Synopsis

A series of tests has been done to try to isolate the cause of the motor failures during the June 2009 FOCE deployment, in which the motors would stop running after 10-20 seconds, when commanded to speeds between ~50-340 counts/sec (8-50 RPM shaft speed).

Procedure

Two sets of tests were performed. The first was a series of qualitative tests (quick and easy to perform) that indicate where to look for possible mechanical components to the problem by showing the relative proportions of the power consumed by various system components.

In these tests, the FOCE motor test fixture was used to test the FOCE motors in several configurations:

- motor w/ drive train [in ~10C air]
- motor w/ drive train [in ~4C water]
- motor w/o drive train
- motor w/o drive train w/o oil

Each configuration was run at two speeds (150 and 300 counts/sec) to cover a large portion of our operation space with a 2x change in velocity.

A comparison of these configurations isolates the contribution of the water loading, the drive train loading and the loading of the oil.

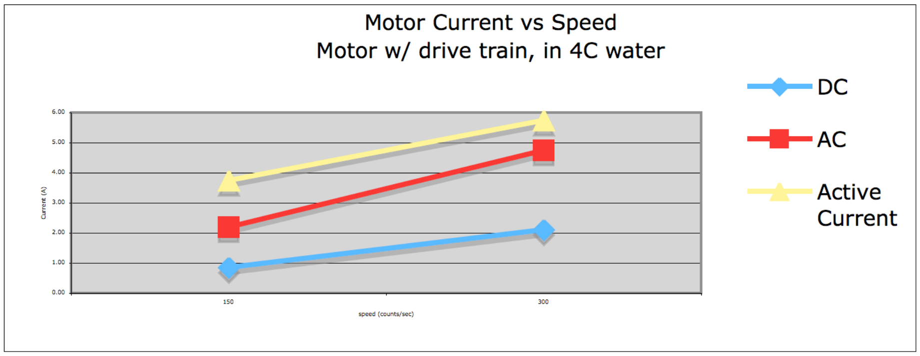
For each scenario, the step response of the system was recorded using Elmo Scope, and the steady state power supply current was recorded using a DVM in both AC and DC modes. The Elmo Scope application records the startup and steady state waveforms for motor currents, velocity and Elmo DC bus voltage. None of the measurements of current are an exact RMS representation, since the DVM is a filtered average of a PWM waveform, and the Elmo Scope application shows Active Current (the torque producing current component) and the sinusoidal phase currents. However, a side by side comparison indicates that they are reasonably proportional, and so any of these provides a reasonable basis for comparing the relative power consumption of each configuration.

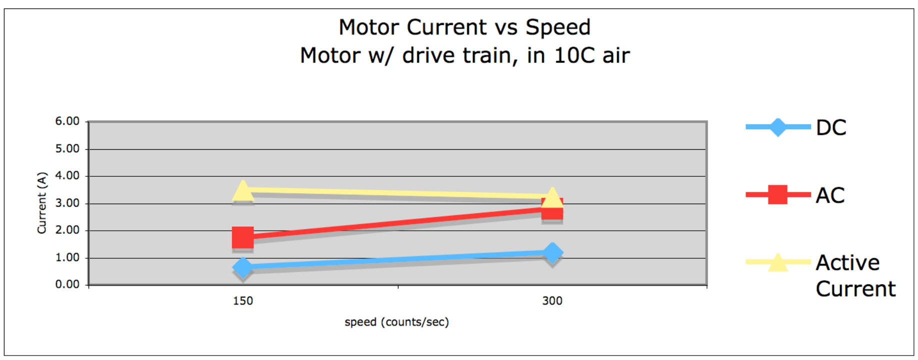
In the second set of tests, a current probe was used to quantitatively measure the current and voltage waveforms during over-current events that cause the Elmo drive to reset. These events are not visible through the Elmo Composer software suite, because it requires continuous communication with the drive to function properly. These tests reveal any electrical components to the problem. The qualitative power isolation tests were repeated to provide a better sense of potential drive train optimizations.

Analysis

Qualitative Tests

The first two plots (see Data Section) show motor current vs speed, measured in terms of AC and DC currents measured with a DVM, as well as the approximate steady state Active current reported by Elmo Scope. The graphs show that while these are different, they are essentially proportional, and so any should be valid for comparing (qualitatively but proportionally) the power used by different configurations.

