

Design, Modeling, and Prototyping of an Actuator Suitable for All Wheel Drive (AWD) Systems

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ABSTRACT

An electromechanical actuator appropriate for various drive-train actuation applications has been developed. Brushless direct current (BLDC) motor technology was implemented to provide the required dynamics and reliability, with an integrated electronic control unit (ECU) to minimize the packaging volume and system cost.

We determined basic performance requirements for the actuator using a simplified mathematical system model, focusing on transforming the required actuation profile into speed and torque profiles for the motor. We incorporated a baseline assumption for the motor sizing into a Simulink model that represented the electrical, magnetic, and mechanical elements of the system. The process created several iterations of the model used to refine the motor sizing and predict the overall performance of the actuator.

The motor requirements developed from the Simulink modeling effort established a magnetic design for the motor. This effort focused on obtaining the required speed-voltage, torque-current, and inertia characteristics while also considering manufacturability. A combination of magnetic finite-element-analysis (FEA) modeling and other analytic techniques determined the motor performance and reliability.

As BLDC motors require external commutation to operate, we designed a robust power electronics module to modulate the direct current (DC) input voltage into a three-phase variable-voltage/variable-frequency alternating current (AC) signal. The goals of minimizing the power losses and maximizing heat transfer to the actuator housing drove the selection of a set of six metal-oxide-semiconductor field-effect transistors (MOSFETs) placed on a printed circuit board (PCB) with an aluminum substrate. A separate PCB packaged a microcontroller and other logic-level devices required for vehicle bus communication and general input/output (I/O). We designed embedded software to commutate the motor using a space-vector technique.

Packaging of the motor and ECU into the overall actuator assembly required the balancing of thermal performance, packaging volume, system cost, and manufacturability. Linear mathematical models established baseline requirements for heat transfer performance, with the results establishing the basic package outline and materials. Subsequent to the initial design, thermal and mechanical FEA verified the proper characteristics of the housing components, with the design iterated as necessary to balance various performance aspects.

The resultant actuator prototypes demonstrated performance that was not only appropriate for the application, but also correlated well to the various models that were created during the design process. With the test data collected from the physical samples, it is possible to obtain better accuracy during future product development cycles.



INTRODUCTION

A differential is a vital component in a typical automobile powertrain configuration. It is responsible for transmitting power from the drive shaft(s) to the drive wheels enabling the vehicle to move. A standard differential holds the ring and pinion in place and gives the vehicle its final drive ratio. When a vehicle negotiates a turn, the outside wheel must travel farther (turn faster) than the inside wheel. Differential gearing allows the outside wheel to turn faster, while the inside wheel turns slower enabling better vehicle control and more efficient power transfer. This differentiating action is simple in a standard open differential and works sufficiently for most of the vehicles on the road today; however, they do suffer when encountering a low traction or slippery surface. When a vehicle with an open differential encounters a low traction surface, it directs power to the wheel with the least amount of traction. The net result becomes the wheel on the low traction side spinning while the opposite wheel with high traction receives little to no power leading to a decrease in vehicle stability and loss of power transmitted.

Several solutions counteract low traction caused by a slipping wheel; limited slip differential (LSD), fully locked differential, and electronic limited slip differential (eLSD). Limited slip differentials transmit equal torque to both wheels via a set of clutch plates; the preload applied to the clutches increases with the input torque to the differential. This system provides torque control that is roughly proportional to the rate of acceleration. This mechanical configuration works well in rain, mud and snow. However, in situations where absolute lockup is needed, a limited slip does not provide enough resistance and the differential acts like its open or standard counterpart. A fully locked differential provides no slipping under a load when locked and acts as an open differential with no load. Several types of these differentials allow the driver to engage or disengage a locker using either a mechanical lever, electronic switch, or an air valve. Automatic type lockers are also available. Problems with differentials of this type (when engaged) occur when turning the vehicle around a corner while accelerating. This tends to drive the car in a straight line due to the two drive wheels rotating at the same exact speed, or in off-road conditions where low traction allows one or more tires to slip when traveling along a curved path.

The above passive devices have a limited ability to change their behavior such that they do not “upset” the vehicle in certain conditions. As such, mechanical limited-slip differential systems are implemented in a very conservative nature that favors stability over ultimate performance. In addition, normal use often wears out a mechanical limited-slip differential early in the life of the vehicle.

Electronic limited slip differentials overcome the limitations of a purely mechanical system by adding active electronically-controlled elements to provide a controlled amount of differential lock-up that is appropriate for the vehicle conditions. This requires an electrical machine (motor) that generates energy transferred to one or more clutches in the differential. Wet or dry clutches may be employed requiring linear motion for actuation. The dry type employs gears at a reasonable cost, but at reduced flexibility in mounting the electric motor (remote mount would be nearly impossible) and requires one actuator per clutch pack. The wet type (hydraulic motor/pump combination) offers an extremely high energy density, allows the independent operation of multiple clutches with one actuator, and provides enormous mechanical advantage. Challenges come through the variation in fluid properties over operating conditions creating difficulty in controlling the amount of force applied to the clutches, leaks, and fluid contamination.

SYSTEM ARCHITECTURE

A Hydraulic Clutch Actuator (HCA) generates a flow of hydraulic fluid to create relative movement between two mechanical components. For the eLSD system, the fluid flows into a piston, accumulates a pressure, and moves the piston. This movement translates force applied to a clutch. The HCA indirectly controls the torque transmitted from a differential to a drive wheel. Engaging a clutch at various forces controls the torque achieved. This system torque capability extends from 100% to 0% torque transmitted. This results in improved fuel economy, enhanced performance, and greater overall safety on a vehicle level.

A pump driven by a BLDC motor creates the fluid force by filling the piston and enables clutch pressure and torque control. The motor receives a message via the vehicle controller area network (CAN) bus (CB) activating it to the appropriate control point. Figure 1 depicts this simplified flow.

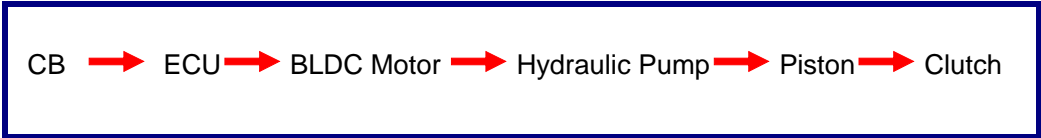


Figure 1: eLSD Actuator Flow Control

As installed in application, the HCA interfaces with the vehicle through mechanical mounting, 2 hydraulic ports (high pressure side & low pressure side), and an electrical interface. The low side line contains an orifice near the piston providing a constant leakage back to sump. A pressure sensor installed inside of the HCA closely monitors the piston pressure. This configuration allows variable pressure profiles to be applied to the clutch, thus allowing optimal torque biasing in the differential. This physical arrangement exposes the HCA to the elements.

From an electronic controls view, the eLSD system architecture is quite complex. Figure 2 diagrams a similar architecture as applied to a yaw stability control system [1]. Over CAN, the HCA interfaces with the engine ECU, the steering wheel ECU, stability system ECU, and a diagnostics controller. Both battery and ignition inputs feed the HCA. Other sensor inputs available on the network include vehicle yaw rate, pedal position, steering angle, wheel speeds, piston pressure, engine speed, and temperature.

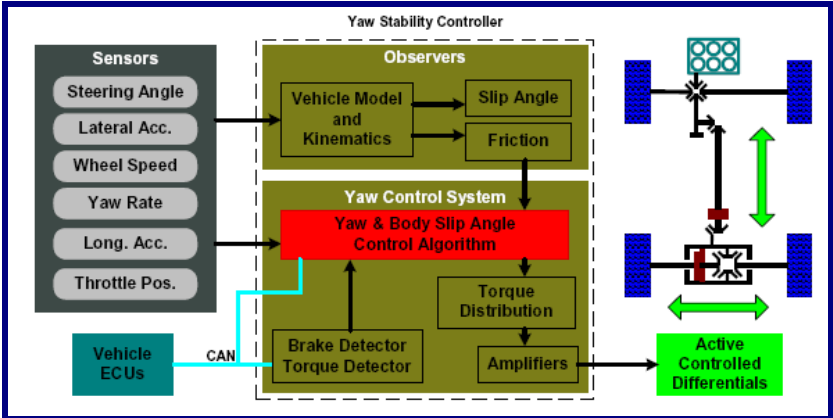


Figure 2: eLSD System Architecture [1]

The basic HCA architecture consists of three main sub-systems; the pump, motor, and ECU. The pump provides the flow and pressure accumulation of the hydraulic fluid (flow and pressure requirements), the motor drives the pump (power requirements), and the ECU controls the motor (control algorithm). The ECU receives a message from the CAN bus, interprets it, and applies the proper power to the BLDC motor. The motor converts this power at the proper speed to the pump for the piston to receive the optimal pressure within specific time durations. A temperature and pressure sensor governs this control. Figure 3 depicts the HCA sub-systems.

