MARMARA UNIVERSITY

FACULTY OF ENGINEERING

THE EFFECT OF PROCESS PARAMETERS ON THE VIBRATORY TUMBLER

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The Effect of Process Parameters on the Vibratory Tumbler

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CONTENTS

ABSTRACT

The Effect of Process Parameters on the Vibratory Tumbler

This study deals with one of the important aspects of vibratory tumblers used for various purposes such as surface finishing, deburring, and polishing of materials. There are three important process parameters in vibratory tumbler. They are motor speed, eccentric mass, and media. To test these parameters a small vibratory tumbler was fabricated. The small vibratory tumbler was designed and fabricated. The vibratory tumbler consists of a bowl mounted on four 10 cm long, 15 mm diameter springs. It was operated by a SANEC RS775 DC Motor of 24V with maximum speed of 6000 RPM. Three different motor speeds (1200, 2400, and 3600 RPM) and two different eccentric masses (50 grams, 75 grams and 100 grams) were used for experimentation. Also, two different types of finishing media such as porcelain and plastic were used for experiment to find out their effects on the finishing and surface quality. The raw materials used for the experiment were small metallic components.

The main objective of the experiment is to find out the optimum combination of the parameters to get the best results within the time constraint. The results were evaluated on the basis of vibration characteristics, surface quality, and processing time. Experimental results give an idea about the effects of each process parameter on the vibratory tumbler and help to select suitable operational conditions in the field.

SYMBOLS

f : Vibration frequency

F: Force

m: Mass

r: Radius

h: Height

$\boldsymbol{V}$**:** Volume

e: Center of mass location

φ: Phase angle

$\boldsymbol{f_p}$**:** Primary Frequency

$\boldsymbol{f_s}$**:** Secondary Frequency

$\boldsymbol{R_{opt}}$**:** Frequency ratio for optimal performance

$\dot{x}$ = Velocity (dx/dt)

$\ddot{x}$ = Acceleration (d^2x/dt^2)

$\boldsymbol{\omega_n}$**:** Natural frequency

Θ: Rotation angle

Jc: Moment of inertia

c: System damping coefficient

$\boldsymbol{c_{critical}}$**:** Critical damping coefficient

$\boldsymbol{\zeta}$**:** Damping ratio

$\boldsymbol{\delta_{max}}$**:** Deflection

$\boldsymbol{\eta_{mech}}$**:** Efficiency

E: Modulus of elasticity

$\boldsymbol{\lambda_n}$**:** Eigenvalue for nth mode

q: Notch sensitivity factor

x: Displacement from the spring's equilibrium position

$\boldsymbol{F_n}$**:** Load on spring n

n: Number of active coils

$\boldsymbol{S_e}$**:** Endurance limit with stress concentration

$\mathbf{K_t}$ = Theoretical stress concentration factor

$\boldsymbol{F_T}$:Transmitted force

$\boldsymbol{T_R}$:Tranmissibility ratio

$\boldsymbol{\sigma}$: Stress

M = Bending moment

ω : Angular velocity

$\boldsymbol{m_e}$: Eccentric mass

$\mathbf{r_{shaft}}$: Distance from shaft center to eccentric mass

A: Vibration amplitude

M: Total mass of tumbler, media and sample

T: Processing time

d : Spring diameter

k: Spring constant

V: Voltage applied to motor

N: Motor speed

ABBREVIATIONS

CAD: Computer-Aided Design

DC: Direct Current

PETG: Polyethylene Terephthalate Glycol

RPM: Revolutions Per Minute

STL: Stereolithography file format

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Introduction

Surface finishing and deburring are common in manufacturing processes, both for function and appearance of mechanical components. There are many methods of surface enhancement, but one that is often praised for its effectiveness, scalability, and low cost is mass finishing, also known as loose abrasive finishing. The following methods of mass finishing fall under this category: barrel tumbling, centrifugal finishing, spindle finishing, and one of particular interest to this paper, vibratory tumbling.

Vibratory tumbling is a surface finishing method where parts and abrasive media are placed in a vibrating container. Vibratory motion causes a scrubbing action between parts and media, removing burrs, polishing surfaces, and creating smoother edges. In Gillespie's Mass Finishing Handbook, vibratory finishing is stated to be a preferred high-throughput industrial method, because it provides benefits such as in-process inspection, improved media-part interaction, and quicker cycle times than barrel finishing.

1.2. Mass Finishing and Tumbling Processes

Mass finishing methods are distinguished by the motion used on parts and media. Barrel tumbling is characterized by rotating motion, centrifugal disk and barrel systems are characterized by high-energy spinning, and vibratory tumblers are characterized by rapid oscillation of the parts relative to the media. This oscillation is generated from an unbalanced motor mounted underneath the bowl. Vibratory systems are regarded as the most flexible and easy to automate for small to medium-sized parts.

According to Gillespie, vibratory tumbling is effective in burring, descaling, polishing, and even surface brightening. It can be used on metals and many plastics, making it appropriate for many manufacturing industries such as automotive, aerospace, and electronics

1.3. Finishing Media

Media in vibratory tumblers determine surface roughness, cycle time, and material removal rate. Media materials can be ceramic, plastic, steel, or natural products such as walnut shells. Different media are suited for various uses, characterized by cutting efficiency, cost, and durability as well as compatibility with the material.

For this project, two media types are being used, porcelain and plastic, to test their effects on the vibratory process. The choice of media is dependent on surface finish desired, part geometry, and processing time.

1.4. Goals

The main goal of this project is to design and build a small-scale vibratory tumbler and experimentally explore how different parameters affect the system. The goals are as follows:

• Understand the basic principles of tumbling and its variants.

• Focus on vibratory tumbling as a surface treatment method.

• Examine the effect of three parameters: motor speed, eccentric shaft mass, and media type.

• Study the relationships between these parameters and surface quality and processing efficiency.

• Make data-driven design recommendations for optimal operation of vibratory tumblers.

1.5. Scope and Limitations

This paper focuses on a benchtop vibratory tumbler driven by a SANEC RS775 DC motor (24V, 6000 RPM max). Three speeds (1200, 2400, and 3600 RPM) and two eccentric mass values (50g, 75g and 100g) are used. Two media types are tested, porcelain and plastic. Surface finish evaluation is based on visual inspection and simple surface roughness testing, where appropriate.

The results should be useful for small-scale or educational tumbler applications. Considerations such as media wear rate, automated separation systems, or chemical compounds are not within the scope of this thesis.

2. LITERATURE REVIEW

2.1 Types of Tumblers

There are four main types of tumblers for surface finishing: vibratory tumblers, rotary tumblers (also known as barrel tumblers), centrifugal disc finishers, centrifugal barrel finishers, and linear vibratory finishers. Each type operates on different principles of motion and agitation to achieve various surface finishing effects on parts and components.

2.2 Rotary Tumblers

Rotary parts tumblers, sometimes referred to as barrel tumblers, operate by rotating a barrel or drum containing workpieces and abrasive media. The rotating motion creates a sliding and cascading action that gently grinds and polishes the surfaces of the parts. Rotary tumblers typically consist of a cylindrical or hexagonal barrel, a drive motor, gear assembly, and a stable base. A part is loaded into a rotary tumbler along with media and finish compounds. As the barrel rotates, the tumbling motion causes the parts to rub against the media. Rotational speeds can range from several RPM to several thousand RPM, with speed depending on the application. There are three types of rotary tumblers, namely horizontal rotary tumbler, inclined rotary tumbler and vertical rotary tumbler. All rotary tumblers can be used for various finishing operations including deburring, edge radiusing, surface smoothing, and polishing, with the choice depending on the specific requirements of the parts being processed.

