

University of Trinity Saint David School of
Engineering



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

Analysis and Simulation of a Centrifugal Clutch
Stress Analysis and Dynamics ACMA5010

Sean Mee

2218461

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1 Centrifugal Clutches Literature Review

1.1 Development of Centrifugal Clutch System

The development of the centrifugal clutch has evolved significantly since its first patent in 1898 (CROWDUS., 1898), with development focusing on enhancing performance, efficiency primarily through the use of material science. The centrifugal clutch system is crucial in various automotive applications, particularly in continuously variable transmissions (CVTs), where it facilitates the transfer of power from the engine to the drivetrain. The centrifugal clutch was developed to address the need for a mechanism that could automatically engage and disengage the engine in response to the engine's RPM; this mechanism utilizes centrifugal force, which is crucial for automatic motor applications (Kholil et al., 2021).

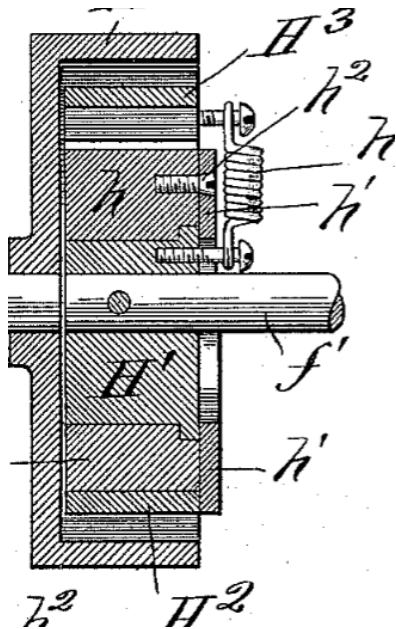


Figure 1 Early Centrifugal Clutch Diagram from W. A. CROWDUS patent. (CROWDUS., 1898)

The principle upon which a centrifugal clutch operates involves the exploitation of the 'centrifugal' force generated by the rotation of a crankshaft. As the engine speed increases, the centrifugal force acts on weights that move outward due to this force; these weights have friction shoes which engage the clutch and allow power transfer. This mechanism can be used to eliminate the need for manual engagement providing a smoother driving experience. These mechanisms are often used in small engines such as in motorcycles. (Kholil et al., 2022; Kholil et al., 2021).

In recent years, research has had focused on the materials used to construct of centrifugal clutches and how these might be improved for performance and environmental requirements. The use of natural fibre composites, such as coconut fibre and wood powder have been shown to be effective substitutes for more traditional materials while being significantly more environmentally friendly (Kholil et al., 2022). Moreover, the design and performance characteristics of centrifugal clutches can be improved

through design choices enhancing material benefits. Experimental investigations on dry centrifugal clutches with grooved friction liners, reveal that such designs can significantly improve the clutch's performance characteristics in areas such as friction coefficient and component lifespan (Panchal et al., 2023). The design of centrifugal clutches has even evolved to incorporate more sophisticated engineering principles. For example, the introduction of the floating-opposing-arm (FOA) presents a model which can predict a clutch's performance with the application based on mathematical models and equations, taking in various numerical parameters (Crane et al., 2004). The operational efficiency of centrifugal clutches is also influenced by thermal characteristics. The time-varying thermal characteristics of dry clutches emphasizes the importance of managing heat generated during operation through various cooling methods to prevent performance degradation (Wang et al., 2014).

These innovations in aggregate represent a significant leap in clutch technology. The development of centrifugal clutch systems reflects a continuous interplay between mechanical design, material science, and performance optimization.

From the early mechanical designs to the incorporation of advanced materials, centrifugal clutches have evolved into sophisticated components which are still key in automotive engineering.

1.2 Operational Conditions & Suitable Material Used

Understanding the operational conditions and material requirements of these systems is essential for optimizing their performance and durability. The operational conditions of centrifugal clutches split into three phases: disengagement, sliding, and engagement.

During disengagement, the clutch drive is effectively separate from the engine transmission to prevent power transfer at low RPMs. This phase also minimizes wear and overheating, which can occur if the clutch remains partially engaged. The sliding phase is the transitional state, where the clutch is neither fully engaged nor disengaged, and can cause excessive wear if used too frequently. Finally, during engagement, the clutch transmits torque, the efficiency of which is influenced by the materials used in its construction and the design of its components (Panchal et al., 2023).