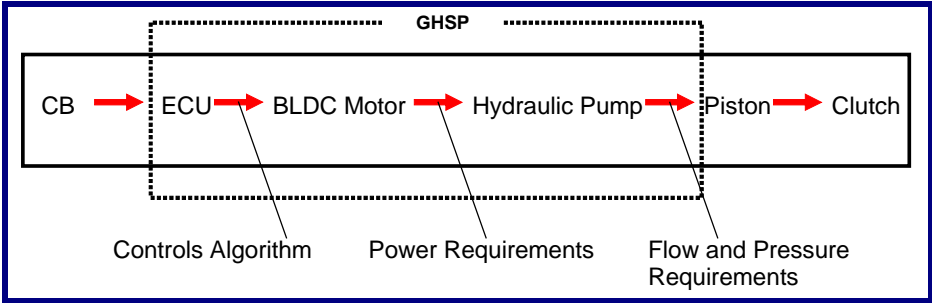


Figure 3: HCA Sub-Systems

SYSTEM SPECIFICATIONS

The HCA must survive harsh environmental conditions. It must perform through a wide temperature range, high and low frequency vibrations, and several other uncontrollable conditions. The following list identifies the general specifications of the HCA [2].

- Operating Voltage: 9 to 16 Vdc
- Operating Ambient Temperature: -40 to +120°C (adjusted performance at temp extremes)
- Pressure Response: full pressure step response in 0.1 s and < 30 A of current peak
- Nominal Current Draw (12 V): 3 A to produce 20 bar (290 psi), 10 A to produce 45 bar
- Expected Life: >10 years of life in underbody automotive environment
- Each On Minute: 44% full pressure for 10 s, preload = 0.2% full pressure for 50 s
- Duty Cycle: above cycle active 50% of time for 10 years
- Communication: high speed, dual wire CAN
- Temperature Sensor Input: external negative temperature coefficient thermistor
- Internal Sensors: temperature and pressure
- Mass: < 2.5 kg

PRESSURE ACCUMULATION TIME IMPORTANCE – the 0.1 second pressure response for this type of application is absolutely required to meet the proper performance characteristics. For example, if the specification read pressure build up achieved in 1 second, it allows the slipping wheel to rotate freely for about 4 revolutions (assuming traveling at 45 mph and torque transfer begins at about mid-point). This starves the traction wheel from torque for an undesired duration. Building up the pressure in 0.1 seconds stops the slipping in under a half of revolution enabling stable vehicle dynamics.

DUTY CYCLE - the duty cycle determines the performance and thermal effects of different actuation profiles. The specification calls out an aggressive duty cycle of 50% with 80% of the on time at 0.2% pressure. This level needs to be held for 50 seconds. This operating point requires little hydraulic power, but high current consumption due to the inefficiencies of the motor at low speeds. The BLDC motor may have an overall efficiency of 89% at 3000 rpm (revolutions per minute); however, at 200 rpm it may only have a 30% efficiency. The majority of energy gets wasted and leaves the system though heat raising the issue of thermal dissipation and component durability.

MATHEMATICAL MODEL

When developing an HCA to specification, system model development ensures the components will perform as desired. The modeling provides insight to frequency characteristics, correct sizing of components, and overall performance characteristics. The basic components involved in the system model for the HCA include the clutch pack, piston, pump, BLDC motor, and the hydraulic fluid flow paths. The modeling effort starts by characterizing and analyzing the behavior of the hydraulic fluid.

OBJECTIVE & IDENTIFICATION - develop a Simulink model of the HCA system that includes a brushless DC motor, an external gear pump and a spring loaded piston load as its main components [3]. The Simulink model developed in this task integrates:

- open-loop 3-phase BLDC motor
- modulation index (MI) calculation block [4]
- incorporate the BLDC model with gear pump model
- a speed control and torque control block to run the overall simulation

Figure 4 gives the block diagram of the external gear pump along with BLDC motor [3]. This model includes the BLDC motor model as a separate block. The inputs to the BLDC motor are requested torque and motor speed. We run the model to verify the BLDC block.

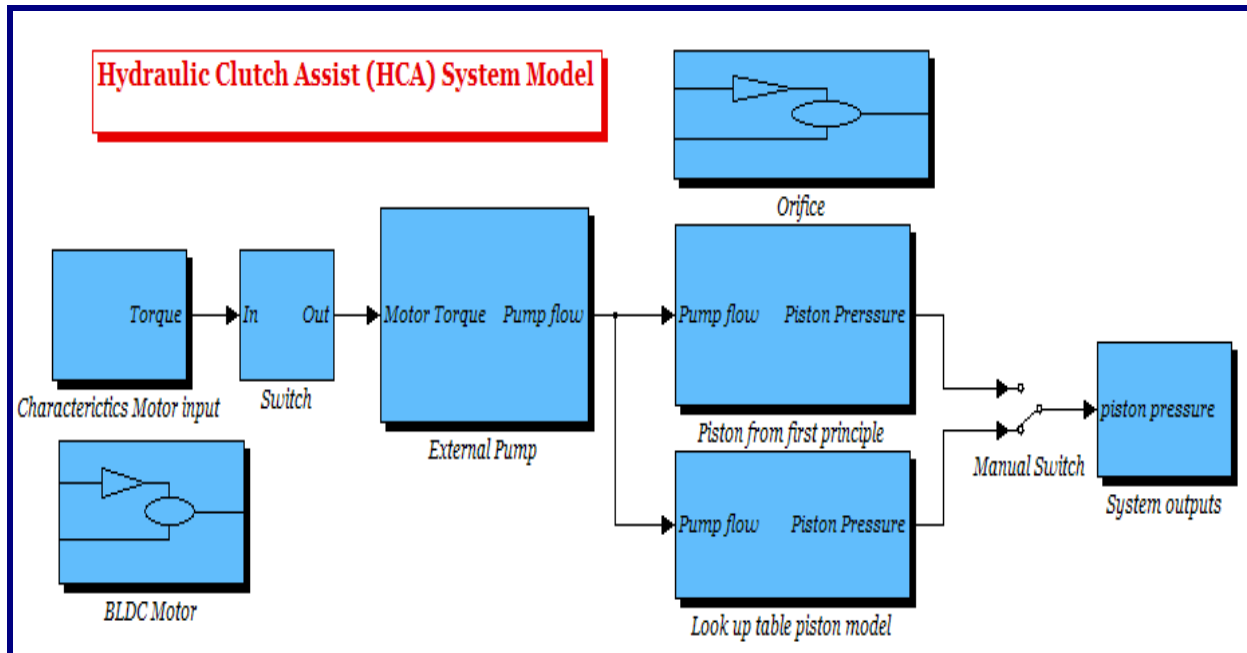


Figure 4: Modeling Block Diagram

Starting at the motor torque input of this model, the torque is applied to the pump (gerotor) which then generates a flow and pressure. The pressure is fed back to the motor simulating the load that is being produced on the system. Also, the speed of the motor is directly proportional to the flow rate. This gives the model the ability to predict the required performance of the motor. In addition, all the frictional and inertia loads are modeled to behave dynamically with the system to produce an accurate real time simulation.

Each variable plays a roll in the system performance and may affect another variable. Piston area determines the force applied on the clutches as a certain pressure is applied. The force applied on the clutches dictates the maximum allowable torque transfer that can occur. Piston stroke and the orifice characteristics impact the time for clutch engagement leading to the required pump flow rate. The mass and the spring stiffness of the moving parts help determine the initial load that the system must overcome as clutch engagement occurs. Adding fluid flow characteristics and other frictional forces into the model effectively provides a simulation of the HCA performing an actuation. Figure 5 lists key variables considered in simulation.

| <u>Given Variables</u> | <u>Assumed Variables</u> |
|-------------------------------------|--|
| Theoretical displacement of pump | Piston Surface Area |
| Fluid Volume per Tooth | Piston Mass |
| Calculated Pump Inertia | Mass of Piston and Clutch Pack |
| Motor Inertia | Spring Stiffness of Piston |
| Kinematic Viscosity of Oil at 40°C | Chamber Volume at Zero Displacement |
| Kinematic Viscosity of Oil at 100°C | Effective Bulk Modulus of Fluid |
| Volumetric Efficiency | Clutch Travel |
| Load Characteristics | Flow or Discharge Coefficient of Orifice |
| Desired Pressure Profile | Orifice Diameter |
| | Mass Density of Fluid |
| | Mechanical Efficiency |

Figure 5: System Model Input Parameters

RESULTS – four key characteristics result in exercising the mathematical model through a typical clutch maneuver of the eLSD system. These are: 1) piston pressure as a function of time, 2) pump flow as a function of time, 3) piston displacement as a function of time, and 4) motor speed as a function of time. Figures 6 and 7 plot these characteristic curves for a new clutch system at a typical operating point.

