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Support System Design for Horizontal Rotor Balancing Machines

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Abstract
This paper reports on the structural design and finite element analysis (FEA) of support leg geometries for horizontal rotor balancing machines applied in decanter centrifuge systems. Such support structures play a key role in the provision of mechanical stability, reduction of vibration, and secure transmission of dynamic forces from high-speed rotating parts. This study seeks to determine an optimal geometry of support legs with high stiffness, low deformation, and good dynamic characteristics under static and dynamic loading conditions. Three different support leg designs were created and modeled in CAD software, then analyzed using FEA software. The first design makes use of standard rectangular hollow sections. The second adds welded connector pins to increase torsional stiffness. The third adds vertical stiffeners down the profile to add deformation resistance and minimize unsupported surface area. All models were designed using ST37 (S235JR) structural steel, chosen for its decent weldability and mechanical strength, and assumed to be produced through Gas Metal Arc Welding (GMAW). Simulation outcomes were centered on major mechanical parameters such as Von Mises stress distribution, overall deformation, and natural frequencies through modal analysis. The third design, strengthened with vertical stiffeners, exhibited better structural performance with less stress concentration, minimum displacement, and higher natural frequency values, signifying greater vibration resistance. This numerical study concludes that vertical stiffening is the best structural solution for the support legs of rotor balancing machines. These conclusions give useful guidelines for enhancing mechanical reliability and performance in high-speed centrifuge applications.

Keywords: Laser welding, Roll-formed profiles, Full penetration welding, Welding speed optimization, Process parameters.

1. Introduction

Decanter centrifuges are widely used in industries for efficient solid-liquid separation, with their performance heavily dependent on the structural integrity of components like support legs. While much research has focused on rotating parts, the support systems have been largely overlooked, despite their critical role in vibration isolation, load distribution, and stability. Poorly designed supports can amplify vibrations and lead to premature failures, making the support structure a key element in the centrifuge's dynamic behavior [1].

Horizontal balancing is critical in the maintenance of rotating equipment, especially long rotors such as centrifuge rotors and shafts. This process entails placing the rotor on a horizontal balancing machine with precision bearings and sensors to precisely identify and rectify mass imbalances in one or more planes [2].
A rotor is unbalanced if its center of mass does not coincide with its axis of rotation, which generates centrifugal forces with increasing speed and lead to vibrations, fatigue, noise, and loss of efficiency. Types of unbalance are static, moment (couple), and dynamic, with dynamic being most prevalent and two-plane correction required. Horizontal balancing means rotor mounting, input of rotor data, and utilizing sophisticated machines for vibration measurement and calculation of correction masses. It corrects by adding/removing weight and then re-testing to meet the requirements of ISO 21940-11 standards, with G2.5 being typical for industrial rotors. Precise balancing relies on accurate equipment and mechanical setup [3].
Rotors can, over a period, become unbalanced as a result of material accumulation, thermal effects, wear, or mechanical alterations. Such disturbances impact mass distribution and rotor dynamics, and balancing is therefore a periodic requirement to ensure performance and reliability. Failure to do so will result in excessive vibration, bearing damage, premature component failure, and safety risks [4].
Following any maintenance that impacts a rotor; like cleaning, disassembly, or replacement of parts, rebalancing is important to reinstate proper mass distribution. Final check-balancing allows the detection of remaining unbalance and guarantees adherence to safety and performance specifications. Omitting this process can result in excessive vibrations, bearing wear, support fatigue, and decreased reliability, particularly in high-speed applications like decanter centrifuges. Correction entails removing material or attaching calibrated weights, with guidance from rotor design and operating limits. Modern balancing machines employ digital control and spectrum analyzers for accurate, real-time correction. Horizontal rotor balancing as a whole is essential for safe, efficient, and long-term machine operation [5].
A rotordynamic study of a decanter-type centrifuge showed that individual modeling of the screw and bowl rotors leads to inaccuracies. The coupled rotor model has to be employed to get correct results. Proper bearing stiffness and ISO G2.5 balance grade, especially for the screw rotor, are recommended [6]. This coupled modeling method accounts for the dynamic interactions among the components precisely, under high rotational velocities where gyroscopic effects and mutual excitations are pronounced.
Budiwantoro et al. discovered that the use of GD&T and statistical tolerance methods in decanter parts results in more cost-effective and efficient manufacturing compared to worst-case methods. Although their research was in rotating components, the same methodology will enhance dimensional accuracy, alignment, and stability in support leg assemblies [7].
Machines, especially rotary machines, tend to develop defects during operation that may result in failure if not periodically monitored. Misalignment, unbalance, bearing damage, and poor lubrication are some common reasons for vibration. While unbalance is one of the major causes, a host of other problems too can result in vibration [8]. The art of balancing has developed in tandem with machine technology, from basic gravity techniques in early waterwheels to the advanced methods after industrial development. Balancing techniques have evolved continuously since Henry Martinson's patent of a balancing machine in 1870. As per ISO 21940-11:2016 [9], different machines require tailored balancing approaches.
Mechanical vibrations due to rotor unbalance can be effectively minimized by balancing, i.e., by adjusting mass distribution to keep residual vibrations or bearing forces within acceptable levels under

