"CENTRIFUGAL CLUTCH"

A MAJOR Project Report submitted to the

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in partial fulfillment of the requirements for the award of the degree of

B.TECH IN MECHANICAL ENGINEERING

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*Date:*________________
Place: BHOPAL

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Introduction

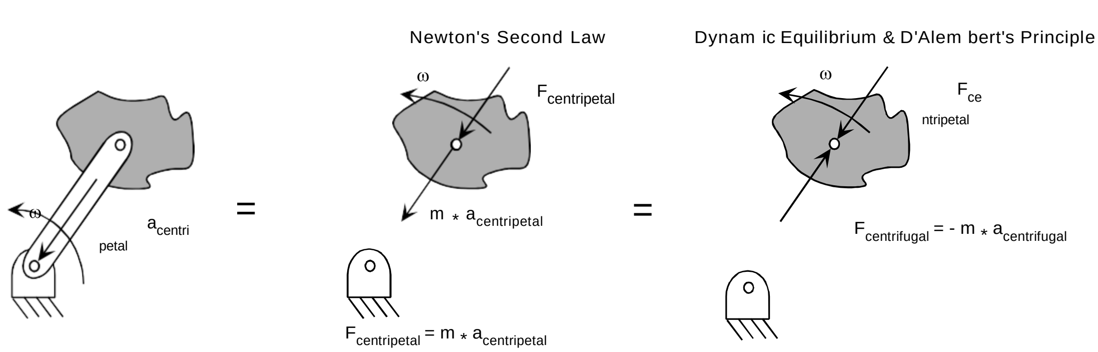
Thesis Statement

This thesis shows that the principles of compliant mechanism technology can be used to develop and analyze cost-effective centrifugal clutch configurations. Two pre-existing and four novel compliant centrifugal clutch configurations are presented. A basic model of each design is developed and the results of prototype testing are discussed. The relative merits of the different designs are discussed and several applications are demonstrated.

Background

Centrifugal Devices

A centrifugal device is actuated by centrifugal force. However, in a strict sense, centrifugal force does not exist, but the term is used because it provides an intuitive way to consider normal accelerations due to constant rotational velocity. Other related terms include centripetal forces, D'Alembert forces, inertial forces and centripetal acceleration. To avoid confusion, each of these terms is reviewed.



$F_{centripetal} + F_{centrifugal} = 0$ $F_{centripetal}$ - $m * a_{centripetal} = 0$

(a) (b) (c)

Figure 1-1 (a) Body rotating at a constant angular velocity and pinned at its center of mass. (b) The motion equations using the standard form of Newton's Second Law. (c) The motion equations using D'Alembert's Principle and centrifugal forces are shown.

A body moving in a circular motion with a constant angular velocity (ω) accelerates continuously due to its constantly changing direction of motion. Figure 1-1(a) shows such a body. The acceleration vector is oriented toward the center of the circular motion and its magnitude is

$$a = \omega^2 r \tag{1.1}$$

This acceleration is termed *centripetal* or *normal acceleration*. The force exerted to cause this acceleration is called *centripetal force (*Figure 1-1(b)). Applying Newton's second law, the centripetal force is

$$F_{centripetal} = m\omega^2 r \tag{1.2}$$

Centripetal forces are also directed toward the center of rotation.

The equilibrium equation for a body rotating at a uniform angular velocity with arbitrary additional forces is

$$\sum F = ma = m\omega^2 r \tag{1.3}$$

This equation may be rearranged as

$$\sum F + (-m\omega^2 r) = 0 \tag{1.4}$$

where the term $(-m\omega^2 r)$ is termed an *inertial* or *D'Alembert force*. It has the units of force, and is directed opposite to the centripetal acceleration. D'Alembert's principle states the equivalency of equations (1.3) and (1.4). *Centrifugal force* is the D'Alembert force caused by the centripetal acceleration of a rotating body. It is expressed as

$$F_{centrifugal} = m\omega^2 r \tag{1.5}$$

For most solid objects, the centrifugal force can be considered a function of rotational velocity only because mass is constant and generally, the radius is nearly constant. Thus centrifugal force is a useful actuation force for many applications requiring a response to rotational velocity. Centrifugal force actuated devices are simple, inexpensive solutions to clutch and switch applications since they require no outside power source or signal for control or actuation.

Many thousands of centrifugal devices are produced annually. Their applications range from yoyos to industrial facilities. Many of these devices are relatively simple and have changed little over the past twenty years. This work systematically applies the principles of compliant mechanism design to these centrifugal devices so that they may benefit from recent advances in compliant mechanism technology.

Centrifugal Clutches

Centrifugal clutches transmit torque as a function of the driving speed. The actuation force and control are provided by centrifugal forces on the clutch. This work seeks to develop novel centrifugal clutch configurations with increased torque capacity and/or load acceleration smoothness while maintaining a cost advantage over rigid-body designs. A successful design increases these performance parameters and/or decreases production costs. Centrifugal clutches are constrained by many factors such as heat, wear, load capacity, and space.

Centrifugal clutches reduce starting torques on AC motors, reduce loads on internal combustion engines at idle speeds, and provide overload protection. They can also isolate torsional vibrations. In many applications, the clutches provide adequate load acceleration and control with minimal expense. Their use can also decrease required motor size by decreasing the current draw of motors accelerating a high-inertia load. This is accomplished by reducing the required torque output at speeds where the motor is least able to generate torque. Figure 1-2 compares torque output and current draw of an electric motor with and without a centrifugal clutch.