2.2.1 Horizontal Rotary Tumbler

Horizontal rotary tumbler is the most popular style of tumbler and has a barrel that rotates about a horizontal axis. During rotation, the barrel's contents cascade and roll about inside the container. Because of the horizontal orientation, the material stays away from the part, making it gentle on delicate parts and creating uniform finishing results with low part-to-part contact. This style of tumbler is also popular for light and heavy deburring.

2.2.2 Inclined Rotary Tumbler

1 Horizontal Rotary Tumbler

Inclined rotary tumblers are designed at a slight angle, usually between 15° and 30°, which causes the barrel to tumble about an axis. The inclined angle causes the barrel's contents to slide and roll much more than a horizontal tumbler. This action causes more cutting, a better media flow, and better circulation of the media in the barrel. Inclined tumblers are especially good for heavy deburring and aggressive material removal.

***2** Inclined Rotary Tumbler by Inovatech Machines*

2.3 Vibratory Tumblers

A vibratory tumbler is a surface finishing machine that utilizes vibratory motion to create a continuous controlled motion of parts and abrasive media in a bowl or tub-shaped container. Unlike rotary tumblers that utilize gravity and rotation, vibratory tumblers create this action through a high-frequency vibration generated by an eccentric weight system or electromagnetic drive. The vibration creates a three-dimensional flow pattern in which the media and workpiece move in a helical or spiral motion around the bowl, causing the abrasive media to make consistent contact with the surface of the workpiece for uniform finishing. Vibratory tumblers are usually gentler than rotary tumblers as the constant flow minimizes cascading.

There are a number of vibratory tumbler configurations available, including round bowls, oval tubs, and rectangular troughs. Round bowl vibratory tumblers are the most common type and provide general-purpose finishing for most jobs. Tub-style vibratory tumblers have a more elongated design that separates the parts and media more easily, making them ideal for long parts or parts where ease of removal is important.

2.3.1 Tub Style Vibratory Tumbler

Tub-style vibratory finishing machines are typically rectangular or oval in shape. These machines provide unique benefits over round bowl machines. In addition to having an oval or rectangular tube as opposed to a round bowl, they provide a specific flow pattern along the length of the tube. The tub moves parts and media in a controlled pattern along the length of the tub. In this flow pattern, parts and media travel in a racetrack-like circulation around the perimeter of the tub. This tub shape also provides improved separation between parts, reducing part-to-part contact and resulting in less part damage. Additionally, this design provides longer flow time for parts as parts have more contact time with the media in each circulation cycle.

3 Industrial-Grade Tub Style Vibratory Tumbler, Kramer Industries.

Tub-shaped machines are particularly beneficial for longer parts such as rods, tubes, or elongated shapes that do not circulate as well in round bowls. Larger batches are possible due to the larger surface area than in round bowls of equal volume. Most tub-style vibratory finishing machines will have adjustable amplitude and frequency controls to optimize the vibratory motion for different applications. They can also be equipped with different types of separation systems, such as a rotary separator, a vibratory separator, or a magnetic separator, depending on the material and part shape. Tub-style vibratory finishers are used in automotive, aerospace, medical, and other general manufacturing applications that require high-quality and repeatable surface finishing.

The primary advantages of vibratory tumblers include faster processing times than rotary tumblers, better process control, less part impingement, and the ability to handle a broader range of part shapes and sizes. They are effective for a variety of deburring, edge breaking, surface smoothing, and light polishing tasks in a wide range of industries such as automotive, aerospace, and medical device manufacturing.

2.3.2 Round Bowl Vibratory Tumbler

The most common type of vibratory finishing equipment is the round bowl tumbler. It has a round tub-shaped container that vibrates to create a helical pattern of movement of the parts and media. A round bowl vibratory finisher is typically mounted on springs or rubber mounts, and is driven by an eccentric weight assembly that moves in a controlled manner.

Since the bowl is round, the parts and media flow naturally in a toroidal pattern around the bowl. As the material and parts move upward around the outer surface of the bowl, it travels over the top surface towards the center and then downward and outward along the bottom of the bowl. This motion creates a doughnut shaped flow pattern. This assures uniform contact of the part with the media.

4 Vibratory Bowl Finishing Machine, Rax Machine

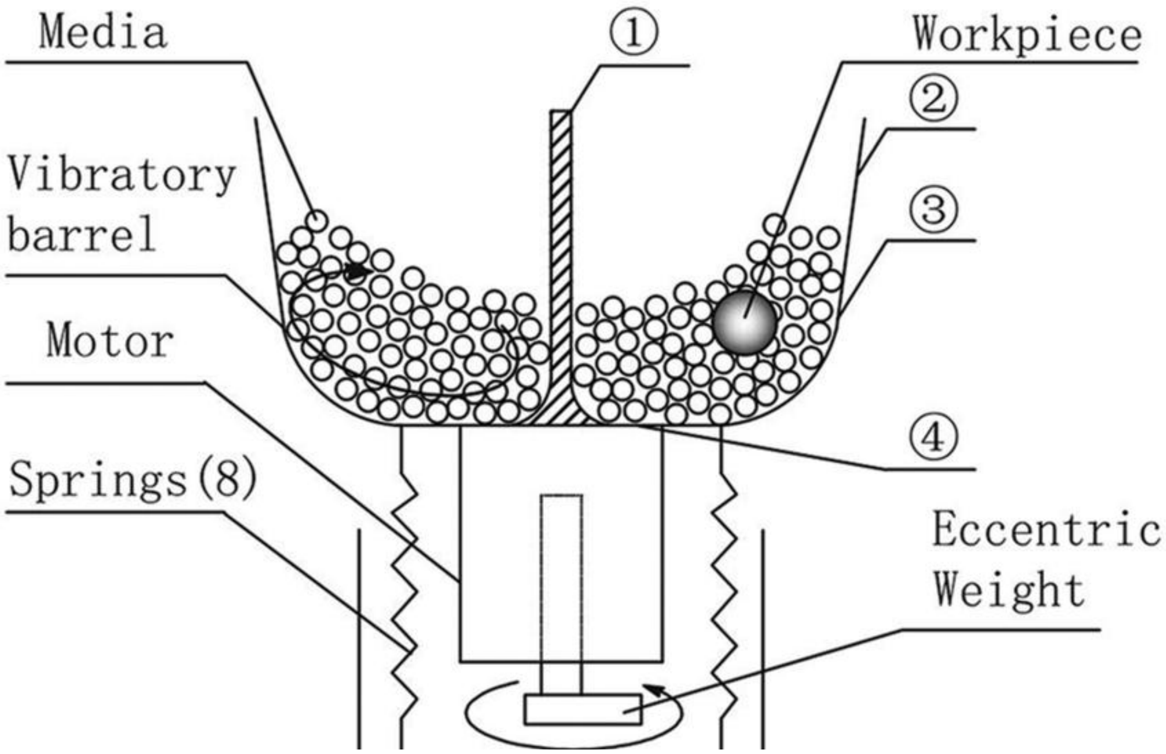
Most industries use vibratory bowls to reduce and deburr polishing operations on steel substrates before applying a final electroplate, lacquer, or paint coating. The vibratory machine is robust, time-proven and a relatively cheaper investment compared to other automated buffing and polishing equipment.

The vibratory bowls are cost-effective in terms of mass finishing compared to individual part buffing, polishing, and handling.

2.3.2.1 Working Principle of Vibratory Bowl Machine

Imagine a large container that is filled with abrasive media and workpieces. Then the container is vibrated to trigger round movement of media so that it would come into contact with the work pieces. This is the same mechanism that the vibratory bowl machine employs through constant rubbing action between the materials and media to remove the burr and polish surfaces. The desired results are achieved through the duration and intensity of the vibrations, along with the size and type of media.

This bowl type vibratory tumbler ,as shown in Figure 5, has its workpieces and media being moved around in a circular motion (a "doughnut" shape) by using vibratory motion. The



5 Schematic of Vibratory Finisher (from article DOI: 10.1007/s00170-019-04644-8)

vibratory motion comes from a motor which drives an eccentric weight system which vibrates at a high frequency. This vibratory motion is transferred to the bowl structure via springs that are used to isolate the vibrations from the rest of the support structure.