The operational environment, such as the loading conditions, can affect the performance of centrifugal clutches. High-speed and heavy-load conditions require robust materials to accommodate these stresses without compromising the functionality of the component (Liu et al., 2017). The relationship between the load on the clutch and frictional wear is partly why centrifugal clutches are often found in applications for smaller engines (such as motorcycles). Studies have shown that the geometry of the clutch components, along with the materials used, plays a significant role in managing heat generation during operation (Gkinis et al., 2019; Marklund et al., 2009), and therefore clutch wearing.

Material selection is a key point in the design of centrifugal clutches. The materials used in the clutch pads must provide adequate grip while also being resistant to wear and thermal degradation. The overall performance of clutch pads is influenced by their coefficient of friction, which determines how much perpendicular force is needed to adequately engage the clutch system. The quality of the component is also influenced by a combination of wear rate and hardness, which are properties of the materials used in their construction (Riyadi, 2023). Thermal management is another critical aspect of centrifugal clutch operation. The dynamic and thermal performance of clutch systems must be optimized to prevent overheating, which can lead to failure.

Composite materials, particularly those incorporating thermoplastics, have gained attention for their advantageous properties that can reduce wear rates and improve torque-carrying capabilities through better heat management. (Pon et al., 2023). This characteristic can improve efficiency and longevity in components when compared to more traditional materials. Metal matrix composites are also prominent in clutch applications; common metallic composites are reinforced with silicon carbide and aluminium oxide. Aluminium composites manufactured by 'stir casting' have been shown to have improvements in tensile and yield strengths, which make them suitable for heavier loads than other material choices. (Ali & Asiri, 2021; Dhanasekaran et al., 2015).

1.3 Fluid Mechanical Clutches' vs 'Centrifugal Clutches'

1.3.1 Fluid Mechanical Clutch Systems

Fluid mechanical clutches and centrifugal clutches are distinct designs with their own set of advantages and disadvantages. These characteristics dictate which applications each type might be used for. Fluid mechanical clutches, often utilizing magnetorheological (MR) fluids, offer several advantages. One of the primary benefits is that they provide smooth engagement and disengagement, which minimizes shocks on the drivetrain during operation (Liu, 2024). The use of fluid allows for rapid response times and more precise control over torque transmission. Additionally, these clutches tend to operate with lower noise levels compared to traditional mechanical clutches, enhancing user comfort due to a simpler structure (Liu, 2024). These characteristics make them suitable for applications requiring variable power distribution or smoother, quieter power transmission (Park, 2024).