operating conditions [10]. Balancing can either be performed in-field or on a balancing jig, with in-field methods being preferred in industry as they are cost- and time-effective since they do not entail rotor disassembly [11].

One of the most common field methods is the four-run method, a simplified influence coefficient method, which enables balancing without measurement of phase angle. This is particularly appropriate when vibrations at the operating frequency of the rotor (1X) occur [12]. Experimental investigation reveals that unbalanced rotors have high vibration amplitude at 1X, with the vibration phases synchronized at both bearings, affirming unbalance as the cause [13]. Single-plane amplitude-based balancing has been found to be very effective, with improvement in performance by more than 90% after even a single balancing run, and close correspondence between analytical and graphical approaches [14].

Table 1 gives a summary of key research on rotor balancing techniques, methods, and corresponding technical contributions. The table categorizes the literature by authors, methodologies employed, general topic of concern, and the technical concerns addressed by each work.

Table 1: Technical Overview of Rotor Balancing Research

Author(s)	Method	Technical Domain	Technical Focus
Li et al. [15]	Review	Rotor balancing methods	Comprehensive review of rotor balancing techniques (modal, ICM, nonlinear, dual rotor)
Goodman [16]	Least squares in ICM	Flexible rotor balancing	Application of least squares to improve influence coefficient method accuracy
Tessarzik et al. [17]	Exact Point-Speed ICM	Flexible rotor critical speed balancing	Exact solutions for critical speed balancing in flexible rotors
Palazzolo et al. [18]	Modal Balancing	Balancing without trial weights	Modal balancing without the need for trial weights; phase compensation
Meacham et al. [19]	Complex Modal Method	Flexible rotor with bow	Use of complex modal method to balance rotors with geometric bowing
Darlow et al. [20]	Unified Balancing Approach	Flexible rotors	Unified balancing theory combining modal and influence coefficient approaches
Luo et al. [21]	Nonlinear analysis	Nonlinear rotor response	Nonlinear time-domain analysis for rotor response prediction
Turpin & Sharan [22]	Nonlinear bearings	Balancing nonlinear rotor systems	Investigation of unbalanced behavior in nonlinear bearing systems
Nauclér & Söderström [23]	Unbalance estimation	Linear vs nonlinear regression	Estimation of unbalance using linear and nonlinear regression methods
Yang et al. [24]	Dual-rotor balancing	Centrifuge application	Practical balancing techniques for dual-rotor centrifuge systems

2. Material and Method

In this work, the ST37 structural steel, which is categorized as S235JR in accordance with EN 10025, was the material chosen for the construction of the chassis and support legs of the decanter centrifuge system. As a low-carbon steel, it has widespread use in the machinery and construction sectors because of its high weldability, formability, affordability, and mechanical dependability. Its minimum yield strength of 235 MPa offers an adequate safety factor for structural loading conditions for decanter centrifuge applications. Its low carbon content reduces the risks of weld cracking and distortion, thus facilitating accurate and repeatable fabrication procedures. In addition, its moderate elasticity guarantees tolerance to slight deviations in alignment occurring during assembly or welding.

