Mehran University Research Journal of Engineering and Technology

https://doi.org/10.22581/muet1982.3248

2025, 44(1) 94-102

Mathematical and finite element modelling of sustainable portable grain segregation system for the HDPE industry

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Received: 24 April 2024, Accepted: 26 December 2024, Published: 01 January 2025

KEYWORDS

HDPE

Contaminants

Linear Segregation Technology

Modal Analysis

FEA

Sustainable

ABSTRACT

High-density polyethylene (HDPE) pipe manufacturers have difficulties when contaminants are introduced in HDPE grains during recycling, resulting in irregular sizes and quality problems. Cleaning by hand takes a lot of time, especially when managing a 130 kg grain load every day. The current research focuses on designing a portable segregation system that replaces traditional techniques while requiring less Labor and a shorter manufacturing time that meets engineering standards with versatile industrial applications. The core objective is to develop a process for efficiently screening HDPE grain with different size meshes while taking care to handle the material with care to avoid any damage or deterioration by replacing traditional methods. The Grain Segregation System is used as a precise and space-efficient linear segregation technology to remove undesirable detritus affordably with three sieve plates ASTM E11 6.3 mm, 3.5 mm, and 2 mm pore sizes. The crank-slider mechanism is the working principle, powered by an AC motor. It works well for separating dry particles but has limitations for wet particles. Substituting sieve meshes, helps companies strive for effective grain segregation because of its easy operation, low maintenance requirements, and versatility. Furthermore, the mathematical modelling, structural, and Modal analysis of the design is investigated, to check the durability of the design under stresses using Finite Element Analysis (FEA) techniques. This research is not only sustainable in terms of safety, but in cost also as it reduces cost up to 65% depending upon the market value which ranges from 1000 – 4000 US Dollars.

1. Introduction

The PVC and HDPE industry in Pakistan is significantly growing with the expansion of urbanization. HDPE pipes demand is increasing because of their durability and cost-effectiveness. These pipes are used in sewage systems, water supply, and in infrastructure [1]. Manufacturers are focusing on high-quality plastic pipes adhering to international standards to reduce the environmental effects and ensure its major application in the water distribution system [2]. Segregation is essential for quality control. Raw material grains quality is significantly important for a good quality product. The purpose of sieving or segregation in this context is to separate or filter out unwanted particles or impurities from the raw materials [3], used in pipe manufacturing. Before the pipe manufacturing process begins, raw materials such as HDPE grains need to be inspected and prepared. Unwanted particles can lead to defects in the final product, making it necessary to monitor and maintain the material's consistency through sieving [4]. The recycling of HDPE pipes through mechanical technologies like shredders leads to small irregular grain size making it necessary to segregate before the manufacturing of the product [5]. Agricultural and Construction industries also require proper segregation. In the Agricultural industry segregation machines help to separate the crops based on their size and quality and most importantly they prevent harmful insects or animals from mixing with the final product [6]. On the other hand, in the Construction industry stones and other unwanted particles are removed from the sand and cement to achieve smooth mixtures [7].

The segregation can be done through a sieve, which is a device for separating unwanted elements using a woven screen such as a mesh or net. [8]. Nanchimuthu et.al highlights durability as a factor that needs to be considered when building the sieve machine. The sieve machine needs to be sturdy when it revolves and vibrates. The material that will be utilized ought to be readily available and appropriate for building the sieve machine. The material and manufacturing process determines this. It ought to minimize the expense. [9]. The segregation technology involves repetitive linear motion, commonly seen in engines and pumps, with strokes representing the two opposite motions in a cycle. Cranks play a crucial role in converting circular motion to reciprocating motion or vice versa, prominently observed in early steam engines [10].

Recycling of HDPE pipes contaminates the raw material due to worker oversight; manual cleaning is time-consuming with a daily load of 130 kg of material. The core objective of this research is to design a portable segregation system for HDPE grains using meshes of varying sizes aiming to replace conventional methods, resulting in reduced production time and Labor costs and ensuring the machine's applicability across a diverse range of industries like Agricultural, Spices and Construction industries. Moreover, this research will investigate the Static structural and Modal analysis of the design, to check the durability under stresses. FEA techniques are utilized for comprehensive analysis.