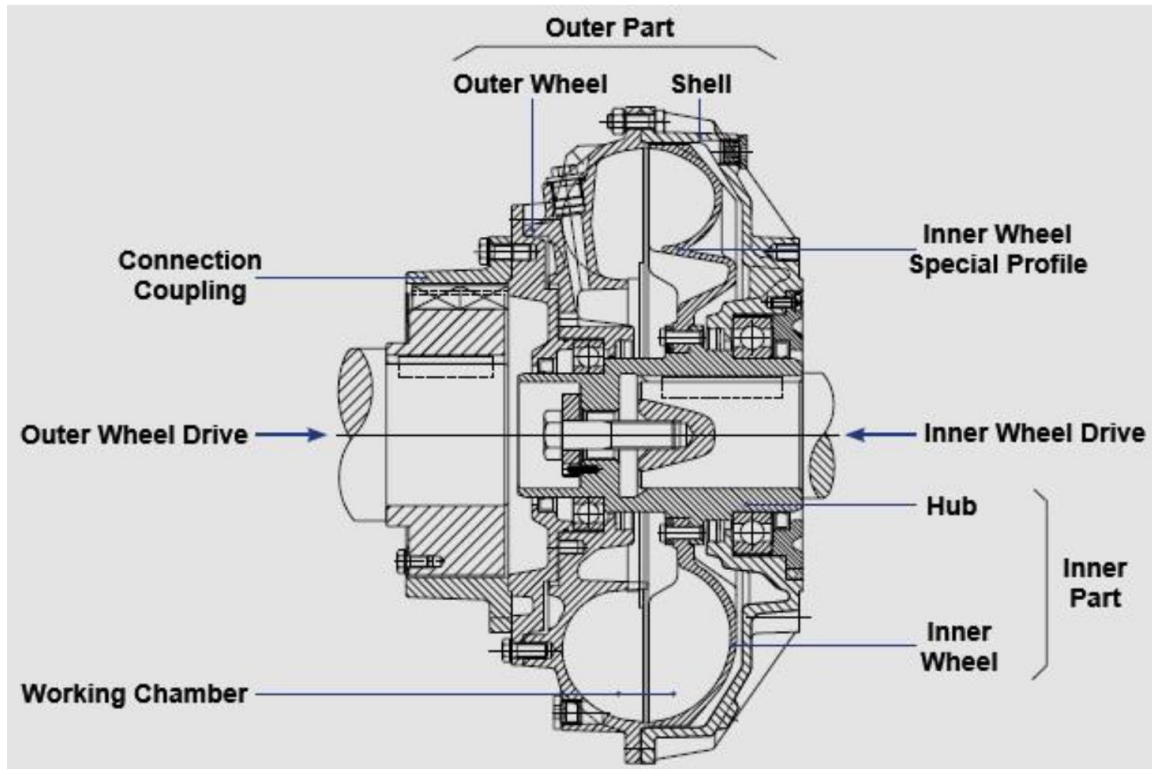


Figure 2 Fluid Mechanical Clutch Diagram (Shah, 2018)

However, fluid mechanical clutches also have disadvantages. Their design complexity can lead to higher costs in manufacturing and maintenance.

The requirement for a sealed mechanism to contain the fluid also increases the overall size, weight and potential failures of the system (Urakami et al., 2011). Furthermore, the performance of MR fluid clutches can be affected by temperature variations, which influences the torque output (Song et al., 2018), and so can introduce additional losses to the system. Aging of the MR fluid also leads to degradation in performance over time, necessitating more regular maintenance. Aging systems also have the potential of needed fluid replacements (Chen et al., 2019).

1.3.2 Centrifugal Clutch Systems

Centrifugal clutches are commonly used in applications where automatic engagement and disengagement are required, such as in automatic transmission systems. Centrifugal clutches benefit from a compact design which leads to reduced power loss during high-speed operation. They are also comparatively simple to manufacture and maintain (Raut, 2014). Despite these advantages, centrifugal clutches can suffer from limitations in torque capacity and can't provide the same smooth engagement as fluid clutches leading to excess wear and tear over time (Panchal et al., 2023), especially on the friction shoes and springs. The friction characteristics of centrifugal clutches also limit their reliability, due to being difficult to predict in varying operational conditions, affecting performance (Panchal & Patel, 2022). Moreover, they may not provide the same control over torque

transmission as fluid mechanical clutches (Panchal et al., 2023). A limited control causes centrifugal clutches to be unsuitable in systems requiring precise power management.

Generally therefore, fluid mechanical clutches offer smoother operation and a precise control over the power being passed through the transmission, but increased complexity and maintenance needs can make them an unattractive option in some applications. Centrifugal clutches provide a simpler and more reliable option for a means of transmission. Yet, centrifugal clutches are characterised by abrupt engagement, causing additional wear on components and rough transitions. They also have less control over torque transmission for more precise applications.

1.4 Electro Magnetic Clutches in modern automated systems

Electro-magnetic (E.M.) clutches utilize electromagnetism to engage and disengage the connection between the engine's drive shaft and the driven components. E.M. clutches allow for increased efficiency in power transmission due to the lack of mechanical engagement.

The basic principle of E.M. clutches is a direct current (DC) being passed through a wire coil, which generates a magnetic field around said coil. This EM field attracts the 'armature', shown in figure 2, and it's this attraction which causes the clutch to engage.

This type mechanism allows for precise highly control over the torque transmitted through the clutch by varying the strength of the magnetic field; this is achieved by in turn varying the current through the primary coil (Özdemir & Hartomacıoğlu, 2022; Diao, 2023).

