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**Analysis and Simulation of a Centrifugal  
Clutch**

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## Abstract

This report analyses Centrifugal Clutches whilst understanding their development over the last century. It investigates the typical applications of these clutches, whilst understanding the types of materials utilised within them.

The report conveys literature, including patents to understand centrifugal clutch development, of which it was discovered that exploitation of centrifugal forces is utilised within clutches producing automatic actuation at given angular velocities.

Many developments of these clutches all work on similar principles, however, each clutch variant has its unique features which allow for various applications. Developments have not only progressed in terms of design but material development has also been utilised throughout the last century, increasing clutch efficiency, decreasing maintenance and allowing for further bespoke applications.

Centrifugal clutches are not necessarily developed to supersede previous generations, but rather have unique designs which allow for specific applications best suited for that type. Electromagnetic Clutches are an example of this, being developed from the idea of centrifugal clutches. These utilise electromagnetic principles to create mechanical torque through electrical actuation.

Electromagnetic clutches can be found within Manufacturing Automation, on conveyor systems, robotics, and servomotors, due to their unique precision, efficiency, and diversity.

Clutches, whether that be centrifugal or electromagnetic have their advantages and disadvantages, thus, an application will have a best-suited clutch type and configuration.

Mathematical calculations discovered that the laws of physics can be utilised to accurately discover set points to when a centrifugal clutch will actuate and how much torque it can produce for a given speed and friction coefficient. The actuation speed and force are dependent upon the weight of the rotating mass and the spring stiffness holding that mass. This will further determine the torque produced for a given speed along with the friction coefficient at the end of the rotating mass which contacts a drum. As both speed and friction coefficients increase, so does torque. However, these calculations do not account for mechanical inefficiencies such as slippage between surface contacts.

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## 1.0. Introduction

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This report will analyse centrifugal clutches, discussing their development, applications, advantages, and disadvantages, whilst discussing electromagnetic clutches within manufacturing automation. It will further analyse centrifugal clutches mathematically, understanding operating conditions within provided parameters.

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## 2.0. Clutch Development and Applications

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### 2.1. Clutches

A clutch is a mechanical mechanism connecting a driving shaft to a driven shaft, allowing the driven shaft to start and stop without needing to stop the driving shaft, providing an interruptible connection, which will transfer smooth orderly motion (Bird and Ross, 2012, p.203).

There are various clutch types such as Positive Clutches and Friction Clutches, both of which have sub-categories, such as Centrifugal Friction Clutches (Patel, Dalwadi, Thakor and Bamaniya, 2013, p.1235).

### 2.2. Centrifugal Clutches

#### 2.2.1. Centrifugal Clutch Principles

Centrifugal Clutches operate on the laws of centrifugal forces. However, Crane (2003) states centrifugal forces are fictitious, utilised within non-inertial frames of reference.

For example, utilising Newton's Second law:

*“The rate of change of momentum is proportional to the resultant out-of-balance force and takes place in the direction of that force”* (Tooley and Dingle, 2021, p.131).

Therefore, a fixed-point mass in a circular path will create **Centripetal Forces** which can be described mathematically:

$$P = m \cdot v$$

$$\therefore F = \frac{\Delta P}{t} = \frac{mv - mu}{t} = m \frac{v - u}{t}$$

And:

$$a = \frac{v - u}{t}$$

$$\therefore F = m \cdot a$$

Also:

$$a_{centripetal} = \omega^2 \cdot r$$

$$\therefore F_{centripetal} = m \cdot \omega^2 \cdot r$$

Whereby:

$P = \text{Momentum}$

$m = \text{Mass}$

$v = \text{Velocity}$

$\omega = \text{Angular Velocity}$

$a_{centripetal} = \text{Angular Acceleration}$

$u = \text{Initial Velocity}$

$a = \text{Acceleration}$

$F = \text{Force}$

$F_{centripetal} = \text{Centripetal Force}$

$t = \text{Time}$

Thus, utilising Newton's Third Law creates an equal and opposite force known as **Centrifugal Force**, thus achieving dynamic equilibrium with D'Alembert's Principle all shown in figure 1 (Crane, 2003).

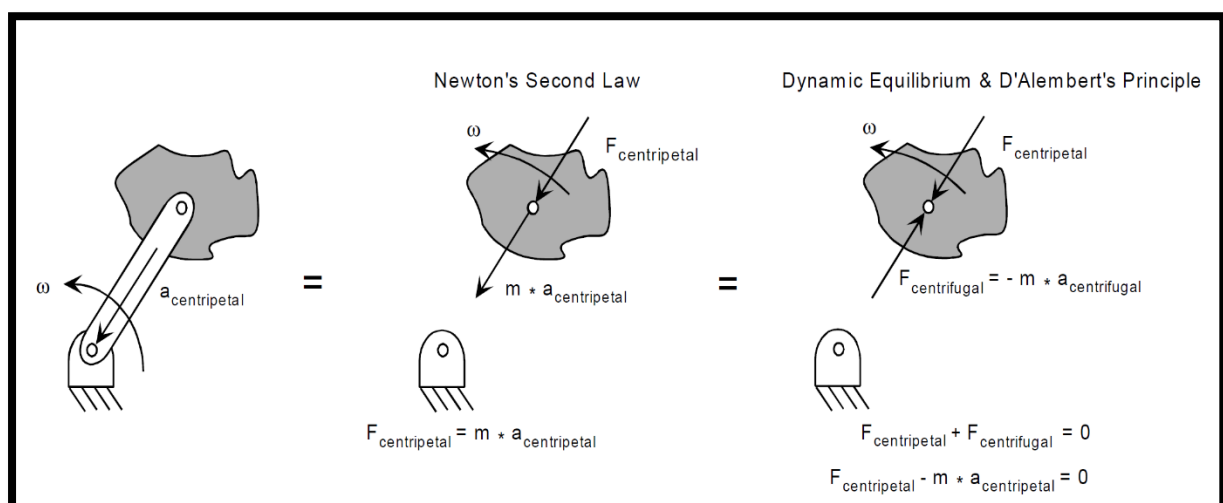


Figure 1 Shows Forces within a rotating fixed mass (Crane, 2003)

Utilising these principles in the centrifugal clutch allows friction forces to develop torque. Figure 2 shows a typical assembly.

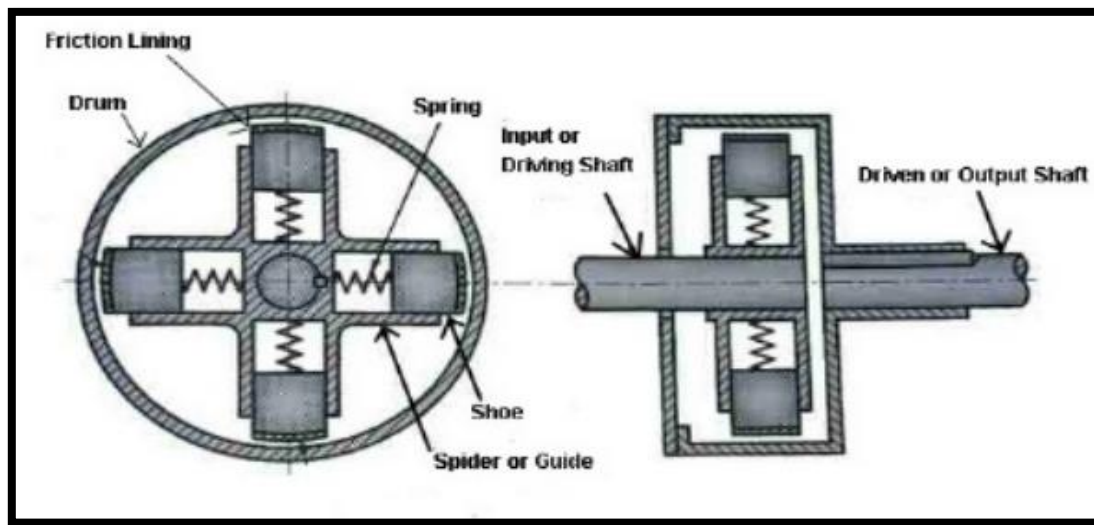


Figure 2 Shows a Centrifugal Clutch Assembly (Centrifugal Clutch - Working, Advantages, Disadvantages and Applications, 2019)

A shoe connected to a spider through a spring has a set spring force determined by shoe to drum clearance and spring stiffness. As angular velocity from the driving shaft increases, centrifugal forces increase until they equal spring force, thus, shoe and drum engagement begin.

Increasing centrifugal forces further, increases normal reaction forces towards the centre of rotation. Torque, thus, rotation at the driven shaft is caused by friction forces from the reaction force and friction coefficient of the friction lining on the shoes (Sehgal, Pratap, Kuhar, 2015, p.22). Figure 3 show the forces which will be described at a later stage.

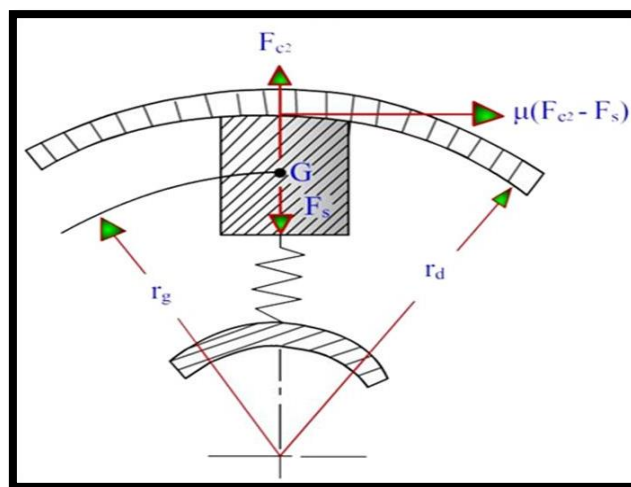


Figure 3 Shows Forces on a Centrifugal Clutch Shoe (Chauhan, 2021)

### 2.2.2. Centrifugal Clutch Development and Operational Conditions

Centrifugal clutches can be tracked to the 19<sup>th</sup> century on railway Locomotives and Automobiles as figure 4 shows in an 1898 patent about an automatically actuated friction clutch utilising a friction shell and a spring connected shoe.

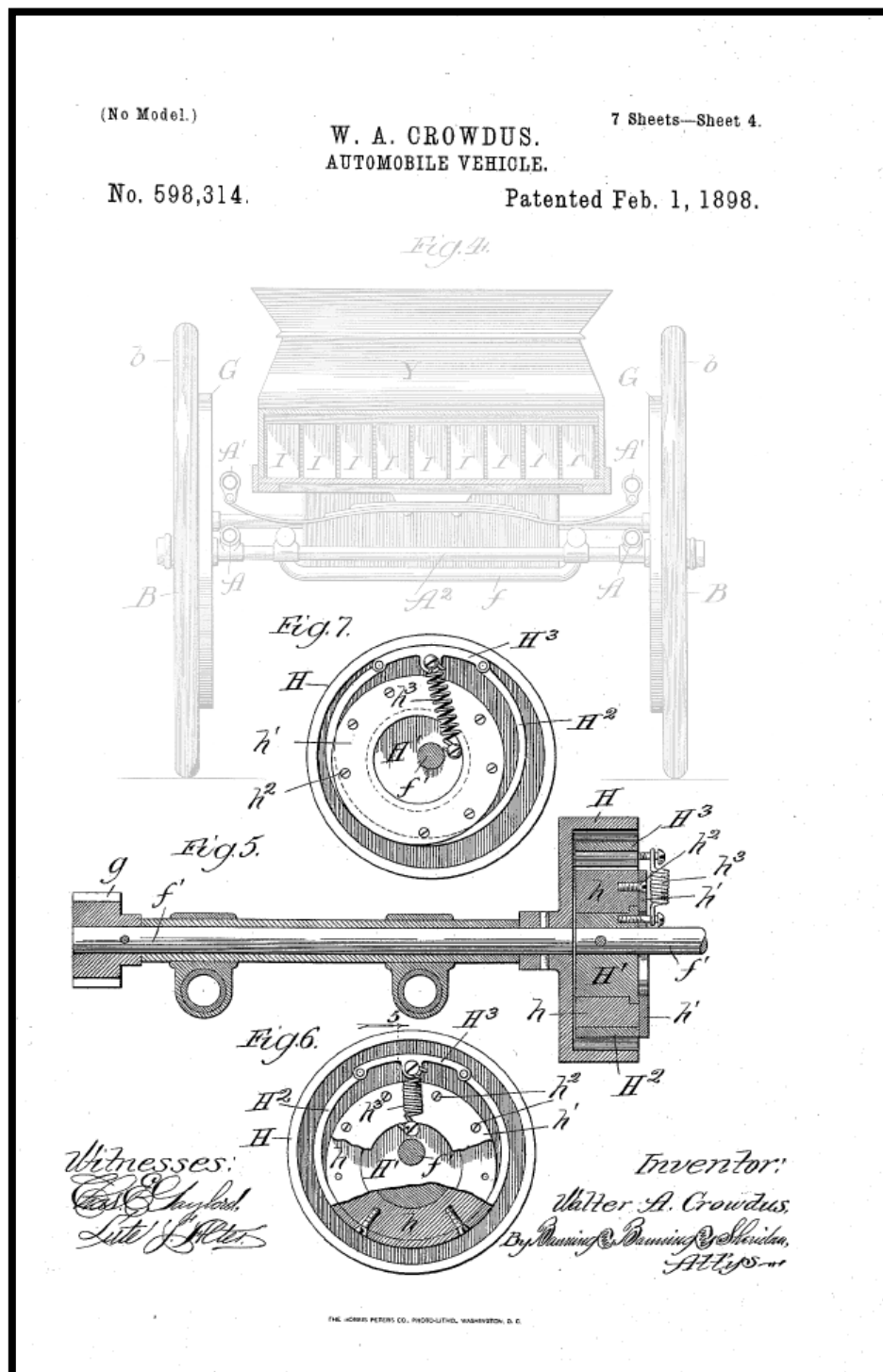


Figure 4 Shows a very early Centrifugal Clutch utilised in Locomotives (Crowdus, 1898)

Early 20<sup>th</sup> Century Toy cars utilised these clutches until Armstrong Siddeley Cars' utilised them in 1936. A Dickson (1927) patent in figure 5 utilised centrifugal forces to throw weighted spheres onto a pressure plate, rotating a driven shaft through frictional torque. This ensured simplicity.