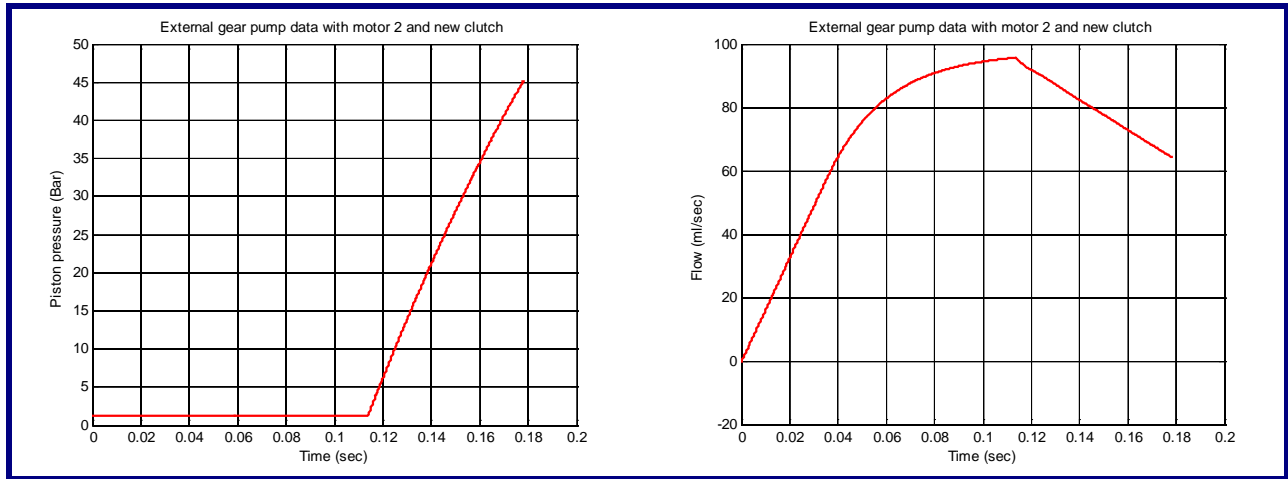


Figure 6: Piston Pressure and Pump Flow Rate vs. Time

The majority of the pressure rise occurs in the last few milliseconds of the actuation. This is due to the volume accumulation needed to fill the piston and move the clutches to the point of engagement and the piston has reached its maximum displacement.

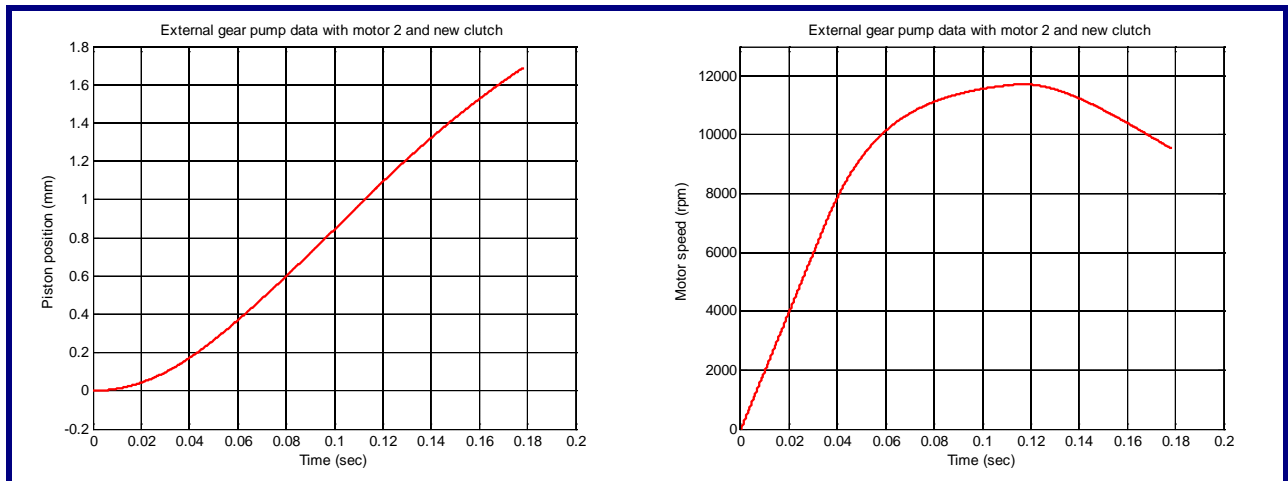


Figure 7: Piston Position and Motor Speed vs. Time

The flow rate decreases as the piston reaches maximum displacement and the piston pressure rises. The motor speed is directly related to the flow rate and also reaches its maximum at the clutch touch point. Given the clutch wear characteristics; these plots may be generated to estimate this affect on pressure, flow, position, and speed.

A motor torque curve can be generated using the simple hydraulic energy equations [5].

| | |
|--|---|
| Hydraulic Power Out, $P_{out} = \frac{P \times Q}{60}$ Watts | Mechanical Power In, $P_{in} = \frac{2 \times \pi \times T \times N}{60}$ Watts |
| P: Pressure Across Pump (kPa, kiloPascal) Q: Flow Through Pump (lpm, liters per minute) | T: Torque (Nm, Newton-meters) N: Speed (rpm, revolutions per minute) |

Correlating that with the speed, the required torque can be calculated. Equating that to mechanical energy, the motor torque speed curve is characterized. Figure 8 graphs the motor torque speed plot.

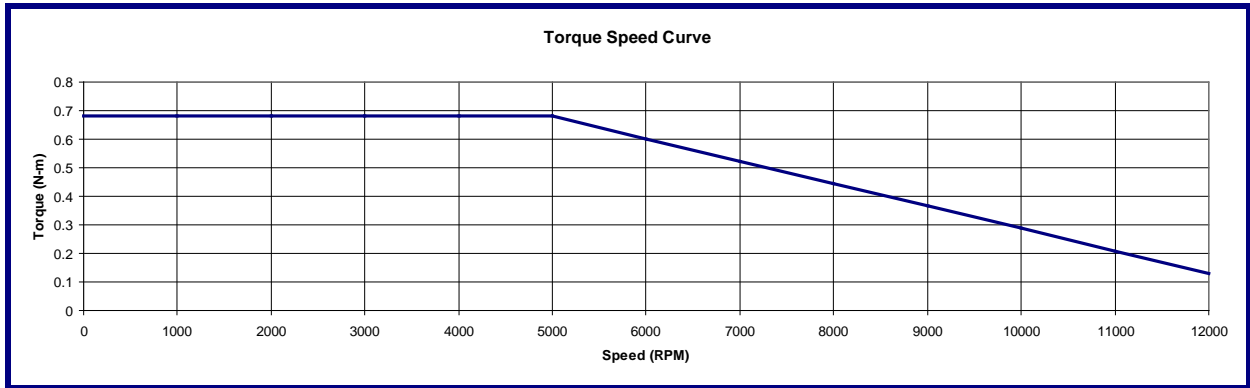


Figure 8: Motor Torque Speed Curve

MECHANICAL ATTRIBUTES

The HCA provides an on-demand pump solution for advanced high performance applications that require dependable, precise delivery of high-pressure fluid. This actuator combines the use of reliable hydraulic components with a high efficient brushless DC motor in an environmentally-sealed package. An integrated control module enables full CAN communication, providing accurate, quick, and flexible response to demand. In concurrence with its compact size, mounting configurations may vary. Figure 9 illustrates a typical form factor achieving an overall package size of 101 x 105 x 162 mm.

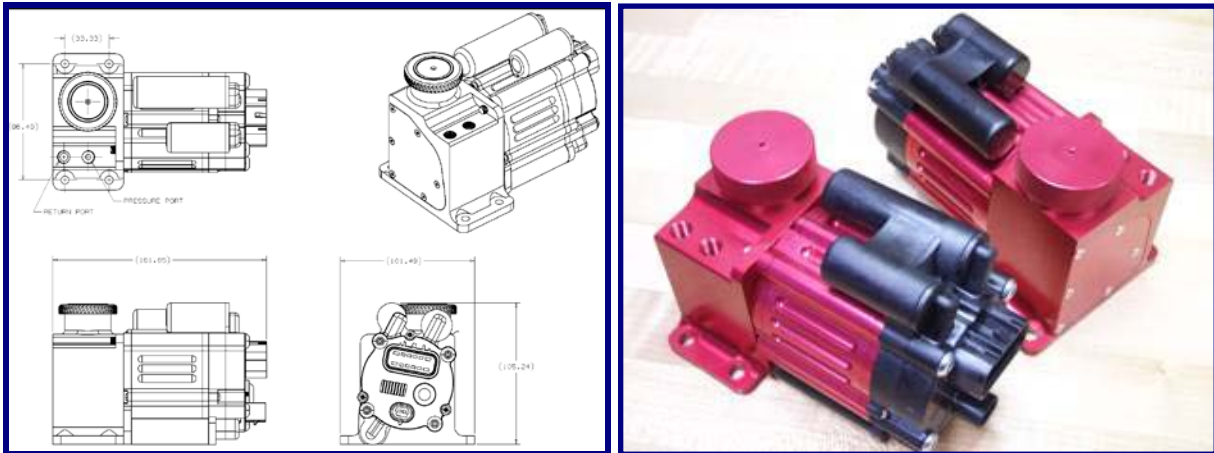


Figure 9: HCA Mechanical Packaging

Major mechanical sub-components include reservoir, pump, motor, housing, and electronics. Figure 10 provides an exploded view with these and other components shown.