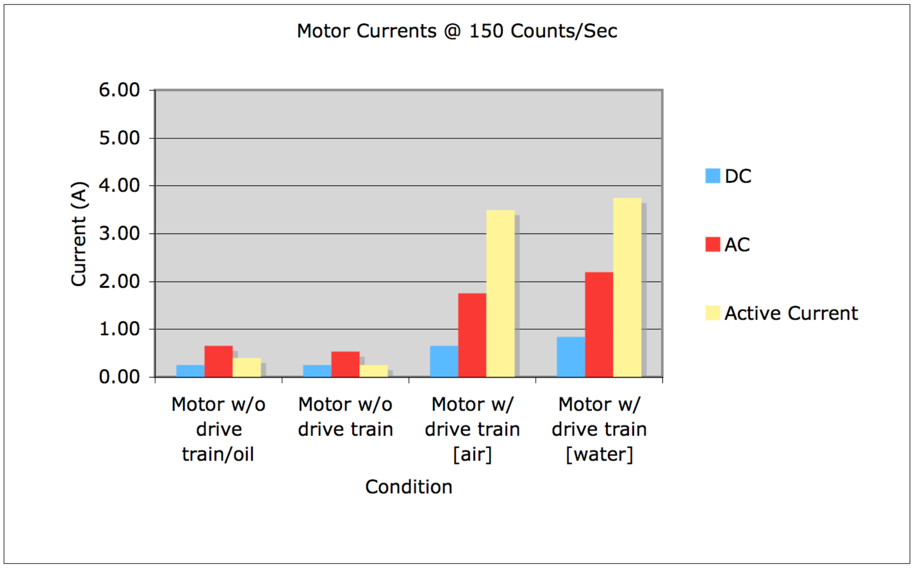


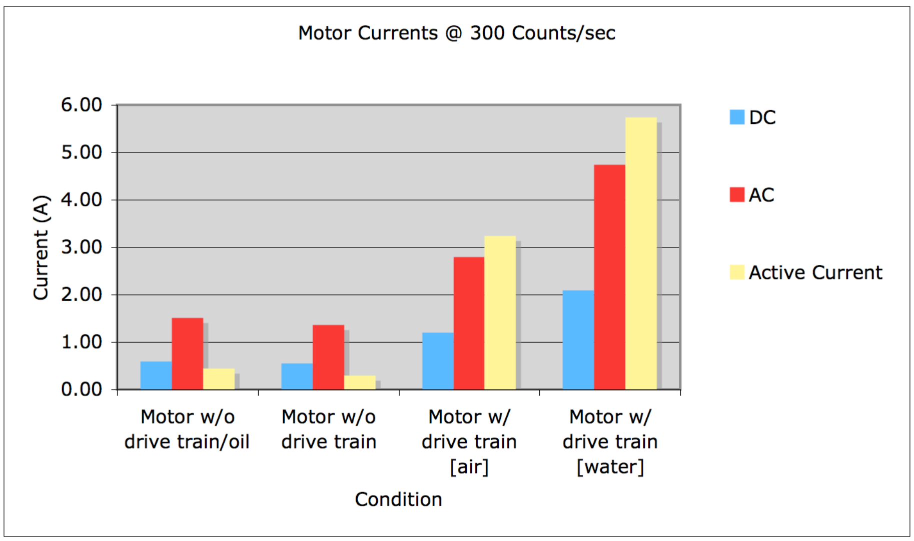


In water, the *difference* in current (not absolute current) required to double the speed is greater than in air by a factor of about 4.

The next two plots (see Data Section) show current consumption vs configuration, each at a different speed (left to right):

- motor w/o drive train or oil
- motor w/o drive train (w/ oil)
- motor w/drive train (in air)
- motor w/ drive train (in water).





There is a significant difference in the amount of current drawn between the cases with and without the drive train. The difference between the cases in air and water are larger at the higher speed (by factor of about 4).