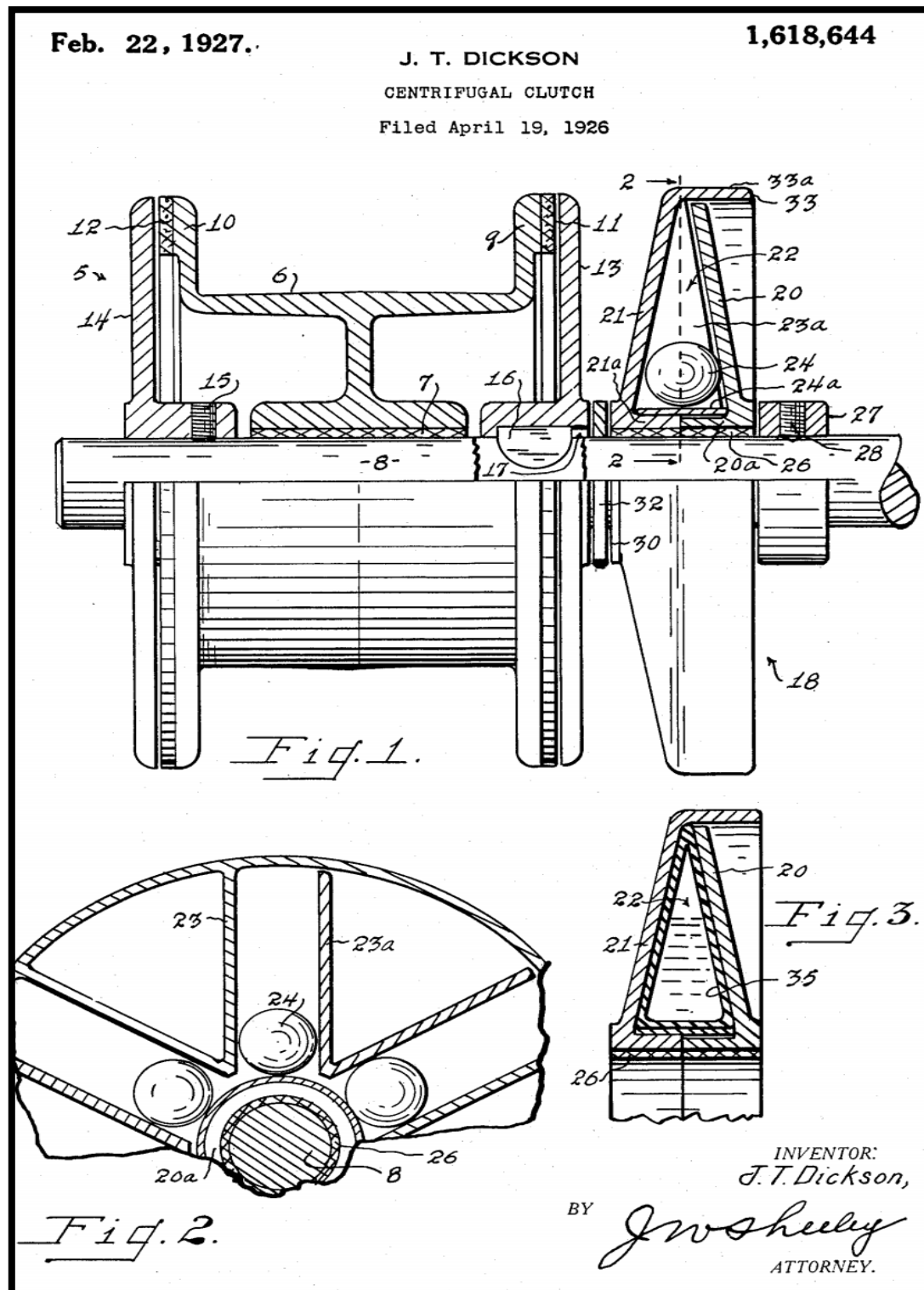


Figure 5 Shows Centrifugal Clutches Utilising weighted spheres (Dickson, 1927)

Developments led to small motor applications by Thomas Fogarty in 1940, pioneering future developments of various types such as the **Flexible Trailing Shoe** type in figure 6 (Crane, 2003).

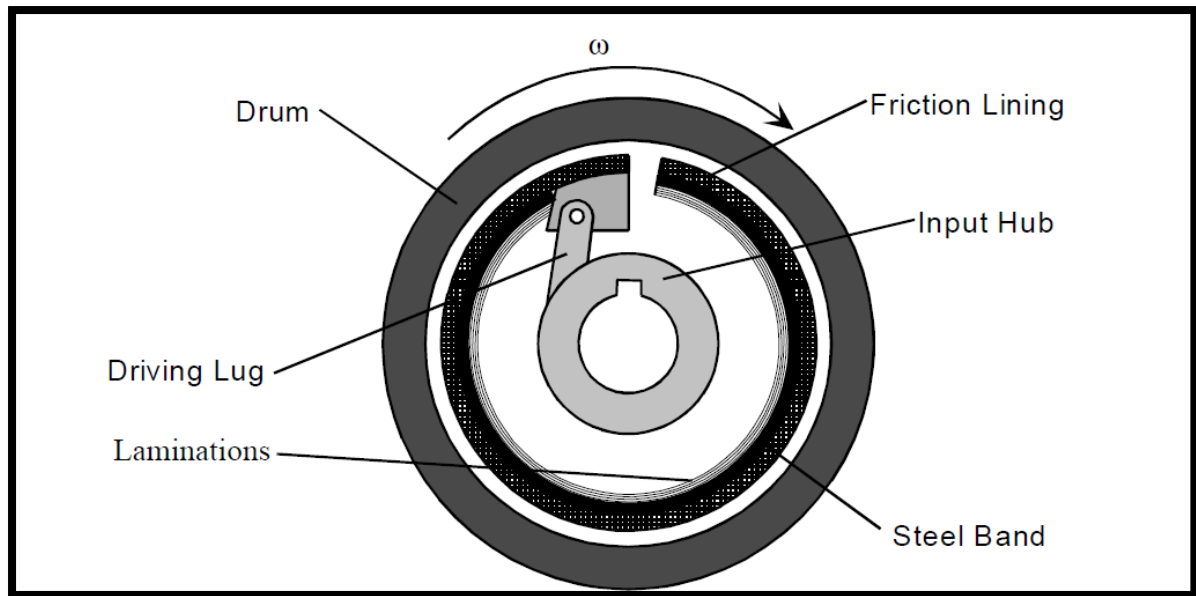


*Figure 6 Shows a Flexible Trailing Shoe Centrifugal Clutch (Crane, 2003)*

Weight (2004) described this development as less sensitive to friction coefficients, with 30% friction changes causing only 5% torque change. A steel band with friction linings, expand with centrifugal forces, contacting the drum.

With high torque capabilities, increased lifespan and up to two-ten thousand horsepower, it can be utilised within machines (Crane, 2003).

**Connected Shoe** clutches in figure 7 have delayed engagement with shoes connected to rotating links with springs. Clockwise rotation ensures smooth engagement but low torque, deemed non-aggressive. Anti-clockwise rotations have high torque which self-energises but has abrupt engagements, deemed aggressive. They are utilised with one-two thousand horsepower applications (Weight, 2004).

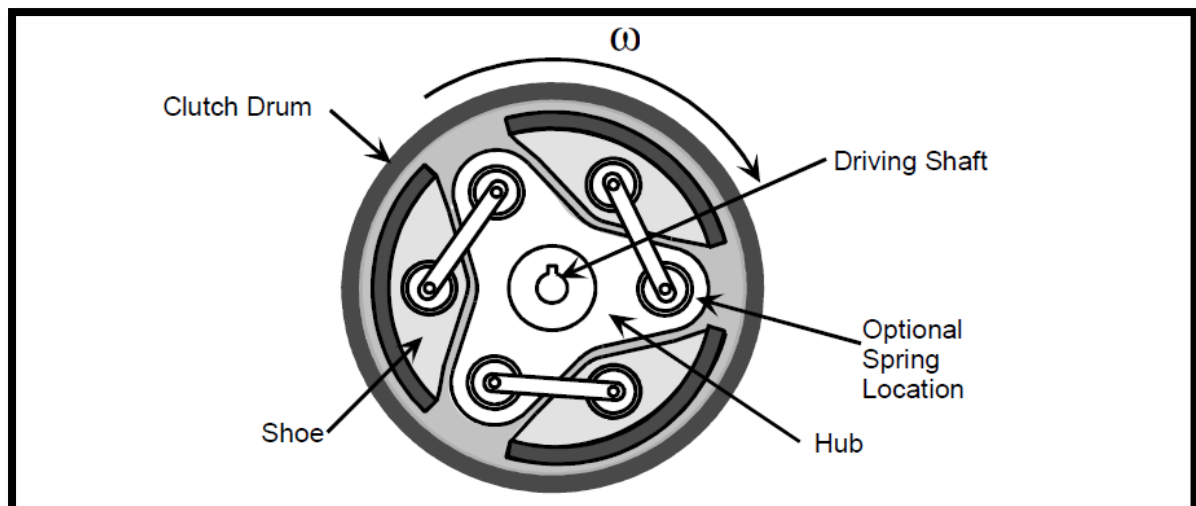


Figure 7 Shows a Connected Shoe Centrifugal Clutch (Crane, 2003)

**Floating Shoe Type** in figure 8 have simplicity whilst maximising frictional contact for given volumes due to shoes sliding on lugs, contacting a drum with spring stiffness determining engagement velocity, operating up to one-four thousand Horsepower (Crane, 2003).

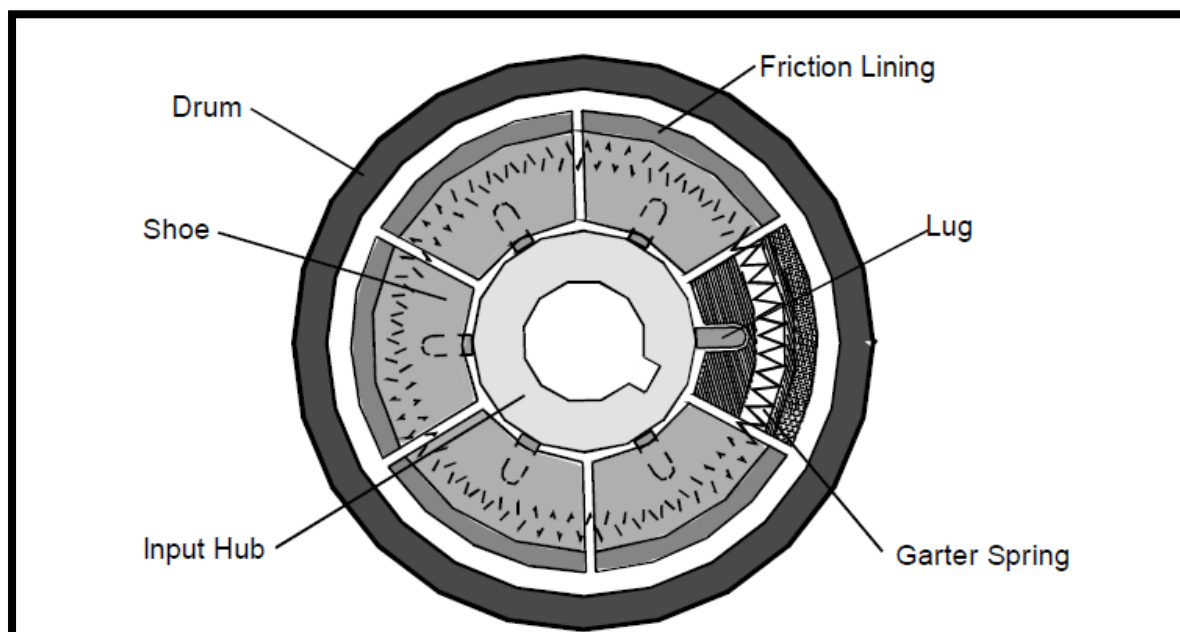


Figure 8 Shows a Floating Shoe Centrifugal Clutch (Weight, 2004)

Recent developments have led to **Tuneable Centrifugal Clutches** in figure 9, which have changeable springs and shoe-end weights. Altering spring stiffness and ball weights alter engagement speeds for various applications (Barron, Averill and Heater, 2010).

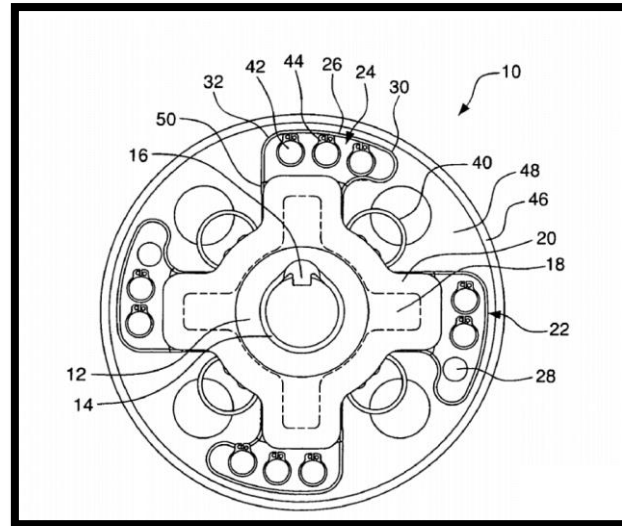


Figure 9 Shows a Tuneable Centrifugal Clutch (Barron, Averill and Heater, 2010)

Developments have led to **Centrifugal Fluid Clutches**. A **Mercury Clutch** in figure 10 allows mercury from the reservoir to flow by centrifugal forces to an orifice that expands on the shoe, engaging the drum. Springs restrain the shoe for slower engagements. This clutch has capacitance, allowing slow torque response to sudden speed changes, further controlled by spring stiffness and orifice size. A slow increase in torque can prevent sudden damage. They operate up to seventy-five Horsepower. Lower temperature operating conditions are required as mercury expands with heat, thus, altering engagement and torque (Crane, 2003).

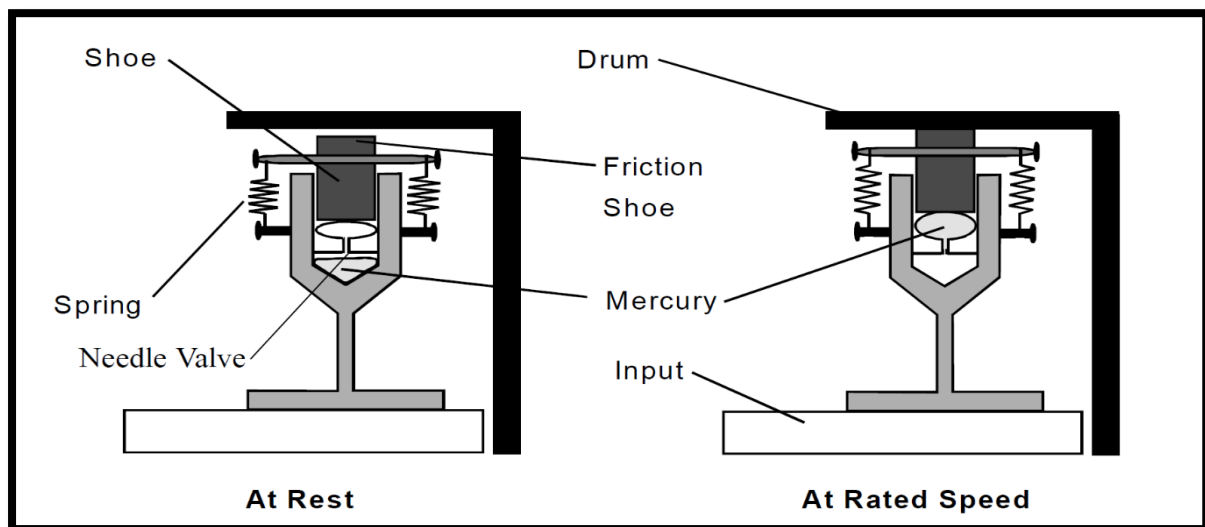


Figure 10 Shows a Centrifugal Mercury Clutch (Crane, 2003)

Zimmermann (1950) patented the Mercury Clutch in figure 11. However, the Environmental Protection Agency prevented utilisation due to health concerns (Mercury clutch mystery, 2009).