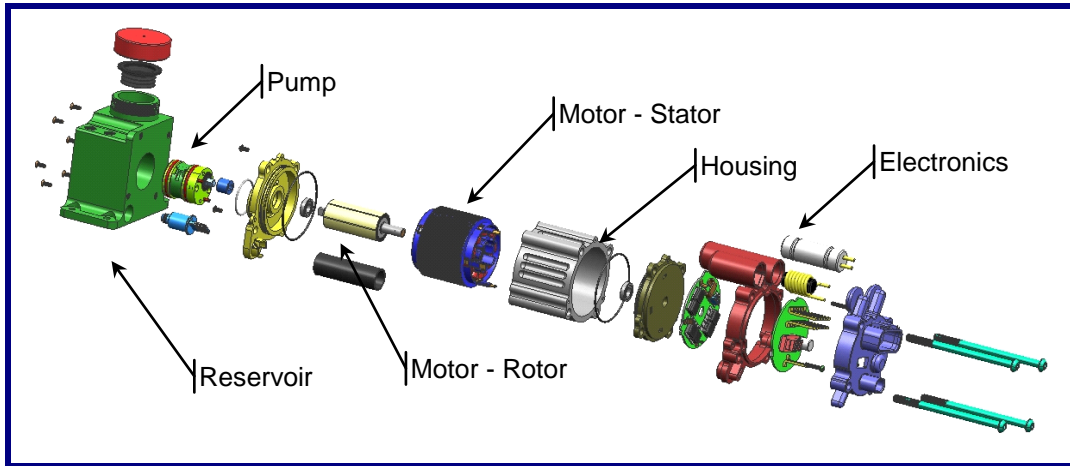


Figure 10: HCA Expoded View

The reservoir houses the pump and pressure sensor, provides for HCA mounting, and keeps enough fluid present to conduct an actuation. The motor includes the wound stator, rotor assembly, bearings, and end plates. The electronics include a power board, a logic board, and power electronics.

PUMP - The pump provides a hydraulic flow and pressure to the piston. Among the several types of positive displacement pumps, three types fit the performance requirements of the hydraulic clutch actuator. The three types of pumps are: 1) screw pump, 2) external gear pump, and 3) gerotor. The single screw pump achieves performance goals, but exceeds cost goals. The external gear pump lacks performance and exceeded cost goals.

Internal Gear Pump (Gerotor) - two different sized gears with one being inside of the other. The inside gear contains one less lobe than the outside gear. It works by the gears creating voids as they come out of mesh and liquid flows into the pump. As the gears come back into mesh, reducing volumes force fluid out the exhaust port. Advantages with an internal gear pump include a low relative velocity between the meshing gears, compact packaging design, low pressure ripple, and long service life. Disadvantages of this design include moderate bearing loads and complex porting geometry. HCA prototypes with this basic configuration meet cost goals with acceptable performance. Figure 11 explains this pump principle.

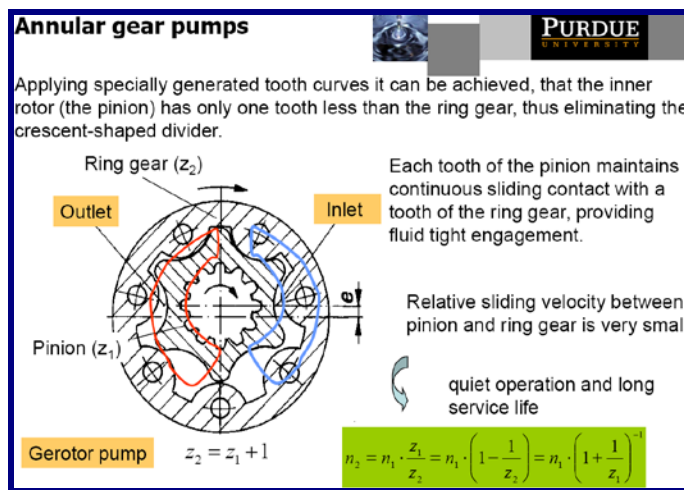


Figure 11: Gerotor Pump [6]

Sealing - The HCA specified to provide pressures in excess of 45 bar requires reliable and durable sealing. The two types of seals used in this system include a dynamic seal for the shaft entry and static seals to seal hydraulic fluid from exiting the pump into other components. The dynamic seal must also provide sealing for shaft speeds up to 12000 rpm. The static sealing utilizes o-rings that are specified to withstand the proper conditions.

Filtration - The pump requires a strainer to filter the hydraulic fluid before it enters the pump. Including a filter in the design is beneficial for the purpose of prolonging the life of the pump and reducing any buildup from obstructing the fluid flow paths, particularly the orifice.

Other Hydraulic Considerations – pump and motor sizing must strike a proper balance between the flow rate (motor rpm) and reaction forces (torque) on the system. The driving factor of this balance comes down to volumetric efficiency and motor efficiency. The smaller the pump elements the less efficient it is in terms of volume transfer requiring more energy to make up for the lost volume. The larger the pump elements requires the motor to run a low speeds (due to higher pump displacement) which ultimately leads to a decreased efficiency in the motor.

Another consideration comes in balance between number of pump elements (lobes or teeth), pump displacement, and pressure ripple. Lobe or tooth count relates inversely proportional with pressure ripple. The more elements, the less pressure ripple, but unit displacement decreases resulting in a decrease in volumetric efficiency as stated above.

The pump outer diameter impacts mechanical energy consumption and dissipation. The larger the diameter, the more mechanical energy dissipated into the fluid caused by the hydrodynamic effect from the hydraulic fluid. Pump element contact (rubbing) as the two gear sets rotate relative to each other causes energy loss as does inertia effects and other frictional forces. To minimize the frictional forces, the pump must be manufactured to the correct tolerances. The tolerances also greatly affect the volumetric efficiency where an appropriate tip clearance to compensate for thermal expansion of the assembly must be counterbalanced against decreased efficiency.

Tolerances of the pump housing drive an efficient pump design. These include eccentricity, axial clearance, and inside diameter clearance. Eccentricity of the two gears causes irregular meshing between the elements which decreases the volumetric efficiency and increases the frictional forces. Axial clearance also causes a decrease in the volumetric efficiency by becoming too large allowing excessive fluid leak. However, a tight axial clearance increases the frictional forces and ultimately causes poor performance and substantial wear as is the case with the inside diameter clearance.

THERMAL ANALYSIS

With the integration of the drive electronics into the mobile actuator, thermal stress of sensitive electronic components becomes a key design consideration. Analysis begins with a simplified geometric model and a list of basic environmental initial conditions. Figure 12 lists these conditions and shows the model.

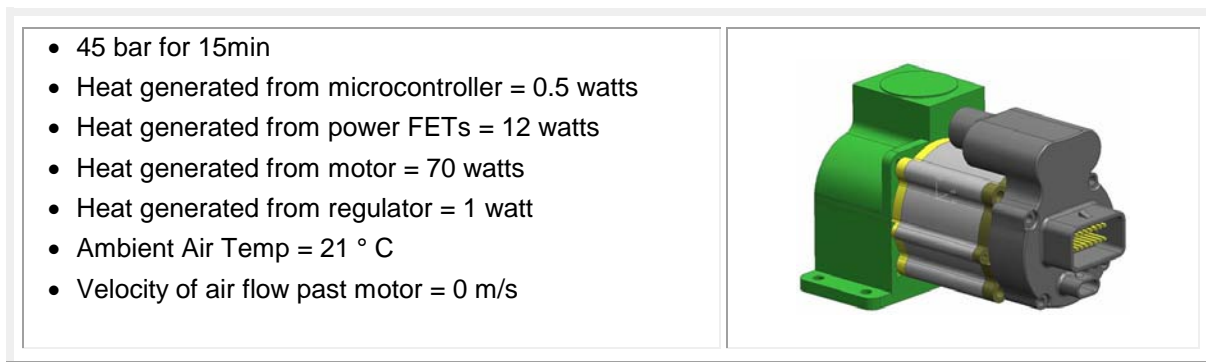


Figure 12: Thermal Model Initial Conditions & Geometry

The test case for thermal analysis centers on a 15 minute continuous operation at room temperature. This has been confirmed to closely match resulting temperatures in application using a real actuation cycle plan at 100°C ambient temperature. Using this test enables model correlation with a relatively simple set-up (accounting for duty cycle differences).