Each year, centrifugal clutches provide power transmission and/or control for thousands of string trimmers, chainsaws, radio-controlled cars and helicopters, and go-karts. They also control torque transmission in large industrial motors transmitting hundreds or even thousands of horsepower. These applications use centrifugal clutches due to their simplicity and low cost relative to competing solutions such as magnetic, electric, and pneumatic clutches. However, the simplicity of the centrifugal clutch also

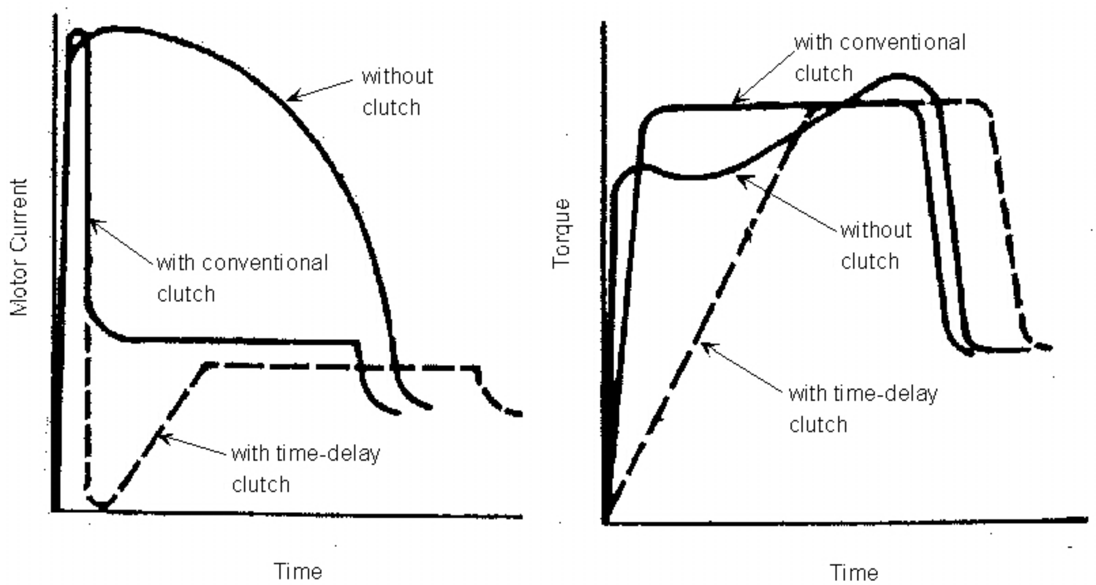


Figure 1-2 Torque and current versus time of an AC motor with a conventional and a time-delay centrifugal clutch. Current draw is dramatically reduced for both clutch types. The time-delay clutch reduces initial torques to increase the starting smoothness (St. John, 1979).

limits the range of torque control possible from a given clutch. This limits their use in applications demanding smoother starts, or with varying starting conditions.

The squared relationship between torque and speed means there is a cubic relationship between speed and transmitted power. This can be an advantage or disadvantage depending on the application. An apparently small deviation in operating speed can result in a very large change in maximum transmitted power. A clutch should be sized so that no components will be damaged if the clutch transmits its maximum torque.

Centrifugal clutches are friction clutches. As such, wear and heating during load acceleration is an important concern. Clutches may also have problems due to variation in the friction conditions that modify the expected torque-speed relationship. However, centrifugal clutches are very efficient under operating conditions because there is no slippage in the clutch after the load is accelerated. However, if torque increases beyond

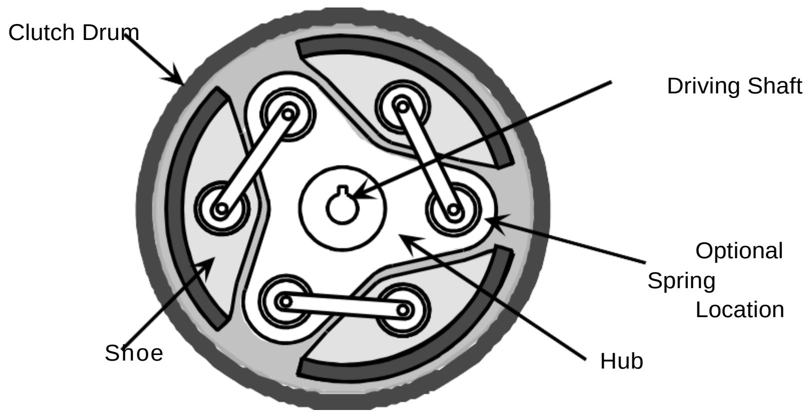


Figure 1-3 A rigid-body connected-shoe clutch with three shoes.

the clutch's capacity, it will slip harmlessly. This protects motors and other more expensive components from damage due to excessive torque.

A common centrifugal clutch design is the connected shoe design shown in Figure 1-3. As the clutch speeds up, the arms deflect outward. The movement may be resisted by springs to raise the speed at which the clutch begins transmitting torque. When the arms contact the cylindrical drum that surrounds them, they begin to transmit torque. Torque transfer capacity will continue to increase as the speed increases.

Overspeed Brakes

Some overspeed brakes are based on centrifugal clutches. Centrifugal clutches are well suited to this applications since speed is the input. The variation of centrifugal force with the speed squared can be a very positive factor in these devices. This relationship would ensure that the brake torque and power dissipation increase quickly until the brake halts the acceleration of the system. This effect could be amplified by the use of a brake

with centrifugal switching action so that the brake “snapped” on. However, this could also cause significant shock loading.

Overspeed brakes are not addressed in detail here because they are simply a kinematic inversion of a centrifugal clutch. A centrifugal overspeed brake is a centrifugal clutch with the output fixed to a frame. Any of the clutches discussed in this work could be modified for use as an overspeed brake.

Compliant Mechanisms

Compliant mechanisms are mechanisms that obtain some or all of their motion through the deflection of their members. In a compliant mechanism, a single flexible link often replaces two or more rigid links of an equivalent rigid-body mechanism. This decreases the mechanism’s part count, wear points, and backlash. Due to these advantages, compliant mechanisms have been used in both inexpensive mass-produced parts and low-volume precision parts. Compliant configurations of centrifugal devices may decrease manufacturing costs compared to rigid-body designs. Their lower cost may also allow new applications of centrifugal devices in low-cost products. Compare the rigid-body and compliant clutch designs in Figure 1-4. This clutch demonstrates part count reduction through compliant mechanism technology.

The advantages of compliant mechanisms come with increased design challenges.