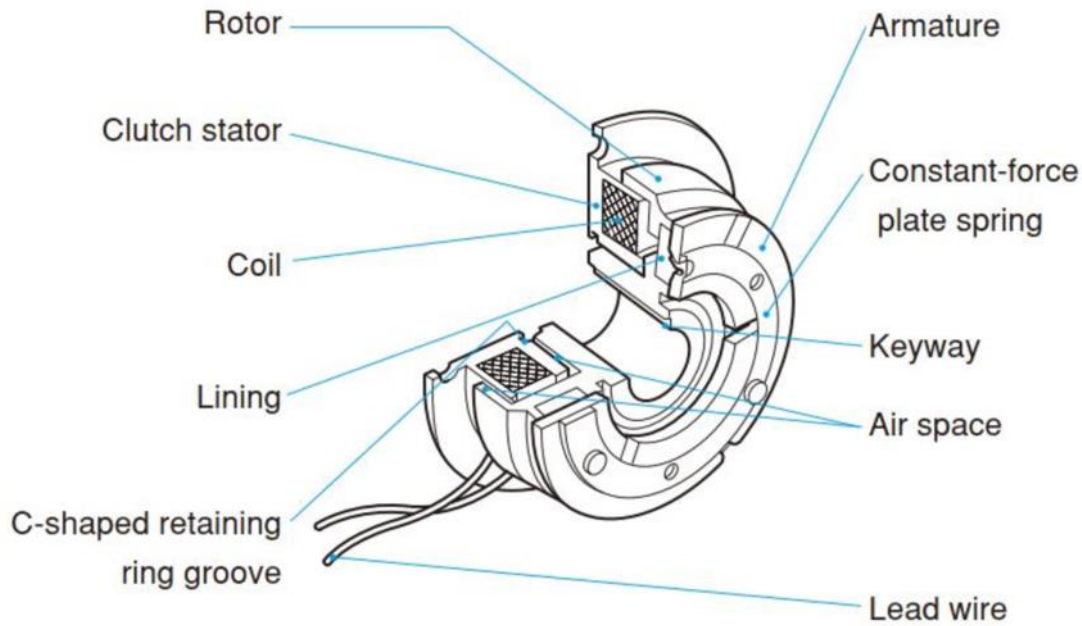


Figure 3 Magnetic Engagement Clutch (Özdemir & Hartomacioğlu, 2022)

In addition to the magnetic engagement of the clutch, the input of DC current can be connected to a digital control system to enable real-time adjustments based on varying operational conditions. This provides high levels of flexibility in the overall performance of the driven component(s). The implementation of control systems in automotive applications has demonstrated significant improvements in fuel efficiency. (Molina, 2024; Shin et al., 2013).

One of the primary advantages of electromagnetic clutches is rapid engagement and disengagement which is essential in high-speed processes which need reduced disengagement periods.

Electromagnetic clutches are commonly found where quick response times are critical. Examples of use cases include wire tensioning units and printing machines (Özdemir & Hartomacioğlu, 2022).

This technology is particularly beneficial in applications requiring human-machine interaction. These application types are an environment where safety and adaptability are paramount. Hybrid MR clutches, which combine permanent magnets with electromagnetic coils, further enhances their performance by providing a bias magnetic field that optimizes the clutch's operational efficiency (Moghani & Kermani, 2016).

2 Centrifugal Clutch Mathematical Model

2.1 Questions 1 - 3

The outer diameter of the driven drum is 216mm, including the material thickness. However, through these subsequent calculations it's important to keep in mind that many will be using, where relevant, the inner diameter which the centre of mass of the shoes are being taken to act at.

The engagement speed of the clutch is determined by the speed at which the centrifugal force equals the force needed to extend all 4 springs the 9mm clearance in the drum. This force is 270N, (67.5N per spring). Therefore, using $F = mw^2r$, the speed at which $mw^2r = kx$ is 464RPM.

The 'radial force' is taken to be the force acting perpendicular to the face of the friction shoes, which is equal to the centrifugal force minus the force applied by the spring. This resultant force will be expressed as 'R'. At 550RPM, the centrifugal force acting on all four feet is 380N, and so $R = 380 - 270 = 110\text{N}$.

