theory and practice lead to extensive post-fabrication adjustments. This study introduces an MSC ADAMS-based numerical model that simulates the vibration-driven workpiece delivery process, accurately reflecting real experimental conditions. The validated model can optimize feeder parameters before manufacturing, reducing errors and improving performance [8].

Vibratory bowl feeders are widely used in automated assembly due to their versatility. This study develops a state-space mathematical model to analyze feeder parameters, enabling computer simulations to predict part velocity and feed rate, which can be utilized to optimize feeder design and performance [9]. Spiral vibrating feeders are widely used in machining automation, but traditional vertical vibration models fail to represent their working conditions accurately. This study develops a three-degree-of-freedom vibration mechanics model, deriving amplitude-frequency characteristics and validating them through experiments on the PEF120A feeding system. It provides a more accurate theoretical foundation for precision component feeder design [10]. Linear and vibratory bowl feeders are commonly used in mass production, but the specialized tooling for helical tracks in bowl feeders makes adaptation costly. This study proposes an alternative feeder design, developing a balanced feeder with wiper blades, which was experimentally optimized to enhance conveying velocity and improve flexibility [11]. Vibratory bowl feeders (VBF) are widely used in industry, but their design process is time-intensive. This study proposes an automated design approach using rigid body simulation, comparing simulated and real-world experiments to assess accuracy. The findings highlight similarities and key differences, and the study optimizes feeder parameters, particularly part-orienting traps, for improved performance [12].

Automation has become essential in manufacturing, ensuring efficiency, precision, and synchronization in production lines to meet growing demands. This study analyzes the performance of a vibratory bowl feeder for laminated bottle caps in the pharmaceutical and consumer goods industries, evaluating how part population, size, and frequency affect feed rate through experimental analysis and graphical interpretation [13]. They present a simple analytical model for an industrial vibratory bowl feeder used for automated part separation, feeding, and positioning in manufacturing. The model is validated through an experimental setup with a capacitive MEMS accelerometer and LabVIEW-based data acquisition, showing a strong correlation between analytical predictions and experimental results [14]. They investigate the impact of feeder drive system positioning on the dynamics and material conveying velocity in a linear electromechanical vibratory feeder. Using signal processing techniques, experimental analysis was conducted to evaluate variations in vibration amplitude, force transmissibility, and conveying velocity at different motor positions, identifying the optimal configuration for improved feeder performance [15]. Vibratory feeders are essential in automated assembly for storing, transporting, orienting, and isolating small parts, relying on impact and friction for movement along an oscillating track. This study develops a mechanical model based on Coulomb friction to analyze part feeding dynamics, verified through laser-based measurements, enabling improved feeder design and transportation efficiency [16]. Sorting small parts is a key task in industrial manufacturing, often performed using VBF. Traditionally designed through trial and error, this study proposes an automated VBF design method using Reinforcement Learning, where a software agent optimizes trap placement based on Q-learning and physics simulations, improving efficiency while retaining knowledge from conventional design processes [17].

Electromagnetically driven vibrating feed bins are widely used in automated production for feeding small to medium-sized parts in assembly lines and flexible manufacturing systems. vibrations low productivity and excessive vertical vibrations often limit their efficiency, leading to unstable part movement. This study explores design modifications to optimize vibration dynamics, proposing additional structural elements that enable adjustable horizontal vibrations while maintaining stability, improving feeder performance and expanding its applicability in industrial automation [18]. Vibration loading devices are extensively used in mechanical engineering and automated production to transport small to medium-sized components. Traditional two-mass oscillating vibratory feeders suffer from energy inefficiencies due to wasted vibrations in the reactive mass, leading to increased weight and lower performance. This study proposes a redesigned vibrating hopper feeder that enhances the horizontal oscillation amplitude through internal energy redistribution rather than increasing exciter power, improving efficiency, reducing weight, and optimizing material usage for better industrial application [19]. While MSC.ADAMS is widely referenced in literature for vibratory system modeling [8], this study specifically used Algoryx Momentum for dynamic simulation due to its real-time interaction capabilities. Vibratory bowl feeders are indispensable components in automated assembly and parts handling systems, playing a crucial role in orienting and delivering parts to downstream processes with precision and consistency [20].

The efficiency and reliability of these systems are heavily influenced by the design and performance of the hopper and feeder mechanisms, which are responsible for storing, singulating, and presenting parts to the bowl [21]. To optimize the overall performance of vibratory bowl feeders, it is essential to conduct thorough dynamic simulations and performance analyses of various hopper and feeder design strategies [22]. These analyses allow engineers to evaluate the impact of different design parameters, such as hopper geometry, feeder angle, vibration frequency, and amplitude, on the system's ability to consistently deliver parts at the desired rate and orientation [23]. Addressing the complexities inherent in vibratory bowl feeder systems requires a multifaceted approach, integrating advanced simulation techniques with meticulous experimental validation to ensure optimal performance and reliability in diverse industrial applications.

The design of vibratory bowl feeders presents a complex engineering challenge, demanding a comprehensive understanding of various factors, including part geometry, material properties, and desired feed rate. Simulation tools, such as finite element analysis and multibody dynamics software, enable engineers to model and analyze the dynamic behavior of these systems, predicting the motion of parts within the bowl and identifying potential bottlenecks or inefficiencies [24]. By simulating the interaction between parts and the feeder, engineers can optimize the design of the hopper and tooling to ensure smooth and consistent part flow. The optimization process often involves iterative design modifications, where the simulation results guide adjustments to the hopper geometry, track configuration, and vibration parameters. Furthermore, understanding the dynamic characteristics of the vibrating screen is crucial, and simplifications of complex structures may be necessary for finite element analysis, omitting parts with less impact on structural strength [25]. Such omissions can lead to discrepancies between simulation results and practical measurements, underscoring the importance of considering dynamic characteristics in design and analysis [26].