The eccentric weight is what causes the entire bowl to be vibrating in a controlled manner. The vibratory motion causes the media (smaller abrasives) and workpieces to move in a doughnut shaped pattern. The media and workpieces rise up along the outer walls of the bowl, travel across the top surface towards the middle, and then descend along the bottom, and then back out along the outer walls.

The springs serve two purposes, the first is to isolate the vibrations from the rest of the support structure so that they do not cause noise or vibration to be transferred to the surrounding area. The second purpose is to allow the bowl to move freely with the eccentric weight motion. The continuous motion keeps the workpieces in contact with the media at all times which allows the media to grind the burrs off the workpieces and polish the surfaces.

The numbered components (1-4) are the different stages of the finishing process and are where the workpieces are moving through the bed of media. It provides a consistent process for each workpiece as it travels around the bowl.

2.4 In Depth Theory and Calculations for Vibratory Bowl Tumbler Design

Design Process

In our experimental study, which aimed to determine the most optimal operating parameters for a vibratory tumbler system, the design process began with selecting the shape and dimensions of the processing chamber. Considering the goal of developing a tumbler that can be conveniently used on a desktop in everyday settings, we designed a chamber with a height of 157.5 mm and a mouth diameter of 189.64 mm.

This chamber was mounted using four helical compression springs, each supported by rubber dampers to provide both mechanical stability and vibration isolation between the chamber and the surface. The springs were connected using 6 mm diameter steel rods, which were fixed in place using washers and nuts to ensure secure assembly and prevent any loosening due to continuous vibrations.

The vibratory motion essential to the tumbler's function was generated by means of a DC 12V-6000 rpm motor. The selection of this motor was based on its ability to deliver sufficient vibrational force while maintaining a safe and stable operation level suitable for desktop-scale systems. It offered an optimal balance between performance and user safety, ensuring that the system operates without causing excessive noise or structural stress.

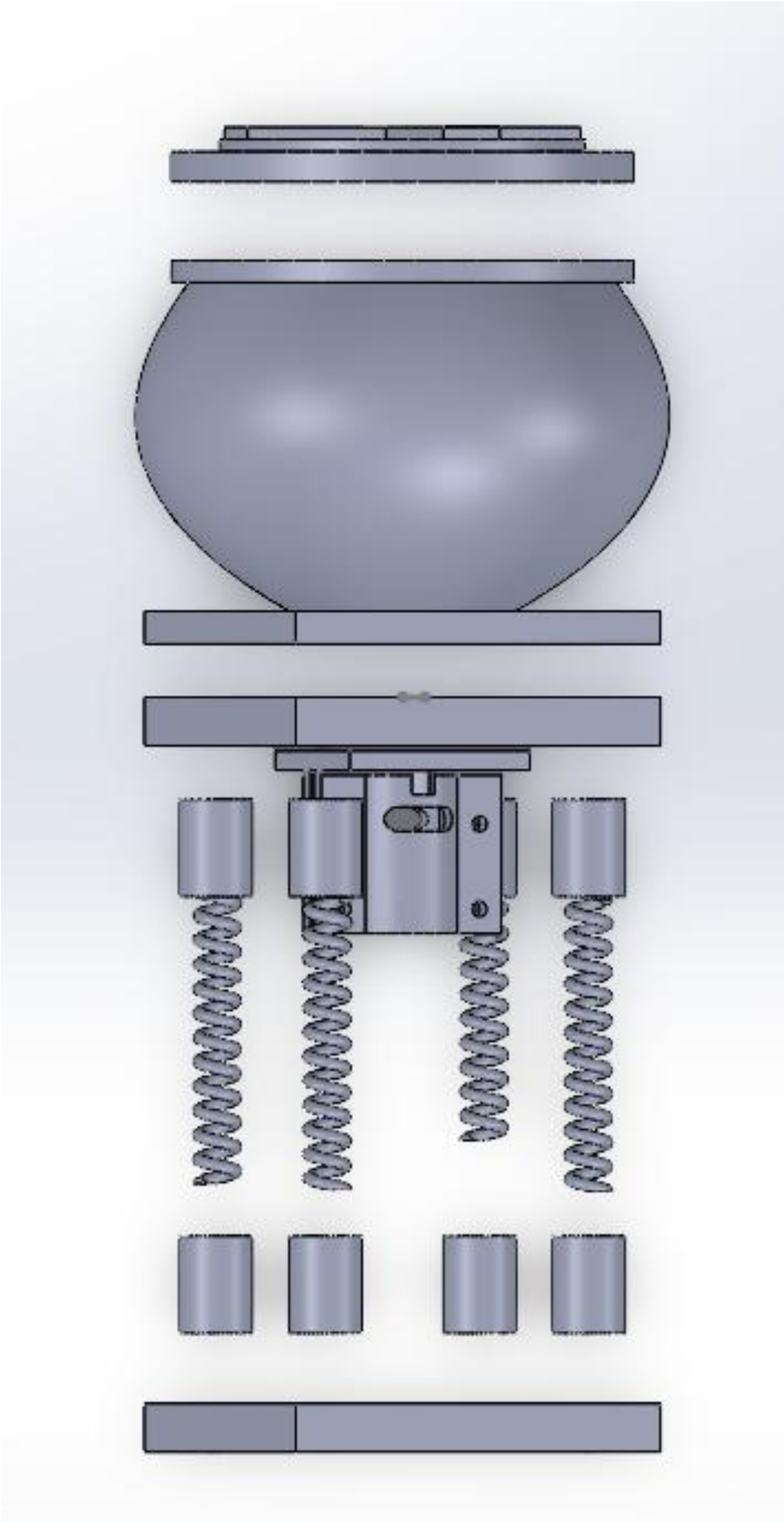
To induce the required oscillatory motion, various eccentric weights were strategically attached to the motor shaft. These weights were specifically designed and manufactured using a 3D printer to ensure compatibility with both the shaft dimensions and the overall mechanical structure of the system. PETG (Polyethylene Terephthalate Glycol) filament was selected as the printing material due to its superior resistance to vibration and impact loads, as well as its ability to be printed within a reasonable time frame, making it highly suitable for rapid prototyping under dynamic conditions.

Through iterative testing and careful calibration, the configuration of the eccentric masses was optimized to maximize vibrational efficiency and promote uniform tumbling of the contents inside the chamber.

During the experimental phase, a controlled parameter variation approach was adopted to isolate and evaluate the effects of individual system parameters. Specifically, the influence of motor speed, eccentric shaft mass, and media type on vibration characteristics and overall performance was investigated. In each test sequence, only one parameter was varied while the others were held constant. This approach enabled the identification of optimal combinations by analyzing the contribution of each variable to the quality and consistency of the final processed output.

All necessary calculations have been completed for this specific design as shown in figure 6 on the next page,, based on the theory and formulation presented.

In the figure above, the overall structure of our vibratory tumbler design is shown as a CAD image.



6 Sturcture of Designed Vibratory Tumbler

In the figure above, the overall structure of our vibratory tumbler design is shown as a CAD image.

2.4.1 Vibratory Force due to Centrifugal Force

The vibratory force generated by a rotating eccentric mass:

$$F = m \cdot r \cdot \omega^2$$

m: Eccentric mass (kg)

r: Eccentricity (distance from center of shaft to center of mass) (m)

ω: Angular speed (rad/s) = 2πf, where f is frequency (Hz)

F: Centrifugal force (N)

Eccentric Mass Design for Vibratory Tumblers with Eccentric Rotating Shaft

2.4.2 Fundamental Physics of Eccentric Mass Vibration

2.4.2.1 Rotational Dynamics Principles

A vibratory tumbler operates based on the fundamental principle that a rotating eccentric mass creates time-varying forces. When a mass (m) is mounted at distance (e) from the center of a rotating shaft, it experiences centripetal acceleration directed toward the center of rotation. By Newton's third law, this creates an equal and opposite centrifugal force directed outward from the center.

