Chapter III

Description of Existing and Alternative Brakes

3.1   Existing Brakes

Figure 3.1: Dynacorp Model 310 Electromagnet Friction Brakes

PTER's actuators are slightly modified electromagnetic friction brakes from Dynacorp. These brakes utilize an electromagnet to generate a normal force between the friction material and armature plate (see Figure 3.2). The armature plate is mounted to the hub through pins. When energized, the armature plate is attracted by the electromagnet; sliding on pins to engage with the friction material. The material is non-asbestos and has a 0.45 coefficient of friction. Springs mounted on the pins provide disengagement force

when the coil is de-energized. Torque is transmitted from the friction material assembly
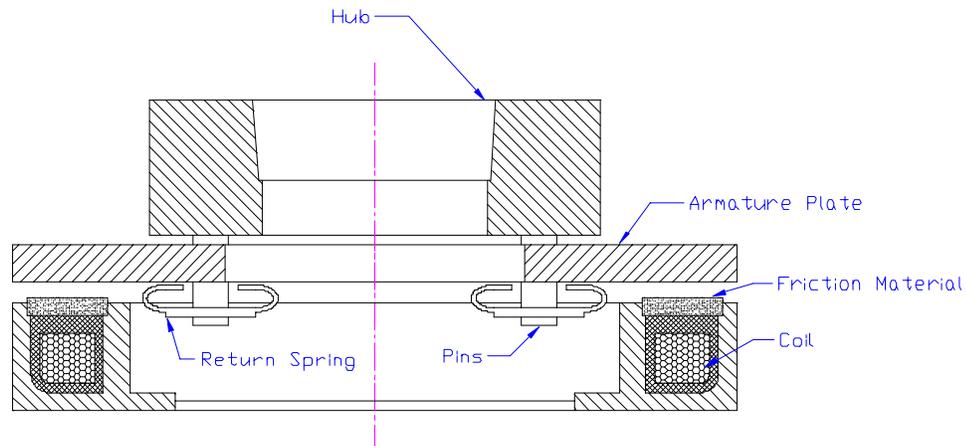
to the hub via the armature plate and pins.

Figure 3.2: Cross Section Sketch of Existing Brake on PTER

Table 3.1: Dynacorp Model 310 Manufacturers Specifications [Dynacorp]

DC Volts V	Cold Resistance Ω	Amps A	Coil Build Up Time to 63%	Static Torque Ft-Lbf (N-M)
12	10.1	2.376	0.105 s	300 (407)

Specifications for the brakes can be viewed in Table 3.1. It is common to assume

the force generated by an electromagnet is a function of applied current. Dynacorp rates

their clutches as having a time constant of 0.105 seconds for coil build up when a voltage

is applied. This obviously accounts for some of the dynamic response characteristics

found by past students. As stated in Chapter II, Gomes also noted that a pure time delay

existed. While using PTER an obvious clanking noise was present when the clutches

engaged and disengaged signifying armature plate motion as it came into contact with the

friction material. It can only be hypothesized that the pure time delay is a result of the

time it takes the armature plate to come into firm contact with the friction pad. In

addition, sliding action of the armature plate along the pins introduces unpredictable

frictional & binding forces against the plate's movement while engaging and disengaging.
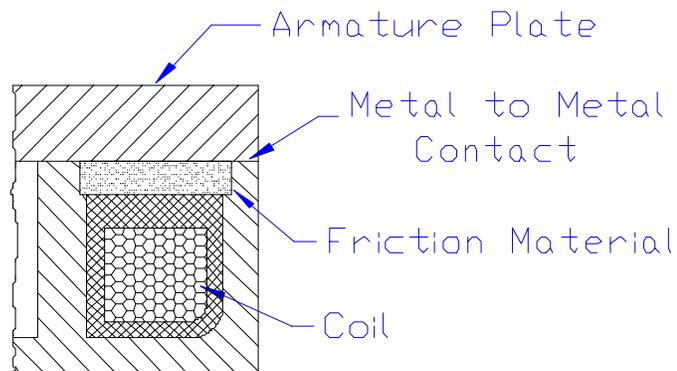