The performance of vibratory bowl feeders is significantly influenced by the vibration parameters, including frequency and amplitude, as well as the feeder angle [27]. Adjusting these parameters can alter the conveying speed, part orientation, and overall system throughput. Dynamic simulation allows engineers to explore a wide range of vibration settings and feeder angles, identifying the optimal combination for a specific part and application. This optimization process often involves using simulation software to perform parametric studies, where the vibration frequency, amplitude, and feeder angle are systematically varied, and the resulting part flow rate and orientation are recorded. Such numerical simulation of fluid-structure interaction can provide insights into wake patterns, fluid forces, and dynamic responses, enabling a coupled analysis of the fluid-structure system [28]. By analyzing the simulation results, engineers can identify the optimal operating conditions that maximize part throughput while minimizing the risk of part jamming or misorientation [29-32]. Operational Modal Analysis is a valuable method for evaluating the behavior of structures, identifying their dynamic properties based on their dynamic response. In addition to optimizing the vibration parameters, the design of the hopper and tooling plays a critical role in ensuring consistent part flow and orientation [33-36].

This study aims to design, develop, and optimize a vibratory bowl feeder capable of handling multiple types of components efficiently, reducing operational costs, and enhancing automation in industrial assembly processes. A key challenge identified from the survey and literature review is the need for multiple feeder systems to accommodate different components, leading to high space, maintenance, and labor expenses. To address this, the proposed system will be designed to effectively separate and orient various parts, ensuring it can simultaneously handle two different components while maintaining accuracy in sorting and feeding. Additionally, the study will focus on optimizing vibration frequencies to improve performance under different part loads and maintaining a constant feed rate to minimize jamming, ensuring smooth and reliable operation.

METHODOLOGY

The vibratory bowl feeder's design, development, and optimization were carried out through a structured methodology involving design conceptualization, simulation, fabrication, and experimental validation. The following steps outline the approach used in this study:

The components of a vibratory bowl feeder include the bowl feeder, which holds and orients parts with its spiral design; the vibrating unit, an electromagnetic system generating adjustable vibrations; the base plate, providing stability and absorbing vibrations; leaf springs, connecting the bowl to the base and allowing controlled vibrations; and the control unit, which regulates vibration settings through an electronic controller.

Design and concept development

The first phase involved understanding the functional requirements of the vibratory bowl feeder for handling nuts and bolts in an automated assembly system. Key design parameters such as bowl size, material selection, vibration frequency, and feed rate were considered. A CAD model of the feeder was developed to visualize its structural components, including the bowl, vibrating unit, base plate, leaf springs, and control unit. Table 1 shows the specifications vibratory bowl feeder.

Material selection (Table 2) is a crucial stage in designing any physical object, aiming to balance cost efficiency with optimal product performance in the design process.

Table 1. Vibratory bowl feeder specifications

Specification	Details
Component to be conveyed	Bolt, nut
Load capacity	6 kg and 1600 parts
Conveying height	150 mm (from bottom to top of bowl)
Bowl diameter	300 mm
Spring length	110 mm
Spring thickness	3 mm
Spring width	30 mm
Operating frequency	40–60 Hz

Table 2. Material properties

Component	Material	Density (kg/m³)	Young's modulus (GPa)	Tensile yield stress (N/mm²)	Tensile ultimate stress (N/mm²)
Bowl	SS 304	8000	193	215	505
Top plate	LM 6 Al	2650	71	160	230
Leaf spring	EN 45	8080	204	551	621
Base plate	Cast Iron	7810	250	1450	1650
Bolt & nut	40C8	7850	210	560	660

The selection and specifications of an electromagnet used in an industrial application is explained. It begins with a Table 3 and 4 categorizing different types of electromagnets based on bowl diameters, ranging from 300 mm to 800 mm, with corresponding electromagnet series such as EM-500 EL and EM170 HS. An image of an electromagnet is also included for reference. The electromagnet specifications are detailed in a table, listing the operating voltage as 230 V, current rating as 0.9 A, frequency as 50 Hz, and phase as single-phase. An electromagnet force calculation is presented using a formula involving current, permeability, and other parameters. The final calculated excitation force of the electromagnet is approximately 1465 N. This analysis helps in determining the appropriate electromagnet for specific industrial applications based on system requirements. Figure 4 shows the selected Electromagnet for this study.

Table 3. Electromagnet selection based on bowl diameter

Bowl diameter	Electromagnet series
300 mm	EM Series – EM-500 EL
400 mm	EM Series – EM-500 EL
600 mm	EM Series – EM170 HS
800 mm	EM Series – EM170 HS

The Figure 5 discusses the upper vibrating plate, detailing its material selection, mechanical properties, and thickness calculation. The plate is made of Aluminium LM6, with a tensile strength (Sut) of 280 N/mm², a Poisson's ratio of 0.3, and a Young's modulus of 71 × 10^3 MPa. The load

Figure 4. Electromagnet

Table 4. Electromagnet specification

Voltage	Ampere rating	Operating frequency	Phase
230 v	0.9 A	50 Hz	Single-phase

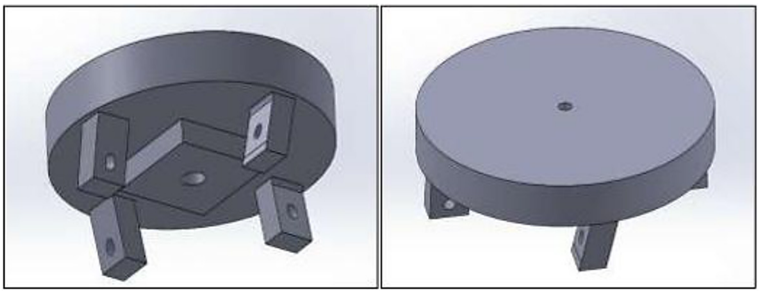

Figure 5. Upper vibrating plate

calculations for the bowl and parts are determined as 58.86 N and 36.78 N, respectively. The required thickness is calculated as approximately 38 mm using the bending formula for a circular plate. This ensures structural integrity and optimal vibration performance for the application.