The active current (see Elmo Scope output below) can go above the current limit set for the DC power supply; this may be because the Elmo PWM scheme may be effectively lowering voltage to increase apparent current to the drive to produce the required torque. We need to repeat the measurements with a current probe and voltage measurement to capture the exact behavior at the power supply terminals.

Quantitative Tests

The it is clear that the addition of capacitance enables the motors to start and run when cold over the full range of speeds required for FOCE (0-340 counts/sec). The filtering capacitance allows the switching power supply to "see" a DC current load.

[amount of capacitance required]
[capacitor ESR]
[appropriate current limit for FOCE electronics]
[start-up and steady state current requirements]

Observations/Conclusions

- Insufficient filtering capacitance across the Elmo drive terminals causes the (switching) DC power supply to erroneously detect an over-current condition. In response, the power supply lowers the DC bus voltage to zero, causing the Elmo drive to reset. It does not happen at low speeds or when the motor is warmed up because the drive current does not reach a critical level under these conditions. It is customary to install large filter capacitors so that the power supply sees a DC load while the drive draws PWM current from the capacitors. Many drives (e.g., EZ Servo, the Tiburon drives) incorporate them into the drive design.
- Adding capacitance (320 uF) at the DC power supply terminals enables the motors to start and run from 0-340 counts/sec when cold
- The relationship between equivalent DC current seen by the power supply and the Active Current reported by the Elmo drive is expressed by
  - Equivalent DC current = [Active Current * PWM Duty Cycle]
  - PWM duty cycle =? AN[7] (our drive reports AN[7]=0)
  - Active Current = IQ
- With filtering capacitance installed, the values of CL[N] and PL[N] function as expected and as described in the Elmo documentation. We should use the following default configuration values for our deployment:
  - PL[1]=10 (Peak Current 10A)
  - PL[2]=3 (maximum time at PL[1]=3s)
  - CL[1]=5 (maximum continuous current=5A)
  - CL[2]=0 (motor stuck protection disabled)
  - CL[3]=60 (minimum motor stuck speed=60 counts/s)
  - LL[2]=-1080 (absolute min allowed speed= -1080 counts/s)
  - HL[2]=1080 (absolute max allowed speed= 1080 counts/s)
  - VL[2]=-340 (absolute min allowed commanded speed= -340 counts/s)
  - VH[2]=340 (absolute max allowed commanded speed= 340 counts/s)
  - AC=100 (acceleration (via BG) = 100 counts/s^2)
  - DC=100 (deceleration (via BG) = 100 counts/s^2)
  - SD=1000000000 (stop deceleration (via ST) = 1000000000 counts/s^2)
  - UM=2 (velocity mode)
  - PM=1 (enable profiling (acceleration, deceleration)
  - RM=0 (reference command is generated internally)
  - SF=0 (no smoothing factor)
  - TS=90 (drive sampling time=90 usec)
  - SP=300 (PTP speed < |VL|, |VH|)
- The problem writing configuration parameters to Elmo drive flash was due to a configuration parameter that was out of range. Elmo firmware requires the SP parameter, which is not used in velocity mode (UM=2), to be set to a value less than |VL[2]| and |VH[2]|. With SP set correctly, the problem resolved and all drive parameters were written correctly to flash. This is only an issue when writing the defaults to flash, and does not affect normal operation since it isn't used in velocity mode; it should not require that SP be set by FOCE software unless it writes configuration values to flash (it currently does not).

- The drive train appears to have a greater affect on loading than oil viscocity does.
- The change in current (not absolute current) required to double the speed in water is 4x the change in current required to double the speed in air.

Acknowledgements
Thanks to:
Jim Scholfield
Chad Kecy
Thom Maughan
Bill Kirkwood
Ed Mellinger
Ryan Butler [ELMO Motion Control]

Recommendations

- Perform the current probe measurements using the FOCE hardware; CK will determine appropriate capacitance values. KH will ask RB from Elmo about appropriate capacitance values. We will run tests next week (Tuesday) to
  - capture wave forms to document the problem,
  - test on FOCE hardware,
  - produce quantitative data about the power consumption associated with the water, drive train and oil.