Torque is given by $T = Fr$ and is expressed in Nm. When calculating torque, this value is only valid if the force is acting perpendicular to the distance or radius. In this scenario, all forces are perpendicular to each other, but some scenarios would require the use of $T = Fr \cdot \sin(\theta)$. This is because $\sin(90) = 1$ (maximal transmission of torque) while at zero degrees no torque would be transmitted (the force wouldn't cause any radial movement)

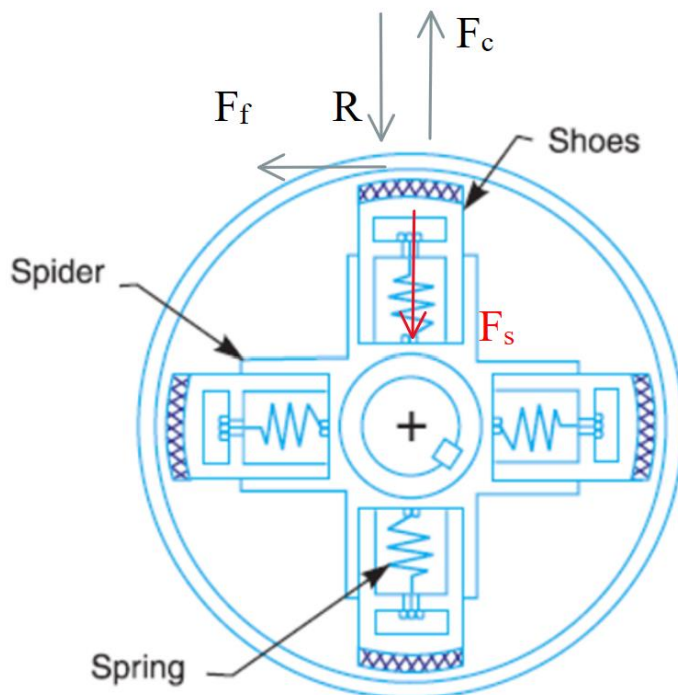


Figure 4 Diagram of Forces acting on the Clutch in Motion

In this case, the horizontal force transmitting force to the 'driven' drum is the force generated perpendicular to the direction of travel, which is the force generated by the frictional resistance. This friction force is proportional to the force acting on the inner surface of the drum (110N). The perpendicular frictional force is equal to $110\text{N} \times 0.35 = 38.5\text{N}$; where 0.35 is the coefficient of friction between the shoe and the drum. With this, we can use $T = Fr$ and find $T = 38.5\text{N} \times 0.104 = 4.01\text{Nm}$.

2.2 Computer Modelling

Table 1 shows a table of values which relate the RPM of the driving shaft to the transmitted torque to the driven drum. The first value in this table for friction shows a negative value. This is because at 450RPM, the clutch is yet to engage, and so calculated linearly, the value for friction-induced force would be negative. This needs to be interpreted through the context of the clutch system it represents, and so we can see the transmitted torque is actually zero.

RPM	'w'	F	R	Fr	T
450	47.1	253.7861	-16.2139	-5.67486	0
475	49.71667	282.7679	12.76785	4.468748	0.46475
500	52.33333	313.3162	43.31618	15.16066	1.576709
525	54.95	345.4311	75.43109	26.40088	2.745692
550	57.56667	379.1126	109.1126	38.1894	3.971698
575	60.18333	414.3606	144.3606	50.52623	5.254727
600	62.8	451.1753	181.1753	63.41135	6.594781
625	65.41667	489.5565	219.5565	76.84478	7.991858
650	68.03333	529.5043	259.5043	90.82652	9.445958
675	70.65	571.0187	301.0187	105.3566	10.95708
700	73.26667	614.0997	344.0997	120.4349	12.52523
725	75.88333	658.7473	388.7473	136.0615	14.1504
750	78.5	704.9614	434.9614	152.2365	15.83259

Table 1 Table of Values for $u = 0.35$

The values in the table have a higher degree of accuracy, given the assumptions made at the beginning of the calculations. This is due to the fact that excel can easily handle values to a higher number of decimal points than a manual calculation can handle. At an RPM value of 550, the torque of the manual calculation was 4.01, and in excel the same value was 3.972.

From the graph it's clear that the relationship between RPM and torque is linear. The gradient of this line is $0.056\text{Nm} / \text{RPM}$. This can be used as an important metric to measure the effectiveness of the clutch to transmit torque to the driven shaft within this model.