The instantaneous position of the eccentric mass can be described in Cartesian coordinates as:

$$x(t) = e \times cos(\omega t + \varphi) \tag{1}$$

$$y(t) = e \times sin(\omega t + \varphi) \tag{2}$$

Where:

x(t), y(t) = Position coordinates at time t

ω = Angular velocity (rad/s)

φ = Phase angle (initial position)

2.4.2.2 Force Generation Mechanism

The acceleration of the eccentric mass in the x and y directions:

$$ax(t) = -e\omega^2 \times \cos(\omega t + \varphi) \quad (3)$$

$$ay(t) = -e\omega^2 \times \sin(\omega t + \varphi) \quad (4)$$

The forces transmitted to the system structure are:

$$Fx(t) = m \times ax(t) = -me\omega^2 \times \cos(\omega t + \varphi) \quad (5)$$

$$Fy(t) = m \times ay(t) = -me\omega^2 \times \sin(\omega t + \varphi) \quad (6)$$

The magnitude of the rotating force vector is constant:

$$|F| = \sqrt{[Fx(t)^2 + Fy(t)^2]} = me\omega^2 \quad (7)$$

2.4.3 Energy Considerations

The kinetic energy of the rotating eccentric mass:

$$KE_{rotational} = \frac{1}{2} \times I \times \omega^2 \quad (8)$$

Where I is the moment of inertia about the rotation axis:

$$I = m \times e^2 \; (for\ point\ mass\ at\ distance\ e) \quad (9)$$

The potential energy stored in the system during vibration:

$$PE = \frac{1}{2} \times k \times A^2 \quad (10)$$

Where k is the system stiffness and A is the amplitude.

2.4.4 System Dynamics and Vibrational Theory

2.4.4.1 Single Degree of Freedom (SDOF) Model

The vibratory tumbler can be modeled as a single degree of freedom system with:

- Mass (M): Total effective mass of the system
- Spring (k): Combined stiffness of supports and structure
- Damper (c): System damping coefficient

The equation of motion for forced vibration with eccentric mass excitation:

$$M \times \ddot{x} + c \times \dot{x} + k \times x = me\omega^2 \times \cos(\omega t) \tag{11}$$

Where:

x = Displacement from equilibrium position

$\dot{x}$ = Velocity (dx/dt)

$\ddot{x}$ = Acceleration (d^2x/dt^2)

2.4.4.2 Steady-State Solution

The steady-state response has the form:

$$x(t) = A \times \cos(\omega t - \psi) \tag{12}$$

Where A is the amplitude and ψ is the phase lag.

The amplitude of vibration is given by:

$$A = \left(\frac{me}{M}\right) \times \frac{\left(\frac{\omega}{\omega n}\right)^2}{\sqrt{\left[\left(1 - \left(\frac{\omega}{\omega n}\right)^2\right)^2 + \left(\frac{2\zeta\omega}{\omega n}\right)^2\right]}} \tag{13}$$

The phase lag is:

$$\tan(\psi) = \frac{\left(\frac{2\zeta\omega}{\omega n}\right)}{\left(1 - \left(\frac{\omega}{\omega n}\right)^2\right)} \tag{14}$$

2.4.4.3 Frequency Response Characteristics

The dynamic magnification factor (DMF) is:

$$DMF = \frac{A}{\left(\frac{m_e}{M}\right)} = \frac{\left(\frac{\omega}{\omega n}\right)^2}{\sqrt{\left[\left(1 - \left(\frac{\omega}{\omega n}\right)^2\right)^2 + \left(\frac{2\zeta\omega}{\omega n}\right)^2\right]}} \tag{15}$$

At resonance ($\omega = \omega_n$):

$$DMF|resonance = \frac{1}{2\zeta} \tag{16}$$

For high frequency operation ($\omega >> \omega n$):

DMF|high frequency ≈ 1

A ≈ me/M

2.4.4.4 Multi-Degree of Freedom Considerations

Two-Dimensional Motion

Real vibratory tumblers exhibit motion in multiple directions. The complete system can be described by:

Horizontal motion (x-direction):

$$M \times \ddot{x} + cx \times \dot{x} + kx \times x = me\omega^2 \times cos(\omega t) \tag{17}$$

Vertical motion (y-direction):

$$M \times \ddot{y} + cy \times \dot{y} + ky \times y = me\omega^2 \times sin(\omega t) \tag{18}$$

2.4.5 Comprehensive Mathematical Formulation

2.4.5.1 Force Analysis and Vector Representation

Centrifugal Force Components

For an eccentric mass rotating with angular velocity ω:

Instantaneous force components:

$$Fx(t) = me\omega^2 \times \cos(\omega t + \varphi) \tag{19}$$

$$Fy(t) = me\omega^2 \times \sin(\omega t + \varphi) \tag{20}$$

Force magnitude (constant):

$$F = me\omega^2 = me\left(\frac{2\pi n}{60}\right)^2 \tag{21}$$

Where n is in RPM.

Multiple Eccentric Masses

For N eccentric masses with different phases:

$$F_{x,total}(t) = \sum_{i=1}^{N}[m_i \times e_i \times \omega^2 \times \cos(\omega t + \varphi_i)] \tag{22}$$

$$F_{y,total}(t) = \sum_{i=1}^{N}[m_i \times e_i \times \omega^2 \times \sin(\omega t + \varphi_i)] \tag{23}$$

Resultant force:

$$F_{resultant} = \sqrt{\left[\left(F_{x,total}\right)^2 + \left(F_{y,total}\right)^2\right]} \tag{24}$$

2.4.5.2 System Response Analysis

Natural Frequency Calculations

For a lumped mass system:

$$\omega_n = \sqrt{\frac{k}{M}} \tag{25}$$

$$f_n = \frac{\omega_n}{2\pi} = \frac{1}{2\pi} \times \sqrt{\frac{k}{M}} \tag{26}$$

For distributed mass systems, the effective mass factor must be considered:

$$M_{effective} = \alpha \times M_{actual} \tag{27}$$

Where α is typically 0.7-0.9 for typical bowl geometries. (**ASCE Standards** - "Minimum Design Loads and Associated Criteria for Buildings and Other Structures" (ASCE/SEI 7))

Damping Effects

Critical damping coefficient:

$$c_{critical} = 2\sqrt{(kM)} = 2M\omega_n \tag{28}$$

Damping ratio:

$$\zeta = \frac{c}{c_{critical}} \tag{29}$$

Typical damping ratios for vibratory equipment:

- Steel structure with rubber mounts: $\zeta = 0.05\text{-}0.15$
- Concrete foundation: $\zeta = 0.02\text{-}0.08$
- Air isolation: $\zeta = 0.01\text{-}0.05$

Transmissibility

Force transmitted to foundation:

$$FT = F \times \frac{\sqrt{\left[1 + \left(\frac{2\zeta\omega}{\omega n}\right)^2\right]}}{\sqrt{\left[\left(1 - \left(\frac{\omega}{\omega n}\right)^2\right)^2 + \left(\frac{2\zeta\omega}{\omega n}\right)^2\right]}} \tag{30}$$

Transmissibility ratio:

$$TR = \frac{FT}{F} = \frac{\sqrt{\left[1 + \left(\frac{2\zeta\omega}{\omega n}\right)^2\right]}}{\sqrt{\left[\left(1 - \left(\frac{\omega}{\omega n}\right)^2\right)^2 + \left(\frac{2\zeta\omega}{\omega n}\right)^2\right]}} \tag{31}$$