2. Mechanism

A linear segregation mechanism is proposed as it can efficiently separate fine particles from the material, ensuring high accuracy. It is more compact and space-efficient compared to Trommel machines. Suitable for applications with limited space, allowing for better integration into existing production lines. Easier to maintain and clean due to a simpler design and accessible parts. Beneficial in terms of customizable with different sieve sizes and configurations to match specific material processing needs. Versatile across various industries due to its adaptability [11]. On the other hand, in the trommel mechanism at low speed, a slumping motion is observed, where material gently rises and then cascades down the cylinder's surface. [12]. Moreover, in trommel designs reverse phenomena of material are also observed. Linear segregation uses a crank-slider mechanism which represents a configuration of mechanical components crafted to transform rotary motion into straight-line motion. [13].

3. Methodology

3.1 Sieve Plate Design Consideration

The main challenge is that the sample is not of uniform size because of the recycling of the pipes. The material is divided into three groups according to the range of size to determine mesh sizes as shown in Table 1.

Table 1

HDPE grain size observation

Sr	Large Grains		Medium Grains		Virgin Grains	
	Dia. mm	Height mm	Dia. mm	Height mm	Dia. mm	Height mm
1	5	6	4	6	3	4
2	4.5	5	4	5	3	4
3	5	5	4	6	3	4
4	4.5	5	4.5	5	3	4

In the linear segregation machine, the design will have three sieve plates of different pore sizes Using ASTM E11 standard, the first plate will have a pore size of 6.3 mm so that large size grains can pass through it, leaving the unwanted waste to the top of the plate. The second plate mesh will be of 3.5 mm pore size passing the grains and leaving the stones and medium size materials. The last plate mesh will be 2 mm so that dust passes through it and leaves the filtered grains on the plate.

For same-size contaminants, the research employs the density differential principle by utilizing a water bath as the density of HDPE material ranges from 0.93 to 0.97 g/cm^3 ($0.0156\ \frac{kg}{in^3}$) [14], a conventional approach aimed at minimizing the overall cost of the system. The water bath serves a dual purpose, as it is also essential in the final stage of segregating HDPE pipes to render grains free of dust.

3.2 Design Material Selection

The component’s materials are listed in the table 2 below,

Table 2

Component material selection

Sr.	Items	Material
1	Siever Net Support Frame	Mild steel
2	Grain Distributer Frame	Mild steel
3	Meshes	Steel with galvanized coating
4	Siever Frame	Mild steel
5	Flywheel	Cast iron
6	Driven Pully	Cast iron
7	Connecting Rod	Mild steel
8	Shaft	Steel
9	Motor	Cast iron
10	V-Belt	Rubber
11	Slider	Steel
12	Bearing	Bearings steel and Cast iron
13	Structural Frame	Hot-rolled carbon steel
14	Fasteners	Alloy steel
15	Hopper	Mild steel
16	Hopper support frame	Galvanized steel

3.3 Design Calculations

3.3.1 RPM reduction calculation

The RPM of the driver pulley is found by the using the Eq. 1,

Speed of Driver Pulley = $N_1 = 900\ RPM$, Speed of Driven Pulley = $N_2 = ?$, Diameter of Driver Pulley = $D_1 = 2\ in.$, Diameter of Driven Pulley = $D_2 = 14\ in$

$$N_1 \times D_1 = N_2 \times D_2 \quad [15] \quad (1)$$

$$N_2 = 128.5\ RPM$$

3.3.2 The maximum displacement of the siever (slider)

The maximum displacement occurs when the crank is at an angle of 180° with the horizontal. So,

$r = 2.15\ in., L = 33.38 in.$

$$X_{max} = r(1 - \cos\theta) + \frac{r^2 \times (\sin\theta)^2}{2L} \quad [16] \quad (2)$$

$$X_{max} = 4.3\ in.$$

3.3.3 Maximum velocity of the siever

The maximum velocity can occur when the acceleration is equal to zero, $as = 0$

$$as = w^2 \mathrm{r}\left[\cos\theta + \frac{\cos 2\theta}{n}\right] \quad [16] \quad (3)$$

$$2\cos^2\theta + n\cos\theta - 1 = 0$$

The Almighty formula in Eq. 4 indicates that,

$$n = \frac{L}{r} \quad [16] \quad (4)$$

n = 15.52

$$2\cos^2\theta + 15.52\cos\theta - 1 = 0$$

Applying the Quadratic formula,

$$\cos\theta = \frac{-(15.52) \pm \sqrt{(15.52)^2 - 4(2)(1)}}{2(2)}$$

Taking positive because the range of the inverse cosine function is between 0 and π radians (or between 0° and 180°), the result will be undefined if put negative value, $\cos\theta = 0.0625$, = $\theta = 86.416°$