These challenges include analyzing nonlinear deflections and increased fatigue-failure concerns. The pseudo-rigid-body model (PRBM) translates compliant mechanisms into nearly equivalent rigid-body mechanisms for early analysis and synthesis. Figure 1-5 shows a compliant mechanism and its PRBM. Using the PRBM, compliant mechanisms

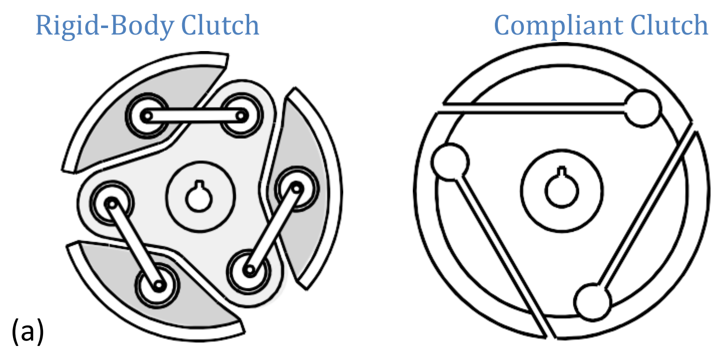


Figure 1-4 Two centrifugal clutches. (a) The rigid-body clutch consists of at least 13 parts while (b) the compliant clutch is just one piece. Both clutches transmit torque when clutch members move outward due to centrifugal force. As they move outward, they contact a drum and transmit torque.

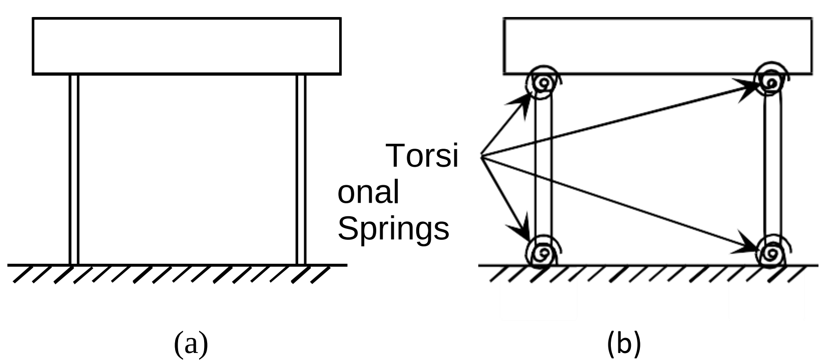


Figure 1-5 (a) A complaint parallel motion mechanism and (b) its pseudo-rigid-body model.

can be designed and analyzed as rigid-body mechanisms without calculating large beam deflections.

Research Approach

This work brings together many recent developments in compliant mechanism design. The work combines the basic PRBM techniques with rigid-body replacement synthesis, recent work in evaluation of compliance potential, and new tools for evaluating different compliant designs. The research procedure and the relationship of these different procedures are outlined in Figure 1-6 and discussed below.

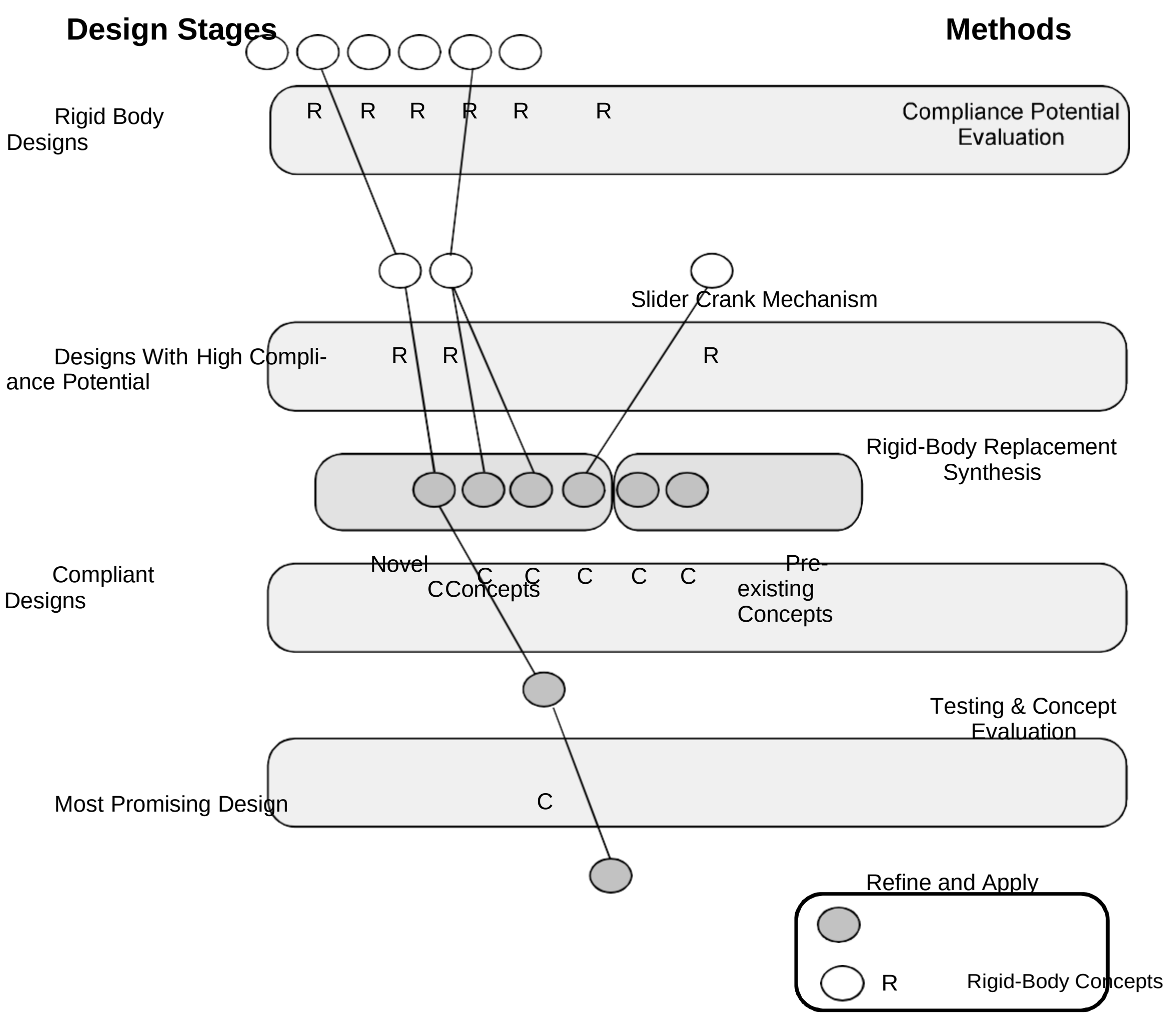


Figure 1-6 Flowchart of the research approach.