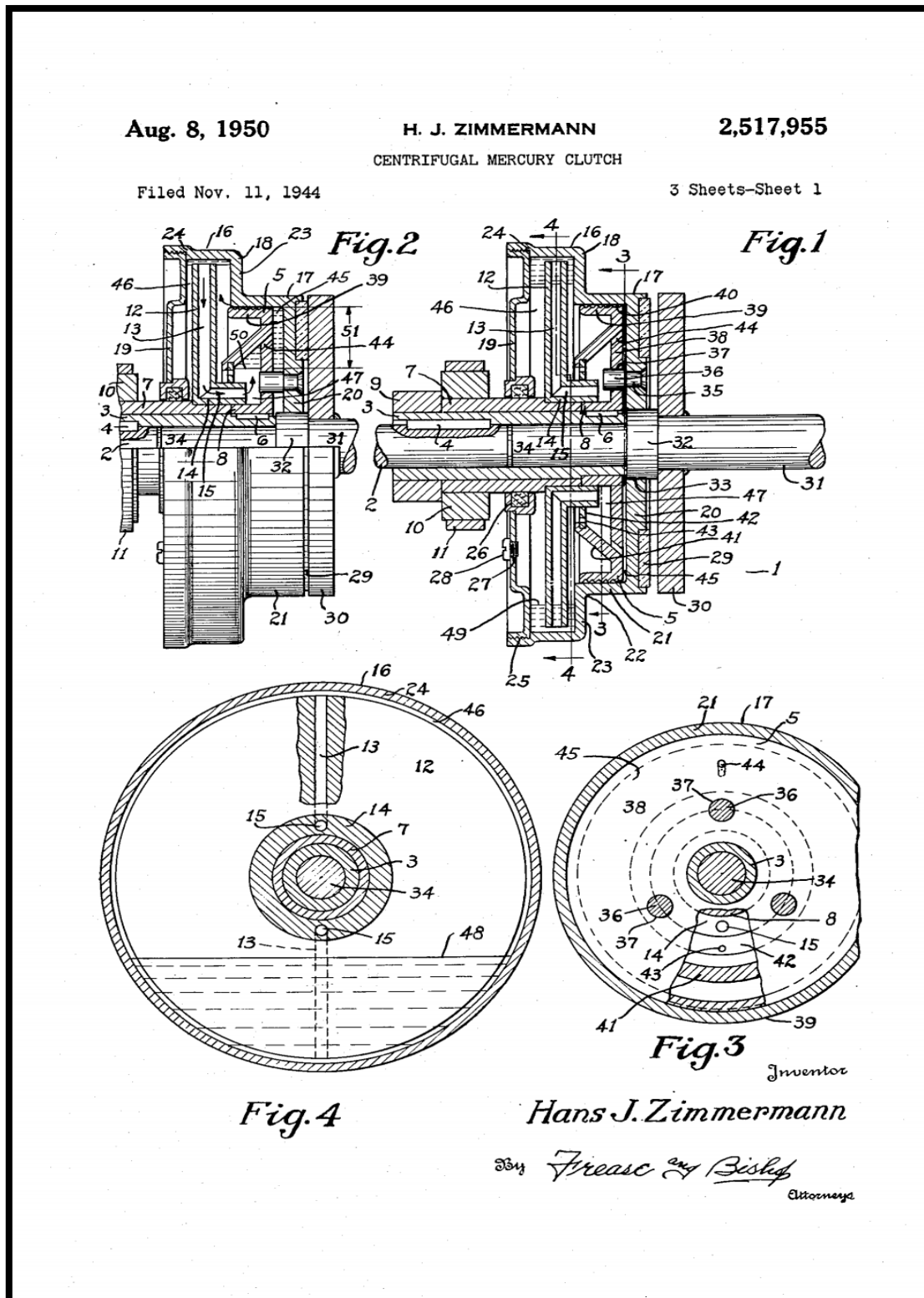


Figure 11 Shows a Centrifugal Mercury Clutch (Zimmermann, 1950)

Recent **Compliant Centrifugal Clutch** developments, which utilise a single part compared to a **Rigid-Body** type, utilising many, both shown in figure 12, utilises centrifugal forces to deflect the part in minimal material areas, causing drum contact. This development reduces clutch maintenance, manufacturing costs, wear, and backlash (Crane, Howell, Weight and Magleby, 2004). Figure 13 shows alternate designs.

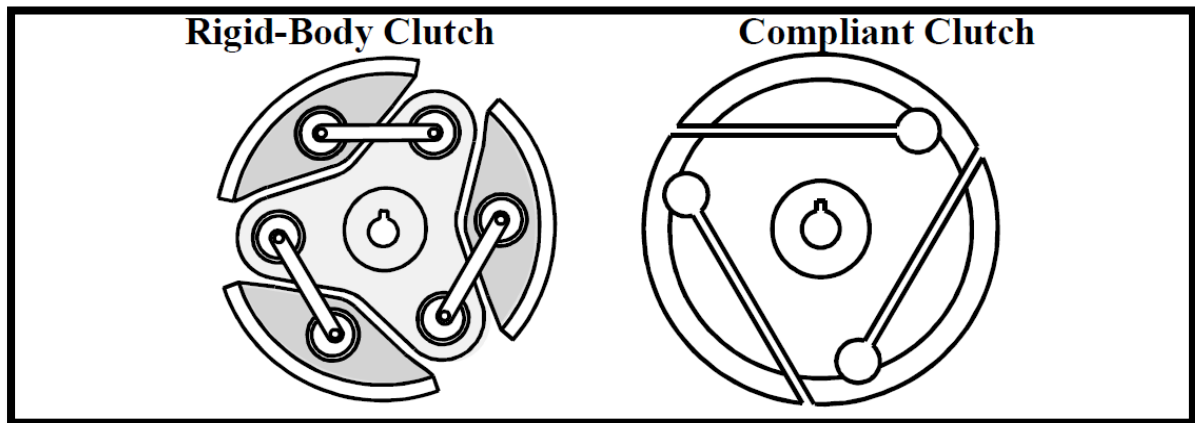


Figure 12 Shows a Rigid-Body and Compliant Clutch Comparison (Crane, 2003)

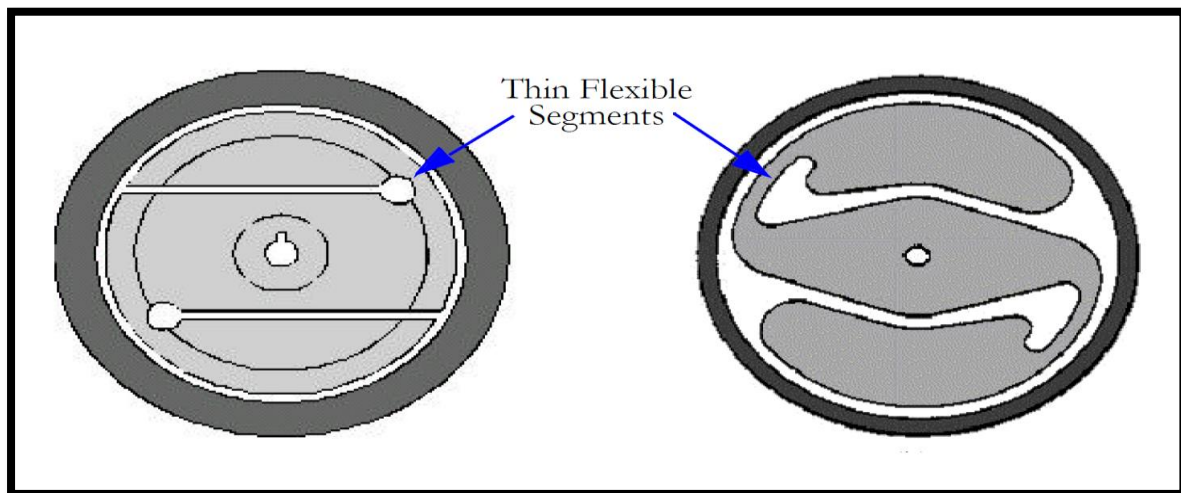


Figure 13 Shows Compliant Clutch Variations (Weight, 2004)

Weight (2004) states a **Floating-Opposing-Arm** clutch in figure 14 develops on compliant clutches with operating characteristics of Connected Shoe clutches, with bi-directional rotation causing aggressive and non-aggressive engagement advantages, which Crane, Howell, Weight and Magley (2004) state applications requiring reservable directions or varied torque at set speeds can utilise this clutch.

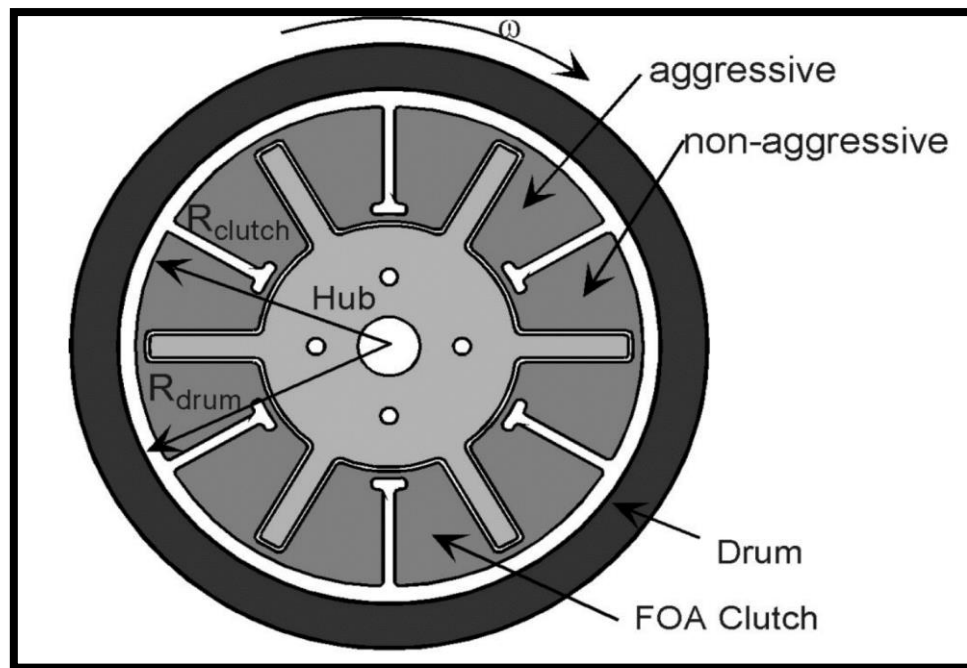


Figure 14 Floating-Opposing-Arm Clutch (Crane, Howell, Weight and Magleby, 2004)

### 2.2.3. Applications and Materials

Centrifugal Clutches have been utilised in many applications from early Locomotives to recent Go-Karts which Randall (1964) supports in a patent in Appendix One. Barron, Averill and Heater (2010) state their tuneable clutch is best suited for karting, due to its adaptability. Hillard shown in figure 15 utilise this clutch for karting providing 40 horsepower.



Figure 15 Shows a Centrifugal Racing Clutch (Hilliard Corporation | Centrifugal Clutches, 2021)

Delayed torque applications utilised in machines to prevent damage would have used mercury clutches (Zimmermann,1950).

Due to their diversity, many applications can utilise Centrifugal Clutches as table 1 shows.

*Table 1 Shows Typical Centrifugal Clutch Applications*

| Centrifugal Clutch Applications                            |                                                                                            |
|------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| Chemical Industry Mixers                                   | Paramotors and Boats                                                                       |
| Compressors & Pumps                                        | Portable Bandsaws                                                                          |
| Concrete Pumps                                             | Power-Tools (Jack Hammers, Compaction Plates and Rammers, Handheld Power Cutters and Saws) |
| Diesel Engines                                             | Rotary Kilns                                                                               |
| Gardening Equipment (Chainsaws, Lawn Mowers and Strimmers) | Sweepers                                                                                   |
| Go-Karts, Scooters and Mopeds                              | Textile Equipment                                                                          |
| Industrial Equipment (Mining and Manufacturing Machines)   | Wood Chippers                                                                              |

Therefore, each application would require varied clutch characteristics such as gardening tools utilising compliant clutches due to their lightweight design and ease of manufacture, with power tools using Floating-Opposing-Arm clutches due to their high clockwise torque and smooth anti-clockwise engagement. Industrial equipment may utilise Flexible Trailing Shoe types due to their reduced maintenance as friction lining wear has a reduced effect on torque.

Material selection is important and depends on the application with Korenjak (2013) and Barron, Averill and Heater (2010), stating material geometry is also important. Most clutch drums, shafts and spiders are **Steel** due to their specific strength and ability to withstand stress and heat. **Aluminium** can be used within power tools due to its strength to density as figure 16 shows (Korenjak, 2013).

However, Aluminium has low fatigue strength as figure 17 shows, thus, should be used in low torque applications (Madhukar†, Harshith Reddy, Kumar and Naik†, 2018). Steel should be utilised for high torque applications for a given volume (Crane, 2003). Tuneable clutches may utilise aluminium for low torque applications, with steel for high torque, as increased density increases forces at given speeds.