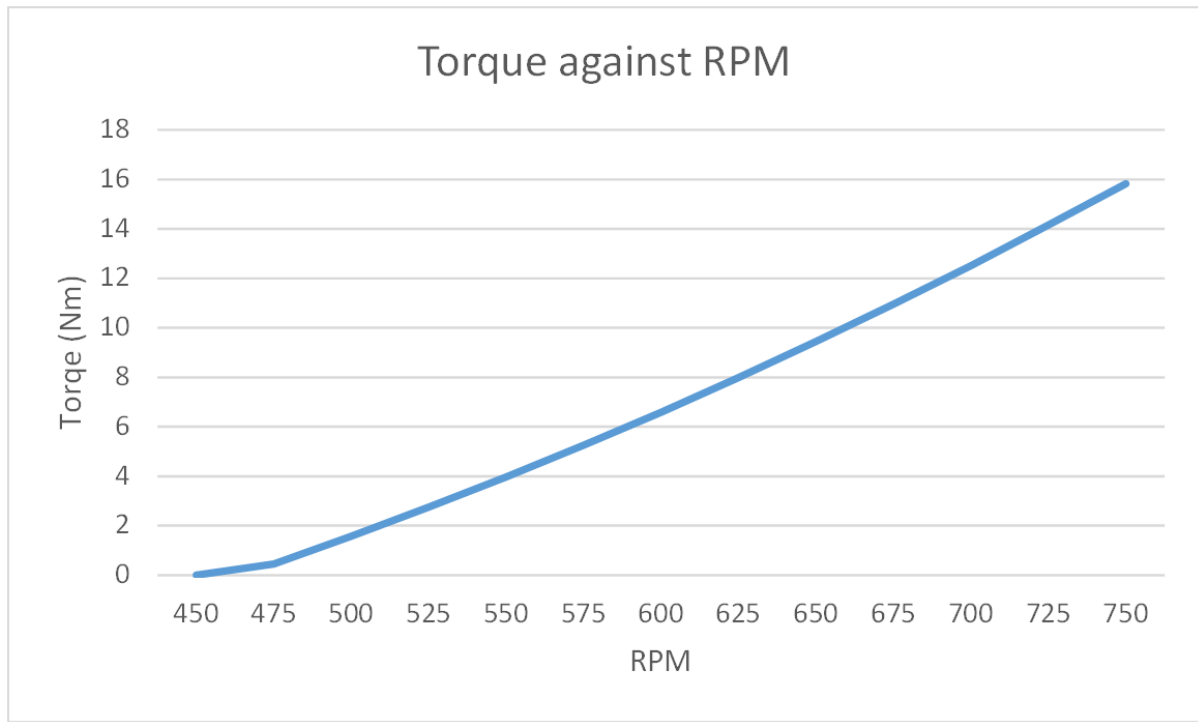


Figure 5 Torque plotted against RPM for question 5

Altering the coefficient of friction has a definite impact on the relationship, and therefore the gradient, between Torque and RPM. At a value of $u = 0.4$, the gradient = $0.0639\text{Nm} / \text{RPM}$.