Development proceeded through the following steps.

1. *Survey existing designs*

   Current centrifugal clutch concepts were identified and reviewed. The primary advantages of each concept are discussed.

2. *Develop evaluation criteria*

   Important challenges and limitations of centrifugal clutches were identified by reviewing technical and commercial literature. This information was used to develop evaluation criteria for the compliant-centrifugal clutches.

3. *Evaluate compliance potential of the rigid-body designs*

   Compliance potential criteria developed by Roach & Howell (1999) and Ber- glund (1998) were used to identify which centrifugal clutch concepts are most adaptable to compliant mechanisms.

4. *Develop compliant designs by rigid-body replacement*

   Compliant centrifugal clutches were developed from concepts that scored well in the compliance criteria evaluation. They were developed by rigid-body- replacement synthesis. Using this method, multiple compliant mechanisms were be generated from a single rigid-body concept.

5. *Explore other novel compliant configurations*

   As the mechanisms generated above were evaluated, other concepts were devel- oped to overcome their limitations. Common mechanism types such as four- bars and double sliders were surveyed for other promising compliant designs.

6. *Prototype designs and collect test data to identify any unique characteristics of a design*

   The new designs were prototyped from sheets of polypropylene using an NC mill. All of the prototype clutches were designed to maximize the actuation mass within a cylinder 4.40 inches in diameter and 0.25 inches long.

   The torque-speed relationships of the clutches were measured. This data was reviewed for unique characteristics such as exceptional torque capability, a non- quadratic torque-speed relationship, or potential for smoother load starting.

7. *Evaluate designs relative to the design criteria*

   The information gleaned from the models and testing were used to rate the dif- ferent designs relative to the design criteria through a scoring matrix.

8. *Develop torque models for promising clutch types*

   The clutches that scored well in the evaluation were analyzed and the PRBM was applied to develop approximate torque models for parameterized clutches.

9. *Demonstrate potential applications for new centrifugal clutch concepts.*

   A current application for centrifugal clutches was selected. The ideas developed from this thesis were applied to this application to show how they may improve cost and/or performance.

Centrifugal clutches interact with a complex, varied environment. This environment requires similarly broad analysis and testing to complete the design and development of a workable device. In developing a device for a commercial application,

no part of the analysis can safely be ignored. However, the primary purpose of this work is to assess potential and to identify principles rather than develop a design for an application. Therefore, the scope of the issues and concerns addressed in this work are limited to those that fulfill this purpose. Many concerns inherent in the centrifugal clutches studied cannot be analyzed here. Such concerns include wear, material selection, fatigue life, vibration modes, heat transfer, and manufacturing concerns.

Research Benefits

Compliant mechanism technology has advanced significantly in recent years. These advances have simplified the design of compliant mechanisms, making it more practical for many applications. The primary benefit of this work is further demonstration of this technology's potential. Also, the work demonstrates that the varied techniques developed for specific parts of the compliant mechanism design process can be integrated into an effective, coherent development method.

Centrifugal clutches have received very little treatment in the technical literature. Therefore, there is little publicly available analysis of centrifugal clutch concepts. While this work will not completely fill this void, it will represent a step forward.

Novel centrifugal clutch configurations developed through this work may have practical value. Previous work, such as the development of the compliant ratchet and pawl clutch (see also page 13, Roach, et al, 1998), has shown that compliant mechanisms can dramatically reduce part counts while maintaining functionality. Similar improvements may be achieved in the centrifugal clutches. Further, these designs may be directly applicable to the design of overspeed brakes since a brake is frequently a kinematic

inversion of a clutch. Lessons from this work may also apply to other mechanisms that are actuated by centrifugal or other inertial forces.

Moreover, this work advances the state of the art in compliant mechanism design by demonstrating the value of the pseudo-rigid-body model (PRBM) in synthesizing and designing dynamically loaded mechanisms. Some of these mechanisms have PRBM's with multiple inputs and multiple degrees of freedom. The PRBM approach facilitates design and analysis of these highly nonlinear applications because it decouples the solution of nonlinear deflections of compliant mechanisms from the solution of nonlinear force-deflection equations. The PRBM is also a helpful tool for converting complicated geometries and interactions into simpler, more familiar forms that the designer can understand more intuitively.

This work also illuminates some weaknesses of the PRBM. Specifically, the work shows the need for a usable PRBM of a fixed-fixed flexible segment. This segment type is frequently encountered in fully compliant devices. However, the designer is left to choose an approximate PRBM of the segment by intuition or use a numerical technique to solve the deflections.

Literature Review

Centrifugal Devices

Clutches and brakes have been used for centuries. In the last century, general design equations for clutches and brakes have been well developed. Most modern machine design textbooks contain such equations and discuss their development (Norton, 1998; Shigley & Mischke, 1989). A more complete treatment of their design can be found in

Orthwein (1986) and South & Mancuso (1994). Goodling (1977) developed equations for torque transfer of a flexible trailing shoe centrifugal clutch.

Many of these books apply these general clutch/brake equations to centrifugal clutches. Additionally, several authors have presented discussions of centrifugal clutch applications and their benefits such as low cost, automatic operation, overload protection, and motor cost reduction (Goodling, 1974; St. John, 1975, 1979; Town, 1988).

Several researchers have sought to mitigate some of the undesirable performance characteristics of centrifugal clutches. Dekhanov & Makhtinger (1987) devised a way to switch a clutch from nonaggressive to aggressive shoe orientation after load acceleration. This increases operating torque transfer while maintaining a reasonably smooth start. Achi (1986) showed how centrifugal clutches may be used to improve simple industrial operations in developing countries where equipment cost is critical. A centrifugally actuated continuously variable transmission and the development of improvements thereto is discussed by Chase et al. (1991).

Industry has also been working on developing centrifugal clutches as evidenced by patents in the area (Gruden & Brooks, 1999; Schultz, 1996; Shimizu & Ogura, 1987; Weiss, 1984). Several patents reference a compliant, one piece design (Figure 1-7) that is well suited to low-cost gasoline-engine applications (Kellerman & Fischer, 1976; Dietzsch et al., 1977; SuchDev & Campbell, 1989).

