Digitized Air Flow Meter (AFM)

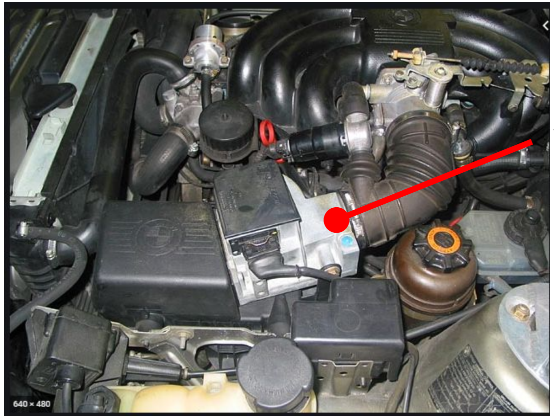
Panzer Performance
Peter Ruggiero - Design Engineer

About Me

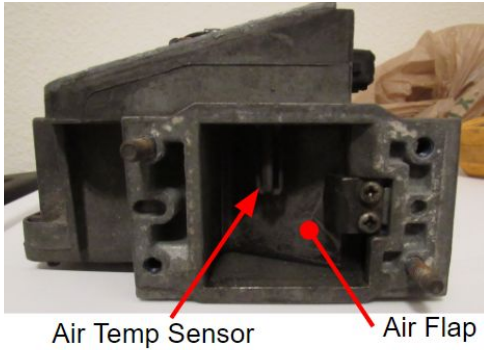
- Born/raised in Bradenton, Fl where I grew up in automotive family with Dad and Uncle being mechanics
  - Worked at Uncle’s automotive shop tinkering with cars, learning how to diagnose, etc
  - Raced at Desoto Speedway in Street Stock… Only got to drive once
- Studied Mechanical Engineering at the University of Central Florida (03-07)
  - Heavily involved in Society of Automotive Engineers where we designed and built off-road buggies from scratch and raced them across the country
- Started working at Harris Corporation as an Electronics Packaging Engineer (08-18)
  - Working directly with Electrical Engineers to help design PWB/CCAs, Heatsinks, Housings, etc
  - Consisted mostly of space based radar systems
- Currently working at Lockheed Martin Missiles and Fire Control (18-Present)
  - Lead electronics packaging engineer for new sensor on F-22 Raptor
- Built (ruined) and ran E36 (328is) in HPDE groups… Sold… Bought C6 Vette
- Track support for NASA SE30 group for ~2 years for Panzer Performance
  - Majority at Florida tracks as well as 2018 and 2019 National Events

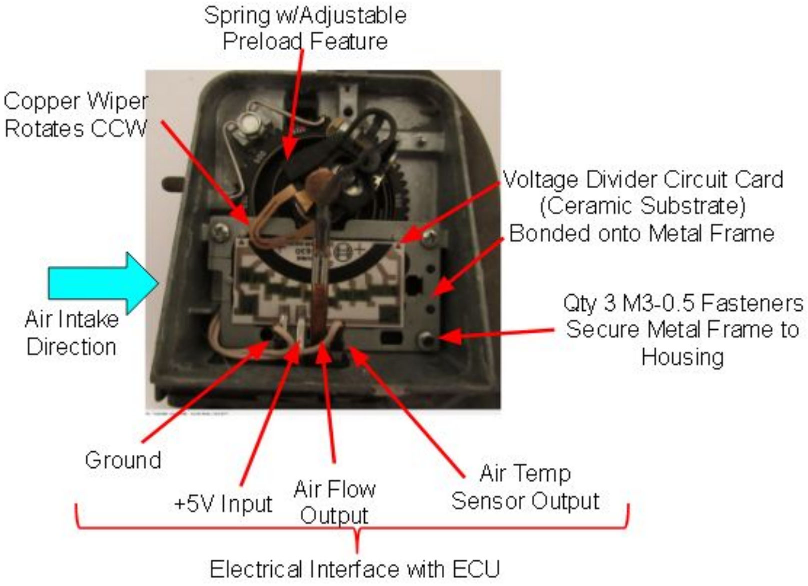
OEM E30 AFM Overview

- The AFM is located just aft of the air inlet and provides both air temperature and air flow data to the ECU
- Air temperature is reported through the temp sensor which varies resistance as a function of temperature (~1-3kΩ for 70-100°F)
- Air flow is reported based off the angular position of the flap which also varies resistance as a function of air flow
    - Note that while the resistance isn't linear as a function of flap angle the resulting output voltage is