- Confirm the appropriate setting of the current limit configuration using the FOCE electronics
- Add explicit configuration settings at service startup to Elmo service
- Review the tuning and flash settings for the deployment Elmos before they go out
- Examine the drive train to find and reduce the sources of steady state loading and stiction (not a must-have for Aug09 deployment)

Data

Qualitative Test Data [5 Aug 2009]

Power Supply	36V 5A
Motor Config	**[4C; In Water; 150,300 Counts/Sec]** **Motor w/ drive train** [10C; In Air; 150,300 Counts/Sec] Motor w/ drive train [4C; Water; 150/300 Counts/sec] Motor w/o drive train [10C; In Air; 150,300 Counts/Sec] Motor w/o oil ~~Motor w/o magnetic coupling~~ [20C; in Air; 150,300 Counts/Sec] ~~Motor w/o magnetic coupling~~
Elmo Config	MC=20; PL[1]=10;PL[2]=3; CL[1]=5;CL[2]=0;CL[3]=60; LL[2]=-1080;HL[2]=1080;HL[3]=1000000000; VL[2]=-340;VH[2]=340; AC=100;DC=100;SD=1000000000; UM=2;PM=1;RM=0; SF=0;TS=90
Notes	[4C; In Water; 150,300 Counts/Sec] Motor w/ drive train - could not start motor at 150 counts/sec initially (would stall) had to bring up very slowly from 50 c/s in increments of 20 c/s or so. - After running for several minutes at 190, the motor could be started at 150 - At 300 c/s, motor current limits (LC=1) and drops back to 240 c/s after several seconds (sometimes a few seconds later than the scope capture)
Results	Step Response/Steady State (20 s) Plots (CurrentA, CurrentB, Vcommand, Vactual, BusVoltage, ActiveCurrent, ReactiveCurrent) Active Current (150/300): 3.75/5.75 DC current (150/300):0.85/2.10 AC current (150/300): 2.2/4.75

Power Supply	36V 5A
Motor Config	[4C; In Water; 150,300 Counts/Sec] Motor w/ drive train **[10C; In Air; 150,300 Counts/Sec]** **Motor w/ drive train** [4C; Water; 150/300 Counts/sec] Motor w/o drive train [10C; In Air; 150,300 Counts/Sec] Motor w/o oil ~~Motor w/o magnetic coupling~~ [20C; in Air; 150,300 Counts/Sec] ~~Motor w/o magnetic coupling~~
Elmo Config	MC=20; PL[1]=10;PL[2]=3; CL[1]=5;CL[2]=0;CL[3]=60; LL[2]=-1080;HL[2]=1080;HL[3]=1000000000; VL[2]=-340;VH[2]=340; AC=100;DC=100;SD=1000000000; UM=2;PM=1;RM=0; SF=0;TS=90
Notes	-
Results	Step Response/Steady State (20 s) Plots (CurrentA, CurrentB, Vcommand, Vactual, BusVoltage, ActiveCurrent, ReactiveCurrent) Active Current (150/300):3.5/3.25 DC current (150/300):0.65/1.2 AC current (150/300): 1.75/2.8

Power Supply	36V 5A
Motor Config	[4C; In Water; 150,300 Counts/Sec] Motor w/ drive train [10C; In Air; 150,300 Counts/Sec] Motor w/ drive train **[4C; Water; 150/300 Counts/sec]** **Motor w/o drive train** [10C; In Air; 150,300 Counts/Sec] Motor w/o oil ~~Motor w/o magnetic coupling~~ [20C; in Air; 150,300 Counts/Sec] ~~Motor w/o magnetic coupling~~
Elmo Config	MC=20; PL[1]=10;PL[2]=3; CL[1]=5;CL[2]=0;CL[3]=60; LL[2]=-1080;HL[2]=1080;HL[3]=1000000000; VL[2]=-340;VH[2]=340; AC=100;DC=100;SD=1000000000; UM=2;PM=1;RM=0; SF=0;TS=90
Notes	-
Results	Step Response/Steady State (20 s) Plots (CurrentA, CurrentB, Vcommand, Vactual, BusVoltage, ActiveCurrent, ReactiveCurrent) Active Current (150/300):0.25/0.30 DC current (150/300):0.25/0.56 AC current (150/300):0.53/1.37