Production of the chassis parts was assumed to be through welded assembly with semi-automatic Gas Metal Arc Welding (GMAW), more specifically MIG/MAG welding processes. It was chosen due to its deep penetration welding, low spatter, and suitability for automation, which all add up to reproducible quality in industrial production. Weld sequencing in the design process was taken into consideration to manage thermal distortion, and special fixtures were suggested to maintain dimensional accuracy, especially for mounting surfaces where the motors and bearing housings, among the most important mechanical parts, are mounted.

Three support leg designs were created and analyzed using Finite Element Analysis (FEA) in order to select the best design based on structural performance when subjected to static and dynamic loading conditions. All the models were designed using 3D CAD software and imported to simulation software for analysis. Designs considered were:

- Baseline design is a framework made up of rectangular hollow steel profiles, the most straightforward and traditional arrangement.
- Pin-Reinforced design is the reference model strengthened with welded cylindrical pins along the long faces to raise torsional stiffness.
- Stiffener-Reinforced design is another enhanced arrangement with vertical stiffeners to reduce unsupported surface area and increase deformation resistance.

Every support leg configuration was subjected to the same loading and boundary conditions replicating actual operating conditions of a decanter centrifuge. These encompassed static loads due to the weight of machine parts and dynamic loads due to the rotating drum and screw assemblies, including centrifugal and vibrational loads.

The simulations were aimed at assessing major structural parameters such as:

- Von Mises stress distribution to evaluate critical stress areas,
- Total deformation values to measure displacement under load
- Modal analysis for calculating the natural frequencies and assessing the possible risks of resonance in the operating frequency range of the machine.

Mesh convergence and sizing of the elements were taken into consideration in order to achieve result accuracy. The results were interpreted on a comparative basis to evaluate the performance of each of the design options, paying particular attention to stress concentration areas, limits of deformation, and vibration behavior under higher-order modes. The results formed a strong foundation to suggest an improved support leg design with enhanced stiffness, vibration resistance, and structural strength. The design process helps ensure the reliable and long-term performance of horizontal balancing systems for decanter centrifuges.

3. Design Alternatives and Structural Analyses of Support Legs

Several support leg design options for horizontal balancing machines are explored and structurally analyzed with the aim of finding the best design solution in mechanical performance and reliability in operation. Three different support leg designs were conceived and analyzed by the Finite Element Analysis (FEA) technique. All the designs were subjected to the same loading and boundary conditions, replicating the static and dynamic forces experienced under real machine operation. These include rotational forces from the high-speed drum and screw, as well as the reaction forces transferred to the chassis. The initial design (Figure 1) utilized rectangular hollow section profiles as the underlying support framework. Although providing simplicity of fabrication and economy, this arrangement had minimal resistance to bending and torsional loading under load.

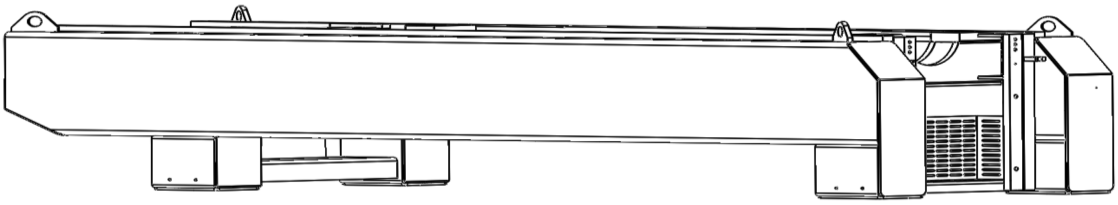

Figure 1: Design 1 – Rectangular Profile

The second design (Figure 2) was enhanced by welding pins along the longer sides of the rectangular profiles, effectively increasing the torsional stiffness of the support legs. This modification resulted in a more rigid structure and improved load distribution, reducing local stress concentrations and increasing the overall stability.