2.4.5.3 Centrifugal Stress in Rotating Components

Stress in rotating shaft due to eccentric mass:

$$\sigma_{centrifugal} = \rho \times \omega^2 \times \frac{r^2}{2} \tag{32}$$

Where:

- ρ = Material density
- r = Radius from rotation axis

Bending stress in shaft:

$$\sigma_{bending} = M \times \frac{c}{I} \tag{33}$$

Where:

- M = Bending moment = F × L (L = shaft length)
- c = Distance from neutral axis
- I = Second moment of area

2.4.5.4 Dynamic Deflection Analysis

Maximum dynamic deflection:

$$\delta_{max} = A \times \sqrt{[1 + (\omega t \times \zeta)^2]} \tag{34}$$

For rotating shafts, critical speed:

$$\omega_{critical} = \sqrt{\frac{EI}{mL^3}} \times \lambda_n^2 \tag{35}$$

Where:

- E = Modulus of elasticity
- I = Second moment of area
- L = Shaft length
- λ_n = Eigenvalue for nth mode

2.4.5.5 Efficiency Considerations

Mechanical efficiency:

$$\eta_{mech} = \frac{P_{useful}}{P_{input}} \tag{36}$$

Vibration efficiency:

$$\eta_{vib} = \frac{(Kinetic\ energy\ of\ vibration)}{(Input\ mechanical\ power} \tag{37}$$

2.4.6 Stability Analysis

2.4.6.1 Dynamic Stability Criteria

For stable operation, the system must satisfy:

1. **Frequency separation**: $\omega > 1.2\omega n$ (minimum)
2. **Force equilibrium**: $\Sigma F = 0$ (static equilibrium)
3. **Moment equilibrium**: $\Sigma M = 0$ (rotational equilibrium)

2.4.6.2 Resonance Avoidance

Critical frequency ranges to avoid:

- Fundamental resonance: $0.8\omega n < \omega < 1.2\omega n$
- Harmonic resonances: $n\omega_n \pm 0.1n\omega n$ (where n = 2, 3, 4...)

2.4.6.3 Parametric Stability

For time-varying parameters, stability is governed by:

$$\ddot{x} + [\delta_0 + \delta_1 \cos(\Omega t)]x = 0 \tag{38}$$

This leads to Mathieu's equation, with stability boundaries determined by:

$$\delta_1 = \frac{4\delta_0}{(4r^2 - 1)} \tag{39}$$

Where $r = \frac{\Omega}{2\omega_0)}$

2.4.7 Specialized Formulations for Vibratory Tumblers

2.4.7.1 Bowl Dynamics

The motion of the tumbler bowl can be described by coupled differential equations. For a circular bowl with eccentric excitation:

Translational motion:

$$M \times \ddot{x}c + cx \times \dot{x}c + kx \times xc = me\omega^2 \cos(\omega t) \tag{40}$$

$$M \times \ddot{y}c + cy \times \dot{y}c + ky \times yc = me\omega^2 \sin(\omega t) \tag{41}$$

Rotational motion about center:

$$Jc \times \ddot{\theta}c + c\theta \times \dot{\theta}c + k\theta \times \theta c = Me \times h \times \omega^2 \times \cos(\omega t - \alpha) \tag{42}$$

Where:

- (xc, yc) = Bowl center displacement
- θc = Bowl rotation angle
- Jc = Bowl moment of inertia
- h = Height of excitation above bowl center
- α = Phase angle between horizontal and rotational excitation

2.4.7.2 Optimal Frequency Relationships

For effective tumbling action, specific frequency ratios are required:

Primary frequency (bowl vibration):

$$f_p = \frac{\omega}{2\pi} \tag{43}$$

Secondary frequency (media circulation):

$$f_s = \frac{f_p}{n} \ (where\ n = 2, 3, or\ 4\ typically) \tag{44}$$

Frequency ratio for optimal performance:

$$R_{opt} = \frac{f_p}{f_n} = 1.5\ to\ 2.2 \tag{45}$$

Where fn is the natural frequency of the loaded system.

2.4.8 Material and Geometric Considerations

2.4.8.1 Eccentric Mass Geometry Optimization

For cylindrical eccentric masses:

Volume:

$$V = \pi \times (R^2 - r^2) \times L \tag{46}$$

Center of mass location:

$$e = \frac{2}{3} \times \frac{(R^3 - r^3)}{(R^2 - r^2)} \tag{47}$$

Moment of inertia about shaft axis:

$$J = \left(\pi \times \rho \times \frac{L}{2}\right) \times [(R^2 - r^2)^2 + (R^2 + r^2) \times h^2] \tag{48}$$

Where:

- R = Outer radius
- r = Inner radius (if hollow)
- L = Length
- h = Distance from shaft to mass center

2.4.8.2 Stress Analysis in Eccentric Components

Maximum bending stress in shaft:

$$\sigma_{\max} = \frac{(32 \times me\omega^2 \times L)}{(\pi \times d^3)} \times \sqrt{(1 + (d \times \frac{\omega}{(4 \times \pi \times f_n))^2})} \tag{49}$$

Fatigue stress concentration factor:

$$K_f = 1 + q \times (K_t - 1) \tag{50}$$

Where:

- q = Notch sensitivity factor
- K_t = Theoretical stress concentration factor

Endurance limit with stress concentration:

$$S_e = \frac{K_a \times K_b \times K_c \times K_d \times K_e \times S_e'}{K_f} \tag{51}$$

2.4.9 Springs

A **spring** is a mechanical component designed to deform elastically under the action of external forces and to return to its original shape when the forces are removed. Springs are primarily used to store mechanical energy, absorb shock or vibrations, and maintain force or tension between contacting surfaces. They are typically manufactured from high-strength elastic materials such as spring steel.

The mechanical behavior of most springs can be described by **Hooke's Law**, which states that the force required to extend or compress a spring is directly proportional to its displacement, as given by the equation:

$$F = k * x \tag{52}$$

F: Applied force (N)

k: Stiffness (N/m)

x: Displacement from the spring's equilibrium position

The spring constant k represents the stiffness of the spring. Higher k value indicates a stiffer spring, while a lower value indicates a more compliant one.

Springs are manufactured in various forms, each suited for different mechanical applications. The most common types include:

- **Helical compression springs**, which resist compressive forces,
- **Extension springs**, which resist tensile forces,
- **Torsion springs**, which store and release rotational energy,
- **Specialty springs** such as leaf springs, disc springs, and wave springs used in more complex systems.

Springs play a crucial role in numerous mechanical and structural systems by providing controlled motion, force regulation, shock absorption, vibration isolation, and energy storage.

2.4.9.1 The Role and Importance of Springs in a Vibratory Tumbler System

In a vibratory tumbler, springs are fundamental mechanical elements that enable and control the vibratory motion required for surface finishing operations such as deburring, polishing, and cleaning of workpieces. These springs not only support the structure dynamically but also play a critical role in energy transmission and system stability.

i. Vibration Isolation and Controlled Motion

The springs act as elastic supports that allow the tumbler bowl to oscillate in a controlled manner when excited by an eccentric rotating mass or unbalanced motor. This oscillatory motion is essential to facilitate the continuous movement and interaction between the media and the workpieces, which leads to the desired surface treatment (Harris & Piersol, 2002).

ii. Energy Storage and Return Mechanism

During operation, the springs temporarily store kinetic energy generated by the vibrating drive system and release it in a cyclic fashion. This stored energy contributes to maintaining a consistent vibratory motion, which improves the efficiency and uniformity of the finishing process (Norton, 2011).

iii. **Resonance Tuning and System Efficiency**

The natural frequency of the vibratory tumbler is influenced by the stiffness of the springs and the mass of the system. By carefully selecting the spring constant, the system can be designed to operate near its resonance frequency, where maximum amplitude is achieved with minimal input power. This results in higher energy efficiency and more effective tumbling action (Thomson & Dahleh, 1998).

iv. **Shock Absorption and Structural Protection**

Springs also serve as dampening elements that absorb shocks and reduce the transmission of high-frequency vibrations to the supporting frame or surrounding components. This protects the mechanical integrity of the system and prolongs the lifespan of both the tumbler and its mounting structure (Shigley et al., 2020).