The maximum velocity is obtained by Eq. 5,

$$Vsmax = w\mathrm{r}\left[\sin\theta max + \frac{\sin 2\theta max}{2n}\right] \quad [16] \quad (5)$$

$$w = \frac{2\,\pi\,N}{60} \quad [16] \quad (6)$$

$w = 13.45\ \frac{rad}{s}$.

So, $Vsmax = 28.97\ \frac{in.}{s} = 0.7358\ \frac{m}{s}$

3.3.4 Calculations for total volume and capacity of the hopper

The shape of hopper contains 3 shapes for which the total volume will be found by Eq. 7 below.

Total $in.^3$ volume = Volume of upper rectangle shaped hopper + Volume of rectangular shaped prismatic hopper + volume of bottom rectangular shaped hopper (7)

The volume of the upper rectangular-shaped hopper is given by the Eq. 8,

$$= L \times W \times H \quad [17] \quad (8)$$

$$= 12 \times 24 \times 18$$

$$= 5184\ in.^3$$

The volume of the Bottom rectangular hopper is also given by the Eq. 8,

$$= 13.8 \times 3.3 \times 7.89$$

$$= 359.31\ in.^3$$

Volume of the rectangular prismatic hopper is given by Eq. 9

$$v = \frac{1}{6} \times H \times (2L_1B_1 + L_1B_2 + L_2B_1 + 2L_2B_2) \quad [18]\ (9)$$

$v = \frac{1}{6} \times 12.88 \times [\{2 \times (24 \times 18)\} + (24 \times 7.89) + (13.8 \times 18) + \{2 \times (13.8 \times 7.89)\}]$

$= 3261.9\ in.^3$

Total Volume V $= 8805.22\ in.^3$

The capacity of Hopper per cycle is found by Eq. 10,

$$C = Total\ Volume \times Density\ of\ HDPE\ Grains \quad [15]\ (10)$$

$C = 137.36\ kg$ per cycle

3.4 Maximum Segregation Efficiency

The maximum segregation will be achieved when the material is distributed uniformly onto the sieve meshes so that each grain passes over the sieve holes for segregation.

Length of sieve meshes net = 36 in., Width sieve meshes net = 30 in., Maximum material height for uniform distribution = 0.23 in.

The volume of the sieve mesh net is found by Eq. 8,

Total volume = 30 ×36 ×0.23 = 248.4 in^3.

The capacity of the sieve mesh net for uniform material over it for HDPE grains can be found by using Eq. 10,

Recommended mass = 248.4 × 0.156 = 3.8 kg

3.5 3D Design

The grain segregation machine is created using Solid Works and is shown in Fig. 1 and Fig. 2 below,