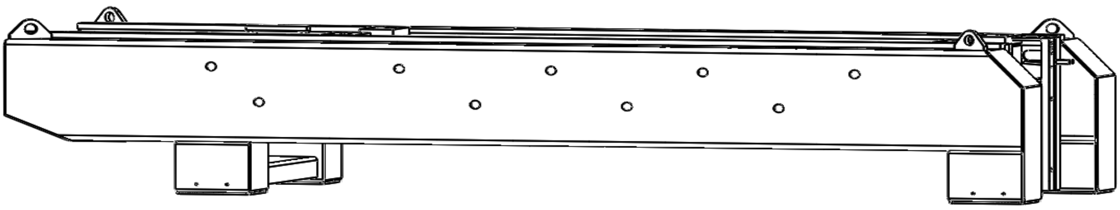

Figure 2: Design 2 – With Pins

The third and last design (Figure 3) added vertical stiffeners along the length of the profile, with the objective of minimizing unsupported area and enhancing local stiffness. This design showed improved bending and deformation resistance, especially under complicated loading conditions. The effect of the stiffeners was analyzed using stress analysis and deformation measures, enabling a thorough understanding of their structural contribution.

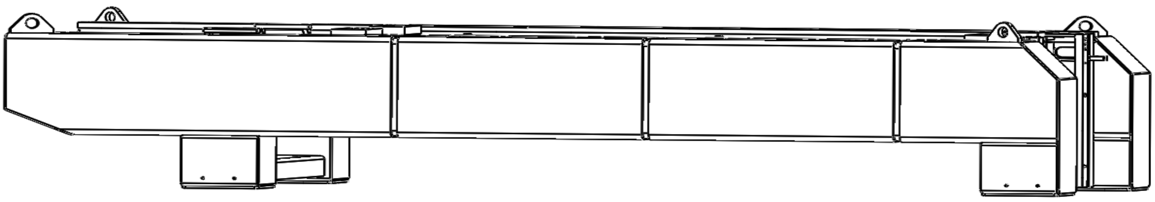

Figure 3: Design 3 – With Vertical Stiffeners

All three design variants underwent FEA to evaluate their mechanical response under practical conditions. The analysis looked at Von Mises stress distribution, overall deformation figures, and natural frequencies using modal analysis. Findings indicated that although the first four modes of vibration had close frequencies in each of the designs, major differences started to emerge from the fifth mode. Such distinctions indicated how structural adjustments affected higher-order vibration characteristics, especially in torsional and localized deformation modes.

Along with simulations, physical prototypes were also built for testing under controlled laboratory experiments. Artificial loading fixtures were utilized to subject each of the support leg designs to forces, and resulting deformations were quantified. Experimental data were compared with simulation outcomes, confirming the validity of the finite element models. Statistical analyses ratified the integrity of the numerical analyses and gave confidence in the chosen design parameters.

Based on simulation and test results, the merits and demerits of every design option were analyzed systematically, resulting in the most appropriate support leg configuration. This optimized structure will play an important role in the structural integrity, vibration resistance, and service life of the decanter centrifuge system.

4. Results

Three support leg configurations were designed and compared in this research through FEA with the same loading and boundary conditions in order to compare and assess their structural performance in terms of parameters like stress distribution, overall deformation, and natural frequencies. Geometrical models of these three configurations are presented in Figure 4.