Figure 3.3: Original Brake with Metal to Metal Contact (Section View)

As mentioned in the section 2.1, the Dynacorp units originally had a metal to metal

contact when engaged. (See Figure 3.3) Evidently the brakes were designed to utilize this

metal to metal contact as a magnetic coupling between both halves, while the friction

material is only present to reduce wear and stabilize torque transmission. Because Robert

Charles originally intended on using contact between the friction material and armature

plate for torque transmission, he modified the brakes by removing the metal to metal

contact. As a result, the maximum torque that is now achievable is reduced from the

manufacturer's specifications. This is attributed to both reductions in friction surface area

and magnetic coupling. Originally, metal to metal contact provided a direct path for the

magnetic circuit. Now the magnetic field has to penetrate an air gap to attract the armature plate, decreasing applied normal force. (See Figure 3.4) Unfortunately it is hypothesized that variations in the air gap from brake to brake cause each unit to behave differently. Will Stone found the available maximum torque available from the brakes ranged from approximately 15 ft-Lbf (20 N-M) to 125 ft-Lbf (170 N-M). [Stone, 1995] Some of the variations in maximum available torque are due to insufficient power supplies used with two of the brakes, but this is not the only contributor.
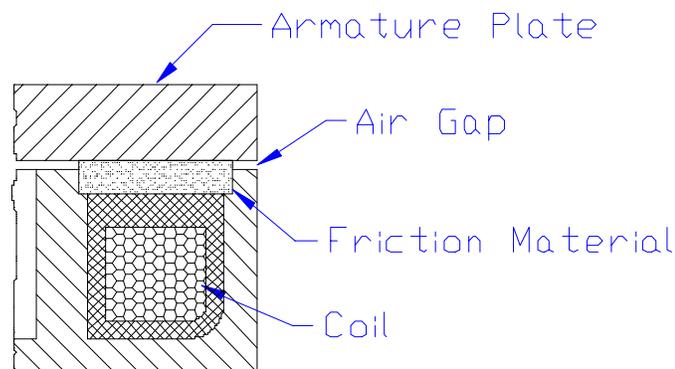

Figure 3.4: Modified Dynacorp Clutch (Section View)

3.2   Alternative Brakes & Clutches

The original Dynacorp brakes are off-the-shelf units intended for industrial use and are not ideal for our objective. They were constructed for large-scale applications where the intention is to slow down or stop heavy loads. By their physical design they were not intended for rapid modulation of desired torque transmission and do not have provisions for measuring actual torque transmitted. Because of their deficiency it was originally

intended to find new or alternative clutches that can be retrofitted to PTER. Several different clutches based on different physical phenomena's are available, but how well do they apply to the application of PTER? Do any of the available clutches have provisions for measuring applied torque for feedback? Of the clutches found, the following will be touched on:

1. Hysteresis
2. Eddy Current
3. Magnetic Particle
4. Electromagnetic Friction
5. Hydraulic & Pneumatic Friction
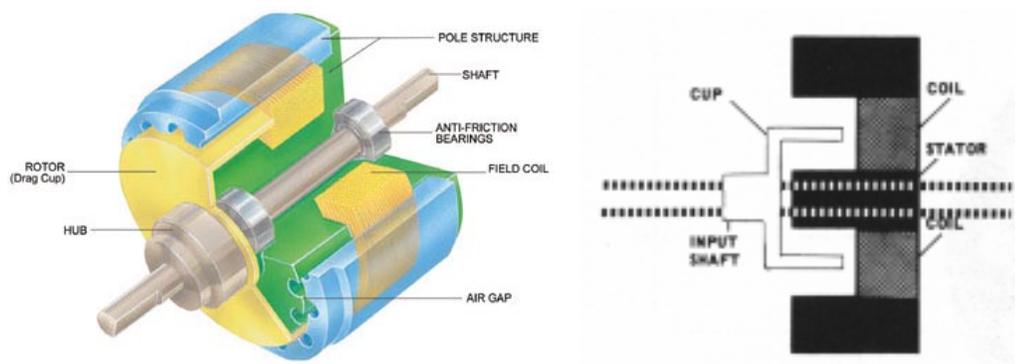6. Others & Custom