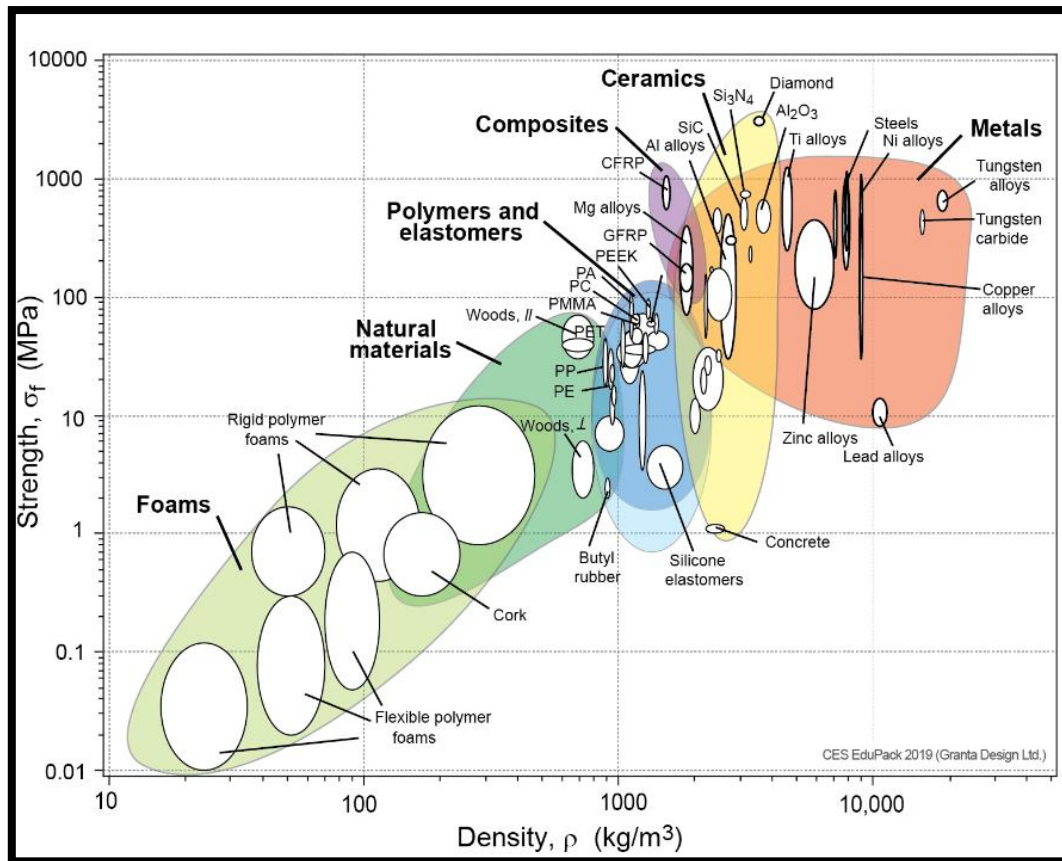


Figure 16 Shows a Strength to Density Merit Function Graph (Strength - Density, 2021)

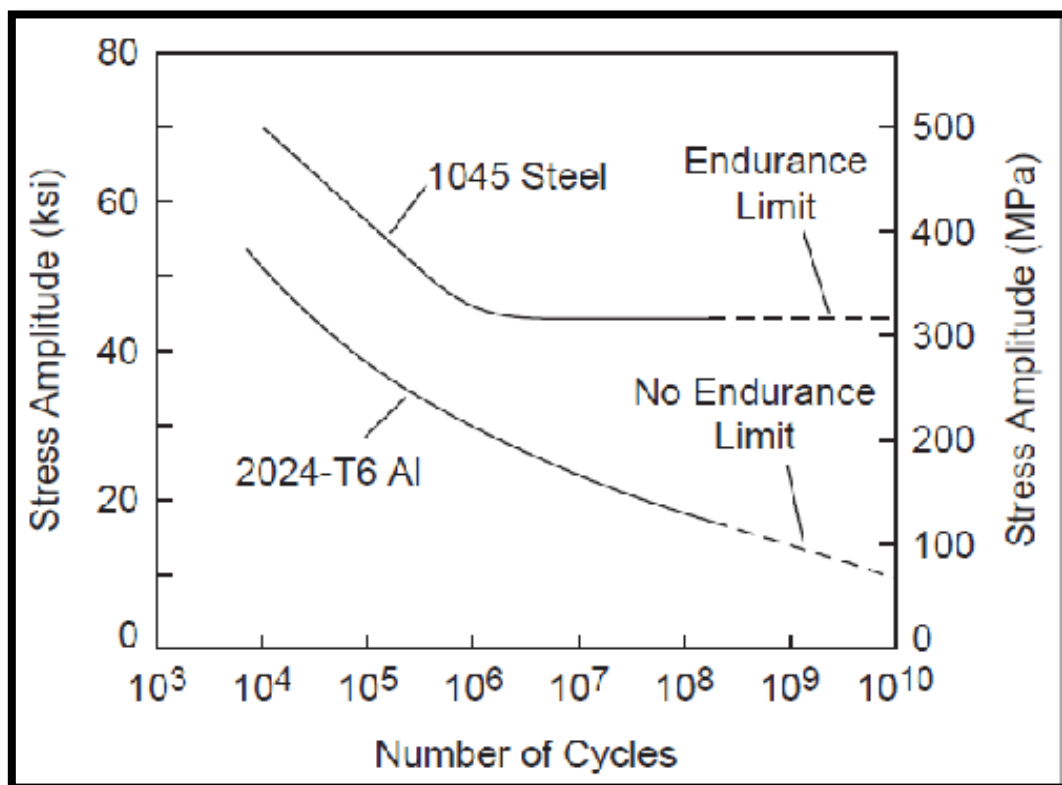


Figure 17 Shows an S-N Curve for Steel and Aluminium (Madhukart, Harshith Reddy, Kumar and Naikf, 2018)

Crane (2003) states Compliant Clutch material Yield Stress to Young's Modulus is more important than strength due to specific deflection requirements, thus, with material density will determine actuation force, thus, torque for a given speed. The merit function graph in figure 18 can help determine suitable materials.

**Steel** is a typical choice due to its high density for a given volume and high fatigue strength, although this can increase stiffness, increasing engagement speeds (Properties of Common Spring Materials for Spring Wire - Quality Spring, Affordable Prices, 2021).

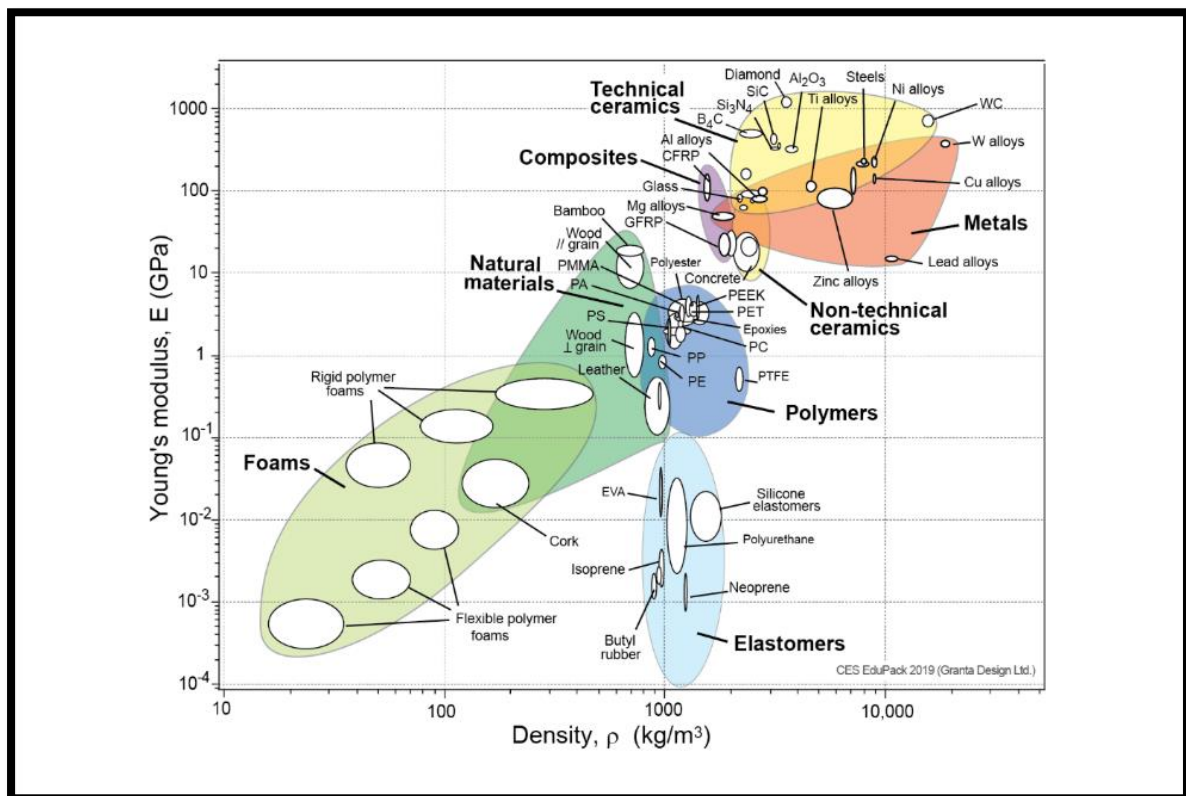


Figure 18 Shows Young's Modulus to Density Merit Function Graph (Young's Modulus - Density, 2021)

Materials that resist strength changes with increased heat are important as this will affect performance (Crane, Howell, Weight and Magley, 2004). Figure 19 shows how developments in alloying have increased desired characteristics. Therefore, as friction clutches generate heat, Nickel Alloys may be a good material choice for the drum, shoes, and spider due to constant strength over increasing temperatures.

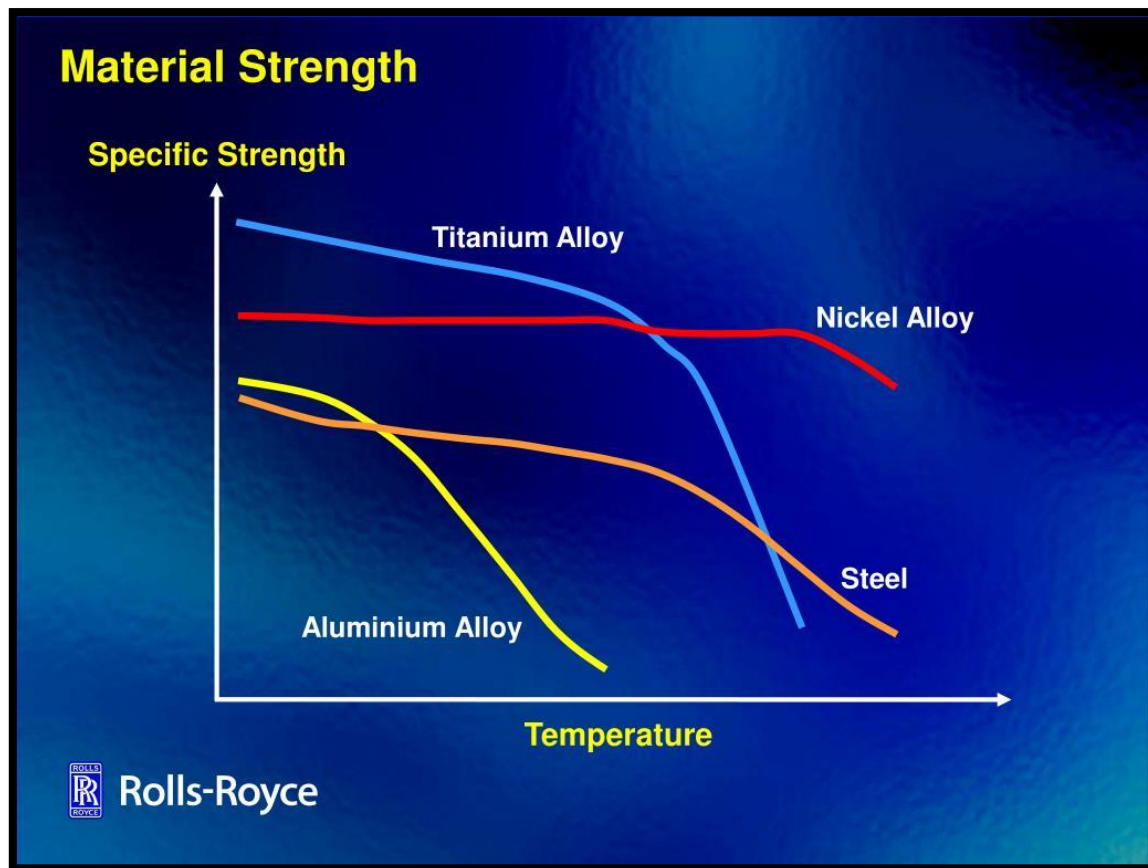


Figure 19 Shows a Specific Strength to Temperature Graph (Cervenka, 2000)

Early Centrifugal Clutches utilised **Felt, Leather, Cork, and Wood** as friction lining materials. Until **Asbestos** was introduced by Herbert Frood, further leading to **Reybestos** and **Ferodo** (Shankardan et al., 2015).

Heat being a by-product of friction means heat resistance in materials is required such as Asbestos being utilised until the mid-1900s due to health concerns, whereby **Ceramic** became an alternative (Friction Materials, 2021).

Semi-metallic materials utilising Copper and Steel Wool bonded with Resin are recent developments due to its' durability. For constant friction contact, Crane, Howell, Weight and Magley (2004) developed a **Polypropylene** clutch, with **Cotton Webbing** lining increasing heat insulation.

Fibre-woven Asbestos with resin and face intertwined copper wire for increased strength is one of the best friction lining materials. Material combinations and manufacturing methods all affect friction coefficients as figures 20, 21 and 22 show, with 21 also showing typical applications. Temperature can affect slippage, thus, must be considered. Friction linings should be sacrificial, preventing clutch damage (Crane, 2003).

| Friction Material<br>Against Steel or CI | Dynamic Coefficient<br>of Friction |           | Maximum Pressure<br>KPa | Maximum<br>Temperature<br>°C |
|------------------------------------------|------------------------------------|-----------|-------------------------|------------------------------|
|                                          | dry                                | in oil    |                         |                              |
| Molded                                   | 0.25-0.45                          | 0.06-0.09 | 1030-2070               | 204-260                      |
| Woven                                    | 0.25-0.45                          | 0.08-0.10 | 345-690                 | 204-260                      |
| Sintered metal                           | 0.15-0.45                          | 0.05-0.08 | 1030-2070               | 232-677                      |
| Cast iron or hard steel                  | 0.15-0.25                          | 0.03-0.06 | 690-720                 | 260                          |

Figure 20 Shows a Materials Properties Table (Govind, 2017)

| Type          | $\mu$ Range | Fade Temp. (°F) | Best Use                                                  |
|---------------|-------------|-----------------|-----------------------------------------------------------|
| Woven Organic | 0.25-0.3    | 600             | Daily Driver                                              |
| HD Organic    | 0.25-0.3    | 700             | Most Street Performance, Towing, and Hauling Applications |
| Kevlar®       | 0.35-0.37   | 500             | Longevity; Off-roading                                    |
| Carbotic      | 0.45-0.48   | 750             | Heavy-Duty Hauling and Towing; Commercial Trucking        |
| Ceramic       | 0.4-0.6     | 1000            | Racing                                                    |
| Feramic       | 0.5-.055    | 1000            | Racing/Agricultural                                       |
| FeramAlloy    | 0.4-0.6     | 1000            | Heavy Duty Hauling and Towing; Commercial Trucking        |

Figure 21 Shows the Type of Material with its' Friction Coefficient Value and Best use (Clutch Friction Materials Explained - Organic, Kevlar, Ceramic, etc., 2021)

| Material Combination                  | Coefficient of Friction |           | Temp.(max) | Pressure (Max) |
|---------------------------------------|-------------------------|-----------|------------|----------------|
|                                       | Wet                     | Dry       | Deg.C      | MPa            |
| Cast Iron/Cast Iron                   | 0,05                    | 0,15-0,20 | 300        | 0,8            |
| Cast Iron/Steel                       | 0,06                    | 0,15-0,20 | 300        | 0,8-1,3        |
| Hard Steel/Hard Steel                 | 0,05                    | 0,15-0,20 | 300        | 0,7            |
| Wood/Cast Iron-steel                  | 0,16                    | 0,2-0,35  | 150        | 0,6            |
| Leather/Cast Iron-steel               | 0,12-0,15               | 0,3-0,5   | 100        | 0,25           |
| Cork/Cast Iron- Steel                 | 0,15-0,25               | 0,3-0,5   | 100        | 0,1            |
| Felt/Cast Iron- Steel                 | 0,18                    | 0,22      | 140        | 0,06           |
| Woven Asbestos/Cast Iron- Steel       | 0,1-0,2                 | 0,3-0,6   | 250        | 0,7            |
| Moulded Asbestos/Cast Iron- Steel     | 0,08-0,12               | 0,2-0,5   | 250        | 1,0            |
| Impregnated Asbestos/Cast Iron- Steel | 0,12                    | 0,32      | 350        | 1,0            |
| Carbon-graphite/Cast Iron- Steel      | 0,05-0,1                | 0,25      | 500        | 2,1            |
| Kelvar/Cast Iron- Steel               | 0,05-0,1                | 0,35      | 325        | 3,0            |

Figure 22 Shows Clutch Material Combinations (Clutch Tech and Torque Calculator, 2021)

### 2.2.4. Advantages and Disadvantages

Centrifugal Clutches have many advantages as shown by table 1. Table 2 also shows their disadvantages with figure 23 showing possible alternatives.