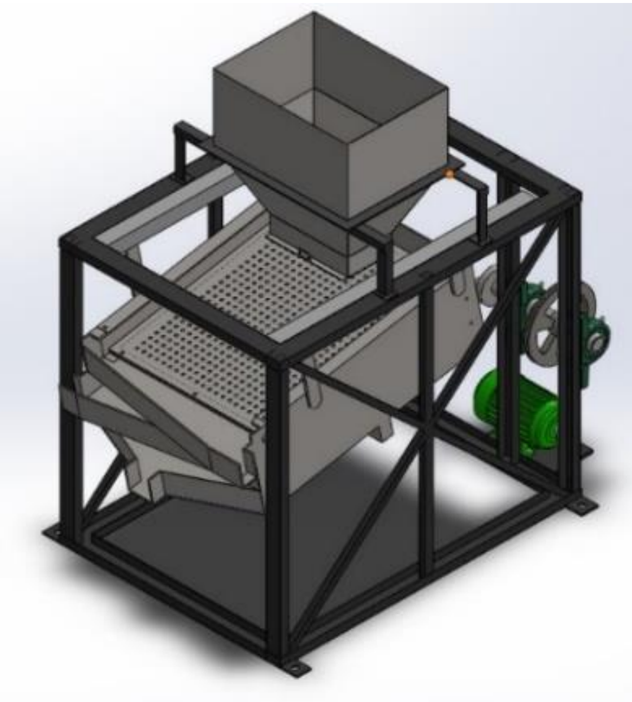

Fig. 1. Grain Segregation System, Design Isometric View

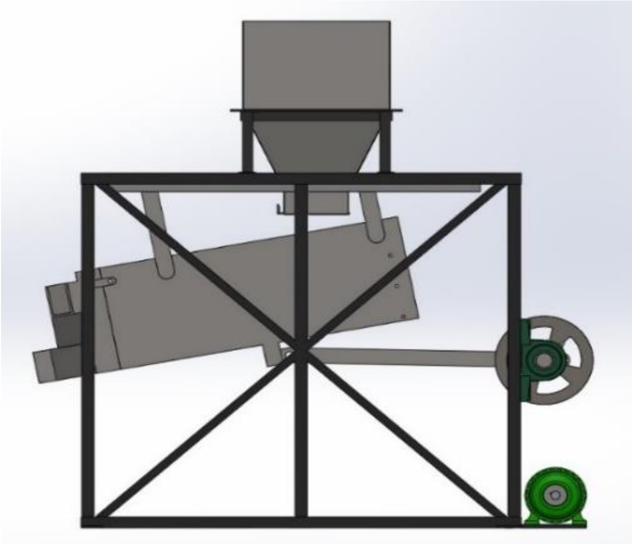

Fig. 2. Grain Segregation System, Design Side View

4. Simulation And Results

In software analysis, the following steps are followed to perform FEA:

- Define the problem and create governing equations that come from fundamental laws of physics.

  $$F = Ku$$

  The Eq. is for static structures, where, F is force or applied load, K is the global stiffness constant, and u is the displacement vector.

  For material behaviour, the linear stress-strain relationship is:

  $$\sigma = D \in$$

  Where, σ is the stress vector. ϵ epsilonϵ is the strain vector, and D is the material stiffness matrix.
- Segregate the domain into elements and nodes.
- Formulate the element stiffness matrix and assemble the global system.
- boundary conditions application.
- Solve equations for unknown displacements.
- Post-process the results to find stresses, strains, and other desired quantities [19].

The research used "ANSYS Workbench 18.1" to find Structural stability and mode shape frequencies (check for resonance) through static structural and vibration modal analysis respectively. In the analysis, the material of the components was specified using the Engineering data shown in Table 3. The IGES file of the part is imported from SolidWorks and the analysis was done after applying loading conditions while considering the tetrahedron mesh.

Table 3

Engineering Material Data In Ansys For The FEA Analysis Of Grain Segregation System

Property	Hot Rolled Carbon Steel	Mild Steel
Density ($\frac{kg}{m^3}$)	7800	7850
Coefficient of Thermal Expansion (C^{-1})	1.7×10^{-5}	1.2×10^{-5}
Youngs Modulus (Pa)	2×10^{11}	2×10^{11}
Poisson's Ratio	0.26	0.3
Bulk Modulus (Pa)	1.38×10^{11}	1.66×10^{11}
Shear Modulus (Pa)	7.936×10^{10}	7.69×10^{10}

4.1 Static Structural Analysis of Structural Frame

Structural analysis of the frame determines the deformation of the frame under the given loading conditions. The Frame of the Grain segregation system is the core component as it withstands all the load of the components.

The mesh of the structural frame under analysis was "Tetrahedron", as it provides more accurate results due to well surface contour approximation.

The pressure of 58717.6 $\frac{N}{m^2}$, 6898.726 $\frac{N}{m^2}$ is applied on one slider (due to sieve assembly) and hopper support frame (due to hopper and material of 137 kg) respectively. The frame is fixed at its bottom. The Fig. 3 and Fig. 4 shows the deformation in the structural frame.