3.2.1   Hysteresis

Figure 3.5: Typical Magtrol Hysteresis Brake / Clutch [Magtrol] [Orthwein,1986]

Hysteresis clutches & brakes consist of two main parts, the rotor/drag cup and pole structure. The pole structure can be further separated into three sections; stator or inner pole, electrical coil, and case or outer pole. The rotor / drag cup is attached to a shaft and resides within a small air gap between the inner pole and outer pole. This rotor is made up of a magnetically hard material that resists changes in magnetization, promoting high-energy loss when magnetization does change. If the coil is energized a magnetic field proportional to applied current is formed within the air gap. As a result the rotor becomes magnetized, aligning (opposite) its induced poles with the inner and outer poles. Strength of the rotor's induced poles are proportional to the strength of the pole structure's magnetic field, which is dependent on the strength of the control current in the coil. Braking torque is generated by rotational motion forcing like poles of the rotor & pole structure together and opposite poles apart. As the rotor rotates it continuously establishes new magnetic fields to realign with the inner and outer poles. A front view of half a cross section can be viewed in Figure 3.6. By making the rotor out of a magnetically hard material the manufacturer can assure energy loss in the brake, which is converted to heat. Magtrol sells units ranging in maximum torque capabilities from 2.5 oz-in (0.013 Lbf-Ft / 0.0177 N-m) to 3200 oz-in (16.67 Lbf-Ft / 22.597 N-m).

Advantages of a Hysteresis clutch/brake is that torque is traditionally constant and smooth as the rotor is forced to rotate. In addition, braking torque is proportional to applied current and fairly independent of speed. There are no rubbing parts so they can provide a long maintenance free life and do not contaminate the surroundings with friction particles. No dynamic response information was given, but with the assumption

of applied torque proportional to applied current, it can be deduced that their dynamic

response would be limited to the dynamic response of the current (electrical) power
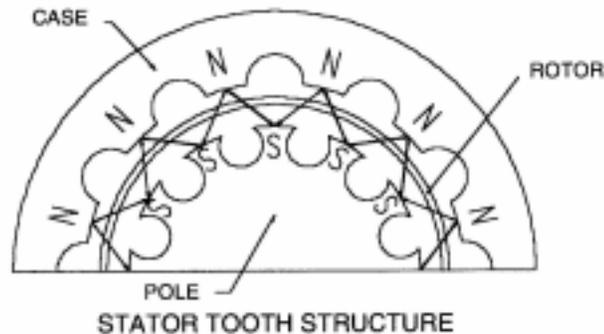
supply.

Figure 3.6: Pole Structure of an Energized Hysteresis Brake / Clutch [Magtrol]

A disadvantage of a Hysteresis clutch/brake is that resulting torque for a given

current has hysteresis. This is illustrated in Figure 3.7, a Torque vs. current plot from the

Magtrol literature. It can be observed that the torque for a given amount of control current

is different when increasing than decreasing. This can be attributed to hysteresis in the

magnetic material.