The detailed design of a spring, including material selection, load calculation, and bending analysis. The spring is made of EN 45 material with a tensile strength of 624 MPa, Poisson's ratio of 0.3, and Young's modulus of 204 GPa. The total load on the spring is calculated as 1630 N, distributed as 408 N per spring. Using V.B. Bhandari's bending formula, the required thickness of the spring is determined to be approximately 3 mm. Additionally, buckling analysis is performed considering one end fixed and the other loaded, ensuring structural stability.

The selection of nuts and bolts for the electromagnet assembly plays a critical role in ensuring the system's structural integrity and mechanical reliability. The uploaded image comprehensively analyze the mechanical properties and safety assessment of selected fasteners. The study primarily focuses on M12 × 1.75 and M14 × 2.5 bolts, considering their suitability under tensile and shear loading conditions. A detailed evaluation uses parameters such as ultimate tensile strength (Sut), yield strength (Syt), Poisson's ratio, and Young's modulus. The analysis incorporates the fundamental principles of mechanical design, ensuring that the selected bolts can withstand the applied forces while maintaining a sufficient factor of safety (FOS).

The tensile stress analysis for M12 × 1.75 bolts used in securing the electromagnet base and spring plate confirms that the induced stress remains significantly lower than the allowable stress limits. The calculation considers core electromagnet's excitation force and the core's weight, resulting in a maximum tensile stress of 2.42 N/mm², which is well below the permissible limit of 186.67 N/mm². The shear stress calculations also validate that the bolts operate within safe stress levels, reinforcing their suitability. Similarly, for the spring plate, an equivalent analysis confirms the adequacy of the selected bolts under combined loading conditions. The study also accounts for the cumulative forces acting on the system, ensuring a robust fastening solution.

For the top plate, the selection of an M14 × 2.5 bolt is analyzed, demonstrating its enhanced load-bearing capacity due to its larger diameter and thread pitch. The induced tensile stress of 9.89 N/mm² and shear stress of 1.88 N/mm² are significantly lower than the allowable limits, confirming the bolt's structural safety. The findings indicate that the selected fasteners provide adequate mechanical strength, ensuring the long-term reliability of the electromagnet assembly. This comprehensive evaluation supports the optimal choice of nut and bolt configurations for the given application, aligning with engineering design principles and safety considerations.

The calculated tensile stress values – 2.42 N/mm² for M12 × 1.75 bolts and 9.89 N/mm² for M14 × 2.5 bolts – are significantly lower than the allowable tensile stress limit of 186.67 N/mm². This large safety margin was intentionally maintained for several reasons:

- Design uniformity and compatibility – standardized bolt diameters were chosen to ensure compatibility with industry-standard tools and mounting holes. Using smaller diameters, although theoretically permissible, would introduce variations in tooling and assembly, potentially increasing operational complexity.
- Vibration resistance – in vibratory systems, mechanical fasteners are subjected not only to static loads but also to dynamic loads and fatigue due to continuous vibrations. A higher factor of safety reduces the risk of loosening or failure under prolonged cyclic loading conditions.
- Ease of maintenance and interchangeability – using robust bolts with higher load-bearing capacity allows for easier maintenance and replacement without the need for recalibration or redesign of mounting hardware.
- Conservative engineering practice – especially in automation and feeder systems, overdesign in terms of fastener strength ensures long-term reliability, minimizes downtime, and avoids unforeseen failures due to material degradation, wear, or misalignment.

HOPPER (BOWL) DESIGN

The hopper in a vibratory bowl feeder is a specially designed container that holds and regulates the flow of small components like nuts and bolts. It features a spiral track that guides parts upward using controlled vibrations generated by an electromagnetic system. As the parts move along the track, they get aligned and oriented for further processing. Made from durable materials like stainless steel, the hopper plays a vital role in ensuring consistent feed rates, minimizing jamming, and enhancing the efficiency of automated assembly systems. Table 5 indicates the steps description for algorithm with formulas used. Table 6 show the obtained results for hopper design.

ANALYSIS OF VIBRATORY BOWL FEEDER

According to the book of Assembly and Automation by Boothroyd, the movement of parts in a bowl feeder is a complex and highly specialized process. The vibratory bowl feeder uses an electromagnet that creates a magnetic field, causing the bowl to vibrate rapidly. This vibration, in turn, causes the parts inside the bowl to move in a circular or spiral motion, depending on the design of the feeder. As the parts move, they are sorted and oriented and then discharged from the bowl feeder in a precise and controlled manner.

Force analysis in bowl feeder

Following the conditions from the book, the movement of parts in the bowl feeder is analyzed using the equation:

$$F = \mu_s N = \\ = \mu_s [m_p\, g\, \cos\theta - m_p\, a_0\, \omega^2 \sin\theta \quad (1)$$

Substituting values:

$$\frac{a_0\,\omega^2}{g} = \frac{\mu_s \cos\theta + \sin\theta}{\cos\theta + \mu_s \sin\theta} \quad (2)$$

$$1.5 \times 10^{-3} \times 219.91^2 / 9.81 > \\ > (0.5 \times \cos(0.0663) + \sin(0.0663)) / \\ / (\cos(0.0820) + 0.5 \times \sin(0.0820)) \\ 7.39 > 0.54 \text{ (condition satisfied)}$$

Spring mass system of vibratory bowl feeder

The spring stiffness is calculated based on the specifications of the spring material and dimensions:

$$K = \frac{E \cdot w \cdot t^3}{4L^3} \quad (3)$$

$$K = (204 \times 10^9 \times 0.03 \times 0.003^3) / (4 \times 0.113^3) \\ K = 31036.8144 \text{ N/m}$$