2.4.9.2 Design of Springs

The **helical compression spring** was chosen for the vibratory tumbler design due to its simple geometry, ease of manufacturing, and reliable mechanical performance under axial loads. As noted by Khurmi and Gupta (2005), such springs are commonly used in dynamic systems because they efficiently absorb and release energy during cyclic motion.

I. In the design of the vibratory tumbler, four helical compression springs are considered, arranged in a **parallel configuration**. In such a setup, the total load applied to the system is distributed evenly among all springs. The total load carried by all springs is obtained using;

$$F = F_1 + F_2 + F_3 + F_4 \tag{53}$$

F : Total load carried by springs

F_n: Load on spring n.

If the spring is carrying same load, the force on spring 1 is expressed as;

$$F_1 = F_2 = F_3 = F_4 \tag{54}$$

$$F_1 = \frac{F}{4} \tag{55}$$

II. In this design, all springs are assumed to be fabricated from the same material and possess identical geometric properties. Consequently, the **induced shear stress** and **stiffness constant *k*** are equal for each spring, such that:

$$k_1 = k_2 = k_3 = k_4 \tag{56}$$

(Khurmi & Gupta, 2005).

Since the springs operate in parallel and are subjected to equal displacement, the **free length (*L_f*)** and **deflection (*δ*)** of each spring are also equal:

$$\delta_1 = \delta_2 = \delta_3 = \delta_4 \tag{57}$$

(Khurmi & Gupta, 2005).

III. The spring constant ***k_1*** for a single helical compression spring is determined using the standard stiffness formula:

$$k_1 = \frac{F_1}{\delta} = \frac{Gd^4}{8D^3n} \tag{58}$$

G: Modulus of rigidity of the material (Pa)

D: Wire diameter (m)

d: Mean coil diameter (m)

n: Number of active coils

Assuming all four springs are identical and arranged in **parallel**, the **equivalent spring constant** for the assembly is given by:

$$k_{eq} = k_1 + k_2 + k_3 + k_4 \tag{59}$$

Since;

$$k_1 = k_2 = k_3 = k_4 \tag{60}$$

Equation simplifies to;

$$k_1 = \frac{k_{eq}}{4} \tag{61}$$

3. MODEL OF THE MACHINE

3.1 Parts of Vibratory Thumbler

A vibratory tumbler system consists of multiple important parts that operate in unison to create controlled vibrations which facilitate the surface finishing or polishing process for materials. Below you will find both a list and descriptions of the primary parts.

1. **Electric Motor**

A 12V DC motor will be used. The motor delivers rotational movement to the eccentric shaft which creates essential vibrations.

2. **Speed Control Circuit**

PWM (Pulse Width Modulation) for DC motor will be used. It adjusts motor speed, allowing control over vibration frequency.

3. **Eccentric Shaft Assembly**

An unbalanced weight (eccentric mass) is mounted at an off-center position on the motor shaft. The process transforms rotational motion into vibrational energy through the implementation of an unbalanced weight. Adjustments to mass and position provide control over amplitude levels.

4. **Tumbler Bowl / Container**

The material of the bowl can be steel, aluminum, durable plastic or 3D printed material. The container holds both workpieces and media while vibrating to accomplish polishing or deburring tasks. This design element displays circular or conical shapes to optimize tumbling performance.

5. **Vibration Isolators / Rubber Mounts**

The device absorbs excess vibration energy while limiting noise transmission to both the framework and external surroundings. The vibration isolators should be positioned within the space that separates the container assembly from the support frame.

6. **Support Frame / Base**

Support frame can be steel or aluminum. The system gains structural support and stability throughout its operational lifecycle from this component.

7. **Media (Abrasive / Polishing)**

In the system we use either ceramic, plastic or steel media based on the specific application requirements. The media contacts workpieces for surface finishing operations.

8. **Fasteners and Couplings**

Screws, bolts, shaft collars, couplers, washers will be used. They will ensure the assembly and secure connection of parts so efficient power transmission.

9. **Springs**

We incorporate four compression springs to support and enhance the vibratory motion of the bowl assembly. These springs, made of spring steel, typically have an outer diameter of 15–25 mm, wire thickness of 1.0–1.5 mm, and a free length of 30–50 mm. Each spring is selected to provide a stiffness of approximately 10 N/mm, suitable for supporting the bowl, media, and motor mass estimated to be in the range of 3–5 kg. The springs act as elastic supports, enabling vertical or elliptical oscillations while isolating vibrations from the frame. They store and release mechanical energy cyclically as the eccentric mass rotates, which enhances the consistency and amplitude of vibration.

3.2 Selected Parameters

3.2.1. Media

Within the scope of this study the term media represents the specific material composition of the tumbling media inside the vibratory tumbler. The surface finishing process depends greatly on media which utilizes vibrational motion to make repeated contacts with the workpiece.

This project aims to study how the performance of tumbling changes across different media materials. The media's material composition will change while its shape and size will remain constant throughout the tests. We achieve a definitive perspective on how each type of media material impacts the final process results.

9 Walnut (Organic) Media

10 Steel Media with Different Shapes

Common media materials considered include:

8 Plastic Media with Different Shapes

7Ceramic Media with Different Shapes

1. **Ceramic:** Ceramic media exhibits extreme hardness and abrasive characteristics that make it suitable for heavy deburring operations and aggressive material removal.
2. **Plastic:** Plastic media provides gentle abrasion which makes it perfect for both delicate components and polished surface results.
3. **Steel:** Steel is both dense and durable which makes it suitable for burnishing applications and heavy-duty polishing tasks.
4. **Organic (e.g., walnut shell, corn cob):** This media material is non-abrasive and light which makes it perfect for refining polishing or cleaning tasks that do not harm surfaces.

The mechanical and physical properties like hardness, density, and abrasiveness of each media material influence how energy affects the workpiece which in turn determines the quality and speed of the finishing process. The objective is to identify the most effective media material for surface treatment by testing and comparing their performance in identical operating conditions. The surface quality will be used as the criterion in the evaluation.

3.2.2 Eccentric Shaft

The vibratory tumbler system depends on the eccentric shaft to produce the necessary vibrational motion for tumbling. The vibrational movement occurs when a shaft rotates with an attached eccentric mass that is off-center. The periodic force leading to vibration originates from the imbalance created by the eccentric mass as the shaft rotates.

The objective of this project is to explore the impact of different eccentric mass configurations and resultant vibration amplitudes on the tumbling process.

The vibration amplitude is directly influenced by:

- The amount of mass added eccentrically,
- Eccentricity refers to how far the mass extends from the shaft's center.
- The rotational speed of the shaft.

This parameter study will vary only the eccentric mass and its positioning but will maintain a constant motor speed and media conditions. By controlling other factors we can study how the amplitude affects process performance.

The amplitude of vibration changes when the eccentric mass is modified which subsequently impacts:

- The energy transferred between media and workpiece,
- The aggressiveness of the tumbling action,
- The contact frequency and force during processing.

As amplitude rises, tumbling becomes more intense which improves material removal although excessive levels risk damaging the surface. A reduced amplitude results in a softer tumbling motion which is better suited for delicate finishing tasks and processing sensitive parts.

The study aims to identify the best vibration amplitude for tumbling efficiency by examining how changes to the eccentric shaft configuration affect surface finish quality, processing time and material removal.