*Table 2 Shows Centrifugal Clutch Advantages*

| Advantages                                  | Description                                                                                                                                                                                            |
|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Simplicity</b>                           | No external signal or power for control or actuation. Compliant clutches require few components (Crane, 2003).                                                                                         |
| <b>Low Cost</b>                             | Simplicity and few components lead to lower manufacturing costs (Crane, 2003).                                                                                                                         |
| <b>Automatic</b>                            | Engagement and Disengagement are automatic due to the laws of physics (Baksi, 2021).                                                                                                                   |
| <b>Low Maintenance</b>                      | Due to simplicity, the design requires little maintenance, and the wearing of the system is mainly limited to friction pads (Baksi, 2021).                                                             |
| <b>Prevents Overload on Machines</b>        | Gradual smooth engagements mean limited damage to machines occur (Advantages and Disadvantages of Centrifugal Clutches - BLM Automatic Clutch, 2019).                                                  |
| <b>Greater Engagement and Speed Control</b> | Progressive engagements to increase torque ensures lifespan is extended with increased energy storage on start-up (Advantages and Disadvantages of Centrifugal Clutches - BLM Automatic Clutch, 2019). |

*Table 3 Shows Centrifugal Clutch Disadvantages*

| <b>Disadvantages</b>                                                       | <b>Description</b>                                                                                                                                                                                                                                                                      |
|----------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Loss of Power</b>                                                       | This can occur due to slippage of the clutch as well as friction. However, different materials can be utilised to alter this (Advantages and Disadvantages of Centrifugal Clutches - BLM Automatic Clutch, 2019).                                                                       |
| <b>Overheating</b>                                                         | This occurs due to the slippage and friction causing a by-product of heat which can further damage the clutch (Baksi, 2021).                                                                                                                                                            |
| <b>Lower Torque Applications</b>                                           | Higher torque can cause slippage at heavy load conditions. Although different designs can be utilised for higher torque applications as previously mentioned (Baksi, 2021).                                                                                                             |
| <b>Clutch Size Varies Speed Requirements Greatly (Lack of Versatility)</b> | Smaller clutches for example require very high acceleration and velocity due to centrifugal force requirements. Although Tuneable clutches can be utilised to accommodate for this (Advantages and Disadvantages of Centrifugal Clutches - BLM Automatic Clutch, 2019).                 |
| <b>Speed Requirement limitations</b>                                       | These clutches are bound by higher-speed applications due to centrifugal forces. However, alterations to the clutch as previously mentioned can be made for lower speed applications, however, these clutches will always be bound by the laws of physics, thus, limited (Crane, 2003). |

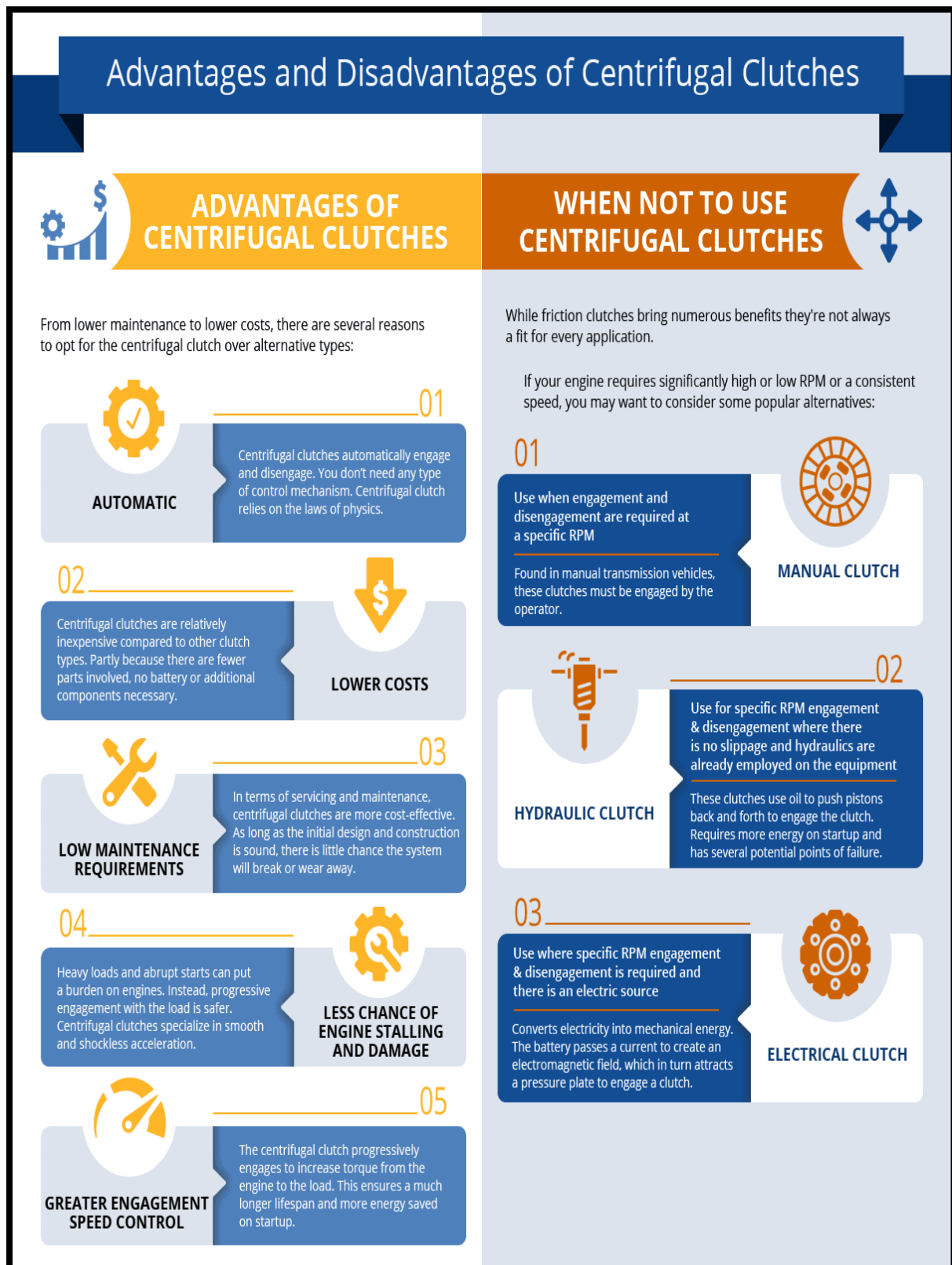


Figure 23 Shows When to Utilise Centrifugal Clutches and When to Utilise Alternatives (Advantages and Disadvantages of Centrifugal Clutches - BLM Automatic Clutch, 2019)

### 2.3. Electromagnetic Clutches

Centrifugal Clutches benefited from automated actuation at set RPM, however, developments have led to faster more precise actuation with Electromagnetic clutches shown in figures 24 and 25 which produces mechanical torque through electrical actuation (Shankardan et al., 2015).

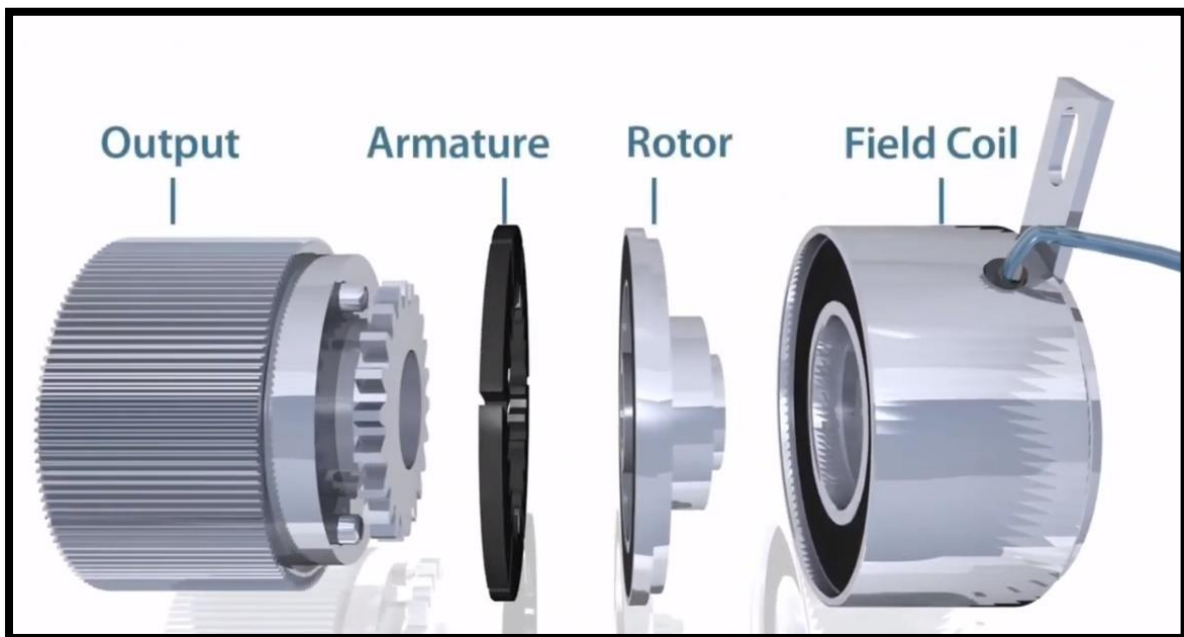


Figure 24 Shows an Electromagnetic Clutch Expanded Assembly (Electromagnetic-clutches, 2019)

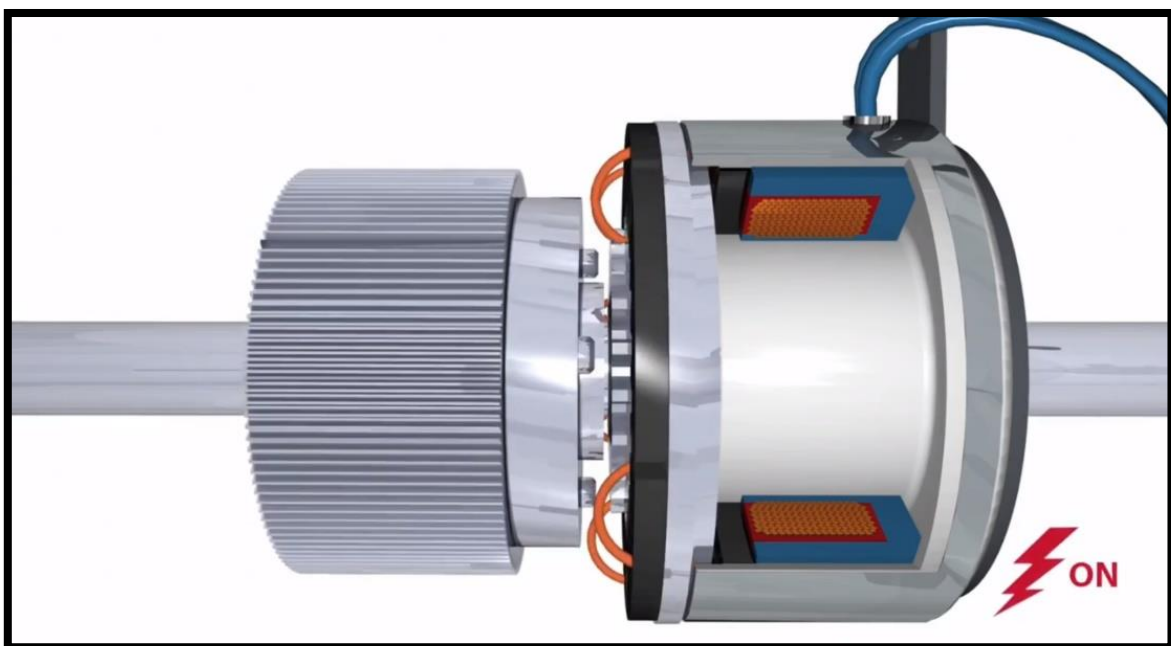


Figure 25 Shows an Electromagnetic Clutch Attached to the Shaft (Electromagnetic-clutches, 2019)

As figure 26 shows, an Armature attached to an output is held from a rotor by springs. The rotor attached to a driving shaft that rotates is placed within a field coil made from steel and copper. Current passes through the coil making the rotor an electromagnet which attracts the armature, overcoming spring tension, which then rotates with the rotor due to friction materials, or teeth for increased torque, therefore, rotating the output with 100% efficiency and zero slippage (What Are Electromagnetic Clutches and Electromagnetic Brakes, 2021).

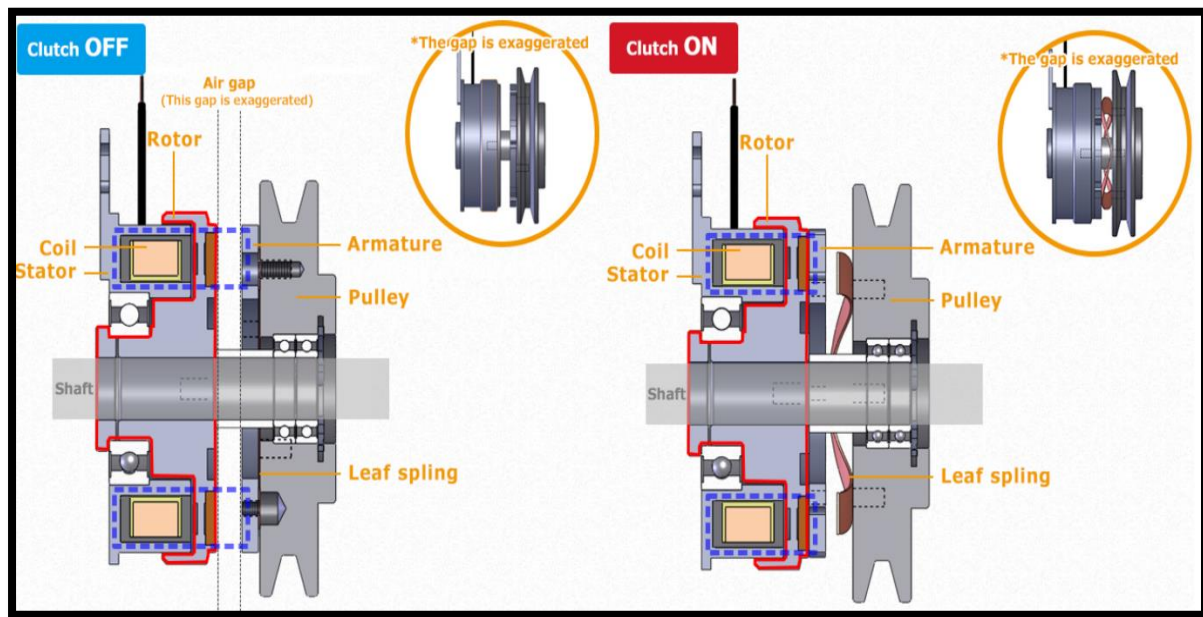


Figure 26 Shows an Electromagnetic Clutch in Operation (What Are Electromagnetic Clutches and Electromagnetic Brakes, 2021)

With set RPM and precise actuation, many applications can utilise these clutches, such as **Conveyor Systems** within automation. This is due to the utilisation of one driving shaft with multiple clutches operating conveyors individually as figure 27 shows. This allows for the driving shaft to have a set RPM and the conveyors operating instantaneously when required, allowing for manufacturing efficiency (Electromagnetic Actuated Clutches, 2021).