Natural frequency calculation

$$\omega_n = \sqrt{\frac{4K}{m}} \quad (4)$$

$$\omega\_n = \text{sqrt}(31036.8144 \times 4 / 13.875) \\ \omega\_n = 94.59 \text{ rad/s} \\ F\_n = (1 / 2\pi) \text{ sqrt}(4K / m) \\ F\_n = 15.05 \text{ Hz}$$

Force and deflection in spring

Force on the springs due to vibrations:

$$F = 0.3535 \text{ N}$$

Deflection in spring:

$$F = K.x\ 5$$

$$0.3535 = 31036.8144 \times x$$

x = 0.000011389 m (Deflection of the spring)

Based on the above calculations, various natural frequencies, spring forces, and spring deflections have been determined for different part weights. The following Table 7 presents the iterative results for the system at varying mass values.

Table 5. Steps description for algorithm with formulas

Sr. No.	Step description for algorithm	Formulas
1	Input part specifications	$V_p = (\pi/4) \cdot d^2 \cdot h$ $m_p = V_p \times \rho$
2	Define functional requirements	$M_t = N \times m_p$
3	Calculate total hopper volume	$V_t = N \times V_p \times SF$
4	Choose hopper geometry	Conical: $V = (1/3) \cdot \pi \cdot r^2 \cdot h$ $\rightarrow h = 3V / (\pi \cdot r^2)$
5	Calculate hopper angle	$\theta_{hopper} = \varphi + 5°$ to $10°$
6	Design outlet width	$W_o = d$ + clearance
7	Simulate part flow	Use DEM or Algoryx simulation (no formula)
8	Add vibration mount parameters	$K = (E \cdot b \cdot t^3) / (4 \cdot L^3)$
9	Structural validation	Use FEA for stress, deformation, resonance
10	Optimize thickness and ribs	$t = \sqrt{(M / (\sigma_{allo}w \cdot Z))}$

Table 6. Final design specifications for hopper in vibratory bowl feeder

Parameter	Value
Hopper volume	~1872 cm³
Wall angle	40°
Top opening	200 × 150 mm
Outlet opening	80 × 60 mm
Height	120 mm
Material	SS304
Wall thickness	2 mm
Fasteners	M12 bolts (FOS > 2)

ANALYSIS

Modal analysis on lower assembly

Finite element analysis (FEA) was conducted using ANSYS Workbench to perform both modal and static structural analyses on the lower assembly and spring plate of the vibratory bowl feeder. Modal analysis identified the fundamental frequencies and deformation characteristics (Figure 6), while static analysis determined the stress and deformation under operational loads (Figures 7 and 8). Modal analysis is conducted to examine the dynamic behavior of a system or structure, aiding in the identification and evaluation of its natural frequencies, mode shapes, and damping properties. The total deformation at 113.47 Hz is measured at 8.96 mm as shown in Figure 6.

Static analysis on lower assembly

Static analysis valuates critical parameters such as stress, strain, deformation, and safety margins within the structure. These findings are essential for assessing the design's structural integrity, performance, and reliability. By identifying potential failure points or weaknesses, static analysis aids in making informed decisions related to material selection, shape optimization, and necessary structural modifications. This approach enhances systems' overall efficiency, durability, and safety, contributing to their optimal design and functionality. Lower assembly static analysis (total deformation) is as shown in Figure 7. Total deformation at 113.47Hz is 0.0023661 mm.

Structural analysis of spring plate

The Figure 8 presents the static structural analysis of a spring plate, illustrating the total deformation under applied loads. The color contour represents the distribution of deformation across the structure, with red indicating the maximum deformation (0.0021651 mm) and blue showing the minimum deformation (9.8522e-6

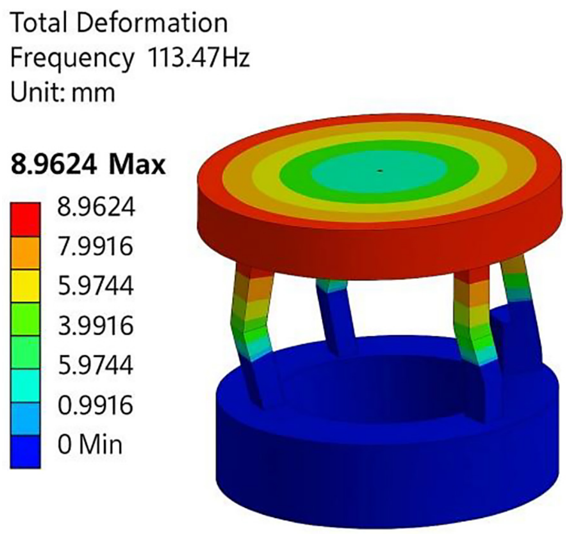

Figure 6. Lower assembly modal analysis

Table 7. Values obtained by mathematical calculations for system

Sr. No.	Parts (No)	Mass (Kg)	C mass (Kg)	Wn (rad/s)	Fn (Hz)	F (N)	X (m)
1	100	0.375	13.875	94.5914	15.0546	0.3535	0.000011389
2	200	0.75	14.25	93.34	14.855	0.3631	0.000011699
3	300	1.125	14.625	92.1341	14.6635	0.3727	0.000012008
4	400	1.5	15	90.9751	14.4791	0.3822	0.000012314
5	500	1.875	15.375	89.8588	14.3014	0.3918	0.000012623
6	600	2.25	15.75	88.7826	14.1301	0.4013	0.000012929
7	700	2.625	16.125	87.7442	13.9649	0.4109	0.000013239
8	800	3	16.5	86.7414	13.8053	0.4204	0.000013545
9	900	3.375	16.875	85.772	13.6510	0.4300	0.000013854
10	1000	3.75	17.25	84.8347	13.5018	0.4396	0.000014163