Power Supply	36V 5A
Motor Config	[4C; In Water; 150,300 Counts/Sec] Motor w/ drive train [10C; In Air; 150,300 Counts/Sec] Motor w/ drive train [4C; Water; 150/300 Counts/sec] Motor w/o drive train **[10C; In Air; 150,300 Counts/Sec]** **Motor w/o oil** ~~Motor w/o magnetic coupling~~ [20C; in Air; 150,300 Counts/Sec] ~~Motor w/o magnetic coupling~~
Elmo Config	MC=20; PL[1]=10;PL[2]=3; CL[1]=5;CL[2]=0;CL[3]=60; LL[2]=-1080;HL[2]=1080;HL[3]=1000000000; VL[2]=-340;VH[2]=340; AC=100;DC=100;SD=1000000000; UM=2;PM=1;RM=0; SF=0;TS=90
Notes	-
Results	Step Response/Steady State (20 s) Plots (CurrentA, CurrentB, Vcommand, Vactual, BusVoltage, ActiveCurrent, ReactiveCurrent) Active Current (150/300):0.4/0.45 DC current (150/300):0.26/0.60 AC current (150/300):0.65/1.52

[Attachments]

- Elmo Scope trace plots
- Analysis spreadsheet

[Observations, Notes]

- When the motors have been sitting cold for some time, they will often fail to start even at low speeds (100 counts/sec). In our test fixture, they can be started at very low speeds (50 counts/sec); after running at this speed for a few minutes, the speed can be incrementally increased. After this warm up, the motors can be commanded to the higher speeds from zero without a problem.

- Even when warmed up, the motors will not run at more than about 240 counts/sec for more than 20 sec or so. Because this exceeds the current limit we have set for the Elmo, the drive will drop the torque command (current) down, resulting in a lower velocity. The current limit we have set (5A) may correspond to the Elmo drive's Active current, not necessarily the power supply current. If that is true, it isn't clear how it relates to the current seen by the power supply, but we may be able to increase this limit to attain the top end of our desired speed range. Otherwise, we are running up against the limit of our power supply.
- The largest contributor to loading at low temperature appears to be the drive train, though at high speed the water also adds considerable load as well
- It is a little surprising that the oil viscosity did not appear to contribute much, if anything to motor loading
- There is a relatively large overshoot in current (but not in velocity) on startup; this may indicate some "stiction" (see Elmo Scope plots)
- When the Elmo drive resets as noted above, it assumes the configuration values stored in flash memory. The Elmo Composer software throws an error when writing values to flash, and it appears that some configuration values are not written. As a result, some configuration values (LL, HL, VL, VH and possibly others) are set to factory defaults on Elmo reset. We should change the Elmo driver software to explicitly write all relevant (the ones we set that are not factory defaults) parameters at service startup to ensure that they have the intended values. Some of the parameters specified are already being set by SIAM software, and these would not cause a motor failure if they are set to factory defaults, so they are not likely to have caused a problem.

Quantitative Test Data (current probe tests)

Thu 7 aug 2009
kecy, headley
[mellinger, butler (Elmo)]

Current and voltage probes were place on the DC power supply (dcps) inputs to observe the startup behavior of the system when it stalls under cold conditions.

MC is an Elmo (read-only) parameter defining the maximum allowable current for the Elmo drive. For our Elmo, MC=20.
PL[1] defines the peak current limit; its maximum allowed value is MC.
CL[1] defines the continuous current limit; its maximum value is MC/2.

The motor current (torque) command is normally limited to its peak limit, as defined by PL[1].
After a short period of torque demand higher than CL[1], the torque command limit is decreased to CL[1]. If the current
command has been raised to PL[1] from zero, after the time specified for peak duration (PL[2], in seconds), the motor current command will be limited to CL[1]. The motor current command remains limited to CL[1] until enough time has passed for the average requested torque command to fall below 90% of CL[1].