Roach et al. (1998) reported a compliant ratchet and pawl one-way clutch with centrifugal throw-out (Figure 1-8). This device shows that compliant mechanisms can be successfully employed in mechanical power transmission devices. It also demonstrates,

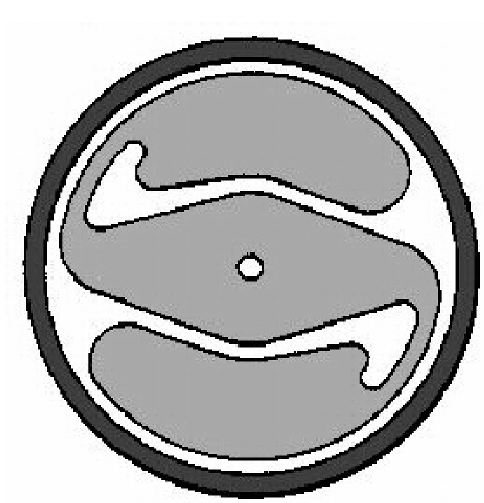


Figure 1-7 A compliant centrifugal clutch. This clutch is well suited to production by powder metallurgy. It is commonly referred to as an “S-clutch” (Suchdev & Campbell, 1989).

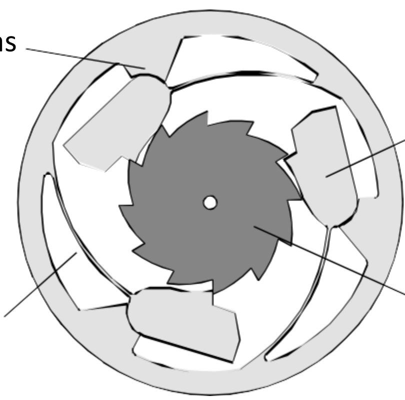


Figure 1-8 A Compliant ratchet and pawl clutch with centrifugal throw-out (Roach, 1998)

together with the existing compliant centrifugal clutches, the potential to develop additional compliant centrifugal devices.

Centrifugal switches have also been the subject of several patents (Moore, 1980; Kramer et al., 1982). However, no compliant designs are currently found in the patent or technical literature.

Mechanism Synthesis and Design

The kinematics fundamental to this research are described in any basic kinematics textbook (Norton, 1999; Erdman & Sandor, 1997; Paul, 1979; Hartenberg & Denavit, 1964;). An efficient method for developing force-deflection relationships is the method of virtual work (Paul, 1979; Norton, 1999).

Recent research in bistable mechanisms support the study of centrifugal switches.

Howell & Midha (1995c) observed that the required input force of a toggle mechanism acting on a compliant workpiece reaches a maximum before passing through the toggle point. Opdahl et al. (1998) reviewed and classified the mechanism types that can generate bistable behavior. Jensen (1998) identified the spring locations that generate bistable behavior in four-bar mechanisms.

Compliant Mechanisms

Compliant mechanisms are mechanisms that obtain some or all of their motion from the deflection of their members. They frequently require fewer parts than comparable rigid-body designs since revolute joints are often replaced by flexible segments. The potential energy stored in the flexible segments can replace springs and the reduction in revolute joints reduces problems with backlash and wear. In many applications, compliant mechanisms can maintain or even improve performance relative to conventional rigid-body designs. (Sevak & McLarnan, 1974; Her 1986; Salamon, 1989)

These advantages are bought with the price of greater design difficulty.

Frequently, these mechanisms undergo large, nonlinear deflections. The mechanical advantage of the mechanism is reduced because some of the input work deflects the members (Salamon & Midha, 1998). Further, stress analysis and fatigue become much more important in the basic design of the mechanism.

Compliant mechanisms frequently deflect far beyond the linear range. The deflection of these members must be calculated and understood to analyze and design them. Bisshopp and Drucker (1945) laid the foundation for consideration of compliant mechanisms by their application of elliptical integrals to solve problems involving large deflection of cantilever beams. Shoup and McLarnan (1971a) examined the range of mechanisms that can have one or more flexible segments and lower pairs. Efforts were also made to develop qualitative understanding of flexible segment deflections (Shoup & McLarnan, 1971b; Shoup, 1972). Burns (1964) and Burns and Crossley (1968) developed rigid-link approximations for flexible link deflections. Gorski (1976) provides a good review of analytical methods for the calculations of elastic deflection of bars. Boronkay & Mei (1970) made an early effort to analyze a compliant mechanism using finite element analysis. Gandhi & Thompson (1980) developed the equations to apply finite element analysis using a mixed variational principle to flexible link mechanisms. Hill & Midha (1990) developed a graphical Newton-Raphson technique to aid in the solution of compliant mechanism deflections.

Some researchers have built on these numerical analysis techniques in developing compliant mechanism synthesis techniques. They have employed topological synthesis methods based on optimization techniques that remove material or adjust material properties until the optimal force or deflection characteristics are achieved

(Anathasuresh et al., 1994; Anathasuresh et al., 1995; Frecker et al., 1996; Frecker et al., 1997).

Parkinson et al. (1997) defined compliant mechanisms by a series of splines. The location

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of the control points and the section properties at the points were design variables modified to find an optimal mechanism. These techniques can yield unique designs outside the design space considered by the human designer.

A new approach to compliant mechanism design began with the development of the pseudo-rigid-body model (PRBM) through which a compliant mechanism is modeled as a rigid-body mechanism. The PRBM predicts the displacement and force characteristics of the compliant mechanism accurately enough to support preliminary analysis and synthesis of compliant mechanisms. The rules for creating a PRBM of a compliant mechanisms or vice versa were developed to make this approach feasible (Howell & Midha, 1994a, 1994b, 1995a, 1995b, 1996a; Howell et al., 1996). These conversions replace flexible segments with rigid segments connected by lower pairs. Torsional springs are placed at joints to model the effects of the compliance on the force deflection characteristics of the mechanism. A summary of the basic rules for creating a PRBM is included as Appendix A.