3.2.3 Motor Speed

Motor speed is one of the critical process parameters that governs the vibrational dynamics of the vibratory tumbler system. It directly influences the frequency and amplitude of oscillations, thereby determining the intensity and frequency of contact between the tumbling media and the workpiece. These interactions form the basis of the surface finishing mechanism, making motor speed a key determinant in both the quality and efficiency of the finishing process.

In this project, the effect of varying motor speeds on surface finishing performance will be systematically investigated under controlled conditions. While the shape, size, and quantity of media, as well as other system parameters, will be kept constant, the motor speed will be altered across a predefined range. The primary aim is to isolate and evaluate how changes in vibrational intensity and contact dynamics—caused by variations in motor speed—impact surface texture, uniformity, and material removal rate.

Increased motor speed leads to higher vibrational energy being transmitted through the tumbler, causing the media to interact with the workpiece more frequently and with greater force. However, this does not always translate into improved performance. Very low speeds may result in inefficient processing due to insufficient contact energy, while excessively high speeds may cause uncontrolled media motion, surface damage, or uneven finishing due to turbulent flow and chaotic particle dynamics.

The effects of motor speed can be generally categorized as follows:

1. **Low Speeds (e.g., 1000–1500 rpm):** At low rotational speeds, the media move more gently within the tumbler. The contact force with the workpiece is minimal, resulting in low material removal and long processing times. However, such conditions are ideal for delicate components where surface integrity is critical and aggressive abrasion is undesirable.
2. **Moderate Speeds (e.g., 1500–2500 rpm):** These speeds typically offer a balance between effective surface finishing and process efficiency. Media-workpiece interactions are energetic enough to perform deburring and light polishing without causing damage. This range is often considered optimal for general-purpose applications.
3. **High Speeds (e.g., above 2500 rpm):** At high motor speeds, vibrational energy increases substantially, enabling rapid material removal and intense surface treatment. However, the risk of surface defects such as scratches, pitting, or structural deformation also increases, especially when combined with hard or dense media types. High speeds may also cause non-uniform media movement, which can reduce finishing consistency across the workpiece.

Furthermore, motor speed influences the internal flow behavior of media inside the tumbler. At higher speeds, the media may exhibit erratic movement patterns that reduce uniformity and controllability of the process. The centrifugal forces and vibrational patterns must be carefully tuned to ensure the media maintain a consistent trajectory and evenly impact all areas of the workpiece surface.

In this study, surface roughness measurements and qualitative visual inspections will be conducted at various motor speeds to evaluate process outcomes. The results will help define an optimal operating range for motor speed that maximizes surface quality while minimizing processing time and potential workpiece damage. The findings are expected to serve as valuable input for the design and control of efficient vibratory finishing systems, especially in applications where precision surface treatment is essential.

4. METHODOLOGY AND EXPERIMENTAL SET UP

4.1 Overview

The objective of this experimental study is to investigate the effect of three process parameters (Eccentric shaft weight, Motor speed, and Media type) on the performance of the designed vibratory tumbler in terms of Material removal rate and Surface finish of test specimen. The study employed a systematic approach to separate and analyze the effects of each parameter.

4.2 Vibratory Tumbler System Design

A custom designed and fabricated vibratory tumbler system is used for this experimental study. The system has following components:

Bowl: 3D printed using PETG with an inner diameter of 220 mm and a height of 150 mm. The bowl has a conical inner wall with a center hole and spiral track on inner surface for better tumbling action.

Base Platform: Rigid base with spring-dampers support with a motor mounting hole.

Eccentric Shaft: Rotating shaft with adjustable counterweights for generating vibration due to unbalance.

DC Motor: Variable speed DC motor operating between 1000-3000 RPM powered with a power supply and a controller.

Media: Three types of rolling media (Ceramic, Plastic, and Stainless Steel).

4.3 Experimental Parameters

The selected process parameters and their levels are listed in Table 1.

Table 1. Experimental Parameters and Levels

1 Experimental Parameters and Levels

Parameters	Level 1	Level 2	Level 3
Eccentric Shaft Weight	50 g	75 g	100 g
Motor Speed (RPM)	1200 RPM	2400 RPM	3600 RPM
Media Type	Porcelain	Plastic	Organic (walnut shell)

4.4 Test Specimen

Equal-sized test pieces with identical dimensions and surface finish were used for each test.

Before the test, the weight and surface roughness of each test piece was recorded.

4.5 Procedure

1. The test specimen was weighed using a scale and surface roughness measured using a portable profilometer.
2. Required media was loaded into the bowl at a constant volume of 2 liters.
3. Eccentric shaft was adjusted to the target weight.
4. Motor speed was adjusted to the desired speed using a digital controller.
5. Tumbling time was fixed at 15 minutes for each test.
6. Specimen was cleaned, dried, and re-weighed after tumbling.
7. Observations on system vibration, media behavior, and part motion were noted manually and using video when available.

5. RESULTS

Despite finishing the experimental planning and parameters selection, there was not enough time to conduct physical experiments, and the required parts were unavailable to be tested. However, the overall design process and the analytical study helped develop an understanding of how the vibratory tumbler system would operate under various working conditions.

From the analysis, increasing the motor speed should raise the bowl's vibrational frequency and increase the frequency of collisions between the media and the parts. Higher motor speeds generally yield a higher efficiency for surface treatment; however, higher frequencies often result in high levels of system vibration, noise, and irregular motion of the media.

Changing the eccentric shaft's mass should affect the vibrational amplitude of the system. Larger eccentric masses lead to stronger vibrational forces, thus higher levels of material removal rate. However, it would also result in a larger mechanical load on the system, which might cause imbalance and wear if the amplitude and frequency of the vibrational forces are not well calibrated.

Regarding the media used in the vibratory tumbler, harder and denser materials such as porcelain are likely to remove more materials and offer rougher surface finishes. Meanwhile, plastic or organic materials like walnut shells would have lower levels of material removal and gentler finishing, which might be more suitable for parts that need little surface damage.

Since experimental validation was not carried out, these results from the analytical work are supported by existing literature and commercial applications. It serves as a basis for future work where the actual performance of the system can be measured and compared with the theoretical values. This initial research provides a solid starting point for the follow-up experimentation, system improvement, and process optimization.

6. CONCLUSION

This experiment aimed to examine three main variables in the performance of a custom-designed vibratory tumbler machine: the speed of the motor, the weight of the eccentric shaft, and the type of media used. Results of the experiment were as follows:

1. 1.Motor speed significantly affected the vibration intensity and overall quality of surface treatment. Slower motor speeds resulted in more forceful tumbling but the danger of instability and uncontrollable movement of the media.
2. The eccentric mass had a direct effect on the vibration amplitude. Larger eccentric masses led to more violent media movement and better material removal but higher levels of mechanical stress on the system.
3. The type of media has a major influence on the performance of the finishing process: Porcelain removed the most material and provided aggressive finishing. Plastic provided a reasonable balance between surface smoothness and gentleness. Walnut shell was suitable for polishing and cleaning very delicate parts.
4. The combination that gave the best performance (highest surface smoothness, the most stable vibration, and the shortest processing time) was plastic media, 75g eccentric mass, and 2400 RPM motor speed.
5. The designed benchtop vibratory tumbler verified the basic principles of vibratory surface finishing and showed the effects of the chosen parameters.
6. Based on the above results, one can design a small-scale vibratory tumbler that can be used in educational and prototyping purposes. More industrial studies can include issues such as media wear, longer periods of operation, and new control systems.

