Introduction: Digital motor controllers based on pulse width modulation (PWM) generally rely on the inductance of the motor windings to stabilize the current flow through the motor. When a purely resistive load has a PWM voltage applied to it, the resulting current is directly proportional to the voltage – an unsmoothed pulse waveform. The inductance of a motor coil acts to filter the resulting current, with a time constant of L/R, where R is the resistance of the coil.

The initial electronics on Ranger used a 20 kHz PWM, a standard relatively high frequency often chosen for its inaudibility. Based on the Faulhaber 2657 data sheet (90 uH inductance, 0.7 ohm resistance), the resulting time constant of about 130 uS seemed to compare well to the 50 uS period of the PWM.

However, we found much higher losses due to brush contact resistance than we expected from the data sheet. It said “Terminal Resistance,” but apparently they actually meant just the coil resistance. According to a Faulhaber spokesman, they didn’t include the brush resistance because they couldn’t measure it. (How about a graph?) At low currents, the effective resistance approached 100 ohms. Put differently, there is a voltage drop at the brushes. This could lead to much higher ripple currents, and thus higher RMS current and more power dissipation in the rotor coils. We didn’t see as much effective brush resistance at higher currents, but the losses were still so much higher than expected that several motors overheated and burned out.

Therefore, for the next iteration of Ranger electronics we decided to increase the PWM frequency substantially, to 100 KHz. This, we thought, would solve the problem of ripple current losses. And indeed power losses seemed quite low, in initial testing. Unfortunately, power losses at low currents and high motor speeds were still much higher than predicted by our motor models.

Purpose: We aim to identify the major causes of power loss in the motors, and find ways to minimize it. We observed higher than expected ripple currents in the motor, and higher than expected power losses for a given ripple current. These losses were clearly in the motor, not the controller. It follows that the rotor inductance is lower, and the resistance is higher, than expected from the data sheet.

Experimental apparatus:

Test equipment:
Tektronix AM503 isolated current probe
Tektronix TDS2024 digital oscilloscope
Tektronix signal generator
Fluke 87 digital multimeter
Extech digital multimeter
Extech 0 – 30V, 0 – 5A power supply
B2A2 custom motor controller board plus “main brain”
LabView simulator for motor controller and motor losses

Devices tested:
Faulhaber 2657 DC brush motor
Maxon DC brushless motor
Coiltronix 90 uH toroidal inductor
Vishay 100 uH powdered iron surface mount inductor
  100 uH ferrite core surface mount inductor

Procedure:

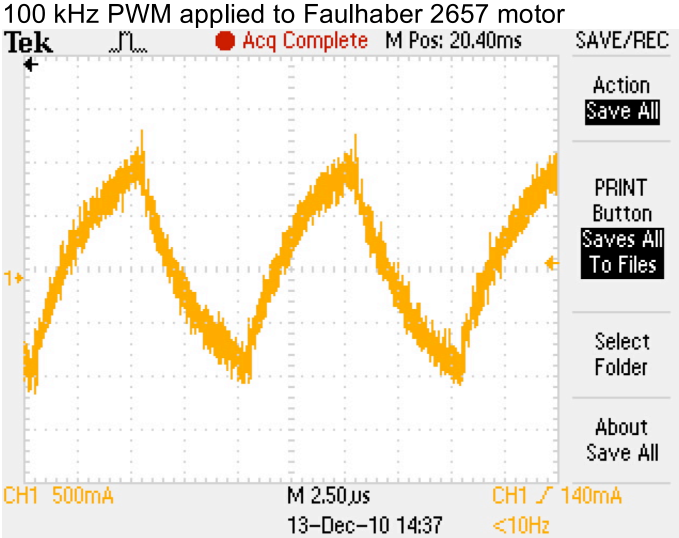
A) The motor controller was set for "locked anti-phase" operation and a 50% duty cycle, with an applied PWM voltage of 12.5 volts. In locked anti-phase mode, this will give ripple current equivalent to that of sign-magnitude control with a 25-volt supply. Locked anti-phase just means that the two half-bridges turn on and off alternately, in such a way that bridge A is always on while bridge B is off, and vice versa. Choosing a 50% duty cycle gave a substantial current ripple, flowing alternately back and forth through the motor coil, but a zero average current. This was confirmed by the Fluke ammeter in series with the motor, which showed less than one mA of net current flow. Input power to the motor controller was measured by multiplying voltage as measured on the power supply, by supply current as measured by the Extech multimeter. Current ripple was measured by the AM503 and oscilloscope and saved to disk. Inductance and resistance values were chosen by iteration to make the simulated graph, power loss, and ripple current approximate the measured values. Note that the simulation uses the case of a sign-magnitude PWM controller, so the input power supply voltage used is 25V, not 12.5V. Another change needed to replicate the locked anti-phase case is to set the back EMF of the simulated motor to exactly 12.5V. This was done by setting the motor speed in radians/sec equal to 12.5V divided by the torque constant.