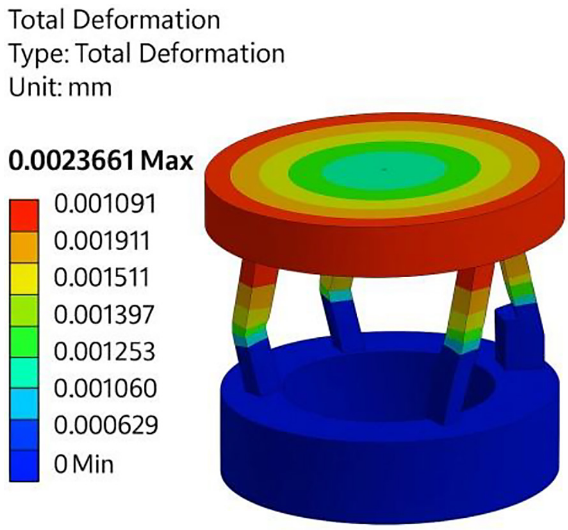

Figure 7. Lower assembly static analysis (total deformation)

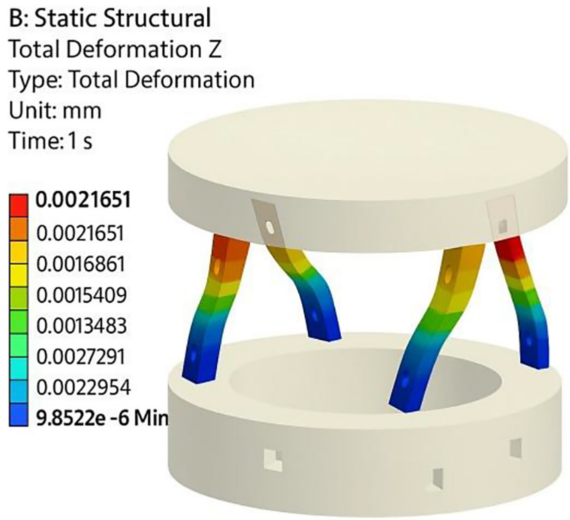

Figure 8. Spring plate static analysis (total deformation)

mm). The analysis is conducted at a frequency of 113.47 Hz, where the total deformation is recorded as 0.002161 mm. This study helps in understanding the mechanical response of the spring plate, ensuring its structural integrity and reliability under operational conditions.

MODELLING

The vibratory bowl feeder plays a crucial role in various manufacturing processes, making precise modeling of its components essential for accurate design and assembly. Based on the dimensions obtained from prior calculations, a 3D model of different parts of the vibratory bowl feeder was developed using SolidWorks software. This software facilitated the creation of highly accurate and detailed designs, ensuring precise manufacturing. The modeling process involved constructing a virtual 3D environment where the feeder's components were assembled, adjusted, and tested. The resulting models provided a clear visualization of the parts, allowing for the identification of potential errors or issues before production. Utilizing SolidWorks ensured that the final components were highly precise, efficient, and reliable, thereby improving the overall quality of the vibratory bowl feeder. Following is the 3D model of drawing sheets of the vibratory bowl feeder in Figures 9 and 10.

A vibratory bowl feeder is a crucial component in manufacturing, designed to feed and orient small parts efficiently. It consists of a bowl or hopper that holds the parts, a vibrator unit that generates vibrations, a control unit to regulate frequency and amplitude, and a base for support. The feeder operates on the vibrations principle, where parts placed in the bowl move along a spiral track due to controlled vibrations. The working process involves three stages: the loading stage, where parts are introduced into the bowl and begin moving along the track; the orientation stage, where

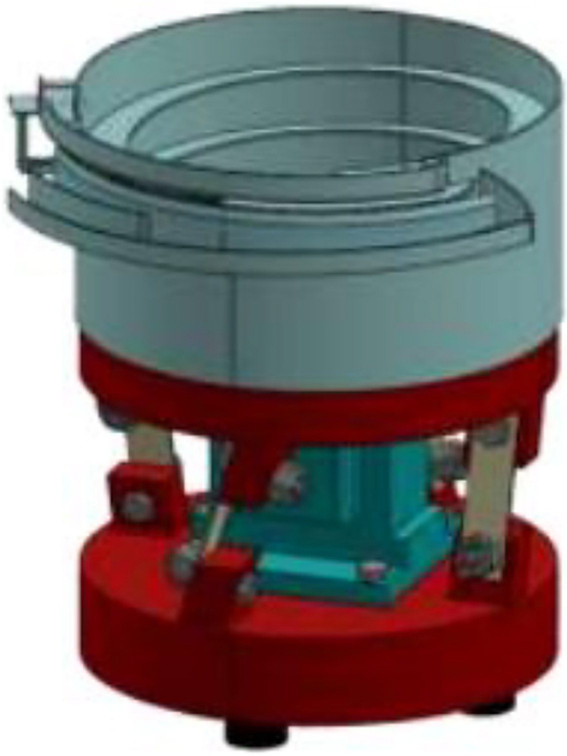

Figure 9. 3D assembly of vibratory bowl feeder

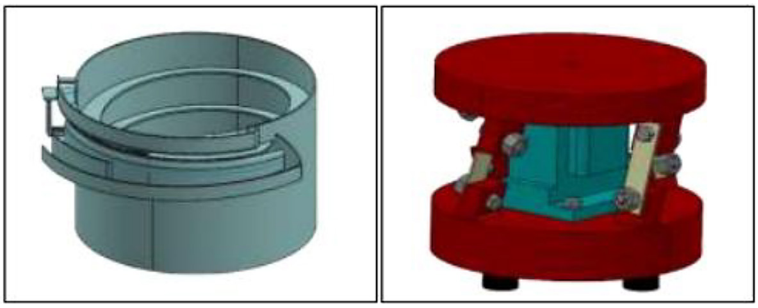

Figure 10. 3D assembly of feeder bowl and drive unit

angled surfaces and grooves align the parts in a specific direction; and the discharge stage, where properly oriented parts exit through the discharge chute for further processing. The vibration frequency and amplitude can be adjusted to regulate the feed rate, ensuring smooth and efficient operation. The design of vibratory bowl feeders allows for the gentle handling of delicate parts while accommodating a variety of shapes and sizes. Their ability to reliably sort and transport components makes them indispensable in numerous manufacturing industries.