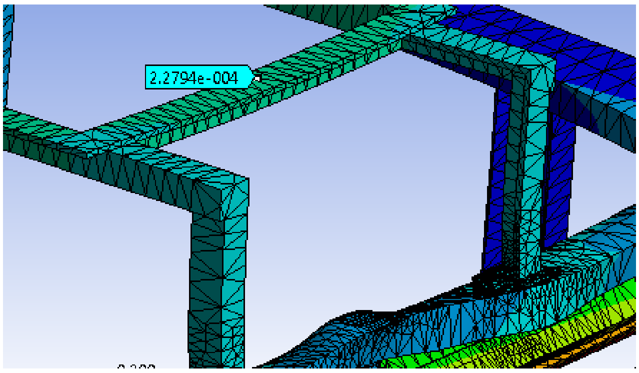

Fig. 3. Maximum Deformation In The Angle Iron Beam Of The Structural Frame

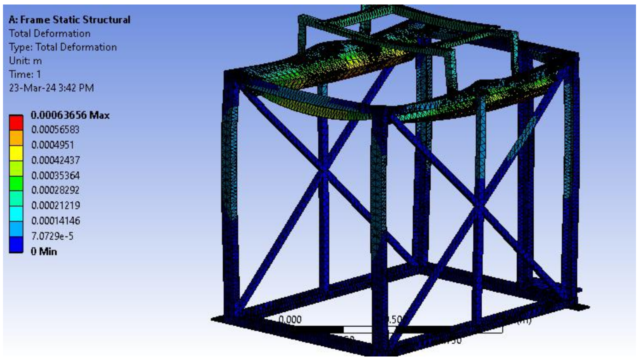

Fig. 4. Total Deformation in Structural Frame

4.1.1 Analytical validation of static structural analysis of frame

4.1.1.1 C-Channel

Mass applied on one side = slider mass + hopper mass on one side

Mass = 19.054 Kg, W = 280.09 N, Length = 1.3716 m, I=$387\times 10^{-7}\ m^4$

The total deformation in the Channel Beam considering Uniformly distributed load and simply supported beam is found by Eq. 11 below,

$$\delta = \frac{5WL^4}{384EI} \quad [20]\ (11)$$

$\delta = 1.19\times 10^{-4}\ m$

4.1.1.2 Angle Iron (L Beam)

Length= 0.536 m

Mass = Hopper + Hopper capacity

Mass= 22.14+ 137 =159.14 kg

The total weight considering the safety factor can be found by Eq. 12 below,

$$\text{Weight} = W = mg \times \text{factor of safety} \quad (12)$$

W= 2339.354 N

Weight on 1 L beam W= 584 N, and I = $5.419\times 10^{-8}\ m^4$

The Total deflection is found by Eq. 11.

$\delta = 2.018\times 10^{-4}$ m

4.1.1.3 Slider

Total mass of Sieve Assembly = 174.35 kg, Maximum Material on first plate = 3.8 kg, Length = 1.163 m, Safety factor= 1.5

The total weight including the factor of safety is found by Eq. 12. So, W= 2618.805 N. Now weight on one slider = 1309.4025 N

The total deformation in L-Beam considering Uniformly distributed load and simply supported beam is found by Eq. 11 below,

$\delta = 6.27\times 10^{-4}$ m

4.1.2 Summary of static structural analysis of frame

The comparative summary of the Frame's FEA is shown in Table 4,

Table 4

The summary of frame analysis

Components of Structural Frame	Deformation (Software) m	Deformation (Analytically) m
Hopper Support Frame	2.27×10^{-4}	1.19×10^{-4}
C- channel	1.82×10^{-4}	2.018×10^{-4}
Slider	6.36×10^{-4}	6.27×10^{-4}

So, the deformation considering a safety factor of 1.5 is minimal so the design of the structural frame is safe.

4.2 Static Structural Analysis of Sieve Plate Holder Frame Hinges

There is a pair of 9 in. and 14 in. hinges in the system, so the process is done twice first for 14 in. hinge and then for 9 in. hinge. The mesh of the hinges under analysis was "Tetrahedron", as it provides more accurate results due to well surface contour approximation.

The total load on each hinge is 1265.6 N and it is fixed from the hole through which the roller's pin passes. The deformation is as shown in Fig. 5 and Fig. 6 below,