Recently, Saxena and Kramer (1998) proposed an approximation for a flexible segment subject to both end forces and moments. This loading condition occurs in fixed- fixed flexible segments. This work yields insight into the relationship between force and moment loading, but does not represent a full PRBM that permits application of rigid- body kinematic techniques to analyze compliant mechanisms with fixed-fixed segments.

The PRBM allows the wealth of knowledge of rigid-body kinematics to be employed in the analysis and synthesis of compliant mechanisms. An example of the application of rigid-body approaches to compliant mechanism design via the PRBM is the

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Application of Burmester theory for dimensional synthesis of mechanisms (Mettlach & Midha, 1996).

There are two primary synthesis methods associated with the PRBM: rigid-body replacement and synthesis for compliance. In rigid-body replacement, a rigid-body mechanism design is converted through the PRBM into a compliant design. This process usually generates multiple compliant designs equivalent to the original rigid-body design. Further considerations such as stress, fatigue life, and manufacturability may be used to select a specific design. Synthesis with compliance introduces energy equations. The energy equations are solved with the rigid-body loop closure equations to meet the design goals. The designer using this method can solve for variables such as the equivalent spring constants of compliant members. Through synthesis with compliance, mechanisms with specific force-deflection relationships may be synthesized. (Howell et al., 1994; Howell & Midha, 1996b)

The PRBM has been applied to several design problems. It has been used in the design of parallel mechanisms (Derderian et al., 1996), functionally binary pinned-pinned segments (Edwards, 1999), and pantographs (Nielson & Howell, 1998).

The PRBM is the basis for extending rigid body type synthesis techniques to compliant mechanisms. Murphy et al. (1994a, 1994b) proposed a systematic way of identifying all possible compliant mechanism configurations that would be equivalent to an existing rigid-body design. Midha et al. (1994) assisted synthesis efforts by developing a more rigorous and thorough terminology for discussing compliant mechanism configurations. They suggested a definition of links compatible with traditional rigid-body definitions. Additionally, segments, segment kinds and categories, and their structural and functional types are defined to describe the compliant mechanism design space.

The mechanical advantage of compliant mechanisms does not follow directly from rigid-body-mechanism theory. In rigid-body mechanisms, work is generally assumed to be conserved between the input(s) and the output(s), making mechanical advantage a function of position only. However, Salamon & Midha (1998) showed that these assumptions do not hold for compliant mechanisms. In compliant mechanisms, mechanical advantage is a function of position *and* applied forces. Each of several possible mechanical advantage definitions yields insight into different characteristics of the mechanism.

Roach & Howell (1999) have developed criteria for evaluating the degree of benefit possible from replacing an existing rigid-body mechanism with a compliant version. These techniques help to systematically identify those mechanisms in which compliance would be of greatest benefit. These procedures capture some of the intuition of experienced engineers in assessing proposed designs so that less experienced engineers may more easily design compliant mechanisms. Berglund (1998) has also proposed criteria for evaluating compliance potential, comparing compliant mechanism concepts, and comparing compliant and rigid designs. These criteria with some modifications will be used in this work.

Advantages

The primary advantage of centrifugal devices is their simplicity. They do not require any external signal or power for actuation or control. They generally use fewer components than competing solutions. This simplicity leads to lower costs and high reliability. Often, centrifugal devices are the lowest cost solution to a problem. This cost difference can be quite significant in some applications. Many years of experience in designing and using centrifugal devices has permitted steady improvements in their performance.

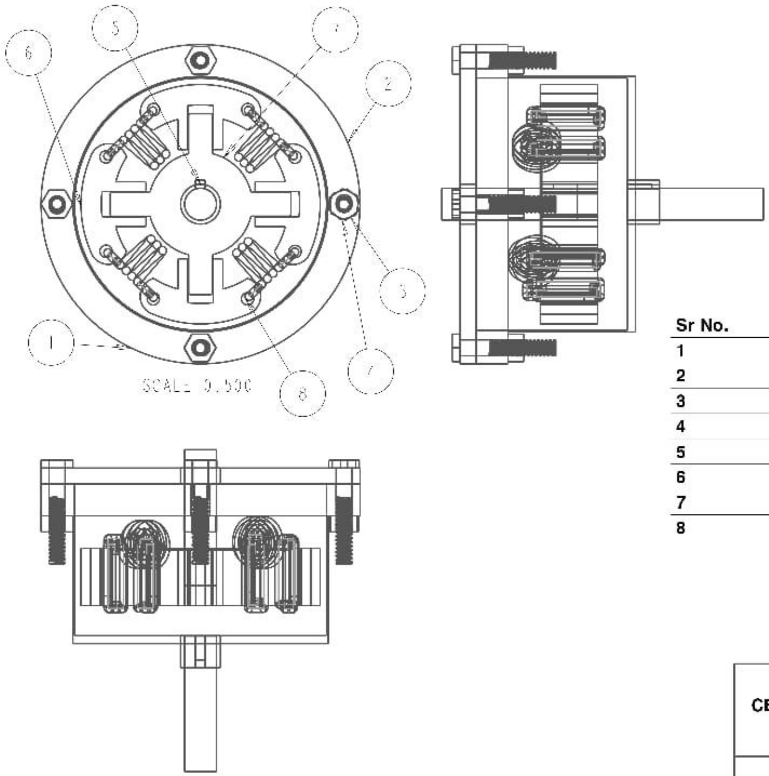
Another advantage is their sensitivity to small changes in speed since the actuation force varies with the speed squared. This sensitivity can be very advantageous in applications such as centrifugal switches and overspeed brakes. A small increase in speed can cause a larger increase in actuation force. This helps an overspeed brake stop a larger than expected load at only slightly higher speeds.

Disadvantages

The largest disadvantage of centrifugal devices is their lack of versatility. Centrifugal force is always proportional to the square of the speed. This relationship is set by the laws of physics and cannot be modified to meet the needs of a specific application. Most centrifugal devices are designed or modified for a specific application with specific operating conditions. They cannot easily be modified to operate under different operating conditions. By comparison, many electric or magnetically actuated devices can be precisely controlled for nearly optimal performance under varying conditions.