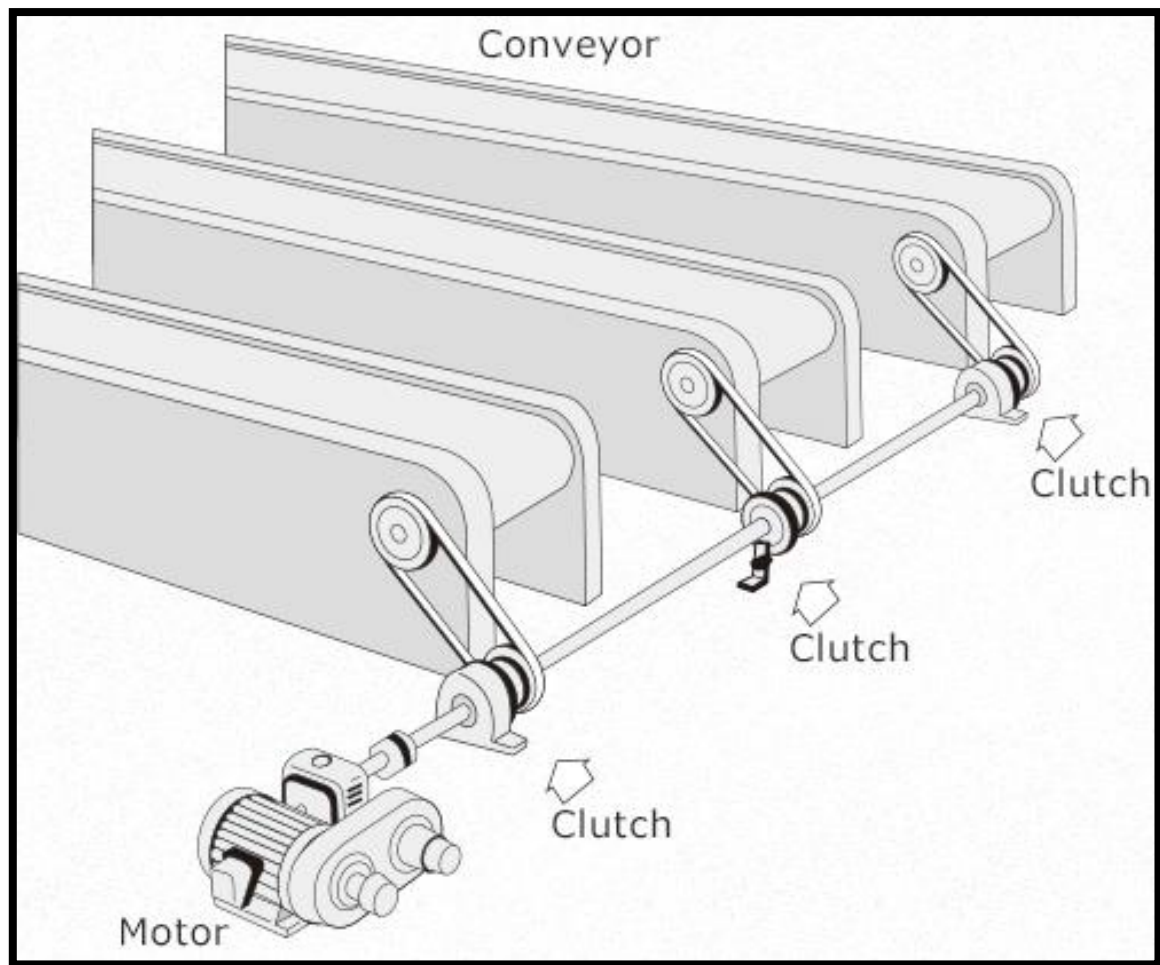


*Figure 27 Shows Conveyors Utilising Electromagnetic Clutches (What Are Electromagnetic Clutches and Electromagnetic Brakes, 2021)*

**Robotic Axis'** shown in figure 28 utilise these clutches due to their precise and fast actuation which robotics require for pick and place applications.

**Collaborative Robotics** benefit from instant actuation and disengagement whereby human contact causing increased force, disengages the clutch, thus, complying with safety regulations. This can be combined with Electromagnetic breaks which instantaneously stop the axis in position (Electromagnetic Clutches and Brakes for the Robotics Industry, 2021).

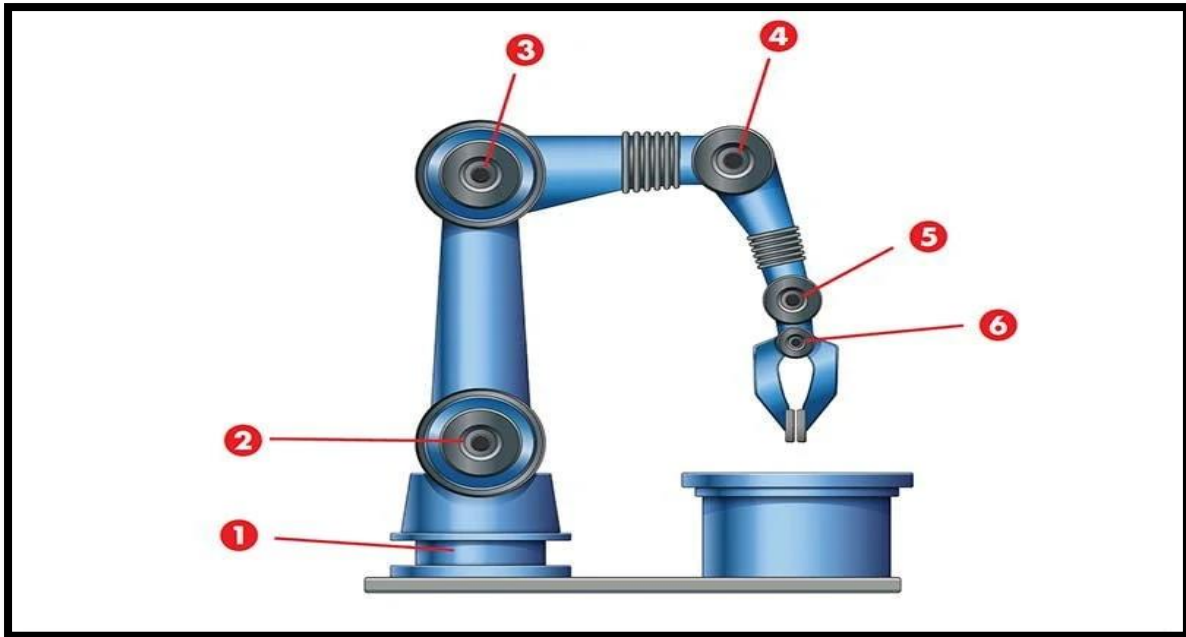


*Figure 28 Shows Electromagnetic Clutches and Brakes within Robotics (Electromagnetic Clutches and Brakes for the Robotics Industry, 2021)*

**Gantry Systems** as figure 29 shows, utilise **Servomotors**, which use these clutches for similar reasons to robotics. Gantry systems can be utilised within general automation processes requiring rotary or linear motion, such as packing, pick and placements, or food processing machines (Electromagnetic clutches, 2021).

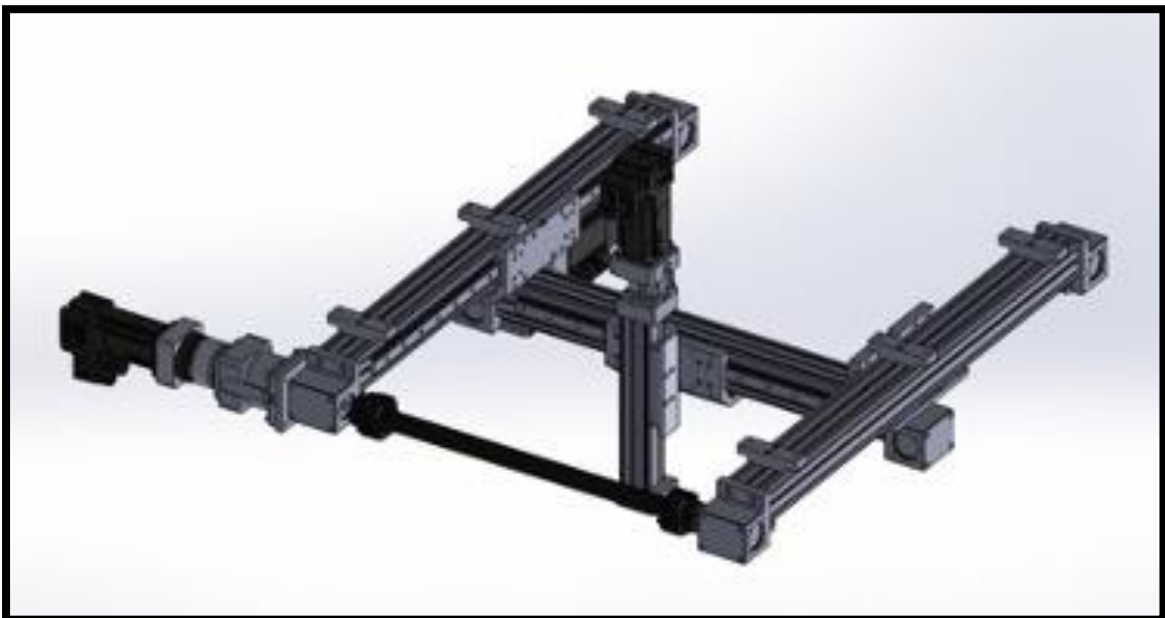


*Figure 29 - Shows a Gantry System which utilises Servo-Motors (Zaske, 2021)*

Electromagnetic clutches have diverse applications within manufacturing automation, ensuring high efficiency, precision, and safety. However, high operating temperatures affect an electromagnet, thus, input speeds must be monitored as high-speed engagements cause clutch failures through increased heat.

### 3.0. Centrifugal Clutch - Mathematical Analysis

This section will analyse a given centrifugal clutch, calculating different variables with given boundaries. Some boundaries have to be assumed and are noted throughout.

#### 3.1. Outer Drum Diameter

To calculate the outer drum diameter, one can utilise the given dimensions as follows:

$$r_d = r_0 + x$$

$$r_d = 95 + 9$$

$$r_d = \mathbf{104mm}$$

$$\therefore r_{ed} = (r_d + \text{Wall Thickness})$$

$$r_{ed} = 104 + 4$$

$$r_{ed} = 108mm$$

$$\therefore d_{ed} = 108 \cdot 2$$

$$d_{ed} = \mathbf{216mm}$$

Whereby:

$r_0 = \text{Centre of Mass Radius at Rest}$

$r_d = \text{Drum Radius}$

$x = \text{Clearance Distance}$

$r_{ed} = \text{External Drum Radius}$

$d_{ed} = \text{External Drum Diameter}$

**Note:** It is assumed that the resting centre of mass  $r_0$  is at the end of the friction pad. Therefore, the centre of mass of engagement  $r_g$  which will be used throughout this report will be as follows:

$$r_g = r_0 + x$$

Due to this, it can be seen that  $r_g$  and  $r_d$  have the same dimensions.

### 3.2. Engagement Speed

To calculate engagement speed, one can utilise centrifugal forces and spring forces as follows:

$$F_{c_1} = m \cdot r_g \cdot \omega_1^2$$

$$F_{c_1} = F_s$$

$$F_s = k \cdot x$$

$$\therefore F_{c_1} = m \cdot r_g \cdot \omega_1^2 = k \cdot x$$

Whereby:

$F_s = \text{Spring Force}$

$F_{c_1} = \text{Engagement Centrifugal Force}$

$r_g = \text{Centre of Mass Radius at Drum Engagement}$

$m = \text{Mass}$

$\omega_1 = \text{Engagement Angular Velocity}$

$k = \text{Spring Stiffness}$

$$F_{c_1} = F_s$$

$$\therefore F_s = 7.5 \cdot 10^3 \cdot 9 \cdot 10^{-3}$$

$$F_s = 67.5 \text{ N}$$

$$\therefore F_{c_1} = 67.5 \text{ N}$$

$$\therefore \omega_1 = \sqrt{\frac{F_{c_1}}{m \cdot r_g}}$$

$$\therefore \omega_1 = \sqrt{\frac{67.5}{275 \cdot 10^{-3} \cdot 104 \cdot 10^{-3}}}$$

$$\omega_1 = 48.58 \text{ Rad/s (Two Decimal Places)}$$

$$\therefore \omega_1 = \frac{48.58 \cdot 60}{2\pi}$$

$$\omega_1 = 464 \text{ RPM (Nearest Whole Value)}$$

### 3.3. Radial Force

Radial Force is the net force acting on the drum. Firstly, one must turn RPM into Rad/s:

$$550 \cdot \frac{60}{2\pi} = \frac{55}{3} \pi$$

$$\omega_2 = \frac{55}{3} \pi \text{ Rad/s}$$

Now one can calculate the Net Force of each shoe acting on the drum:

$$F_{net} = F_{c_2} - F_{c_1}$$

$$F_{c_1} = F_s = 67.5 \text{ N}$$

$$F_{c_2} = m \cdot r_g \cdot \omega_2^2$$

$$\therefore F_{net} = m \cdot r_g (\omega_2^2 - \omega_1^2)$$

Accounting for the number of shoes:

$$F_{net} = m \cdot r_g (\omega_2^2 - \omega_1^2) z$$

$$F_{net} = 275 \cdot 10^{-3} \cdot 104 \cdot 10^{-3} \left( \left( \frac{55}{3} \pi \right)^2 - 48.58^2 \right) \cdot 4$$

$$F_{net} = 109.51 \text{ N (Two Decimal Places)}$$

Whereby:

$$F_{c_2} = \text{Final Centrifugal Force}$$

$$\omega_2 = \text{Final Angular Velocity}$$

$$z = \text{Number of Shoes}$$

### 3.4. Transmitted Torque

To calculate the torque one can utilise the formula:

$$M_t = \mu \cdot r_d (F_{c_2} - F_s) z$$

Whereby:

$$M_t = \text{Friction Torque}$$

$$\mu = \text{Coefficient of Friction for Each Friction Pad}$$

Derived from:

$$T = F \cdot l$$

Whereby:

$$T = \text{Torque}$$

$$F = \text{Force}$$

$$l = \text{length}$$

$$\therefore M_t = F_f \cdot r_d$$

And:

$$F_f = \mu \cdot R_n$$

Whereby:

$$R_n = \text{Normal Reaction Force}$$

$$F_f = \text{Friction Force}$$

Normal Reaction Forces are the equal but opposite of the net force, acting towards the centre of rotation, therefore:

$$R_n = F_{c2} - F_s$$

However, one can calculate torque incorporating all the steps with one equation:

$$M_t = \mu \cdot m \cdot r_g \cdot r_d \cdot z (\omega_2^2 - \omega_1^2)$$

$$\therefore M_t = 0.35 \cdot 275 \cdot 10^{-3} \cdot 104 \cdot 10^{-3} \cdot 104 \cdot 10^{-3} \cdot 4 \left( \left( \frac{55}{3} \pi \right)^2 - 48.55^2 \right)$$