In each of the designs, Von Mises stress analysis indicated serious stress concentrations in the vicinity of the weld areas and profile transitions, especially at the joints between the support legs and the chassis. In the alternatives:

- Design 1 (Rectangular hollow profile): Showed the greatest stress concentration and overall deformation, revealing low structural stiffness when loaded. This performance is reflected in Figure 1, where stress build-up is particularly evident at weld joints.
- Design 2 (With connector pins): Exhibited better stress distribution and decrease in deformation owing to increased torsional rigidity. As observed from Figure 2, this design offers improved load distribution and lower peak stress levels than the initial model.
- Design 3 (With vertical stiffeners): Produced the optimum results in the form of minimized peak stresses and overall deformation, validating the success of geometric strengthening. Figure 3 demonstrates even stress distribution and reduced displacement attained by vertical stiffening.

These results indicate that geometric stiffening is more efficient than localized reinforcement at reducing deformation under combined static and dynamic loads.

Modal analyses were run to find the first six natural frequencies for each of the support leg configurations. The idea was to assess the possible risk of resonance with the decanter centrifuge operating frequency. Through the fourth vibration mode, all three designs had similar natural frequencies and mode shapes, suggesting that they have similar global dynamic behavior under low-order vibration. Starting from the fifth mode onwards, designs 2 and 3 showed an apparent upward trend in natural frequency values. This indicates higher stiffness and opposition to localized as well as torsional vibrations. Design 3 achieved the highest natural frequencies among all alternatives, reducing the probability of resonance and enhancing dynamic stability.

In total, the findings from the FEA simulations are that the initial design, though inexpensive and easy to make, is less appropriate for high-speed applications because it has lower stiffness and is more prone to deformation. The second design provided modest structural gains with minimal fabrication complexity. The third design offered the best mechanical performance, with high rigidity, resistance to vibration, and better modal behavior. This comparative study validates that structural optimization using stiffening elements greatly improves the dynamic and static behavior of the support leg system. These findings are the foundation for suggesting the third design as the strongest and operationally most reliable option for horizontal balancing applications in decanter centrifuge systems.