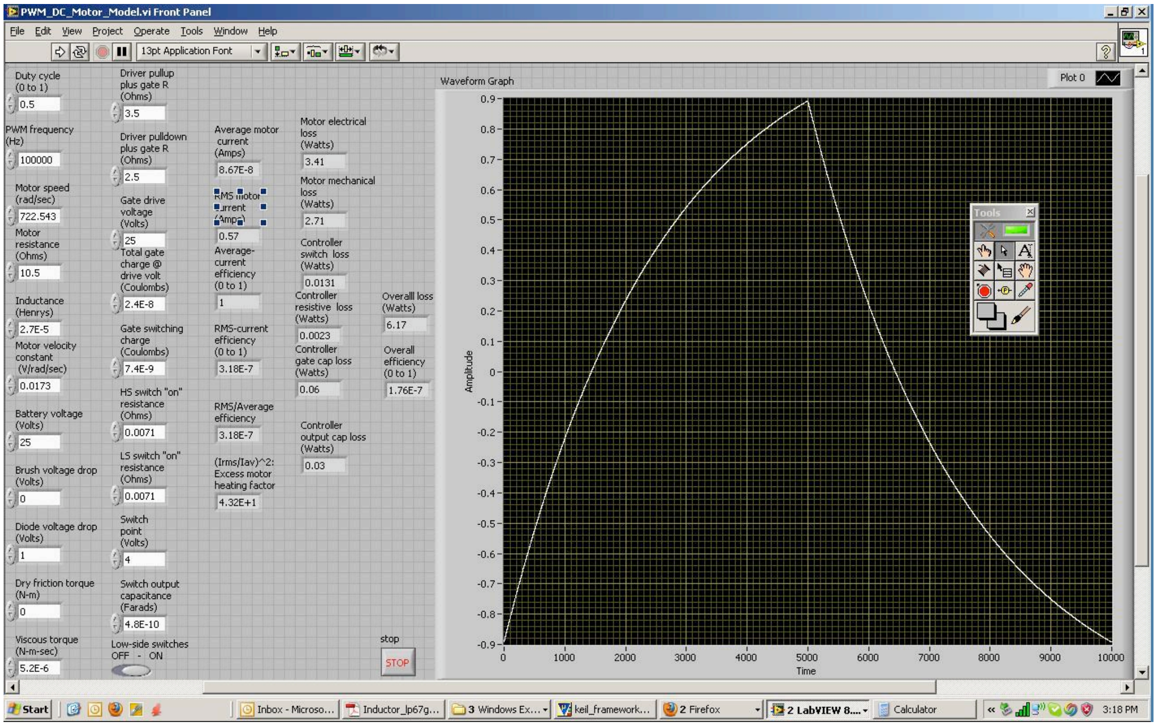
B) A 16V sine wave was applied to a 1000 ohm precision metal film resistor in series with the motor coil or inductor under test, for a range of frequencies from 1 to 1000 kHz. The resulting voltage and phase across the inductor was measured; from that data the inductance and equivalent series resistance (ESR) were estimated for each frequency.

Results:

A)