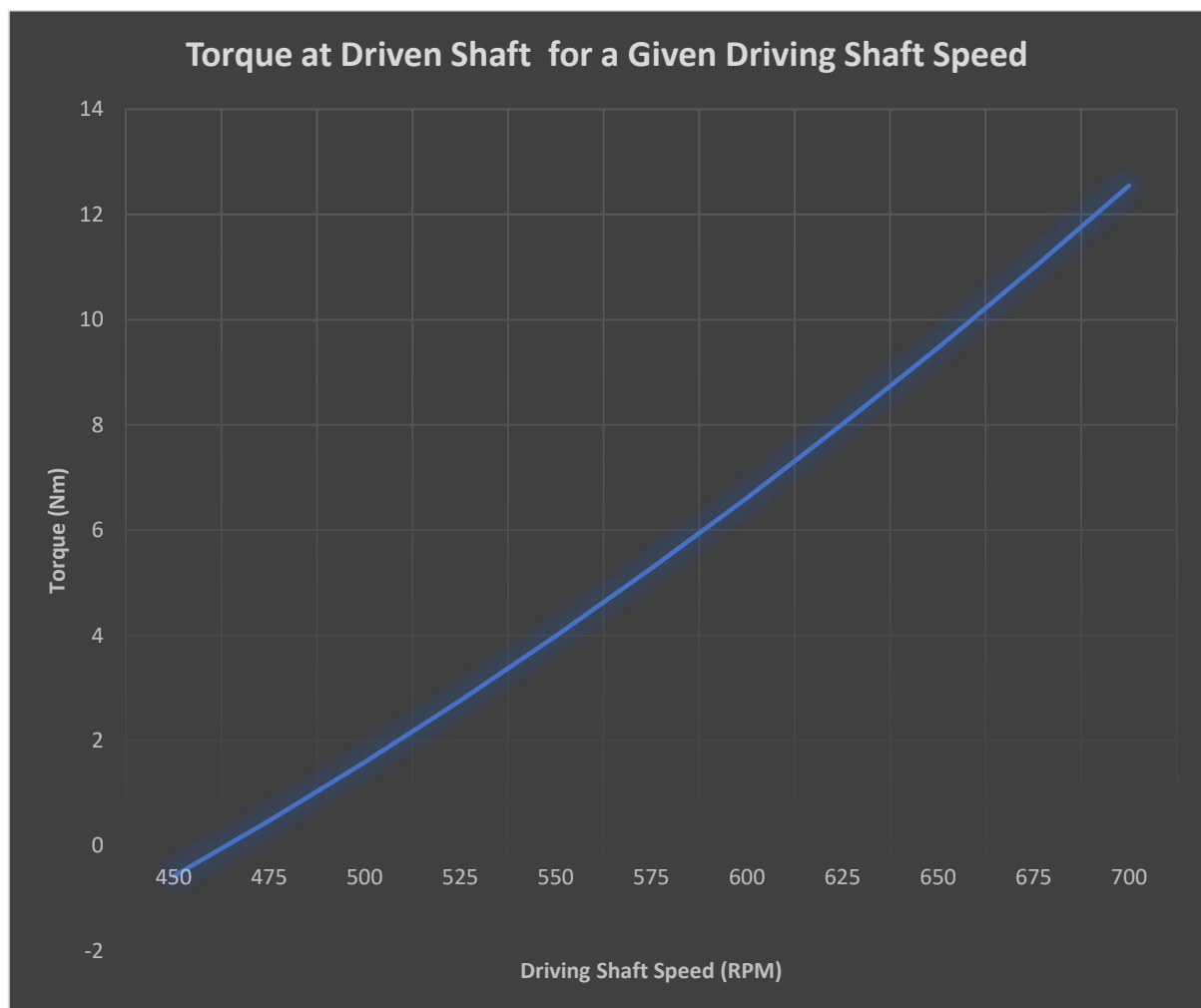
$$\mathbf{M_t = 3.99 Nm (Two Decimal Places)}$$

### 3.5. Transmitted Torque Graph

Utilising the previous equation:

$$M_t = \mu \cdot m \cdot r_g \cdot r_d \cdot z (\omega_2^2 - \omega_1^2)$$

A graph has been generated from this equation whereby the table can be found in Appendix Two. This graph supports the previous calculations. At 464 RPM, torque is almost zero due to engagement speed, but at 550 RPM torque is 3.99 Nm. Before 464 RPM, it shows a negative torque, this just indicates a zero torque, not a negative torque.



*Graph 1 Shows Driven Shaft Torque Against Driving Shaft Speed*

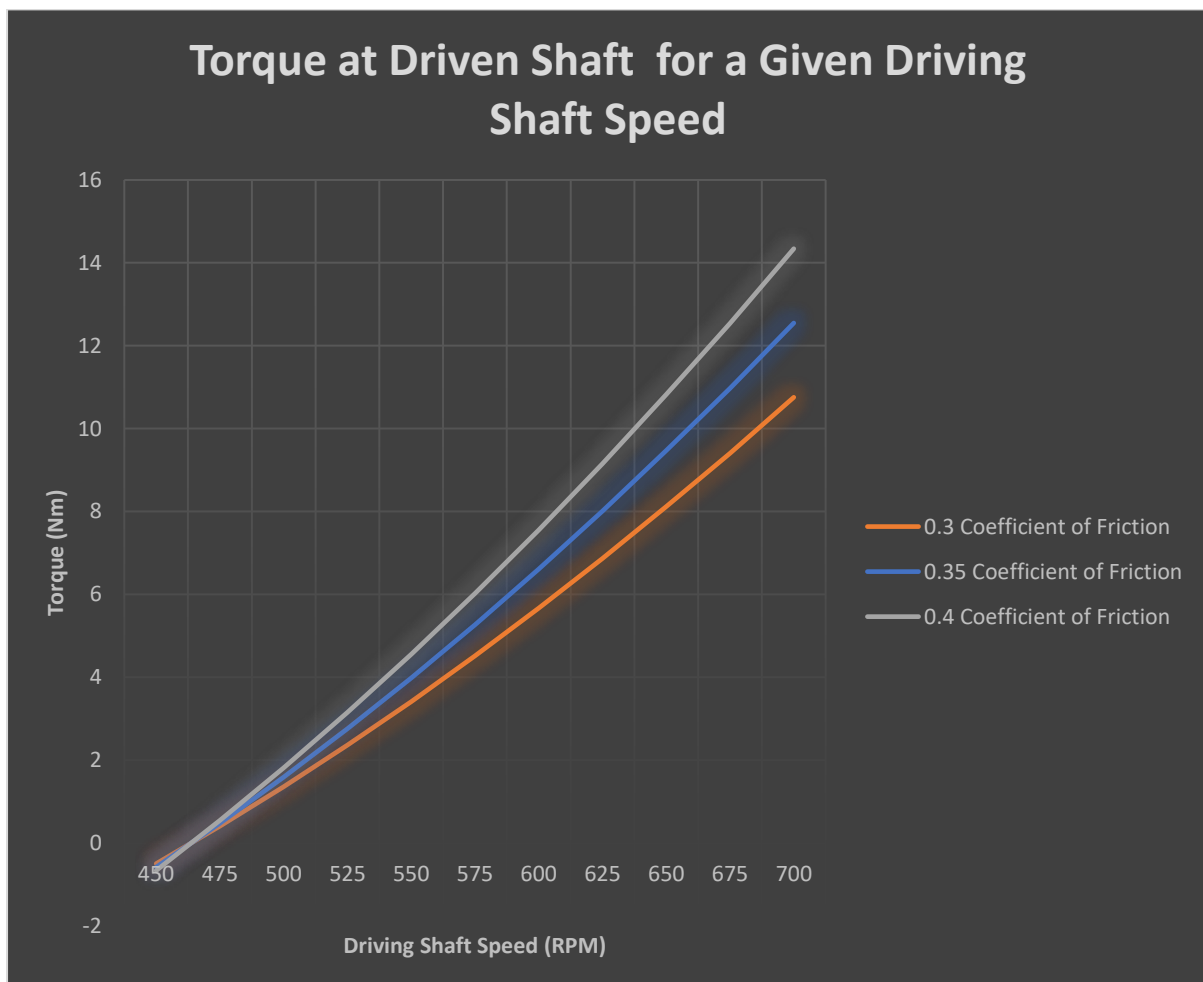
### 3.6. Transmitted Torque Graph with Varied Friction

Graph 2, generated from tables in Appendix Two, shows a friction coefficient increase, increases torque for a given speed. This is due to:

$$F_f = \mu \cdot R_n$$

As friction force and length determine torque, increasing friction force by increasing normal reaction forces or **Friction Coefficients** will, therefore, increase torque. This further explains why at 464 RPM, regardless of the friction coefficient, torque is zero, which is due to normal reaction forces equalling zero.

As friction force increases with increased angular velocities, mechanical efficiency, that being the efficiency of friction, is increased, meaning friction forces are high enough to prevent slippage. However, it must be noted these calculations assume friction efficiency is 100% even at low RPM, hence why torque is almost linearly proportional to speed, but in reality, at low RPM some slippage between the shoes and drum may occur, affecting torque as figure 30 shows.



Graph 2 Shows Torque at Various Speeds with Various Friction Coefficients

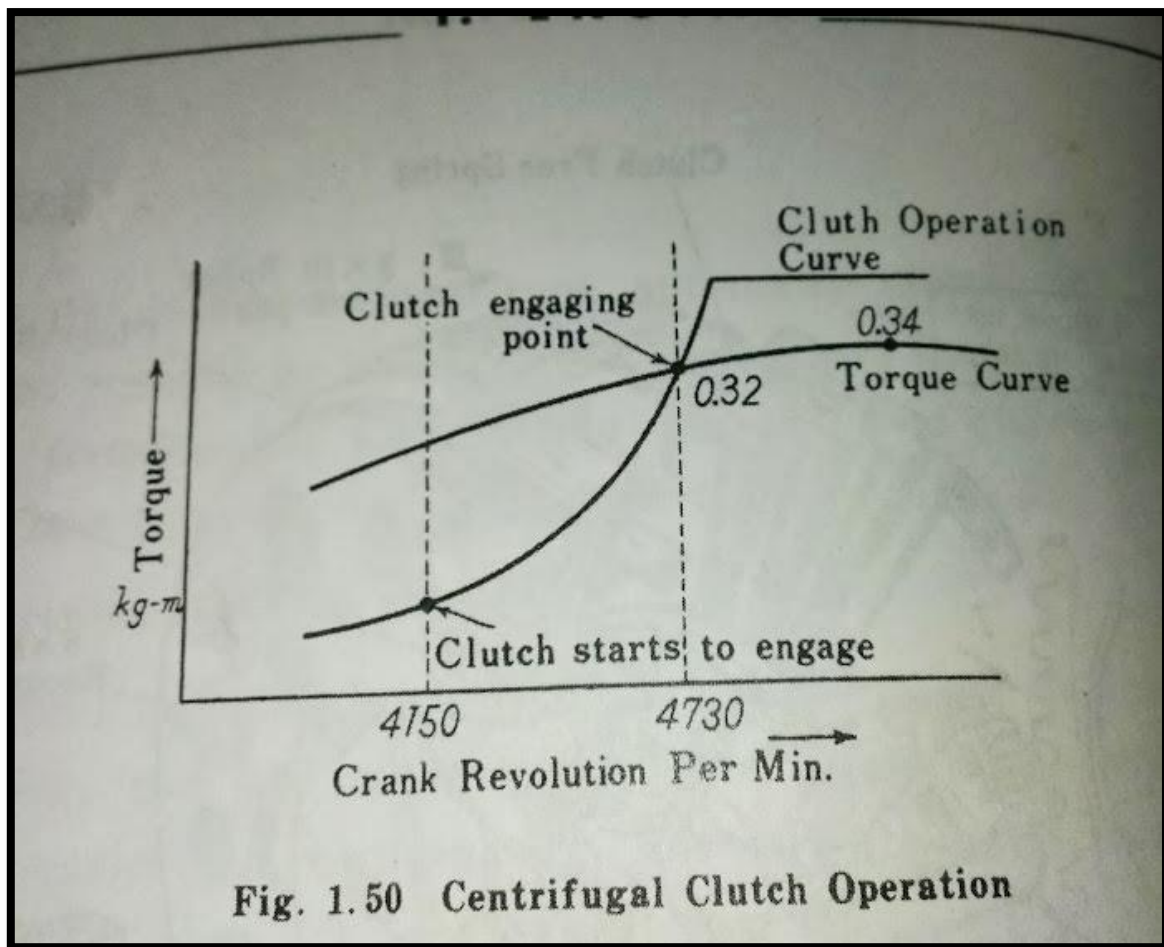


Figure 30 Shows Centrifugal Clutch Operation (Cincycaddy, 2013)

### 3.7. Angular Acceleration for Maximum Torque

To calculate Angular Acceleration one can utilise:

$$T = I\alpha$$

$$\therefore \frac{T}{I} = \alpha$$

Whereby:

$I$  = Mass Moment of Inertia

$\alpha$  = Angular Acceleration

For a solid disc:

$$I = \frac{1}{2}m \cdot r^2$$

$$\therefore \frac{T}{\frac{1}{2}m \cdot r^2} = \alpha$$

Maximum transmitted torque in graph 2 is 14.34 Nm, with the external drum radius previously calculated as 108mm, thus:

$$\alpha = \frac{14.34}{\frac{1}{2}(750 \cdot 10^{-3})(108 \cdot 10^{-3})^2}$$

$$\alpha = \mathbf{3278.46 \text{ Rad/s}^2} \text{ (Two Decimal Places)}$$

### 3.8. Direct Stress

Stress is a measure of internal resistance which is exhibited on an object by an external force, defined as:

$$\sigma = \frac{F}{A}$$

Whereby:

$\sigma = \text{Stress}$

$A = \text{Unit Area}$

Assuming variables from previous calculations remain, the net force from **one shoe** at the given RPM is calculated by:

$$\therefore F_{net} = m \cdot r_g (\omega_2^2 - \omega_1^2)$$

$$\therefore \omega_2 = \frac{700 \cdot 2\pi}{60}$$

$$\omega_2 = 73.3 \text{ Rad/s}$$

$$\therefore F_{net} = 275 \cdot 10^{-3} \cdot 104 \cdot 10^{-3} (73.3^2 - 48.58^2)$$

$$F_{net} = \mathbf{86.17 \text{ N}} \text{ (Two Decimal Places)}$$

Therefore, one can now calculate the area:

$$A = 50 \cdot 10^{-3} \cdot 20 \cdot 10^{-3}$$

$$A = \mathbf{1 \cdot 10^{-3} m^2}$$

$$\therefore \sigma = \frac{86.17}{1 \cdot 10^{-3}}$$

$$\sigma = 86170 \text{ N/m}^2$$

$$\therefore \sigma = \mathbf{86.17 \text{ kN/m}^2}$$

*or*

$$\sigma = \mathbf{86.17 \text{ kPa}}$$

**Direct Stress** is experienced by the drum due to high rotational speeds causing high centrifugal forces, thus, high normal reaction forces, which increases the friction force high enough to create 100% friction efficiency, thus, **Zero Slippage**. This means the drum is rotating directly with the shoe. Because direct forces acting parallel to the drum and shoe are occurring, **Zero Shearing** stress occurs, thus, only direct stress is experienced.