Another disadvantage to hysteresis clutches/brakes is the effect of cogging when

control current is not removed before the unit comes to rest, resulting in a bumpy motion

similar to turning a stepper motor that is not powered. This phenomenon results from

establishment of salient poles on the rotor. As mentioned above, the rotor's poles are

induced from the magnetic field in the air gap. In addition, the rotor continuously

becomes re-magnetized to align its polarity with the pole structure. If the rotor comes to

rest while the coil is still energized, its magnetic poles will become established. Now the

rotor will resist motion even if the coil is energized at a level less then when the salient

poles were established. To prevent this, the control current must be brought to zero before
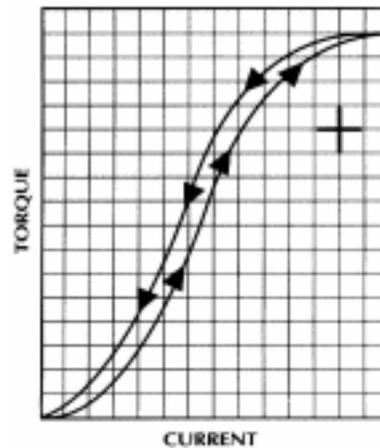
the rotor comes to rest.

Figure 3.7: Torque vs. Current Curve for Hysteresis Brakes & Clutches [Magtrol]

3.2.2   Eddy Current

Eddy current brakes & clutches are very similar to hysteresis units, both having a

pole structure with an inner & outer pole that is magnetized by an electric coil and a

rotor/drag cup that spins in the air gap. (See Figures 3.5 & 3.6) Eddy current clutches use

a magnetically soft instead of hard material for construction of the rotor, permitting the

rotor to easily change its magnetic polarization to match the inner & outer poles as it

rotates in the air gap. This allows the phenomenon of generated eddy currents in a

conducting material whenever magnetic field changes. These eddy currents are formed in

a direction to oppose the varying magnetic field across the rotor (varying as seen by the

rotating rotor). The torque generated by these opposing eddy currents is dependent on both strength of the magnetic field and rate of change for the varying magnetic field seen by the rotor. This translates into a brake whose torque is dependent on both coil excitation and relative velocity of the rotor with respect to the pole structure. Therefore the transmitted torque increases with both control current and slip speed of the clutch. (See Figure 3.7) These clutches can almost be thought of as a programmable damper between the rotor and pole structure where applied torque depends on relative rotational velocity. The fact that they can not deliver torque at low slip speeds makes Eddy Current brakes & clutches not suitable for our application. Furthermore, these clutches are usually designed for applications much larger than PTER.
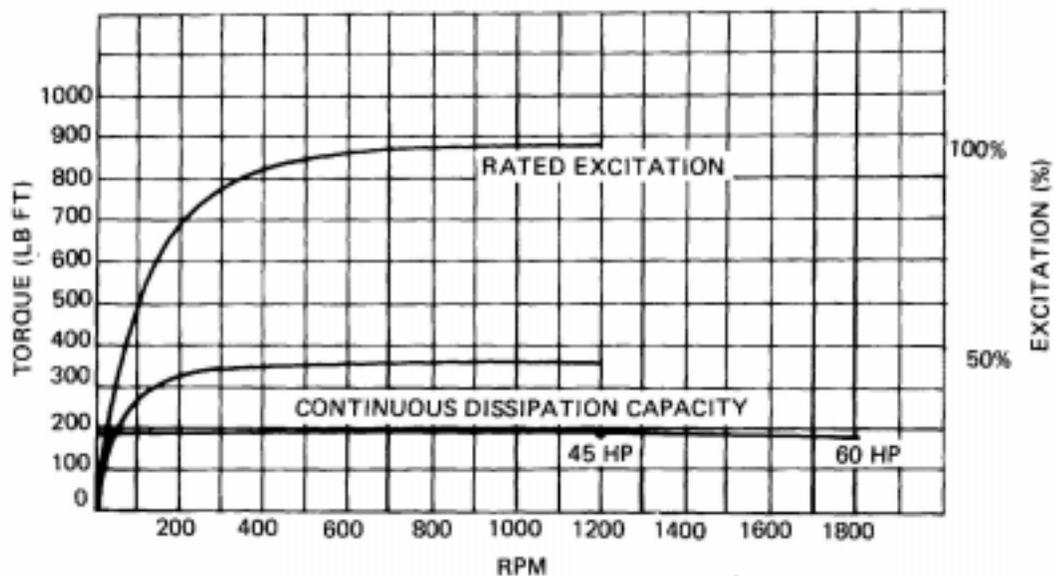