Figures 13, 14, & 15 display the thermal profile for the HCA and gives maximum temperatures for key components.

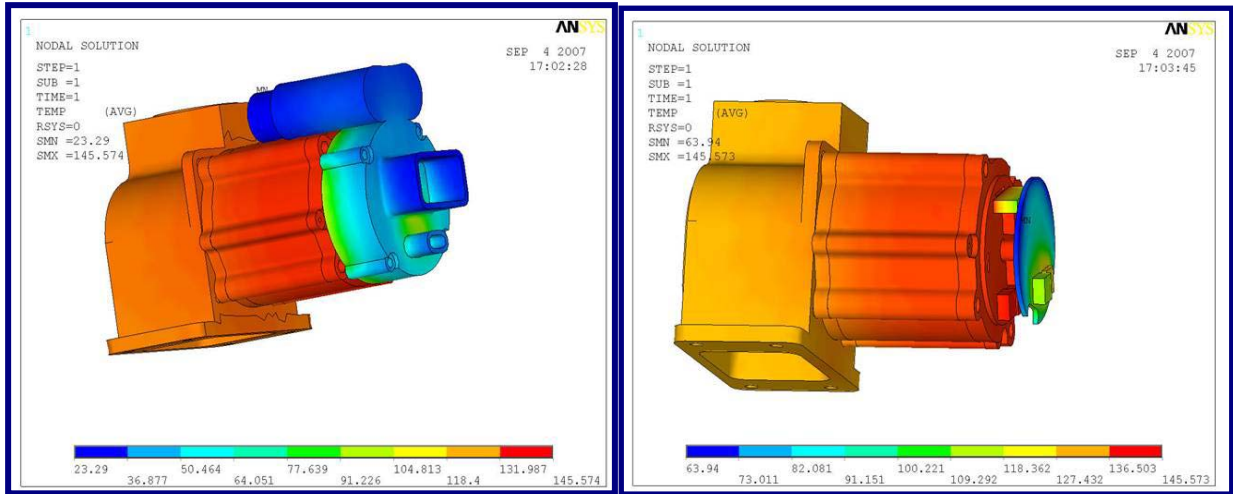


Figure 13: Thermal Results Externally & At Power Board

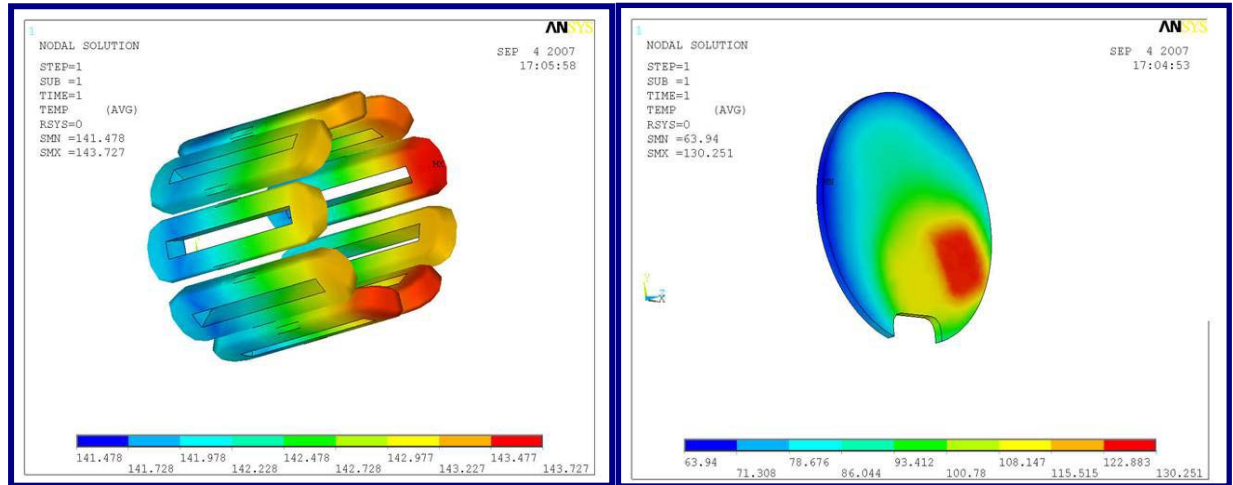


Figure 14: Thermal Results At Coil & At Microcontroller

| Location | FEA Result, °C | ΔT , °C | Predicted Temperature, °C Tamb = 100°C, 50% dc, |
|-----------------|----------------|-----------------|--|
| External Case | 132 | 111 | 156 |
| Power Board | 137 | 116 | 158 |
| Coil | 144 | 123 | 162 |
| Microcontroller | 123 | 102 | 151 |

Figure 15: Initial Thermal FEA Results

The temperatures at the microcontroller exceed the 125°C specification driving the need for this area to have a heat sink of some design. This area experienced a redesign with several iterations of heat sink geometry examined. Figure 16 shows a design achieving the objective.

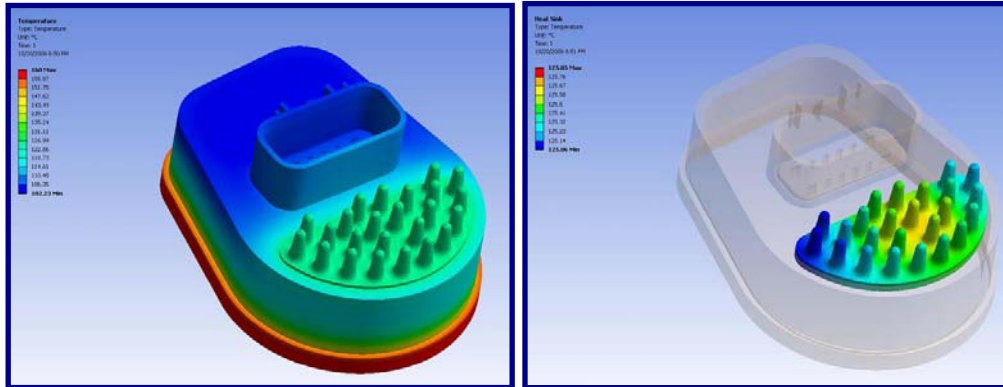


Figure 16: Heat Sink Design

The heat sink maintains a microcontroller temperature of 125°C with an estimated case temperature of 160°C, 100°C air temperature, 0.5 watts of heat transfer in microcontroller, and 1.0 watt of heat transfer in regulator (an electrical component next to the microcontroller).

MOTOR DESIGN

The HCA motor operates on a 12 Vdc system. Full pressure actuations require a peak current of 35 amps. This results in peak power consumption of approximately 420 watts. Figure 17 charts the basic details for the design.

| | | |
|-----------------------|-------|--------|
| Stack OD | 60 | mm |
| Stack ID (inner ring) | 52 | mm |
| Stator ID | 26 | mm |
| Lam stack length | 40 | mm |
| Lamination thickness | 0.35 | mm |
| # of laminations | 115 | |
| Overall length | 56 | mm |
| Magnet length | 46 | mm |
| Magnet diameter | 24 | mm |
| Magnet Br | 1 | Tesla |
| Phase resistance | 0.013 | Ω |
| Phase inductance | 0.9 | mH |
| Drive FET resistance | 0.006 | Ω |
| Pole # | 6 | |
| Turns | 22 | |
| Wire diameter | 1.19 | mm |
| Kv | 637 | RPM/V |
| Kt | 15.78 | mN-m/A |

Figure 17: HCA Motor Details

The motor architecture chosen for the HCA consists of a 3-phase, inner rotor design containing 9 slots and 6 magnetic poles. This configuration allows for a smaller rotor lowering its inertia and enabling a good response time for the HCA during actuations. The design relies on the use of an automatic needle winder and has the necessary features and parameters to accommodate this. Magnetic FEA provides a confirmation of expected tooth flux and possible areas of magnetic saturation. Figure 18 shows the motor cross section mechanically and magnetically.