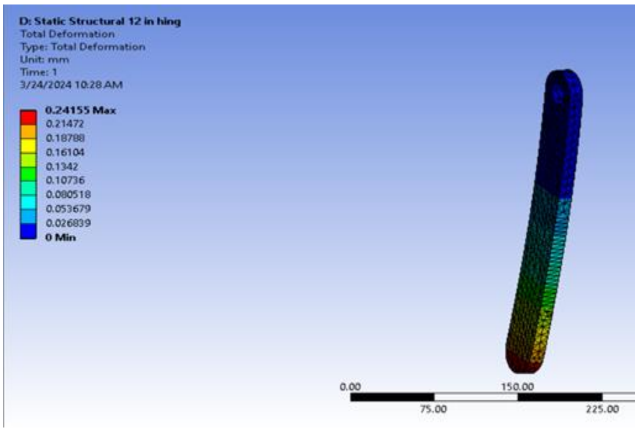

Fig. 5. Deformation in 14 in. Hinge

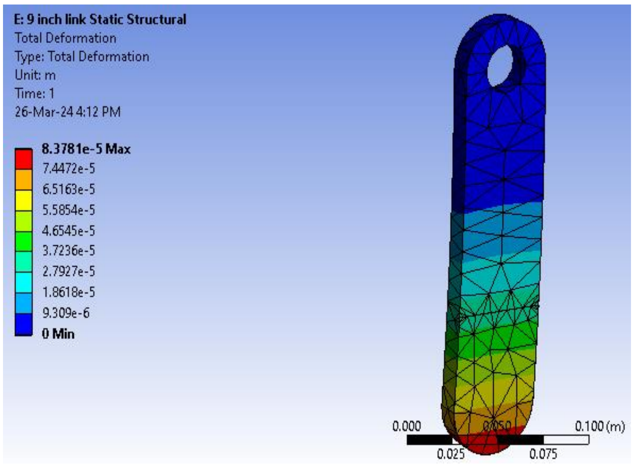

Fig.6. Total Deformation in 9 in. Hinge

4.2.1 Analytical validation of static structural analysis of sieve plate holder frame hinges

For 14 in. Hinges Length of beam = 14 in. = 355.6 mm, Length on which force is applied = b = 2 in. = 50.8 mm, Point Load to UDL = $\frac{1265.6}{50.8} = 24.91\ \frac{N}{mm}$, Moment of Inertia = $\frac{b_i d^3}{12} = 8671.49\ \text{mm}^4$, Young's Modulus = E = $2.0 \times 10^5\ \frac{N}{mm^2}$, W = 1265.6 N

The deformation in the hinge considering a simply supported beam and a point load is found by Eq. 13 below,

$$\delta = \frac{Pb(3L^2 - 4b^2)}{48\ EI} \quad [20]\ (13)$$

= 0.28 mm = $2.8\times 10^{-4} m$

Similarly, for 9 in. hinge the total deformation was found to be $\delta = 0.113\ mm$ = 1.13×10^{-4} m

4.2.2 Summary of static structural analysis of sieve plate holder frame hinges

Table 5 shows the summary of the comparative analysis of the Hinges,

Table 5

The summary of the sieve plate holder frame hinges analysis

Hinge Length	Deformation (Software) m	Deformation (Analytically) m
14 in.	2.4×10^{-4}	2.8×10^{-4}
9 in.	8×10^{-5}	1.13×10^{-4}

So, the deformation considering a safety factor of 1.5 is minimal so the design of the structural frame is safe.

4.3 Static Structural Analysis of Hopper

The hopper of the Grain segregation system should be stable enough to store large amounts of material fulfilling the various industrial requirements. In research, it has a 137 kg HDPE storage capacity.

The total pressure applied on the inner surface of the hopper is 0.001244 MPa and the total deformation is found as shown in Fig. 7.

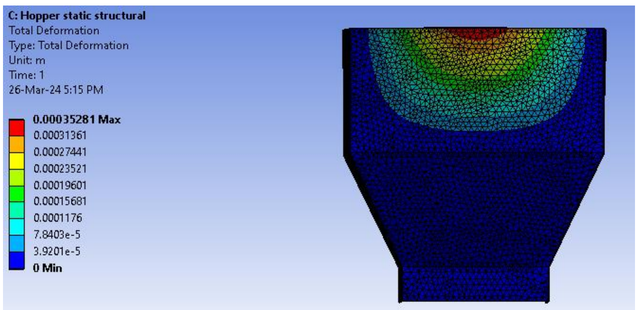

Fig. 7. Deformation In Hopper

The maximum deformation found is 0.352 mm on the upper rectangular shape which is not fixed. The deformation is minimal, so the design of the hopper is safe.

4.4 Modal Analysis of Structural Frame

Modal analysis of the frame determines the natural and mode shape frequencies of the frame at which it can vibrate as shown in Fig. 8. Modal analysis is used to check whether there is a chance for the phenomena of resonance. The IGES file is imported, and the material has been specified as shown in Table 3. The coarse mesh is selected, and the modal analysis is performed after boundary condition applications.