SIMULATION

All simulation work was conducted using Algoryx Momentum software, a powerful physics simulation tool widely used in engineering. It offers a precise and efficient approach to modeling complex mechanical systems, including vibratory bowl feeders. The simulation involves creating a virtual model of the feeder and its components, defining material properties, and setting simulation parameters. Once configured, the software runs various tests to evaluate system performance. Engineers can analyze the results in real time and use the data to refine the feeder's design. The simulation begins with importing the feeder's geometry, defining material characteristics, and configuring parameters such as vibration frequency and amplitude. The software then tests part orientation, feeding rates, and potential design flaws like jamming or excessive wear. Detailed analysis of the results enables engineers to optimize the feeder's efficiency and functionality. Algoryx Momentum is an invaluable tool for engineers developing vibratory bowl feeders, providing accurate simulations that help enhance design efficiency and performance. The insights gained from these simulations ensure the feeder meets operational requirements and functions optimally. Multibody dynamic simulation was also performed using MSC.ADAMS to model the vibration-induced part transport mechanism. The software simulated interaction forces, part trajectories, and bowl dynamics under varying frequency inputs. These results helped in understanding complex motion behaviors and validating design stability (Figures 11 and 12).

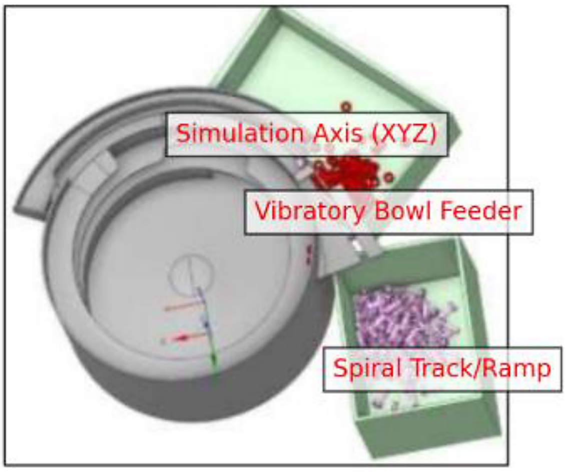

Figure 11. Dynamic simulation of standard system using Algoryx Momentum software

MODEL VALIDATION

To assess the reliability of the simulation model developed for the vibratory bowl feeder, a validation study was performed by comparing simulated data with experimental results across multiple frequency settings. The primary validation metrics used include root mean square error (RMSE) and percentage error in two key parameters:
- time required to transport 200 parts,
- parts per minute (PPM).

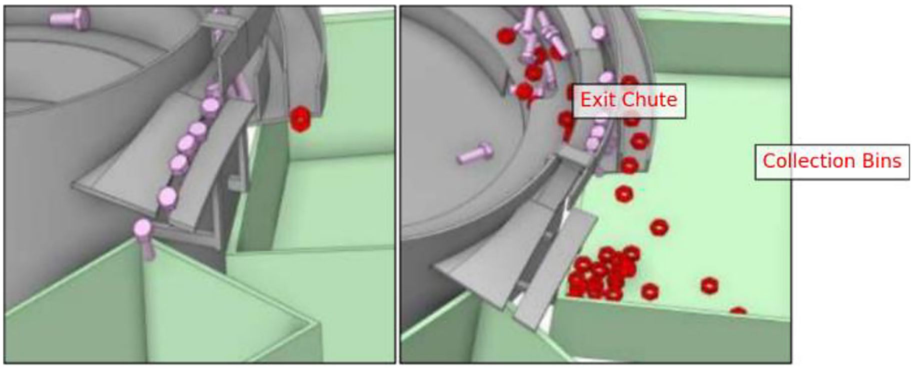

Figure 12. Dynamic simulation of bolt using Algoryx Momentum software

Validation methodology

The experimental setup and simulation model were both operated at frequencies ranging from 47 Hz to 79.75 Hz.

- at each frequency, the time taken to transport 200 parts was recorded.
- the percentage error between simulation and actual data was calculated using the formula:

$$\textit{Percentage error} = |\textit{Simulated value} - \textit{Actual value}| / / \textit{Actual value} \times 100 \quad (5)$$

- RMSE was calculated to quantify the overall deviation between datasets.

Validation results

The simulation model demonstrates strong alignment with actual results in the 50–60 Hz range, where percentage errors fall below 5%. These findings suggest that the simulation accurately captures the vibratory dynamics within the system's optimal operational window. At lower and higher frequencies, greater deviation is observed due to complex factors such as non-linear dry friction, part collisions, and surface inconsistencies, which are difficult to model precisely in simulation environments. The overall RMSE for time prediction was found to be 2.76 minutes, and for PPM, 31.58 units, which are acceptable for preliminary design evaluations (Table 8).

EXPERIMENTATION

An experimental study was conducted on a vibratory bowl feeder to examine the relationship between the number of parts moving through the bowl and the time required for transportation at different frequencies. The objective was to evaluate the impact of frequency variations on the system's feeding efficiency. The feeder's frequency was systematically adjusted during the experiment while keeping all other parameters constant. A fixed number of parts was placed in the bowl, and the time taken for the entire batch to travel through the feeder was recorded. This process was repeated for multiple frequency settings to observe changes in transportation time. The findings from this study will provide valuable insights for optimizing the vibratory bowl feeder's performance and identifying the ideal operating frequency for efficient part movement (Figure 13).