We set PL[1] and CL[1] to their maximum values:
set PL[1]=MC=20
set CL[1]=MC/2=10
set DCPS=36V 5A
set jv=150
started motor (BG)

DCPS indicated current limit
current probe output (PWM waveform) hits CL limit and draws DCPS down to 0, DCPS current limit resets elmo

Does increasing DCPS current limit help?
set PL[2]=3 (max allowed)
set DCPS 36V 10 A [double previous]
DCPS indicates current limit, elmo reset

What is measured current when over-current trip occurs using our deployment defaults with high current?
set DCPS 36V 10 A, PL[1]=10, CL[1]=5
DCPS current limits, probe output reads 11.3A pp

Can it start (and what is measured current) using max PL and CL, and maximum DCPS current limit?

set DCPS 36V 18 A
set PL[1]=20 CL[1]=10
DCPS current limits at 11.3A pp

Not sure if problem is with Elmo, power supply, or probe. CK used known resistor values to verify that
- DCPS will supply 18A at 36V
- Current probe is correctly calibrated

[ck]: Scope probe read 1.3x actual value (e.g. 13A read = 10A actual)

[kh]: Meanwhile, talked to Ed Mellinger about the results so far, described waveforms we were seeing...

[em]: Should not see PWM waveform at supply - would expect to see a smoother DC with some ripple, but not square wave PWM. Is there capacitance at the Elmo terminals? (No)
DC supplies (Xantrex we are using) get confused by fast AC/PWM draws and can trip current limit.
Caps at the drive terminals can filter so DC is supply DC and Cap is supplying AC/PWM to the load.
Also, cap ESR (equivalent series resistance) increases at low temp, making it more difficult to keep bus voltage up.

Test again to verify probe calibration (CL, PL should make sense)
set DCPS 36V 10 A
set PL[1]=8 CL[1]=5
DCPS current limits at 10.6A (probe)
10.4/1.3=8=PL[1]: OK

Test again with different PL and CL
set DCPS 36V 10 A
set PL[1]=6 CL[1]=5
current limit at ?A (higher than expected)

Now try with added capacitance at DCPS terminals (not ideal)
set DCPS 36V 10 A
set PL[1]=8 CL[1]=5
w/ 220 uF at DC supply terminal: can start and run at 150 c/s, but not 340 c/s
w/ 320 UF at DC supply terminal: can start and run at 340 c/s

What steady state current is required to operate at our top speed (340 counts/sec)
set DCPS 36V 10 A,
set PL[1]=10 CL[1]=8
Duty cycle (from scope) is 0.39
Equivalent DC current = [Active Current * PWM Duty Cycle]

Active Current (Elmo composer) is 6.8A (2.7 A DC at supply) to start cold and run at 340 c/s steady state
6.8 A*0.39 PWM duty cycle=2.7 A

Next steps: we need to try this using the FOCE hardware; CK will determine appropriate capacitance values. KH will ask RB from Elmo about appropriate capacitance values. We will run tests next week (Tuesday) to capture wave forms to document the problem, test on FOCE hardware, and produce quantitative data about the power consumption associated with the water, drive train and oil.

[current probe, voltage scope trace output]

Also found this (though our Elmo reports 0 for AN[7]):
AN[1] reports the analog input #1 value after offset correction (AS[1]), in volts.
AN[2] reports the analog input #2 value after offset correction (AS[2]) in volts.
AN[3] reports the measured current in the motor A phase, in amperes.
AN[4] reports the measured current in the motor B phase, in amperes.
AN[5] reports the measured current in the motor C phase, in amperes.
AN[6] reports the line voltage value, in volts.
AN[7] reports the duty cycle value of the PWM signal after offset correction in fractional units

Analog input #1 serves as reference input for analog torque or analog
velocity command while in auxiliary reference mode (RM=1).

AN[7] is available after the first MO=1.

Each of Elmo's SimplIQ drives support a different number of analog inputs.
For specific details consult the drive's Installation Guide.

Wrote RB at Elmo about flash problem, resolved as follows:
Tried to write parameters to flash using SV command

sv
Error [54]: 'sv': Bad Data Base!;
cd
NullAddress=0x0 FailureAddress=0x0 Called Handler= Database Stats:SP
Err=21
ec
54

The error indicates that parameter SP is out of range; it is a parameter that isn't needed in UM=2, but still must be set < VH,VL.
After setting SP<VL,VH there were no problems writing to flash either using SV or Composer. **** Could/Should? add SP to list of parameters to set in software; it only seems to matter for writing flash, but isn't used in our UM, maybe not important

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