100 kHz PWM applied to Faulhaber 2657 motor



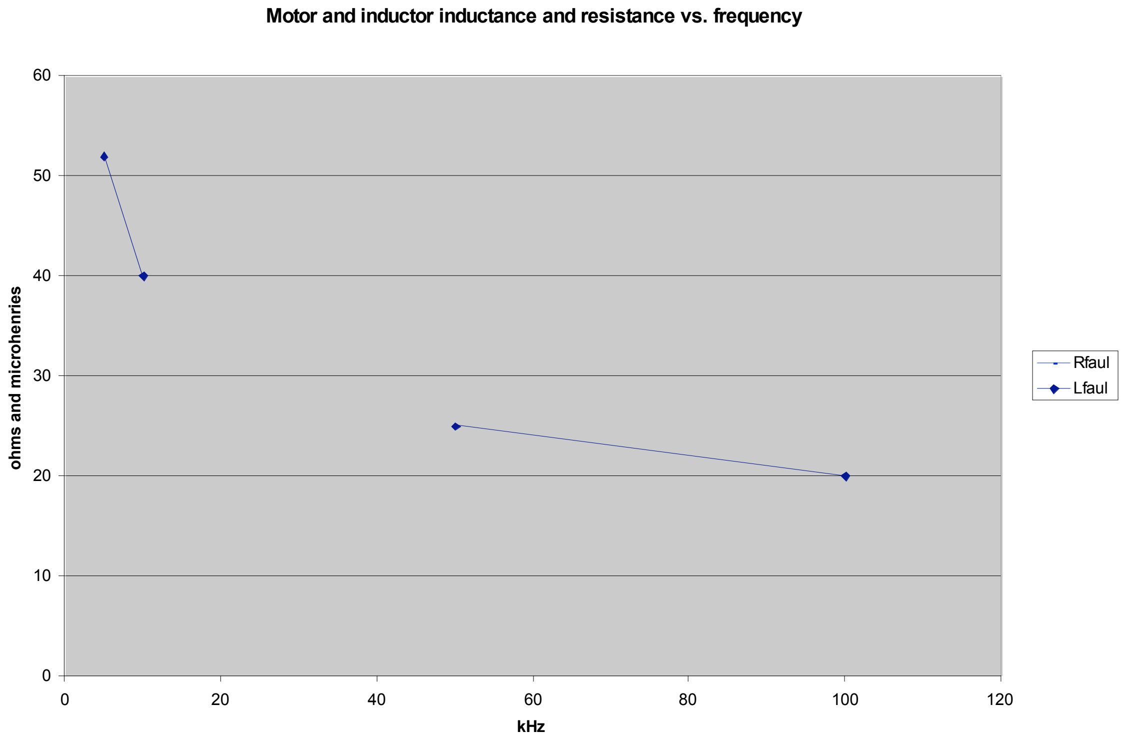


B) Inductance and equivalent series resistance vs. frequency

Faulhaber 2657

Frequency (kHz)	Vfaulhaber	Time (lead)	Phase (lead)	Zfaul	Rfaul	Lfaul
1	0.12					
5	0.135	6	11			52
10	0.16	4	14.4			40
20	0.18					
50	0.24	1.9	34.2			25
100	0.3	1.2	43			20
200	0.44					

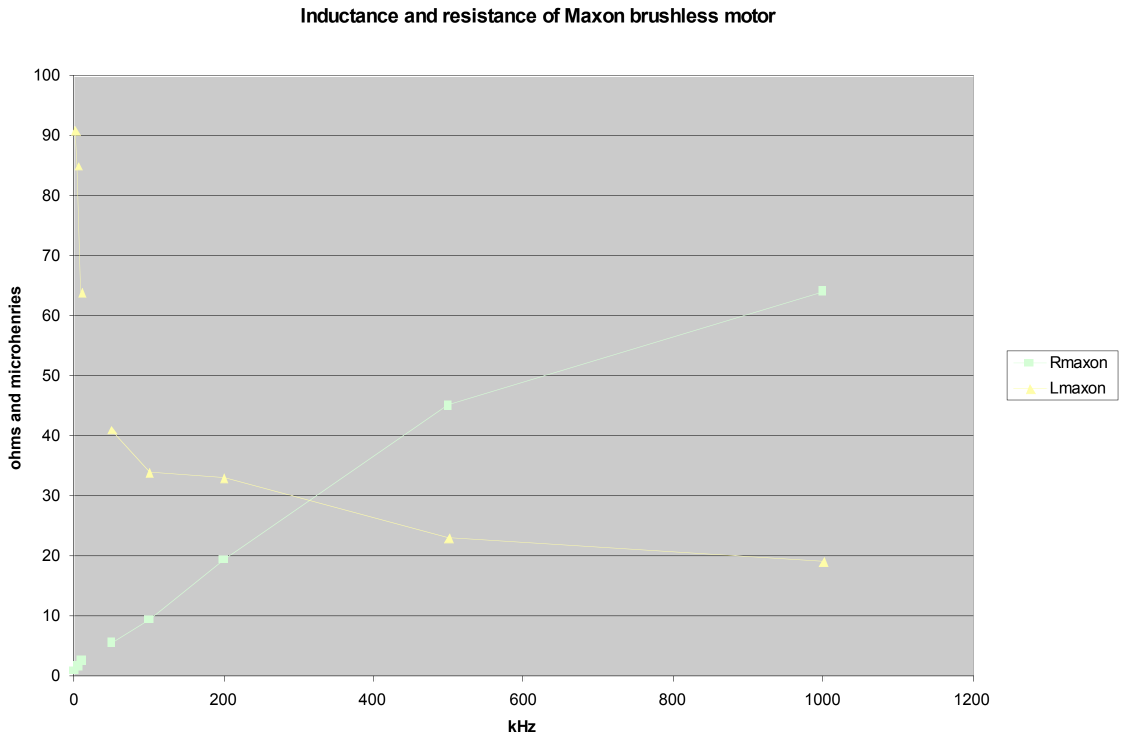
Measurements with the Faulhaber motor itself were difficult, due to the nonlinear effects of the brush contact resistance. This is one reason a Maxon brushless motor was used for comparison.