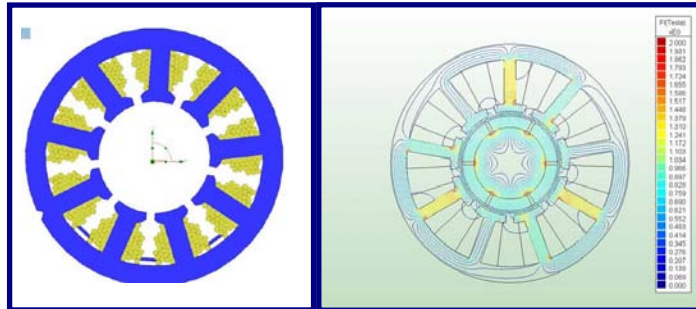


Figure 18: Motor Cross Section

Rotor - A sintered NdFeB magnet assembly provides the magnetic input for the data in Figure 17. This results in a fairly large cogging torque value. One countermeasure for excessive cogging torque comes from an alternative magnet technology; molded permanent magnets. Injection molding techniques allow injection molded magnet material to be more effective when used as a replacement for NdFeB magnet arcs [7]. Other benefits include cost & weight reduction, reduced assembly processes, improved tolerances, and improved quality and consistency. Figure 19 summarizes these comparisons as applied to the HCA.

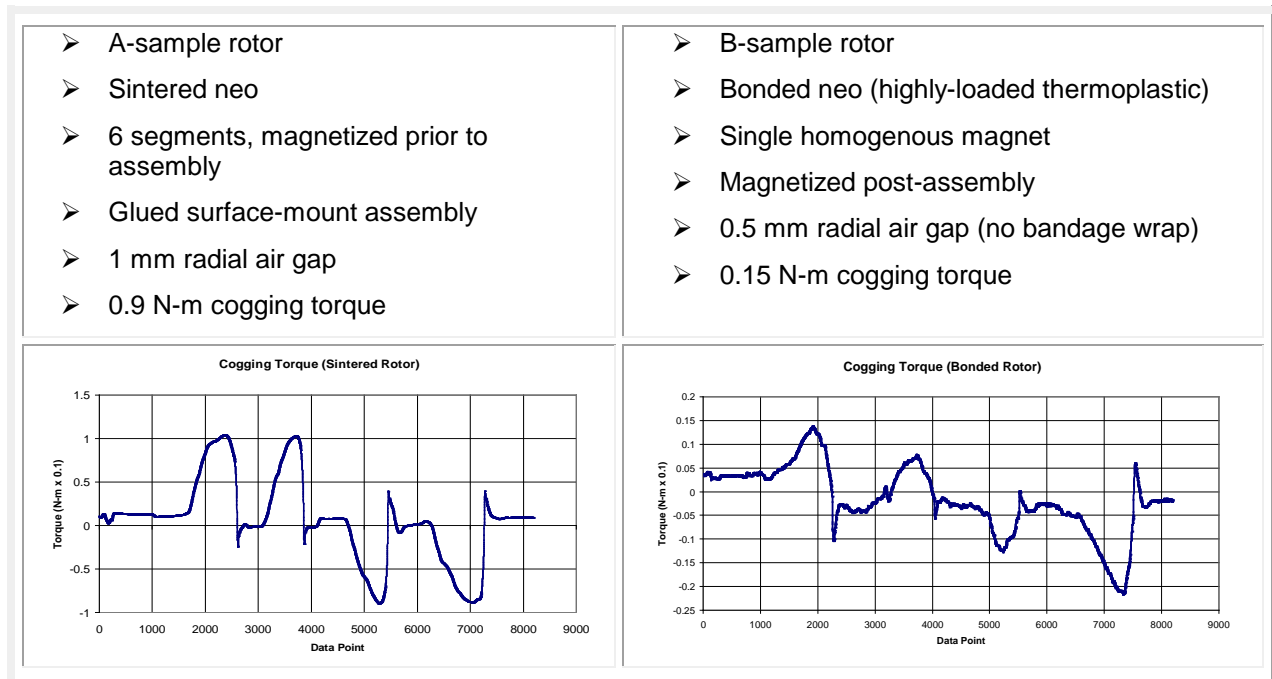


Figure 19: Sintered & Bonded Magnetic Characteristics

The above design and information ultimately leads to the physical design of the motor as shown in Figure 20.

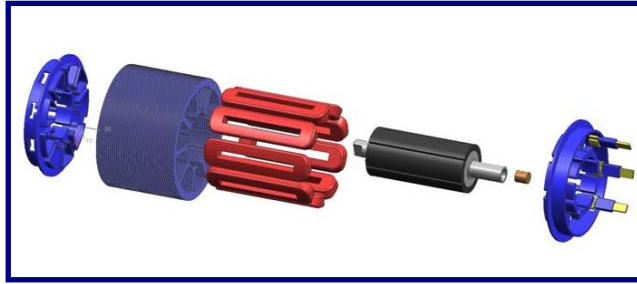


Figure 20: HCA Motor Mechanical Packaging

ELECTRONIC ATTRIBUTES

The HCA electrical sub-system architecture consists of the following elements:

- power supply
- CAN transceiver
- signal conditioning
- microcontroller
- MOSFETs & MOSFET pre-drivers
- motor current & temperature sensors
- rotor position sensor

Requirements - The requirements driving the electrical design come from top level system requirements and demands of the user coupled with the chosen architecture. Figure 21 lists these requirements.

1. PROVIDE HCA LOGIC BOARD POWER SUPPLY FUNCTION & FILTERING FOR MICROCONTROLLER HCA MOTOR CONTROL ALGORITHM & PERIFERAL INTERFACE CIRCUITS
2. PROVIDE HCA MOTOR DRIVE MOSFET GATE DRIVER CONTROL INTERFACE
3. PROVIDE HCA MOTOR CURRENT MONITORING FOR TORQUE CONTROL & FAULT CONDITION
4. PROVIDE CAN COMMUNICATION FROM CAN DRIVER TO CAN TRANCEIVER TO CAN BUS
5. PROVIDE HCA MOTOR ABSOLUTE POSITION & SPEED SENSING FEEDBACK
6. PROVIDE HCA MOTOR SOLENOID CONTROL
7. PROVIDE FOR IN – HCA MICROCONTROLLER BOOTSTRAP FLASH PROGRAMMING VIA CAN INTERFACE
8. PROVIDE HCA SYSTEM THERMAL MONITORING VIA NTCS
9. PROVIDE FAULT CODE, DIAGNOSTIC CODE & EOL TESTER DATE CODE DATA STORAGE VIA NON-VOLATILE MEMORY - EEPROM
10. PROVIDE A SYSTEM OSCILLATOR FOR EXECUTING THE HCA ALGORITHM & CONTROL FUNCTIONS
11. PROVIDE FAIL SAFE MICROCONTROLLER WATCHDOG & RESET FUNCTION
12. PROVIDE HCA EMC & ELECTRICAL CIRCUIT PROTECTION ON ALL CIRCUITS
13. PROVIDE FOR HCA LOW QUIESCENT STATE CURRENT DRAW
14. PROVIDE HCA IGNITION FUNCTIONAL WAKE-UP OUT OF SLEEP STATE
15. PROVIDE FOR FAIL SAFE HCA MOTOR CONTROL DURING A MOTOR OVERCURRENT FAILURE CONDITION
16. PROVIDE DIRECT POWER MOSFET DRIVE OF 3-PHASE BLDC MOTOR

Figure 21: HCA Electrical Sub-system Requirements

Figure 22 diagrams the electrical block diagram for the HCA and its control circuits.

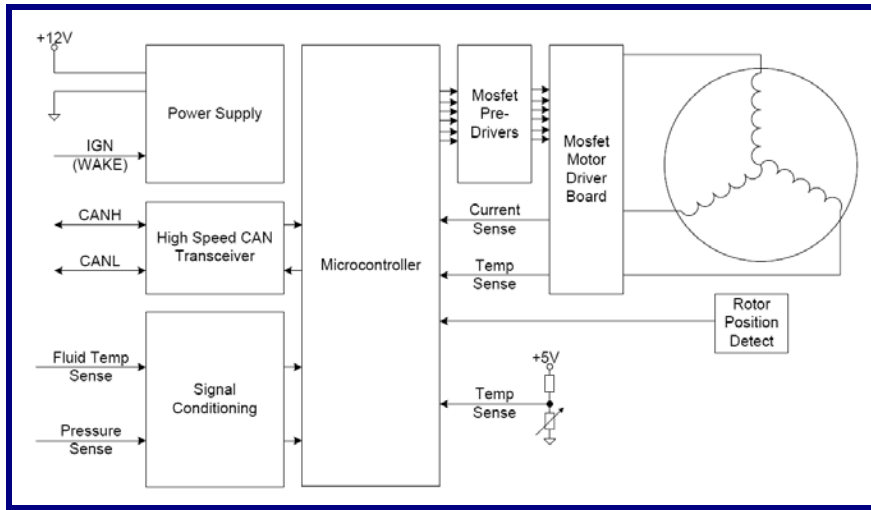


Figure 22: HCA Electrical Block Diagram

Form Factor - The microcontroller features 16 bit, 40 MHz operation (8 MHz crystal w/ PLL multiplier) with 2 CAN channels and a motor control peripheral (6 PWM channels). The form factor for the electrical components takes two forms for a logic board and a power board. Figure 23 illustrates this implementation.