Figure 3.8: Eddy Current Torque vs Slip Speed [Orthwein,1986]
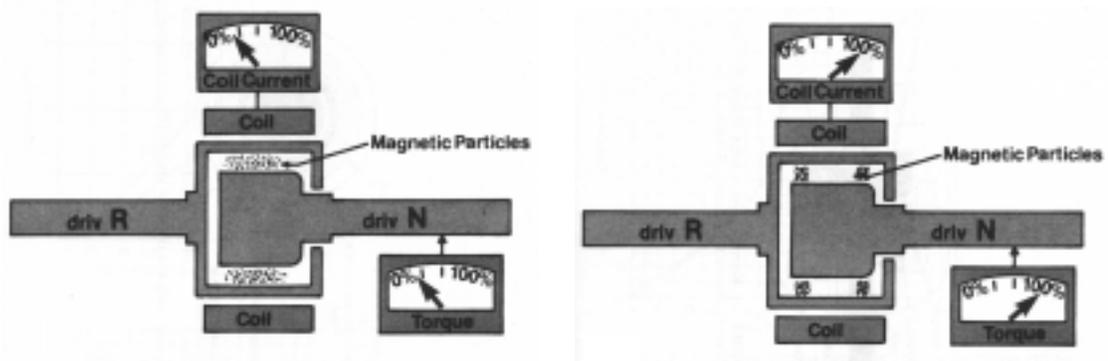
3.2.3   Magnetic Particle

Figure 3.9: Magnetic Particle Clutch / Brake [Orthwein,1986]

Magnetic Particle clutches are constructed of a concentric input shaft and output

shaft (or housing if a brake) separated by a gap filled with a fine dry magnetic powder.

An electric coil is mounted around the outer most members. (See Figure 3.9) When the

coil is not energized the input and output shafts are allowed to rotate independently of

each other. As the coil is energized, a magnetic field is generated across the magnetic

particles causing them to attract each other, align, and bridge the gap between the input

and output shaft. When attracted to each other the particles resist relative motion between

the input and output shaft (or housing if a brake) through tensile and shear stresses. The

strength of the resistance is dependent on the magnetic field generated by the coil,

conversely the amount of control current supplied to the coil. A Torque vs. Current chart

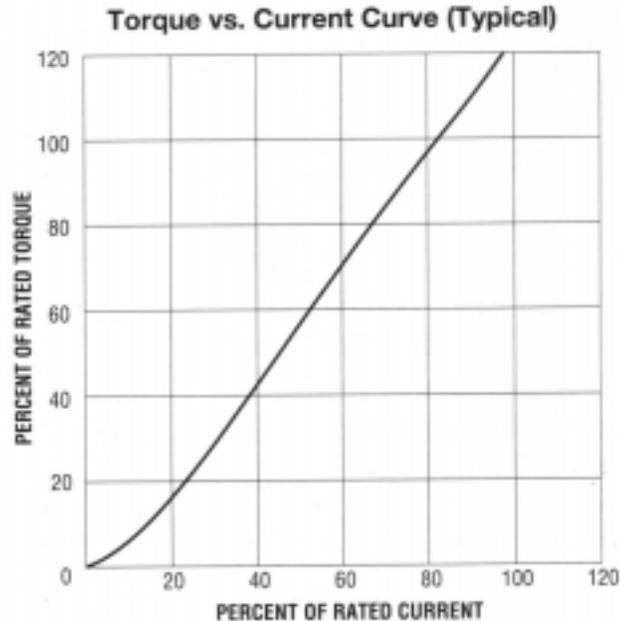from Warner Electric Literature can be viewed in Figure 3.10.