Maxon

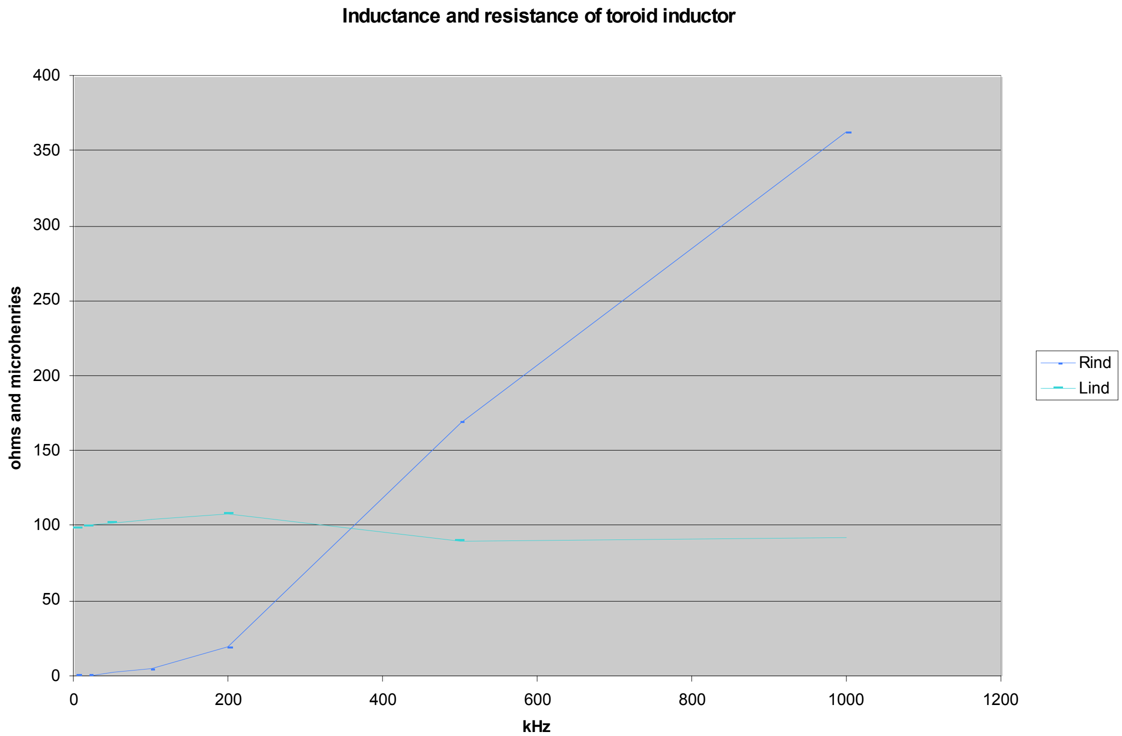
Frequency (kHz)	Vmaxon	Time(lead)	Phase (lead)	Zmaxon	Rmaxon	Lmaxon
1	0.016	96	35	1	0.82	91
5	0.05	33	59	3.1	1.6	85
10	0.075	16	58	4.7	2.5	64
20						
50	0.225	3.7	67	14	5.5	41
100	0.37	1.84	66	23	9.4	34
200	0.72	0.9	65	46	19.4	33
500	1.2	0.32	58	84	45	23
1000	2	0.17	61	133	64	19

The frequency generator used for this test did not appear stable at frequencies above 100 kHz, making the higher-frequency phase measurements quite approximate.



Coiltronix inductor

Frequency (kHz)	Vinductor	Time (lead)	Phase (lead)	Zind	Rind	Lind
1						
5	0.05	48	86	3.13	0.2	99
10						
20	0.2	12.6	90	12.6	0	100
50	0.5	4.8	86	32	2.23	102
100	1	2.4	86	65	4.5	104
200	2	1.14	82	137	19	108
500	4.5	0.33	59	328	169	90
1000	8	0.16	58	683	362	92



Conclusions:

Discussion:

Appendix (data):