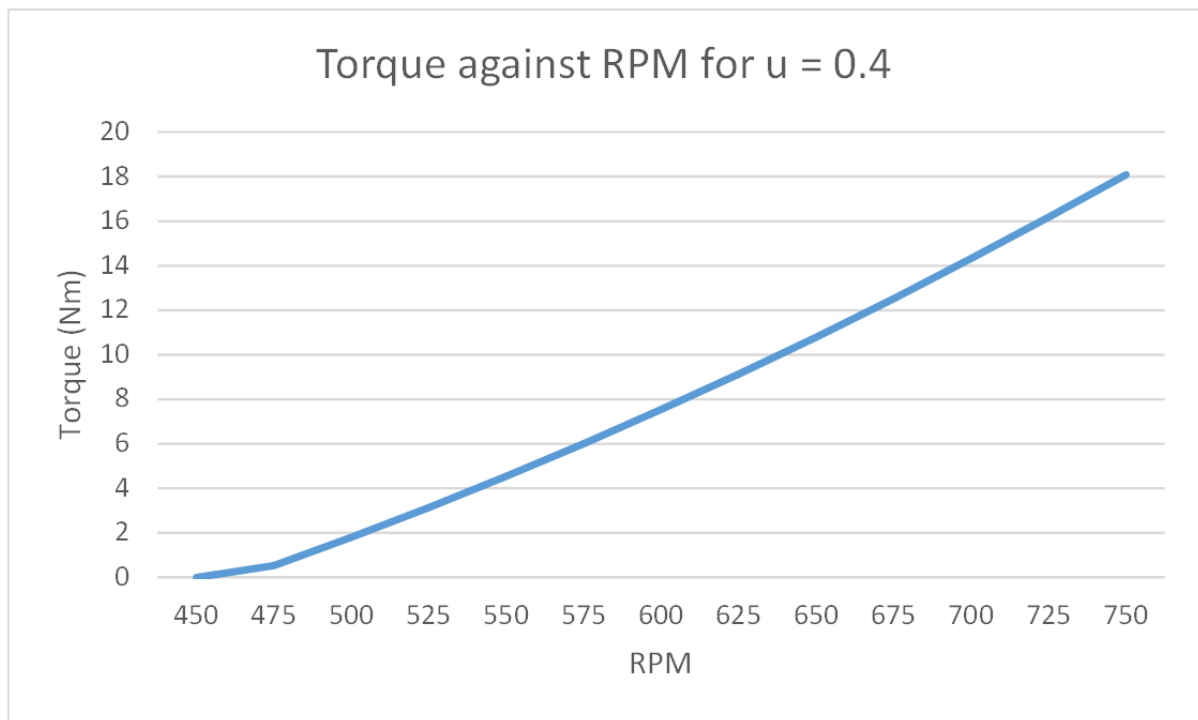


Figure 6 Torque plotted against RPM for $u = 0.4$

Similarly, reducing the effectiveness of the friction lining will reduce the torque transmitted to the outer drum. The gradient at $u = 0.3$ can be shown to be $0.0479 \text{ Nm} / \text{RPM}$.