Figure 3.10: Torque Chart for a Magnetic Particle Clutch [Warner Electric, P-1107 2/97]

Benefits of Magnetic Particle Brakes/ Clutches are that transmitted torque is independent of slip speed and they provide smooth operation at relatively low speeds. Units from various vendors are available with torque limits ranging from 5 Oz-in (0.026 Lbf-Ft, 0.0353 N-M) to 738 Lbf-Ft (1000 N-M). For a step voltage input, magnetic particle brake & clutches have a time constant ranging from .009 to1.31 seconds depending on the size. It should be noted that the magnetic field generated by a coil is more closely related to the applied current, therefore much of the response time is due to the dynamics of coil build up. Dynamic response of the brakes can be drastically improved if current control were implemented. Because these clutches are sealed and the only rubbing parts are magnetic particles, they too provide a long maintenance free life and do not contaminate the environment with friction particles. One disadvantage of

magnetic particle brakes/clutches is that they are required to occasionally turn a full

revolution to keep particles evenly distributed. One manufacturer (Magne Corp.) claimed

that their units required a minimum slip speed of 30 RPM to operate properly. Another

manufacturer (Placid Industries) commented that their units would not perform well if

subjected to back & forth motion through a narrow angle. These requirements prevent

their feasibility of being used with PTER in its current configuration. Presently PTER's

clutches do not turn a full revolution and are subject to back & forth motion through

narrow angles.

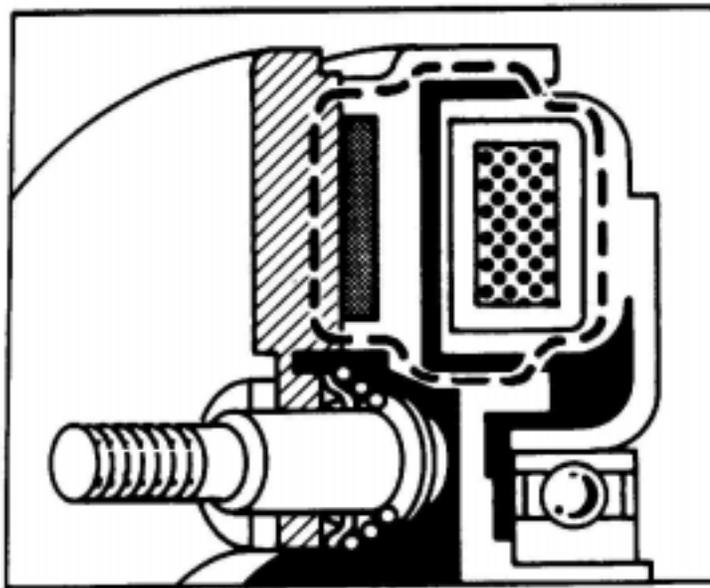### 3.2.4   Electromagnetic Friction

Figure 3.11: Magnetic Circuit Completion [Warner, P-1000 12/94]

The description of PTER's existing brakes is typical of industry available electromagnetic actuated friction brakes & clutches. They consist of an armature plate that is pulled toward a friction surface by an electronic magnet. The friction surface material consists of both steel and a friction material. The purpose of the steel is to complete the magnetic circuit and provide a positive couple between the two clutch halves, while the friction material only serves the purpose of reducing metal wear and stabilizing torque under slip conditions. Figure 3.11 illustrates the completion of such a magnetic circuit as designed by Warner Electric. The armature plate usually is retracted by a spring mechanism when the magnetic field is terminated.