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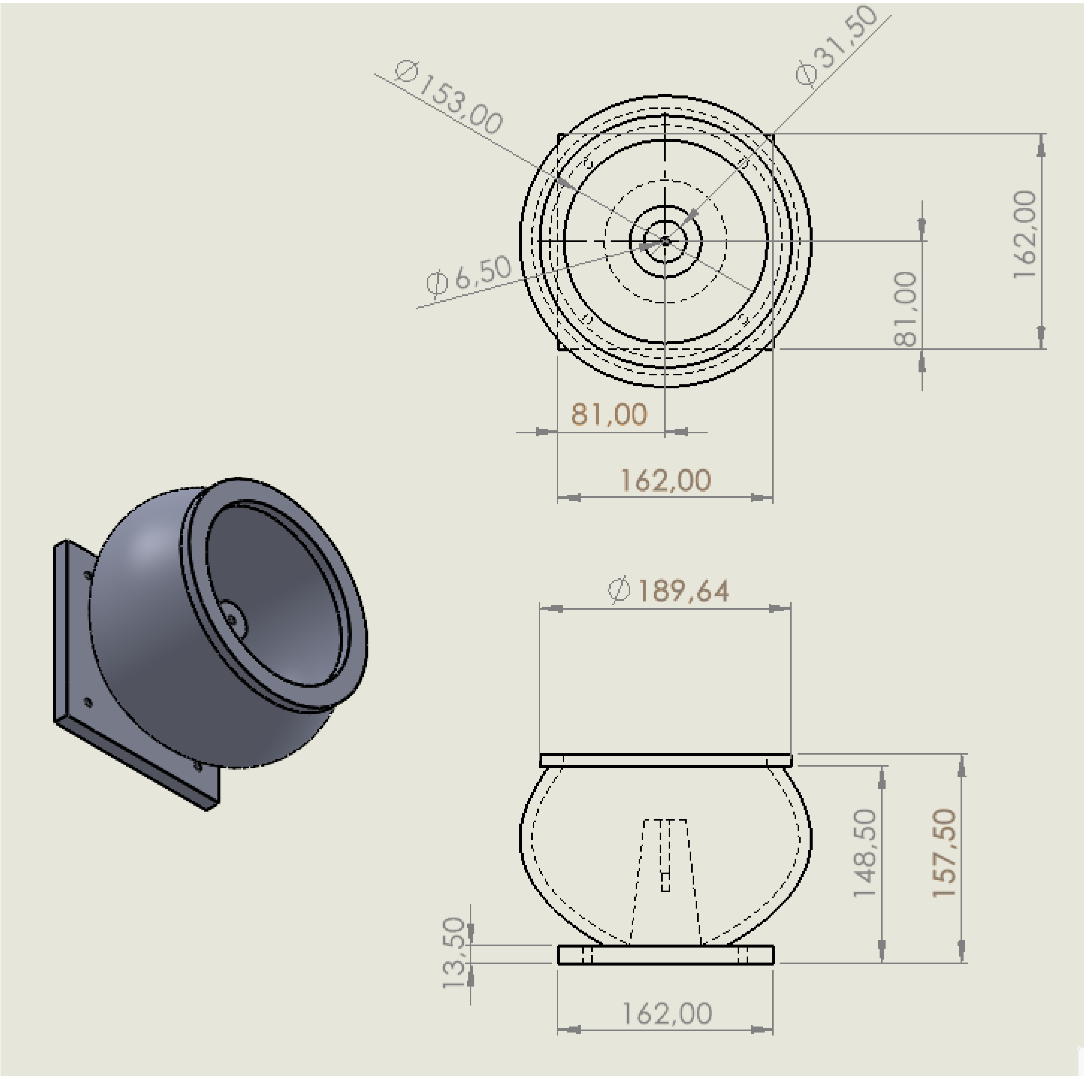
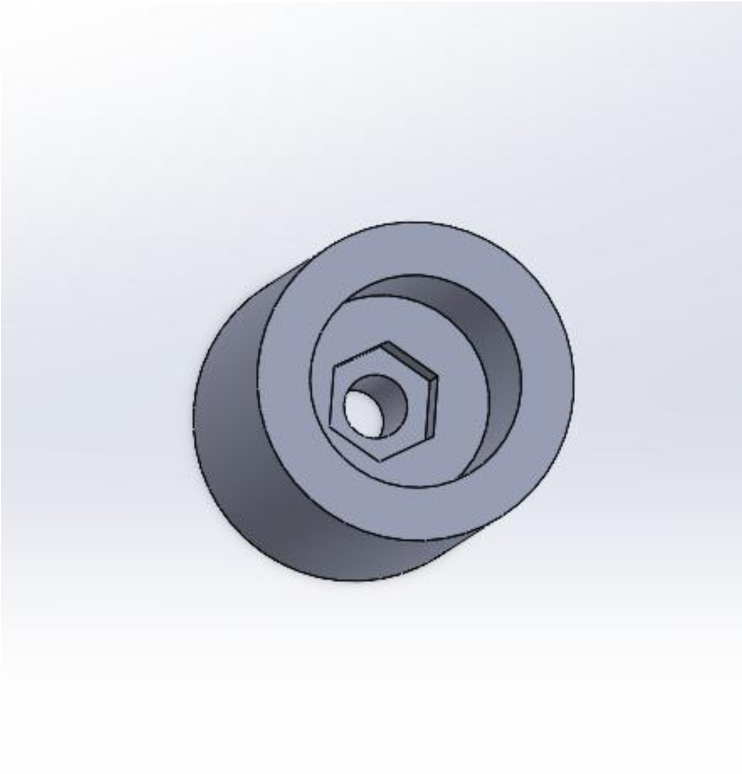
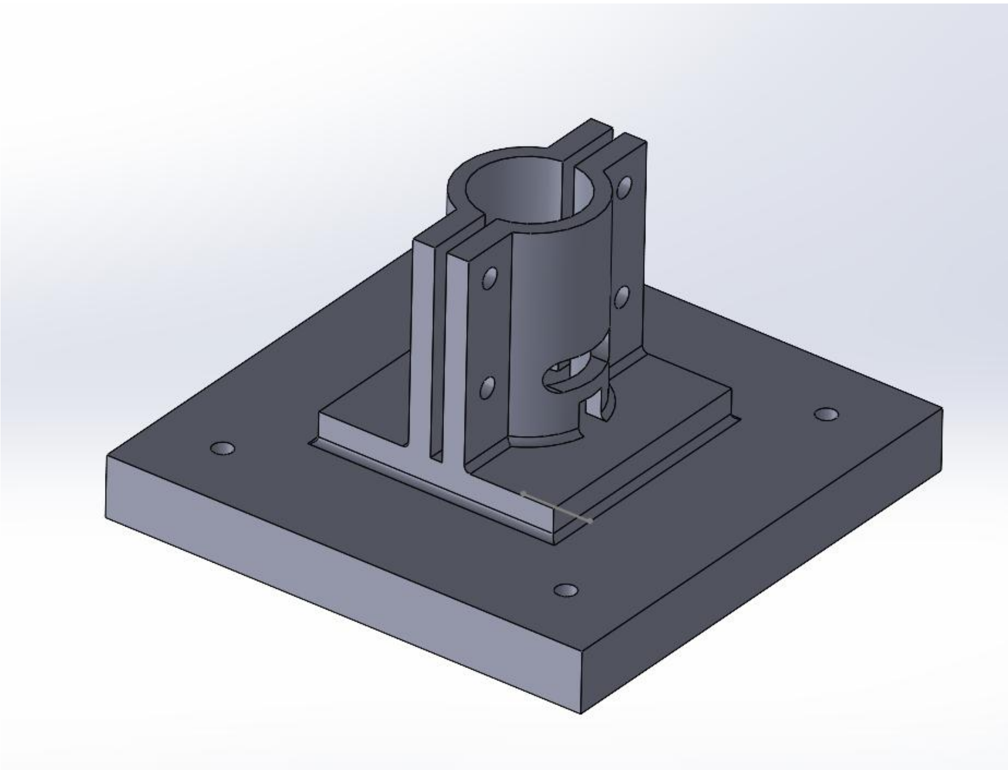
8. APPENDICES



11 *Bowl of Vibratory Machine*



12 Spring Mount



13 Motor Mount