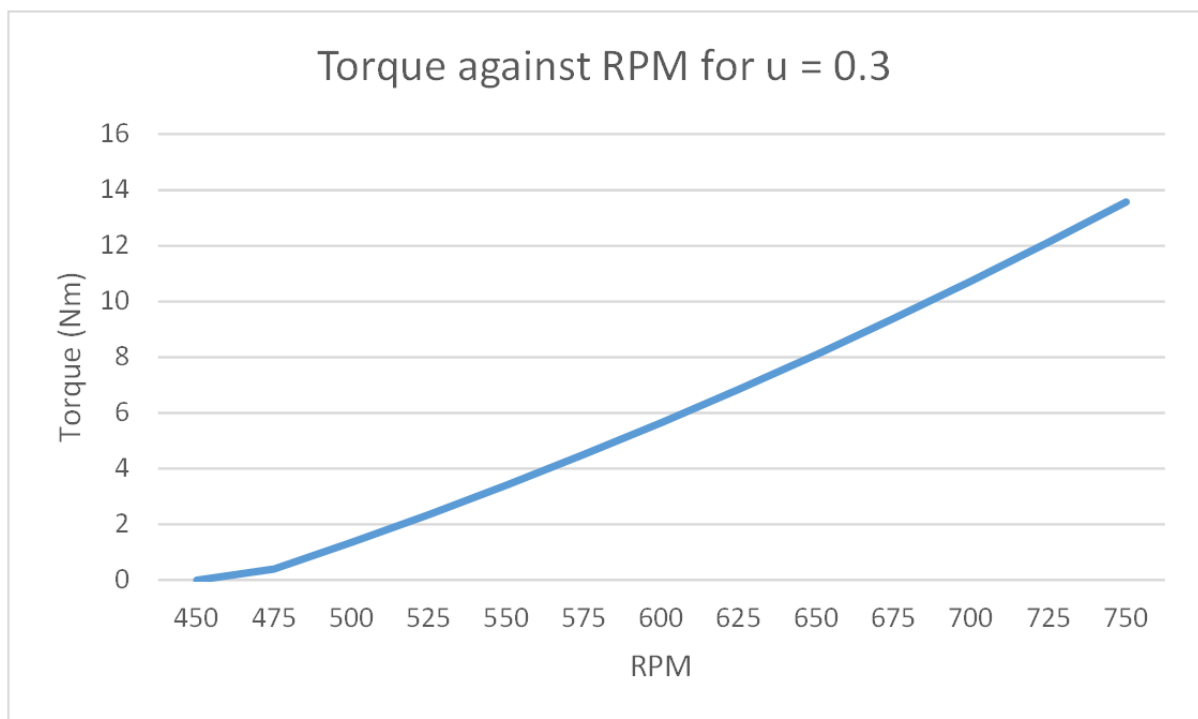


Figure 7 Torque plotted against RPM for $u = 0.3$

Taking these three points as discussed, we can use them to plot a graph which displays the effect on torque as the coefficient of friction is increased. Figure X extrapolates this relationship up to the maximum possible theoretical value for coefficient of friction, which would lead to a relationship of approximately 0.16Nm/RPM. This would represent a perfectly efficient system under the current model.

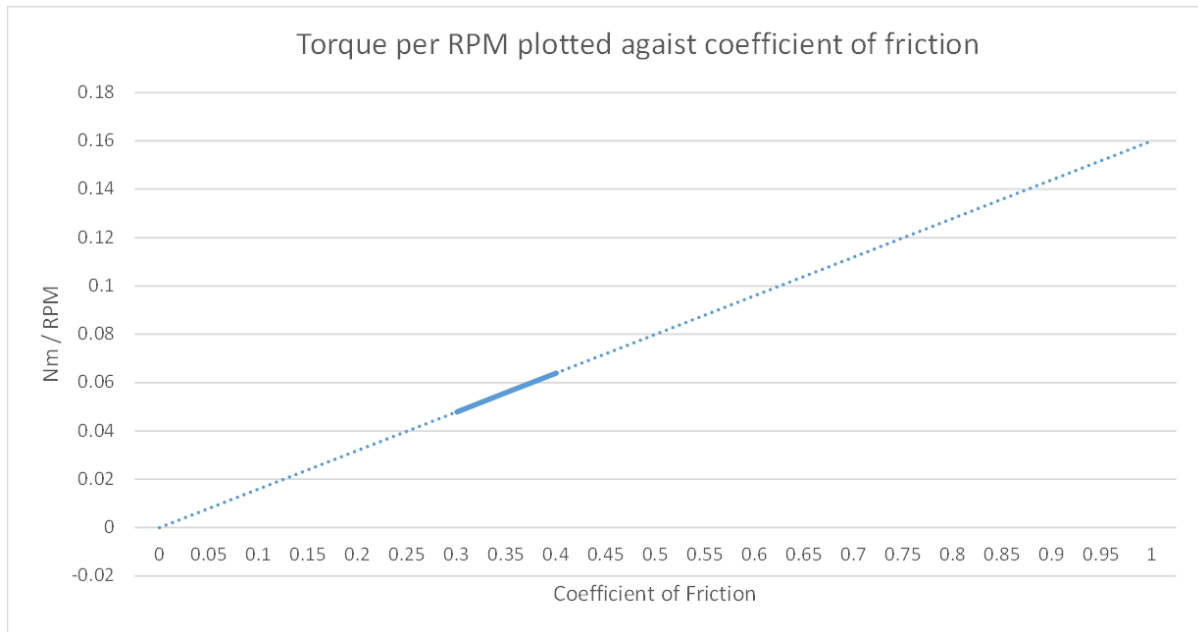


Figure 8 Torque per unit RPM plotted against the coefficient of friction at 550RPM

2.3 Questions 7 & 8

The maximum transmitted torque at 550RPM was calculated at 4.54Nm, as shown previously. Using the mass of the drum, and the equation $T = I\alpha$, the angular acceleration can be shown to be:

$$4.54 / (0.75 * 0.104^2) = 559.7 \text{ rads}^{-1}$$

The radius of the driven shaft is $0.0175/2 = 0.0088\text{m}$. Using this value, we can find the torque placed upon the shaft due to the braking force of 500N. The torque would be equal to 4.375Nm. Since this is a braking force, it would be acting against the direction of travel generated by the clutch. Therefore, the overall torque = $4.54 - 4.375 = 0.165\text{Nm}$. The angular acceleration from such a torque would be 20.34 rads^{-1} .

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