At lower RPM, for example, opposing forces to friction forces will induce some shoe and drum slippage, which would cause shearing stresses as well as direct stresses, thus, complex stresses to occur.

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## 4.0. Conclusion

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Centrifugal Clutches have been developed over a century, with each development being more bespoke than the last. It can be said that there isn't one clutch design better than the other, rather, better for a specific application, whether that be the design or the use of materials, each advantage of a clutch variant will only be utilised for specific applications, thus, its' disadvantages for an application may require a different clutch variant for the same application.

As developments progress, further applications and more efficient methods will surely be discovered, such as centrifugal clutches with 100% efficiency, and limited part wear.

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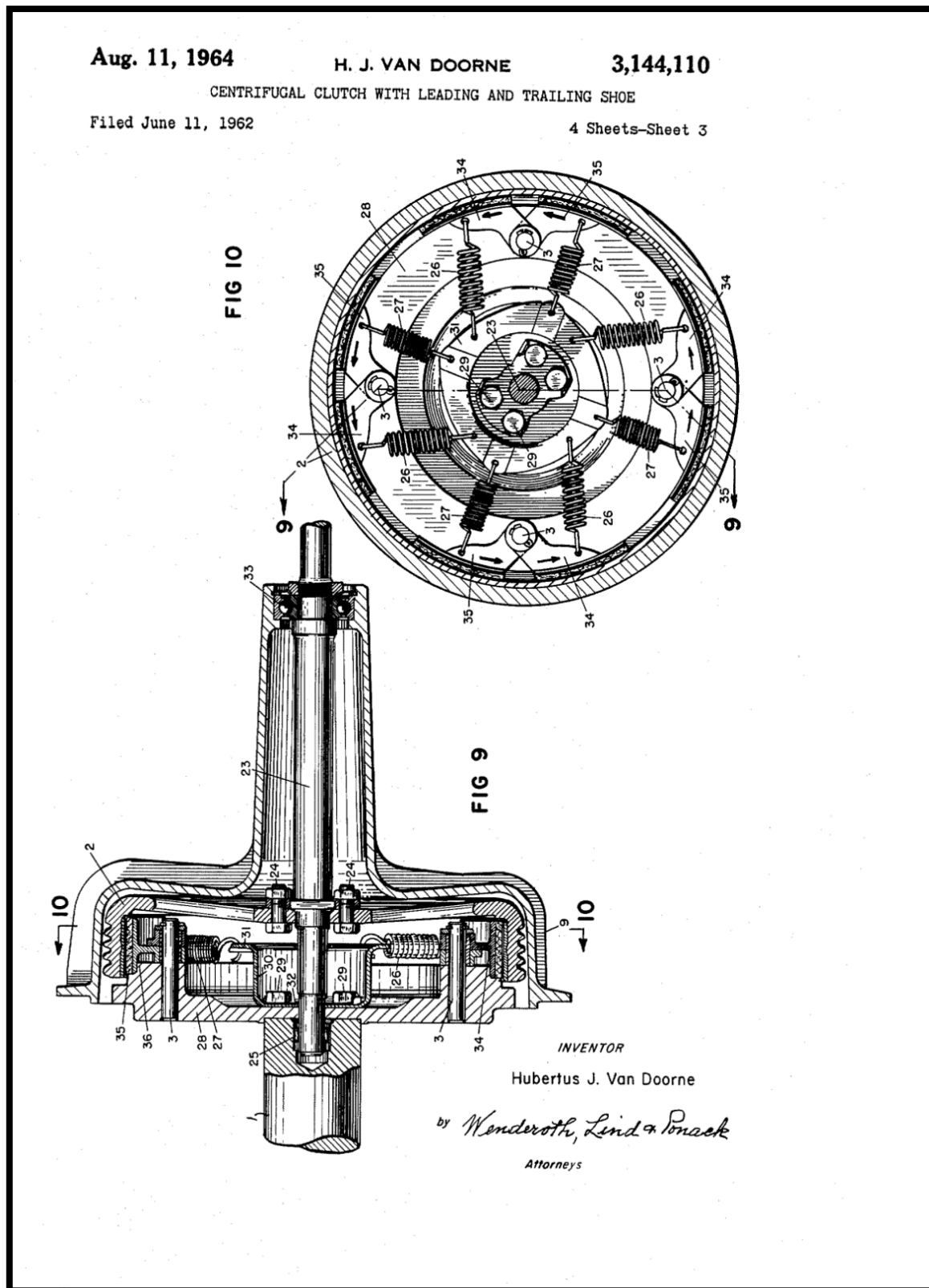
**Figure 27** - Mikipulley.co.jp. 2021. *What Are Electromagnetic Clutches and Electromagnetic Brakes?*. [online] Available at: <<https://www.mikipulley.co.jp/EN/Products/ElectoromagneticClutchesAndBrakes/about.html>> [Accessed 25 September 2021].

**Figure 28** - SEPAC, Inc. 2021. *Electromagnetic Clutches and Brakes for the Robotics Industry* [online] Available at: <<https://sepac.com/industries/robotics/>> [Accessed 25 September 2021].

**Figure 29** - Zaske, A., 2021. *Gantry and multi-axis system: Build it your way*. [online] Tolomatic. Available at: <<https://www.tolomatic.com/blog/artmid/843/articleid/451/gantry-and-multi-axis-system-build-it-your-way>> [Accessed 25 September 2021].

**Figure 30** - Cincycaddy, 2013. Honda C100 Clutch - no 'neutral' in gear. [Forum] *Honda Trail - CT90 & CT110 Forum*, Available at: <<https://www.tapatalk.com/groups/hondatrailcts/honda-c100-clutch-no-neutral-in-gear-t6981.html>> [Accessed 25 September 2021].

## Appendix One – Centrifugal Clutch Patents



Doorne, H., 1964. Centrifugal Clutch with Leading and Trailing Shoe. 3144110.

Aug. 25, 1964

R. R. RANDALL

3,145,817

CENTRIFUGAL CLUTCH

Filed Sept. 11, 1961

2 Sheets-Sheet 2

FIG. 3

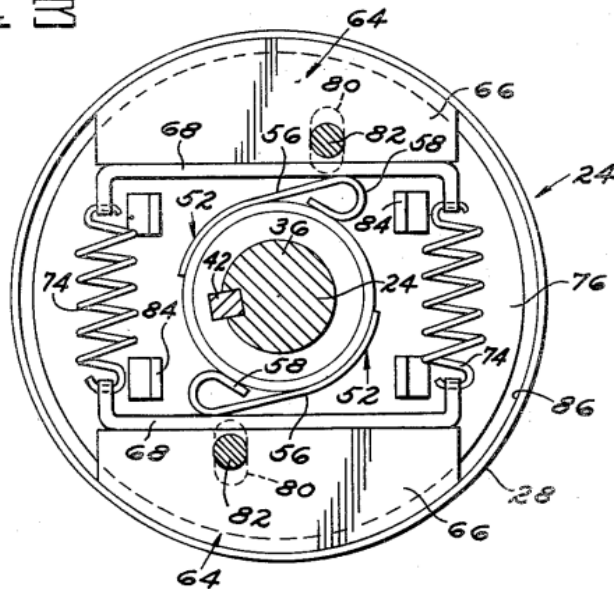


FIG. 4

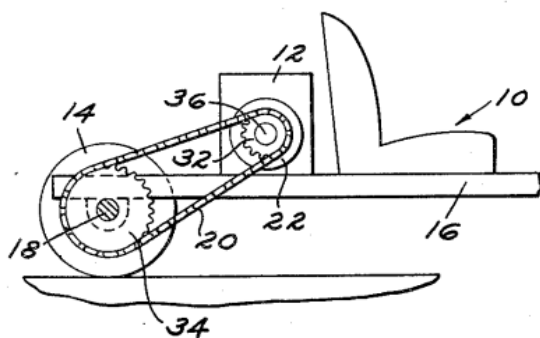
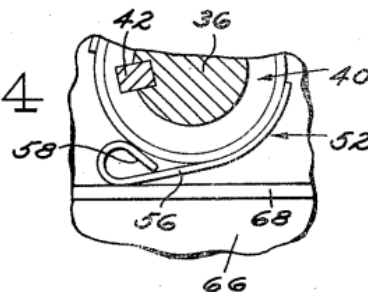


FIG. 5

INVENTOR.

RALPH R. RANDALL

BY

Barney Kisselle, Raich  
& Choate

ATTORNEYS

## Appendix Two – Torque Graph Tables

Table Shows Torque at Various Speeds with a 0.35 Coefficient of Friction

| N (RPM) | $\omega_2$ (Rad/s) | Mt (Nm)      | $\mu$ | z | m     | rg    | rd    | $\omega_1$ (Rad/s) |  | $\omega_2^2$ | $\omega_1^2$ |
|---------|--------------------|--------------|-------|---|-------|-------|-------|--------------------|--|--------------|--------------|
| 450     | 47.1238898         | -0.580298223 | 0.35  | 4 | 0.275 | 0.104 | 0.104 | 48.58              |  | 2220.661     | 2360.0164    |
| 475     | 49.74188368        | 0.475707776  |       |   |       |       |       |                    |  | 2474.255     |              |
| 500     | 52.35987756        | 1.588795181  |       |   |       |       |       |                    |  | 2741.557     |              |
| 525     | 54.97787144        | 2.758963991  |       |   |       |       |       |                    |  | 3022.566     |              |
| 550     | 57.59586532        | 3.986214206  |       |   |       |       |       |                    |  | 3317.284     |              |
| 575     | 60.21385919        | 5.270545827  |       |   |       |       |       |                    |  | 3625.709     |              |
| 600     | 62.83185307        | 6.611958853  |       |   |       |       |       |                    |  | 3947.842     |              |
| 625     | 65.44984695        | 8.010453284  |       |   |       |       |       |                    |  | 4283.682     |              |
| 650     | 68.06784083        | 9.466029121  |       |   |       |       |       |                    |  | 4633.231     |              |
| 675     | 70.68583471        | 10.97868636  |       |   |       |       |       |                    |  | 4996.487     |              |
| 700     | 73.30382858        | 12.54842501  |       |   |       |       |       |                    |  | 5373.451     |              |

Table Shows Torque at Various Speeds with a 0.3 Coefficient of Friction

| N (RPM) | $\omega_2$ (Rad/s) | Mt (Nm)      | $\mu$ | z | m     | rg    | rd    | $\omega_1$ (Rad/s) |  | $\omega_2^2$ | $\omega_1^2$ |
|---------|--------------------|--------------|-------|---|-------|-------|-------|--------------------|--|--------------|--------------|
| 450     | 47.1238898         | -0.497398477 | 0.3   | 4 | 0.275 | 0.104 | 0.104 | 48.58              |  | 2220.661     | 2360.0164    |
| 475     | 49.74188368        | 0.407749522  |       |   |       |       |       |                    |  | 2474.255     |              |
| 500     | 52.35987756        | 1.361824441  |       |   |       |       |       |                    |  | 2741.557     |              |
| 525     | 54.97787144        | 2.364826278  |       |   |       |       |       |                    |  | 3022.566     |              |
| 550     | 57.59586532        | 3.416755034  |       |   |       |       |       |                    |  | 3317.284     |              |
| 575     | 60.21385919        | 4.517610709  |       |   |       |       |       |                    |  | 3625.709     |              |
| 600     | 62.83185307        | 5.667393302  |       |   |       |       |       |                    |  | 3947.842     |              |
| 625     | 65.44984695        | 6.866102815  |       |   |       |       |       |                    |  | 4283.682     |              |
| 650     | 68.06784083        | 8.113739247  |       |   |       |       |       |                    |  | 4633.231     |              |
| 675     | 70.68583471        | 9.410302597  |       |   |       |       |       |                    |  | 4996.487     |              |
| 700     | 73.30382858        | 10.75579287  |       |   |       |       |       |                    |  | 5373.451     |              |

Table Shows Torque at Various Speeds with a 0.4 Coefficient of Friction

| N (RPM) | $\omega_2$ (Rad/s) | Mt (Nm)      | $\mu$ | z | m     | rg    | rd    | $\omega_1$ (Rad/s) |  | $\omega_2^2$ | $\omega_1^2$ |
|---------|--------------------|--------------|-------|---|-------|-------|-------|--------------------|--|--------------|--------------|
| 450     | 47.1238898         | -0.663197969 | 0.4   | 4 | 0.275 | 0.104 | 0.104 | 48.58              |  | 2220.661     | 2360.0164    |
| 475     | 49.74188368        | 0.54366603   |       |   |       |       |       |                    |  | 2474.255     |              |
| 500     | 52.35987756        | 1.815765921  |       |   |       |       |       |                    |  | 2741.557     |              |
| 525     | 54.97787144        | 3.153101704  |       |   |       |       |       |                    |  | 3022.566     |              |
| 550     | 57.59586532        | 4.555673378  |       |   |       |       |       |                    |  | 3317.284     |              |
| 575     | 60.21385919        | 6.023480945  |       |   |       |       |       |                    |  | 3625.709     |              |
| 600     | 62.83185307        | 7.556524403  |       |   |       |       |       |                    |  | 3947.842     |              |
| 625     | 65.44984695        | 9.154803754  |       |   |       |       |       |                    |  | 4283.682     |              |
| 650     | 68.06784083        | 10.818319    |       |   |       |       |       |                    |  | 4633.231     |              |
| 675     | 70.68583471        | 12.54707013  |       |   |       |       |       |                    |  | 4996.487     |              |
| 700     | 73.30382858        | 14.34105716  |       |   |       |       |       |                    |  | 5373.451     |              |