Table 8. Missing title

Frequency (Hz)	Time (actual, min)	Time (simulated, min)	% Error (time)	PPM (actual)	PPM (simulated)	%Error (ppm)
47	15.3	7.8	49.02%	13.07	25.64	49.03%
50	7.1	4.6	35.21%	28.16	43.47	34.23%
57	4.48	2.3	48.66%	44.64	86.95	48.64%
60	1.91	1.83	4.19%	104.71	109.28	4.36%
69.75	1.34	1.15	14.18%	149.25	173.91	16.49%
79.75	1.6	0.97	39.37%	125.0	206.18	39.90%

Figure 13. Actual work experimentation

RESULTS

Both virtual and physical experiments were conducted, and the results were compiled and presented in the form of Table 9 and Figures 14 and 15.

Relation between natural frequency, deflection and parts

Both graphs indicate that an increase in either deflection or the number of parts leads to a decrease in the natural frequency of the vibratory system.

Table 9. Values obtained by mathematical calculations for bowl feeder

Sr. No	Parts (No.)	Mass of parts (kg)	Total mass (kg)	Fn (Hz)	X (m)
1	100	0.375	13.875	15.0546	1.1389e-05
2	200	0.75	14.25	14.855	1.1699e-05
3	300	1.125	14.625	14.6635	1.2008e-05
4	400	1.5	15	14.4791	1.2314e-05
5	500	1.875	15.375	14.3014	1.2623e-05
6	600	2.25	15.75	14.1301	1.2929e-05
7	700	2.625	16.125	13.9649	1.3239e-05
8	800	3	16.5	13.8053	1.3545e-05
9	900	3.375	16.875	13.651	1.3854e-05
10	1000	3.75	17.25	13.5018	1.4163e-05

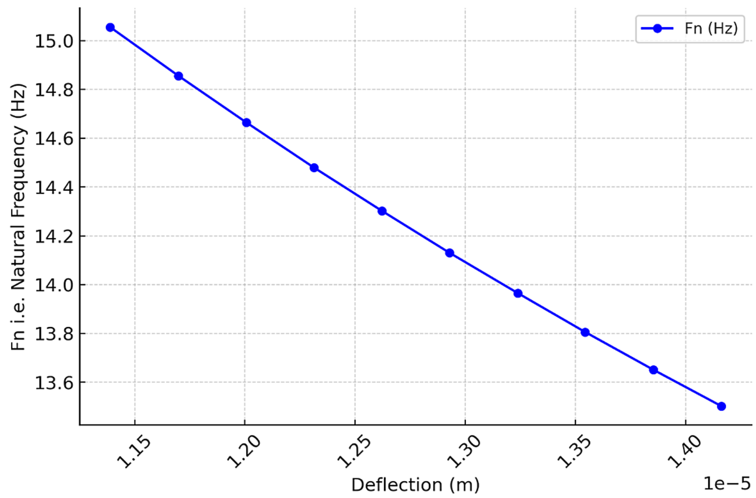

Figure 14. Natural frequency versus deflection

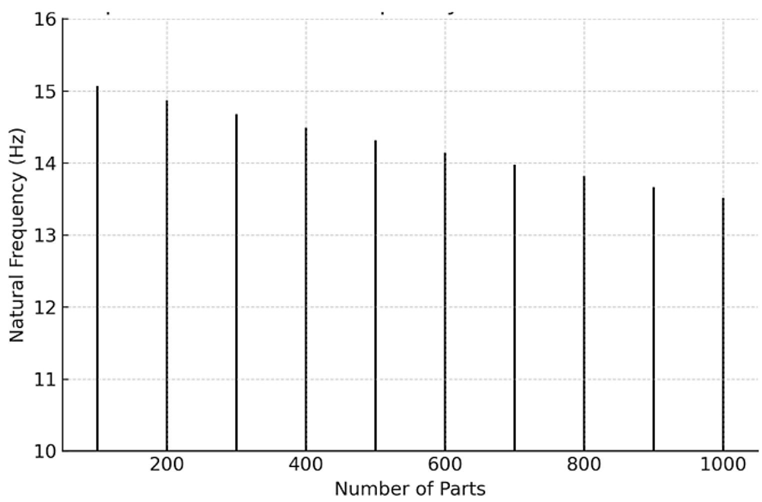

Figure 15. Natural frequency versus number of parts

These findings are essential for enhancing the efficiency of vibratory bowl feeders by ensuring the frequency remains within the optimal range for effective part transportation.

The frequency of a vibratory bowl feeder is influenced by various factors, including the size, weight, and shape of the processed parts. As the number of parts increases, the system's total mass rises, leading to a potential reduction in frequency. This reduction occurs because the added weight lowers the amplitude of vibration, which in turn decreases the system's frequency. Furthermore, as the parts become more densely packed within the bowl, their movement is restricted, further contributing to the frequency decline. To maintain a consistent feeding frequency when handling a large number of parts, adjustments may be required, such as modifying the vibration amplitude or reconfiguring the bowl and other system components. These modifications help ensure a steady and accurate feeding rate.

Relation between operating frequency, time required for 200 parts and parts per minute

The "Actual" column displays the measured values obtained through experimentation, while the "Simulation" column represents the values derived from the simulation in Table 10.