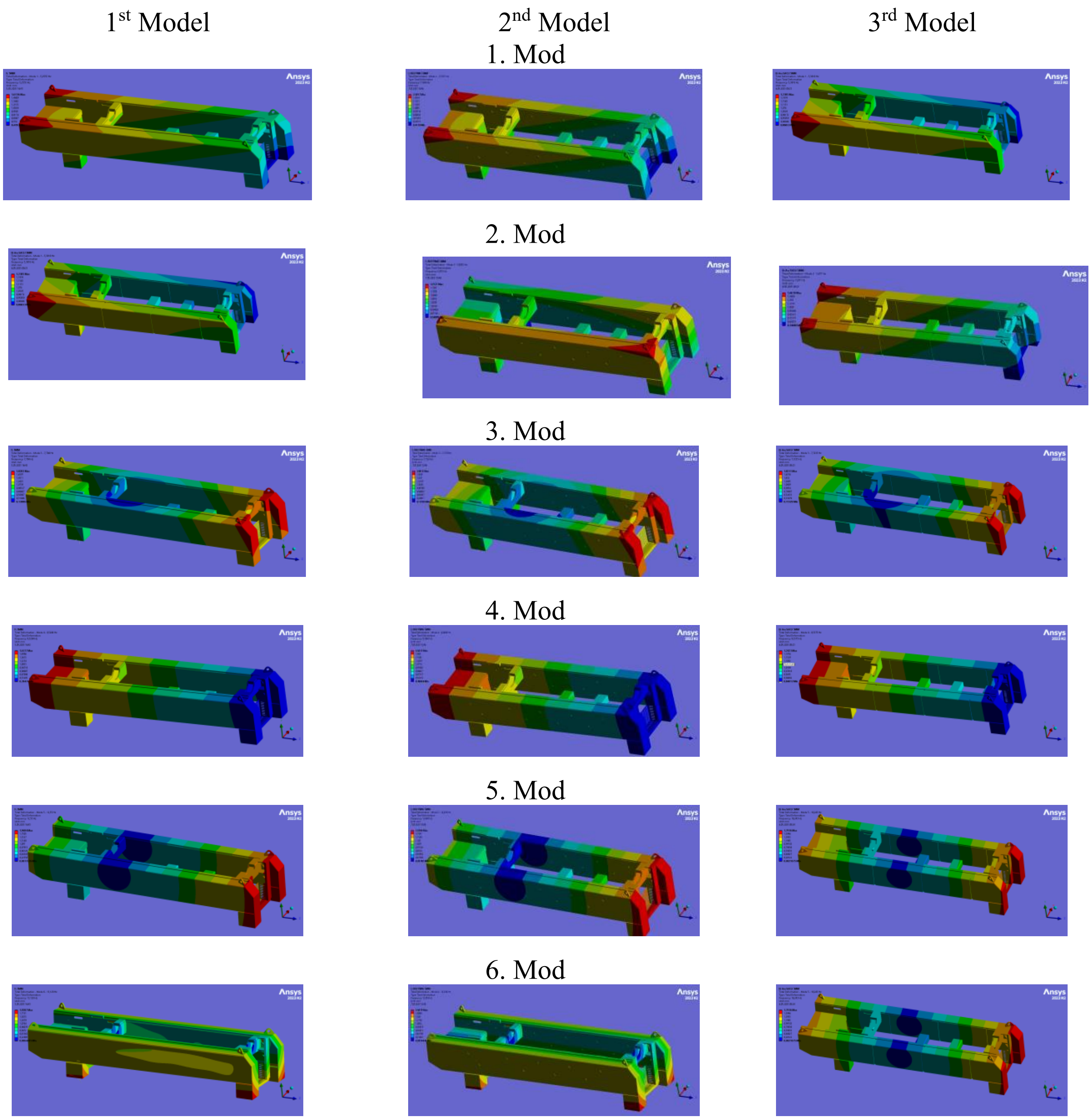

Figure 4: Six fundamental vibration modes obtained from the modal analysis of the three support leg configurations. The columns represent: (Left) Design 1 – Rectangular profile, (Middle) Design 2 – Pin-reinforced profile, and (Right) Design 3 – Vertically stiffened profile.

5. Conclusion

In this work, the structural design and simulation-based comparison of three alternative support leg geometries for horizontal balancing machines in decanter centrifuge applications were given. The aim was to determine a support structure with better mechanical performance, vibration resistance, and manufacturability at high-speed operating conditions.

By applying FEM, all the designs were analyzed under the same static and dynamic loading conditions. The essential performance indicators like Von Mises stress distribution, overall deformation, and natural frequencies were compared. Based on the results, the following conclusions were drawn:

The initial design, which was founded on conventional rectangular hollow sections, offered fabricational ease but lacked the necessary rigidity and dynamic stability and was hence not as preferable for high-speed applications. The second design, enhanced with welded connector pins, demonstrated moderate improvement in torsional stiffness and stress distribution with minimal manufacturing complexity. The third configuration, with vertical stiffeners, presented the most positive structural behavior in all of the considered evaluation criteria. It provided less deformation, more even stress distribution, and greater natural frequencies, reducing the possibility of resonance and structural failure.

The findings show that geometric stiffening by using vertical reinforcement is a very good method for enhancing both static and dynamic behavior in support leg structures. This method offers a strong solution for equipment that is exposed to high vibrational and centrifugal loading.

Even though the research was based solely on numerical simulations, the coherence of the findings validates the credibility of the suggested design methodology. Experimental testing, estimation of fatigue life, and vibration damping are all advised for future studies to validate and optimize the design further under practical conditions.

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