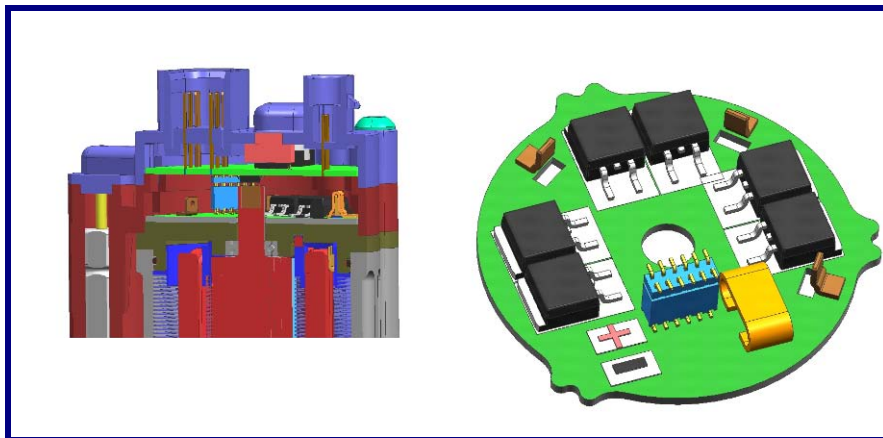


Figure 23: ECU Form Factor

The left image shows a cross section through the ECU (power board mounted to motor housing, with logic board mounted in connector/end cap). The right image shows the power board (six drive FETs, current-measurement shunt, and interconnect). This arrangement enables FET heat to be dissipated through its aluminum substrate to the HCA aluminum housing without excessively affecting the logic board and the microcontroller.

Encoder - The HCA utilizes a Hall-effect based encoder for its rotor position sensing feedback. This contactless magnetic rotary encoder enables accurate angular measurement over a full turn of 360° and over an extended ambient temperature range of -40°C to 150°C [8]. Features include [8]:

- a system-on-chip combining integrated Hall elements, analog front end and digital signal processing in a single device.
- requires only a simple 2-pole magnet rotating over the center of the chip; magnet may be placed above or below the IC

- instant indication of the magnet's angular position
- resolution of $0.35^\circ = 1024$ positions per revolution
- digital data is available as a serial bit stream and as a PWM signal
- operates at either 3.3V or 5V supplies

Figure 24 depicts the position sensor sub-system.

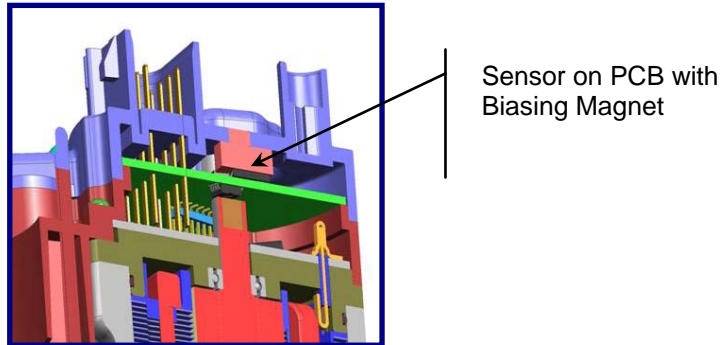


Figure 24: Position Sensor Sub-system

Pressure Sensor - The HCA integrates a MEMS technology based pressure sensor for direct feedback of the pump output used in the eLSD control strategy. The sensor selection process centered on the following attributes:

- | | |
|---|---------------------------------|
| • Compact Size, $\varnothing 14 \times 42$ mm | • -40 to +125°C, 0-60 Bar Range |
| • Cost Effective, Piezoresistive Technology | • Accuracy to $\pm 1\%$ Span |
| • Pressure & Temperature Signals | • Proven Application History |
| • Amplified Output (2-Chip Solution) | • < 5 ms Response Time |
| • Electrical Noise Immunity | |

Figure 25 shows the pressure sensor package used in the HCA.



Figure 25: HCA Pressure Sensor [9]

SOFTWARE ATTRIBUTES

As a BLDC based motor in an automotive electrical sub-system, the HCA requires software to enable proper function. Its software features center on:

- | | |
|---------------------|--|
| • CAN communication | • hosts pressure control and vehicle dynamics SW |
| • motor commutation | • hardware abstraction layer |
| • speed control | • operating system |
| • torque control | |

ADC - The sampling and filtering functions use a state machine strategy to avoid polling [10]. They are called at the 100 uS time interval. The channels are sampled in a round robin strategy with some channels read more often than others. The following lists the analog signals used as software input to properly control the motor.

- Motor Current
- Pressure
- Logic Board Temperature
- Power Board Temperature
- External Temperature
- Pressure Temperature
- Battery Voltage
- Ignition Voltage

Motor Control - For motor control, the HCA software algorithm utilizes space vector commutation; a software technique to set up a sinusoidal voltage at each motor terminal (offset by 120 degrees). Positive torque produces positive pressure and turns motor clockwise looking at the motor from the pump side. Figures 26-28 chart the defined motor inputs, modes, and outputs used in the control algorithms [10].

| Motor Inputs | | | | |
|------------------|------------------|------|-----------|--|
| Variable Name | Type | Unit | Scale | Description |
| motorMode | 16 bits unsigned | Code | - | Motor code |
| speedDemand | 16 bits signed | RPMs | 1 | Speed Demand |
| torqueDemand | 16 bits signed | N-m | 1/256 N-m | Torque Demand |
| motorUpdate_flag | 1 bit | Flag | - | Set to 1 after updating motor inputs. Used as handshake to communicate a change has been issued to the motor inputs. |

Figure 26: Motor Inputs [10]

| Motor Mode Codes | | | |
|------------------|--------------|---------------------|---------------------------|
| Codes | Mode | Speed Demand (RPMs) | Torque Demand (1/256 N-m) |
| 0 | Motor Stops | N/A | N/A |
| 1 | Speed Mode | -12000 to 12000 | N/A |
| 2 | Torque Mode | N/A | -512 to 512 |
| 3 | Blended Mode | -12000 to 12000 | -512 to 512 |

Figure 27: Motor Modes [10]

| Motor Outputs | | | | |
|----------------------|--------|------|-----------|---|
| Variable Name | Type | Unit | Scale | Description |
| motor_speed | SINT16 | RPM | 1 | Measured speed of the motor. |
| motor_torque | SINT16 | N-m | 1/256 N-m | Calculated torque based on open loop current control. |
| motor_demand_torque | SINT16 | N-m | 1/256 N-m | Torque demand. |
| max_motor_dem_torque | SINT16 | N-m | 1/256 N-m | Maximum torque that the motor can generate at a given time. |
| motorUpdate_flag | 1 bit | Flag | - | Clears to 0 after reading motor inputs. Used as a handshake to communicate to that the motor inputs have been read. |
| scsi_flag | 1 bit | Flag | - | Speed control saturation indication flag. |
| csi_flag | 1 bit | Flag | - | Current saturation indication. |
| gf_flag | 1 bit | Flag | - | Global fault flag. Diagnostic of a required control loop component indicates defect. This flag alerts that the motor will be stopped due to safety (e.g. over current or over temperature). |
| openLoopCommFlag | 1 bit | Flag | - | Indicates that the accumulated rotor angle is computed not measured. (sensor fault) |

Figure 28: Motor Outputs [10]

In *torque mode*, the motor attempts to achieve the motor shaft torque requested by the torqueDemand parameter. No addition torque is provided for motor shaft inertia and the speed of the motor is not controlled. In *speed mode*, the motor attempts to maintain the rotor RPMs requested by the speedDemand parameter. The torqueDemand value is ignored. In *blended mode*, the motor attempts to achieve the speed commanded via speedCommand parameter. The torqueDemand parameter should be used as a feed forward to indicate the required shaft torque at the requested speed. Failure to provide the proper torqueCommand value will still result in the motor settling at the requested speed, but may require more time and current. In addition to the motor outputs, the HCA contains 8 hardware abstraction layer (HAL) outputs and up to 23 diagnostic flags.

Diagnosics - When an *over current* situation exists, the motor shuts down and sets a corresponding diagnostic flag. Three (3) samples in a row above threshold causes shutdown in 600 μ s. *Over temperature* of the power board or logic board causes the motor to shut down and the corresponding flag set. A single case of the filtered value exceeding the over temperature threshold for either board causes a shutdown. During *motor shutdown* we clear all 6 PWM values to place the power transistors in an inactive state and the computed torque and speed values set to 0 and the gf_flag sets.

REALIZATION

HCA prototypes successfully create the required pressure control demanded by an eLSD system. Figures 29 & 30 trace the output under a ramp input and step response. Each diagram shows motor speed (magenta), pressure (green), motor current (red), and torque (blue).