The lack of flexibility requires that centrifugal devices be custom designed for many applications. This can increase the cost for applications with unusual requirements. The expense is reduced by designs that use a series of standard parts with built in adjustments. This approach reduces the device cost but sacrifices some performance since the standard parts won't provide optimal performance for every situation.

The nonlinearities of the actuation and the coupling of geometry and kinematics discussed earlier are also challenges. Many designs have been developed as much by testing and intuition as by engineering design.



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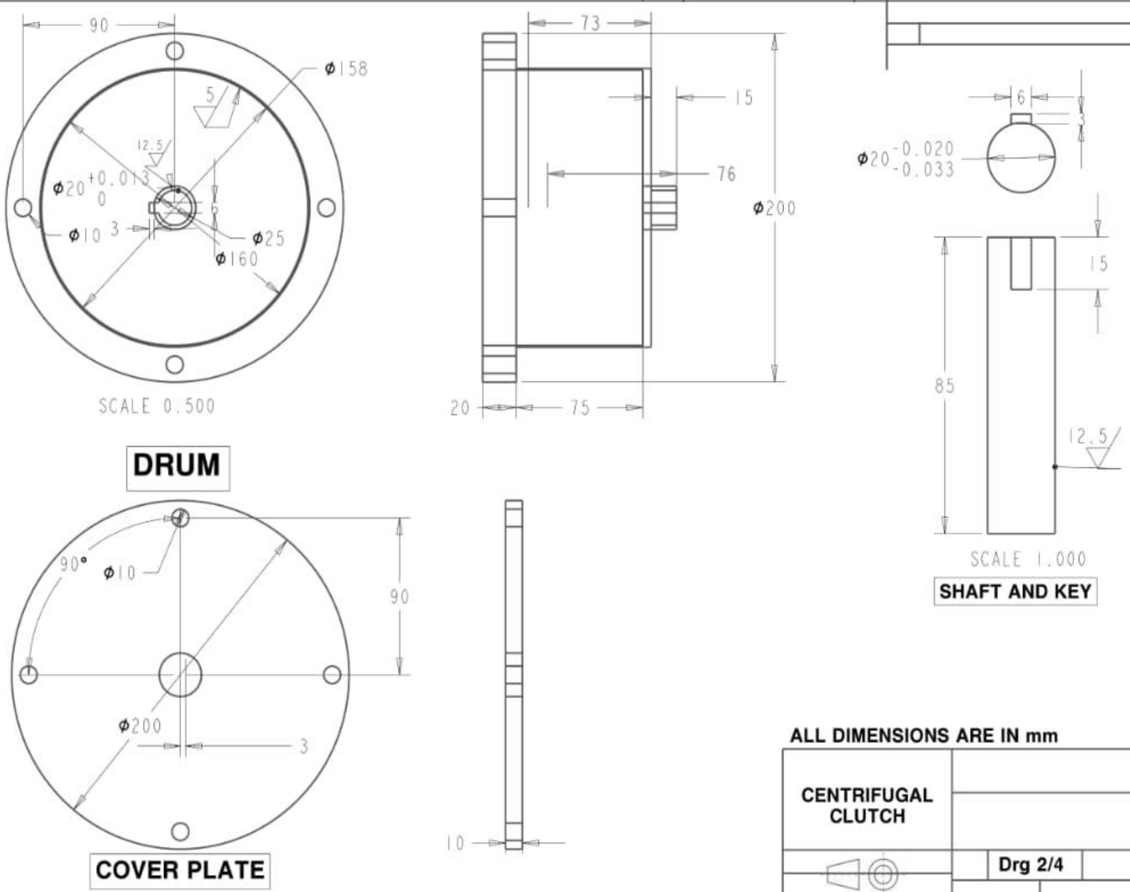
2	DRUM	1	PCS 40C8
3	NUT	4	Steel
4	SCREW	4	Steel
5	SHAFT	2	PCS 40C8
6	SHOES	1	FG 260
7	SPIDER	1	PCS 40C8
8	SPRING	4	Cold Drawn Steel(Gr1)

CENTRIFUGAL CLUTCH

Drg 1/4

Scale 1:2



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CENTRIFUGAL CLUTCH

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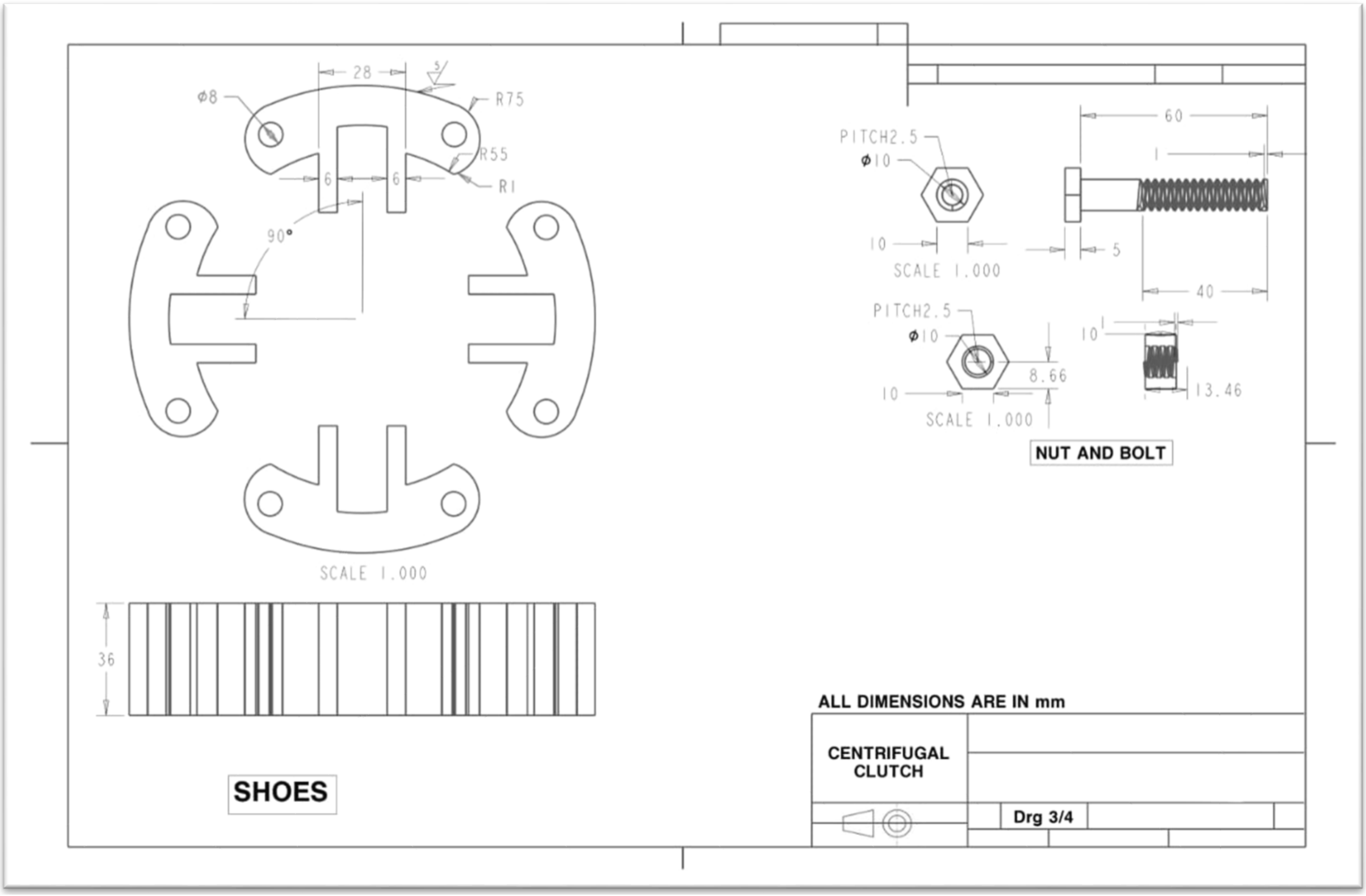