Electromagnetic actuated brakes & clutches with maximum static torque ratings ranging from 5 oz-in (0.026 Lbf-Ft, 0.0353 N-m) to 465 Lbf-Ft (630 N-m) are readily available. Some manufacturers utilize multiple disc surfaces and supply units capable of handling up to 3,000 Lbf-ft (4,067 N-m). Other manufactures use a toothed mating surface instead of a friction face so that both halves interlock when engaged. Brakes & clutches based on this design are not intended for engagement while the two surfaces are rotating at significantly different rates. Because engagement of electromagnetic friction clutches and brakes consist of both an electrical and mechanical response, their dynamic properties are more complex then previously discussed clutches & brakes. The graphs in Figure 3.12 are dynamic response plots from Kebco's literature on their units. Kebco's representation is fairly typical of electromagnetic friction clutches & brakes. The symbols in the figure are as follows:

I   Resulting current running through the magnet

M   Torque

M_{2N} Rated Torque

t_1 Engagement time:
Time to reach 90% of the torque from when control voltage is applied to the coil

t_2 Switch Off Time:
Time it takes to reach 10% of the toque from when control voltage is removed

t_{11} Mechanical delay:
Time it takes for the armature plate to contact the friction surface from when voltage is applied.

t_{12} Rise Time:
Time it takes to reach 90% of the torque from when the armature plate contacts the friction surface
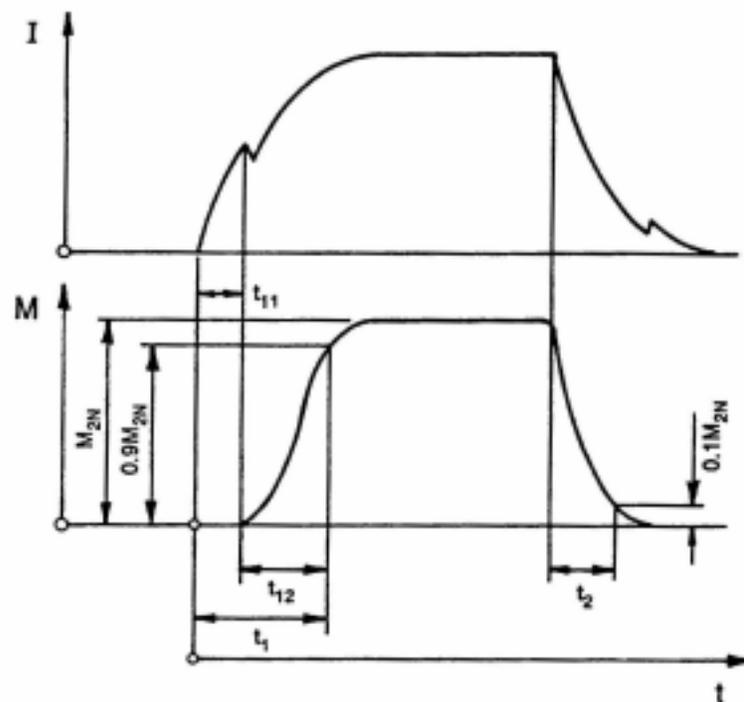

Figure 3.12: Electromagnetic Brake Dynamic Response [Kebco]

From the figure it can be seen that the mechanical delay is a result of both the coil building up enough magnetic force to move the armature plate and the time it takes to complete the motion. It should be noted that the instant the armature plate comes into contact with the friction surface corresponds to a dip in the current curve. This signifies a change in electric circuit properties due to a change in the coil's inductance, a phenomenon resulting from the magnetic circuit changing as the two halves come together. It can be assumed the beginning of the dip represents when current is sufficient to provide enough magnetic force to move the armature plate and the end of the dip corresponds to when the plate comes to rest against the friction surface. It appears the current rise for a step input is 1st order, as expected from a R-L circuit. The figure also shows that decay of the coil current and resulting torque has a dynamic response similar to engaging, except a rise (blip) in the current curve represent the armature plate separating from the friction surface. Kebco, which sells units ranging in maximum static torque capabilities of 0.4 Lbf-ft (0.5 N-m) to 370 Lbf-ft (500 N-m), claims initial delay times ranging from 0.004 to 0.055 seconds, rise times ranging from 0.006 to 0.240 seconds, and corresponding engagement times from 0.01 to 0.295 seconds depending on the size of the unit. Most vendors claim dynamic response can be drastically improved through use of initial over voltage. It can only be assumed that if a step current (ideal current source) were supplied instead of a step voltage, the dynamic response would show significant improvements. Disengagement time can also be improved though use of reverse voltage to quicken current drop in the R-L circuit.