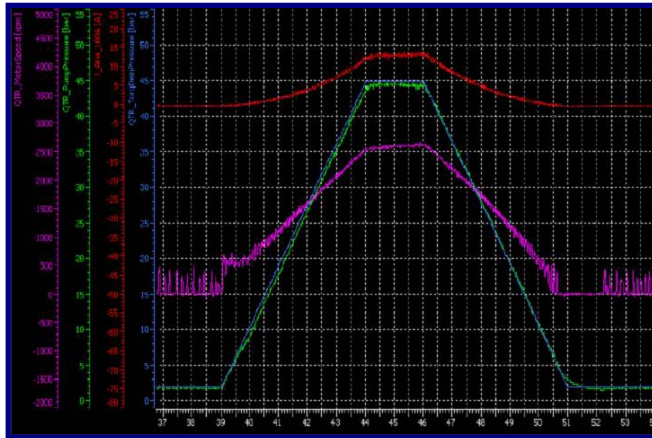


Figure 29: HCA Ramp Response

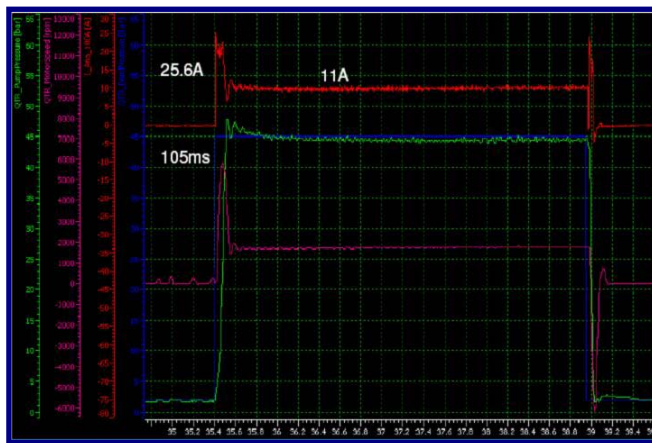


Figure 30: HCA Input Response

CONCLUSION

The HCA development targets on-demand pump solution for advanced high performance applications that require dependable, precise delivery of high-pressure fluid. For the eLSD system, a brushless electric motor (BLDC) drives a hydraulic pump directly, i.e. the clutch pressure is generated as needed [11]. The ECU provides for both motor control, clutch control, and the driving dynamics. The motor utilizes an inner rotor construction due to the required dynamics (0 to 6000 rpm < 50 ms) and ensuring good heat dissipation of the stator. An aluminum substrate holds the power electronics providing direct contact with the motor housing. Pressure measurement leads to torque control and a pressure sensor is mounted in the pump outlet. The actuator measures 101 x 105 x 162 mm and weighs approximately 2.5 kg. At a maximum pressure of 45 bar, less than 10 A flows from the on-board power supply. Average power consumption is less than 2A.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS (FROM WIKIPEDIA UNLESS NOTED*)

(http://en.wikipedia.org/wiki/Main_Page)

AC: Alternating Current – (also ac) the movement (or flow) of electric charge that periodically reverses direction.

ADC or A/D or A2D: Analog-to-Digital Converter - a device that converts an infinite resolution analog signal to a finite resolution digital signal.

BLDC: Brushless direct current (motor) - a synchronous electric motor which is powered by direct-current electricity (DC) and which has an electronically controlled commutation system, instead of a mechanical commutation system based on brushes. In such motors, current and torque, voltage and rpm are linearly related.

BOOTSTRAP LOADER: The small program that starts this sequence of loading into RAM, is known as a bootstrap loader, bootstrap or boot loader. This small boot loader program's only job is to load other data and programs which are then executed from RAM.

CAN or CB: Controller Area Network - a vehicle bus standard designed to allow microcontrollers and devices to communicate with each other within a vehicle without a host computer.

COGGING TORQUE: Cogging torque of electrical motors is the torque due to the interaction between the permanent magnets of the rotor and the stator slots of a Permanent Magnet (PM) machine. It is also known as detent or 'no-current' torque. Cogging torque is an undesirable component for the operation of such a motor. It is especially prominent at lower speeds, with the symptom of jerkiness.

DC: Direct Current - the unidirectional flow of electric charge. Direct current is produced by such sources as batteries, thermocouples, and solar cells.

ECU: Electronic Control Unit - a generic term for any embedded system that controls one or more of the electrical systems or subsystems in a motor vehicle.

***eLSD:** Electronic Limited Slip Differential - differential gear arrangement that allows for some difference in angular velocity of the output shafts, often with pressurized hydraulic clutches, only with sophisticated electronic fine-tuning. The unit electronically monitors input from various wheel sensors and, in the event of slippage, transfers extra torque to the wheel or wheels with the most traction.

FEA: Finite Element Analysis - the finite element method (FEM) (sometimes referred to as finite element analysis) is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as of integral equations.

FLASH MEMORY: Non-volatile computer memory that can be electrically erased and reprogrammed.

GEROTOR: A positive displacement pumping unit. The name gerotor is derived from "Generated Rotor". A gerotor unit consists of an inner and outer rotor.

HAL: Hardware Abstraction Layer - an abstraction layer, implemented in software, between the physical hardware of a computer and the software that runs on that computer. Its function is to hide differences in hardware from most of the operating system kernel, so that most of the kernel-mode code does not need to be changed to run on systems with different hardware.

***HCA:** Hydraulic Clutch Actuator - a component designated to generate a flow of hydraulic fluid to create relative movement between two mechanical components.

HED: Hall-effect Device - a semiconductor-based detector which uses the Hall-effect to allow the strength of a magnetic field to be measured.

I/O: Input/output - refers to the communication between an information processing system (such as a microcontroller), and the outside world – possibly a human, or another information processing system. Inputs are the signals or data received by the system, and outputs are the signals or data sent from it.

LSD: Limited Slip Differential - a modified or derived type of differential gear arrangement that allows for some difference in angular velocity of the output shafts, but imposes a mechanical bound on the disparity.

MAGNETIC FLUX: A measure of quantity of magnetism, taking into account the strength and the extent of a magnetic field.

MEMS: Micro Electromechanical Systems - the technology of the very small, and merges at the nano-scale into nanoelectromechanical systems (NEMS) and nanotechnology. MEMS are made up of components between 1 to 100 micrometers in size (i.e. 0.001 to 0.1 mm) and MEMS devices generally range in size from 20 micrometers (20 millionths of a meter) to a millimeter.

***MI:** Modulation Index [4] - the ratio of pulse width modulation to the peak non-distorted value or specifically the ratio of (1) the fundamental term of the Fourier series which represents a non-clipped sinusoid to (2) the fundamental term of the Fourier series which represents a clipped sinusoid. For example, let the fundamental term of the non-clipped sinusoid be $(A_0)\sin(\omega t)$, wherein A_0 is the amplitude, ω is angular frequency (radians per second), and t is time. Let the fundamental of the clipped sinusoid be $(B_0)\sin(\omega t)$. The modulation index is then B_0 / A_0 .

MOSFET (FET): Metal–Oxide–Semiconductor Field-effect Transistor - a device used to amplify or switch electronic signals. The MOSFET includes a channel of n-type or p-type semiconductor material. It is by far the most common transistor in both digital and analog circuits.

NTCS: Negative temperature coefficient sensor - a negative temperature coefficient (NTC) occurs when the thermal conductivity of a material rises with increasing temperature, typically in a defined temperature range. For most materials, the thermal conductivity will decrease with increasing temperature.

PCB: Printed Circuit Board - used to mechanically support and electrically connect electronic components using conductive pathways (traces) etched from copper sheets laminated onto a non-conductive substrate.

PLL: Phased-lock Loop - a control system that generates a signal that has a fixed relation to the phase of a "reference" signal. A phase-locked loop circuit responds to both the frequency and the phase of the input signals, automatically raising or lowering the frequency of a controlled oscillator until it is matched to the reference in both frequency and phase.

POLLING: In computer science, refers to actively sampling the status of an external device by a client program as a synchronous activity. Polling is most often used in terms of input/output (I/O), and is also referred to as polled I/O or software driven I/O.

PWM: Pulse-width Modulation - a very efficient way of providing intermediate amounts of electrical power between fully on and fully off. A simple power switch with a typical power source provides full power only, when switched on. PWM is a comparatively-recent technique, made practical by modern electronic power switches.

SMT: Surface Mount Technology - a method for constructing electronic circuits in which the components (SMC, or Surface Mounted Components) are mounted directly onto the surface of printed circuit boards (PCBs).

***STATOR:** A stationary part of a magnetic circuit.

THERMISTOR: A thermistor is a type of resistor whose resistance varies with temperature. The word is a portmanteau of thermal and resistor. Thermistors are widely used as inrush current limiters, temperature sensors, self-resetting over-current protectors, and self-regulating heating elements.