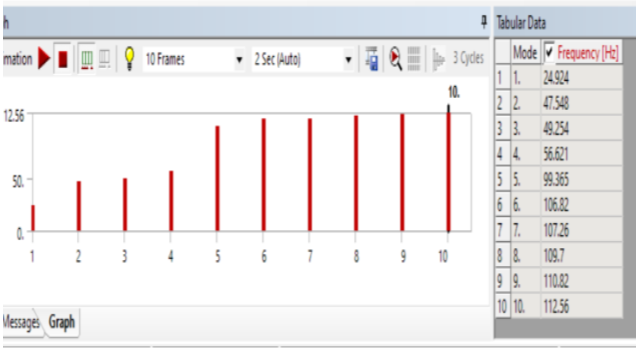

Fig. 8. 10 Modes Shape Frequencies Of Frame From Modal Analysis

4.4.1 Force frequency of grain segregation system

The forced frequency on the system is due to the Motor whose 900 RPM is reduced to 128.5 RPM using a pully reduction mechanism providing reciprocating motion to the sieve. The operating frequency of the motor is 50 Hz, and the number of poles is six.

$$\text{Rotation rpm} = \frac{120\times \textit{frequency operating}}{\textit{number of poles}} \qquad [21]\ (14)$$

Number of poles = 6

Forced frequency can be found by using the Eq. 15 below,

$$\text{Frequency} = \frac{\textit{utilize rpm rotation speed}\times \textit{number of poles}}{120} \qquad [21]\ (15)$$

$$\text{Frequency} = \frac{128.5\ rpm\times 6}{120}$$

Frequency = 6.425 Hz

The exciting frequency of the Grain segregation is 6.425 Hz which is much less than the Mode shapes Frequencies of the frame starting from 24 Hz and so on. So, there is no chance for the resonance to occur and the design is safe. The more mode shape frequencies can be found by increasing the input but they all will be greater than the exciting frequency so there is no chance for the design to fail.

5. Cost Estimations and Sustainability

Sustainable production develops the necessary strategies to replace materials by reducing the use of assets and energy of the earth, reducing emissions and pollutants, and reducing risks related to safety and health. produce finished products and reduce waste, while pursuing the goal of improving and doing business for our customers and leaving the world's best to our future team [22]. The stable working model of the machine includes environmental protection, cost saving, energy saving, long life, no waste, operational safety, and personal health [23]. The cost of the grain segregation system should be minimal for a sustainable approach, but it depends upon the material and manufacturing process [24]. Table 6 shows the cost estimations,

Table 6

Cost Analysis of portable grain segregation system

Items	Prices (US Dollars)
material	433.93
motor	43.11
Bearing (quantity 2)	6.11
V belt	1.80
Flywheel	12.57
Welding and machining	53.88
	Total: 551.39

The different organizations provide industrial segregation technology with a cost range between 1000 – 4000 US Dollars[25]. This research is not only sustainable in terms of safety, but in cost also as it reduces costs by up to 65% depending upon the market value.

6. Conclusion

The designed Grain Segregation system affords a value-effective solution for isolating undesirable debris from bulk High-Density Polyethylene (HDPE) grains. Its linear segregation generation ensures precision and space efficiency, outperforming the Trommel approach. With cautious thing selection and modelling, the device demonstrates performance and flexibility in diverse industries, including creation and agriculture. At the same time as excelling in dry particle segregation, it can no longer be suitable for liquid combinations.

FEA (Static and Modal) of the model shows that the C-channel, hopper support frame, and slider will deflect up to 0.182 mm, 0.227 mm, and 0.637 mm respectively which is much less for a 137 kg capacity machine. The deflection for 14 in. and 9 in. hinges was found to be 0.28mm and 0.113 mm ensuring that the design is safe for loading conditions. Moreover, the modal analysis investigated that the modes shape frequencies start from 24.9 Hz which is much greater than the forced frequency of the system which is 6.4 Hz so the resonance will not occur.

This research is not only sustainable in terms of safety, but in cost also as it reduces costs by up to 65% depending upon the market value. The machine's ease of operation, low preservation, and adaptability make it an asset for businesses seeking efficient grain segregation. The task remains budget-friendly, offering a realistic answer for industries of varying scales.

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