3.2.5 Hydraulic & Pneumatic Friction

Hydraulic and pneumatically engaged brakes are similar to electromagnetic friction units, except they utilize a fluid under pressure for providing normal force of the armature plate against the fiction surface. Because these brakes & clutches do not rely on magnetic coupling of the two halves, no metal to metal contact is necessary. Other configurations may consist of a caliper or cylinder that forces friction pads against a rotor or drum. For example, most vehicles on the road contain either hydraulic or pneumatically actuated brakes. Computer control for hydraulic units can be realized through use of an electronic (solenoid) pressure valve that modulates supply of hydraulic pressure. Similarly, a current-to-pressure (I to P) valve can be used with pneumatic brakes & clutches. One disadvantage of hydraulic units is the introduction of hydraulic oil into the workspace. This may not be desirable for applications where a relatively clean environment must be kept. Because pneumatic brakes & clutches rely on compressible fluid, their dynamic response may not be easily controlled when attempting torque modulation.

3.2.6   Others & Custom

Brakes & Clutches based on electrorheological technology are starting to get more attention. These units are similar to magnetic particle units, except that a special fluid instead of magnetic particles fills the gap. This fluid contains particles suspended in oil that adhere to each other with an adhesion proportional to an applied voltage through the

fluid. At zero excitation the mixture acts like a fluid but as voltage increases it starts to behave more like a solid. This results in coupling of input and output (or housing if brake) that is proportional to control voltage. Electrorheological clutches & brakes are still an emerging field and not much information is available.

Custom brakes based on alternative technologies may be designed and built in house. Such brakes may be based on traditional mechanical forms, but utilize non-traditional actuation. Such examples might consist of a band or caliper brake that use a servomotor with a lead screw, electric solenoid, or piezo-electric as the actuator providing normal force to the friction surfaces.

3.3   Assessment of Alternatives

Several alternative brake & clutch technologies have been outlined in the previous sections. Unfortunately none of the available brakes & clutches showed ideal characteristics. Hysteresis clutches were not selected because of the cogging phenomenon and hysterisis characteristic of applied current vs. torque. Eddy current clutches were disregarded because resulting torque was a function of slip velocity, preventing them from applying torque at low speeds. Hydraulic actuated units were not considered because of their impact on the environment. Pneumatic units were avoided because it was hypothesized that compressible fluid would hinder bandpass capabilities, preventing quick modulation of applied torque. Additionally, it was decided that alternative electromagnetic friction brakes & clutches would not offer any advantages over the existing Dynacorp models.

This leaves either Magnetic Particle clutches & brakes or a custom in house design as remaining options. Stated earlier, magnetic particle clutches are required to turn a full revolution to redistribute particles and should not be subjected to back & forth motion through small angles. One option to overcome this is to modify PTER by mounting timing belt pulleys in place of the existing brakes. Magnetic particle units could then be mounted behind PTER. By connecting magnetic particle clutches to PTER's shafts through a geared timing belt, the clutches can be forced to turn at a rate much faster then the existing units; increasing the angle of travel the clutches rotate, allowing them to complete a full revolution. This solution was not pursued because the complexity of the system would be increased. In addition, by spinning the clutches at a faster rate their inertia becomes magnified by the square of the gear ratio. A component that had little impact on the system could now become a dominant factor in the system's dynamics.

None of the available clutches & brakes incorporated provisions of measuring applied torque for feedback control. To make matters more complicated, very few of the available units could be bolted in without extensive modifications to PTER. For this reason it was decided to modify in house and thoroughly model the existing Dynacorp brakes to better suit our needs.