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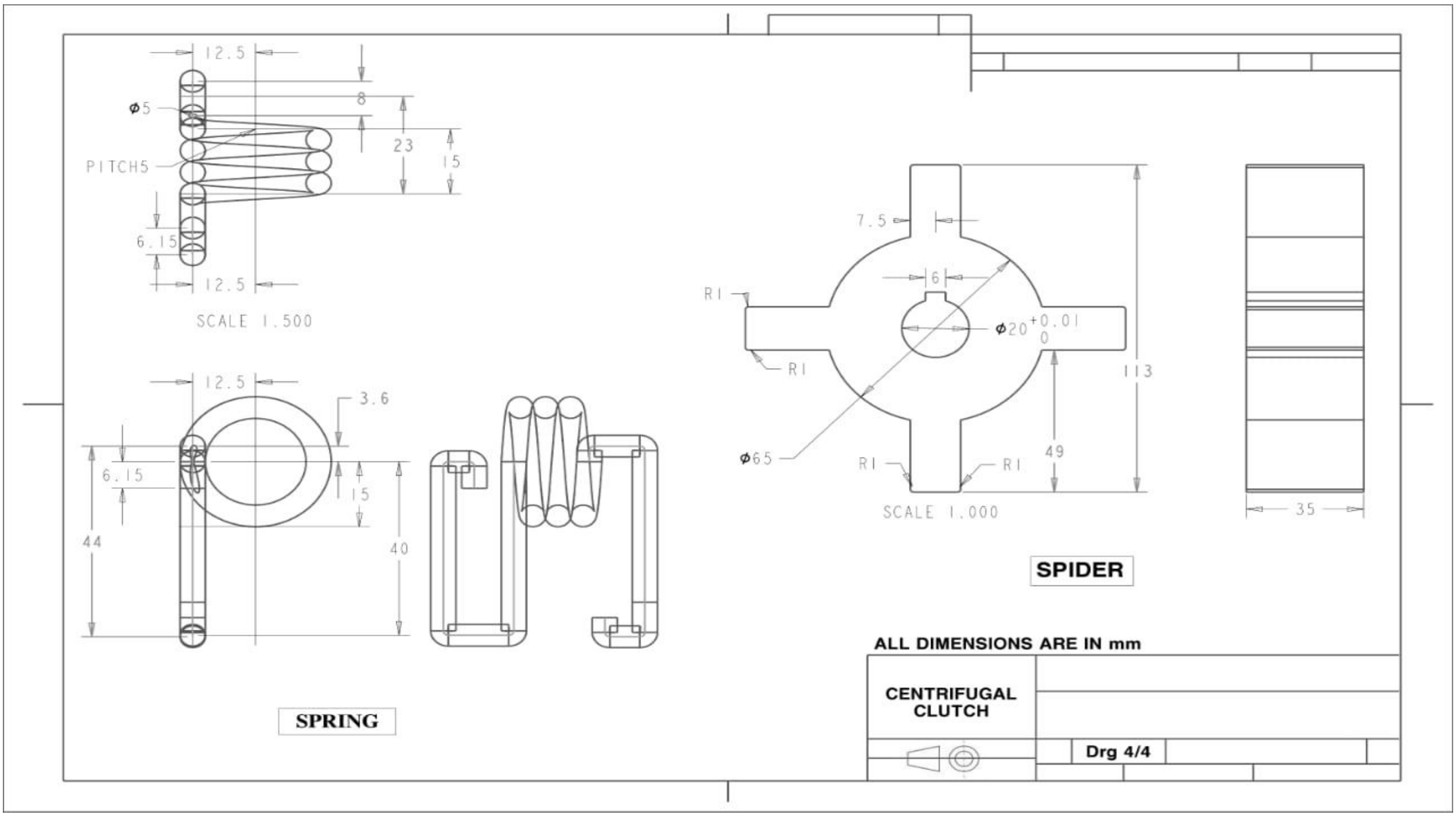
13.46
NUT AND BOLT
ALL DIMENSIONS ARE IN mm
CENTRIFUGAL CLUTCH
Drg 3/4



12.5
Φ5
8
23
15
PITCH5
6.15
12.5
SCALE 1.500
12.5
3.6
6.15
15
44
40
SPRING
7.5
6
R1
Φ20 +0.01 0
R1
113
Φ65
R1
R1
49
SCALE 1.000
35
SPIDER
ALL DIMENSIONS ARE IN mm
CENTRIFUGAL CLUTCH
Drg 4/4