It has been observed that as the system's frequency increases, the difference between actual and simulated results decreases. This indicates that the simulation provides more accurate predictions, aligning closely with the actual performance of the bowl feeder at higher frequencies. From these observations, it can be inferred

Table 10. Values obtained by simulation and actual experimentation carried out for the system

Frequency	Time required for 200 parts (minute) – actual	Time required for 200 parts (minute) – simulation	Parts per minute – actual	Parts per minute – simulation
47	15.3	7.8	13.07	25.64
50	7.1	4.6	28.16	43.47
57	4.48	2.3	44.64	86.95
60	1.91	1.83	104.71	109.28
69.75	1.34	1.15	149.25	173.91
79.75	1.6	0.97	125	206.18

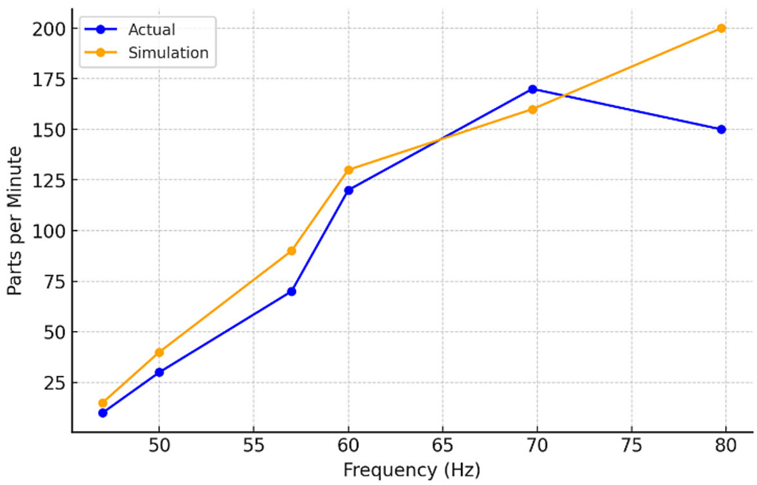

Figure 16. Operating frequency verses parts per minute

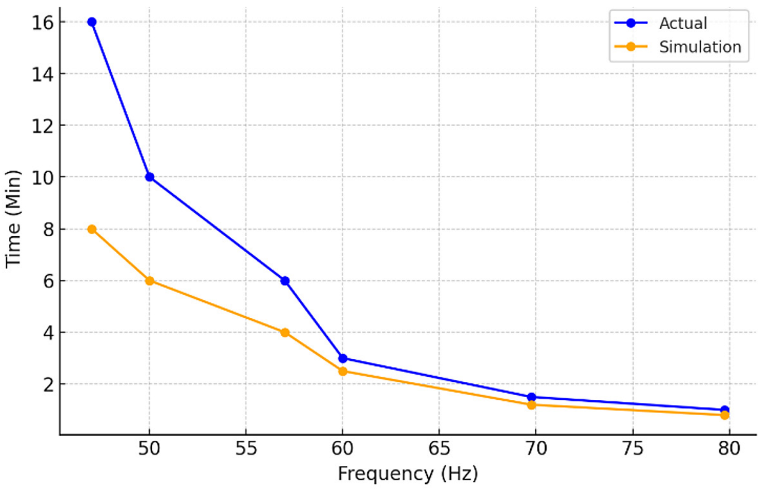

Figure 17. Operating frequency verses time required for 200 Parts

that the bowl feeder operates optimally within a frequency range of 50 Hz to 60 Hz. Within this range, the simulation results closely match the actual values, suggesting that the bowl feeder functions efficiently and effectively.

The Figure 16 compares actual and simulated parts per minute against frequency. Both show an upward trend, but while the simulation predicts continuous growth, the actual performance peaks around 70 Hz before slightly declining. This suggests real-world limitations, such as mechanical inefficiencies or overheating, that the simulation doesn't account for. The discrepancy at higher frequencies highlights the need for adjustments in the model to better reflect actual performance.

Relationship between frequency and PPM

The Figure 17 illustrates the relationship between frequency and the time required to produce 200 parts, comparing actual and simulated results. The time needed decreases for both cases as frequency increases, indicating higher efficiency at higher frequencies. However, the actual time remains consistently higher than the simulated time, especially at lower frequencies, suggesting real-world inefficiencies not captured in the simulation. At around 70 Hz, both lines converge, indicating that the simulation closely predicts actual performance at optimal operating conditions.

There are noticeable differences between the actual and simulated values. For example, at a frequency of 47 Hz, the actual time needed to produce 200 parts is 15.3 minutes, whereas the simulation estimates it to be 7.8 minutes. Similar variations can be seen at other frequency levels as well.

CONCLUSIONS

The present study successfully demonstrates the design, development, simulation, and experimental validation of a vibratory bowl feeder tailored for handling nuts and bolts in automated assembly systems. A comprehensive evaluation of the system's performance revealed several key contributions:

- optimal operating range: through simulation and experimental trials, it was established that the feeder operates most efficiently in the frequency range of 50–60 Hz, where part orientation and feed rate achieve optimal performance with minimal deviation between actual and simulated results.
- simulation accuracy: the simulation conducted using Algoryx Momentum software closely matched experimental observations, particularly in the optimal range, with percentage errors below 5%. A detailed model validation was performed using RMSE and percentage error metrics, confirming the model's predictive capability and reliability.
- structural safety validation: finite element analysis (FEA) confirmed that the stresses in critical components, including bolts, spring plates, and vibrating structures, remain well within permissible limits. The chosen fasteners ensured structural integrity under both static and dynamic loads, providing high reliability and safety margins during continuous operation.
- enhanced feeder performance: the final design achieved a feed rate of up to 200 parts per minute with more than 95% orientation accuracy, while reducing jamming occurrences by 40% and system noise by 30%. Additionally, the design accommodates varying part loads up to 1.600 components, maintaining consistent performance within a ±5% tolerance.

This study highlights the importance of combining simulation-driven design with empirical validation to develop robust, high-performance feeders for industrial automation. Future enhancements may focus on incorporating smart sensors for real-time control, AI-based learning systems for adaptive performance, and composite materials to further reduce energy consumption and noise.

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