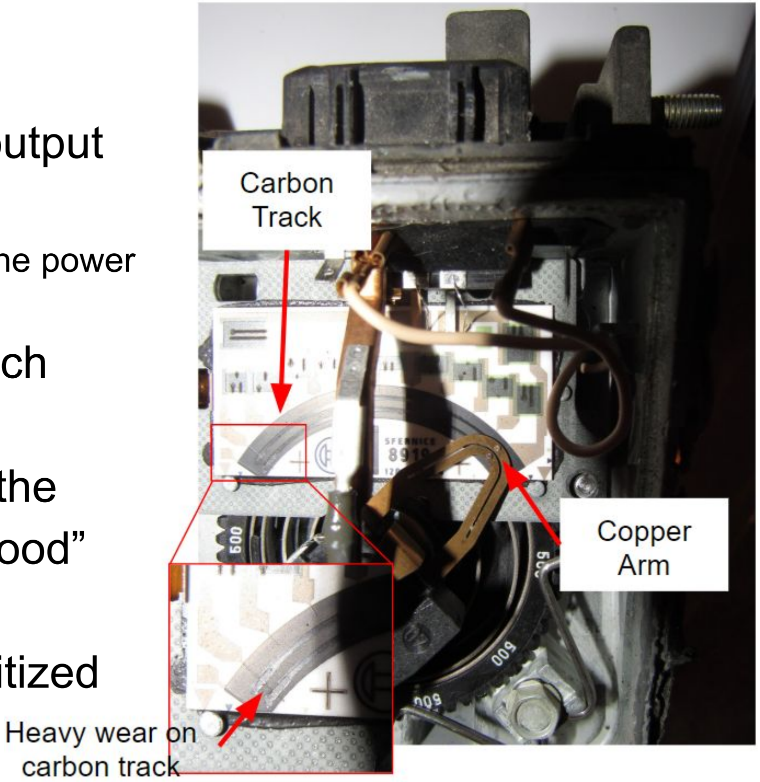
AFM Location in Engine Bay





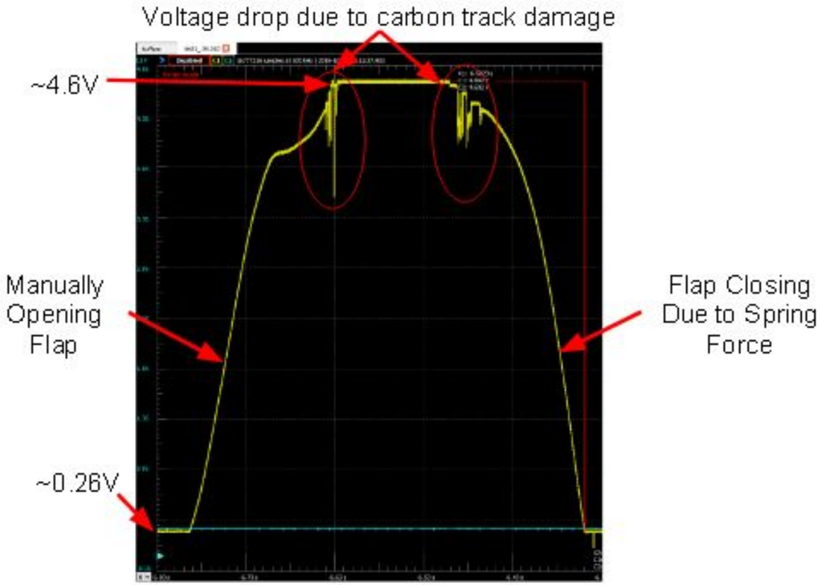
Problem Statement

- The OEM E30 AFM contains a copper arm which rides along a carbon track intended to provide an electrical interface critical to the operation of the sensor
- This interface wears over time resulting in abnormal output from the sensor to the ECU
  - Typically this manifests itself as a lean condition somewhere along the power band
- SE30 cars tend to wear the track towards the end which corresponds with high air flow events
- This behavior can be difficult to predict and results in the owner spending significant money and time finding “good” AFMs
- The intent of this effort is to provide a non-contact digitized replacement that offers more consistent performance

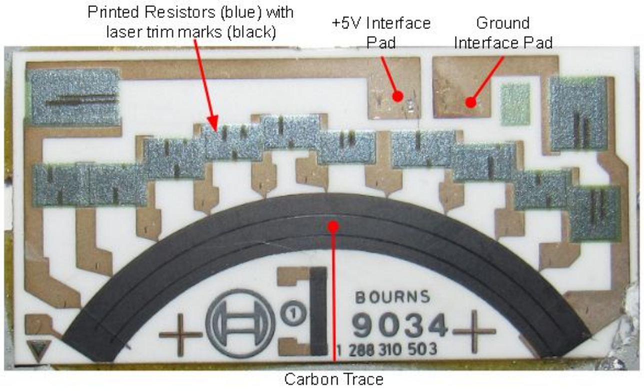


OEM E30 AFM Circuit Details

- The heart of the OEM AFM is the ceramic circuit card containing multiple key features
  - Carbon Trace - Provides interface between Copper wiper and circuit card’s resistor network
  - Laser Trimmed Resistors - Fine tuned (laser trimmed) printed resistors provide ability to tune Air Flow vs Voltage Curve
  - Connector Interface Pads - Discrete plated pads provide contact interface with the sensor’s connector spring fingers for Ground and +5V Input
- Resistance (output to +5V input) doesn’t vary linearly with flap angle but the output voltage does
  - Makes testing AFM more difficult as a voltage source is required
- Detecting a bad or failing AFM is very difficult with a handheld voltmeter as the damage to the carbon track shows up as narrow dips in the output voltage… Oscilloscope required to validate health of sensor



Oscilloscope Capture of Bad AFM Output Voltage
Voltage vs Time

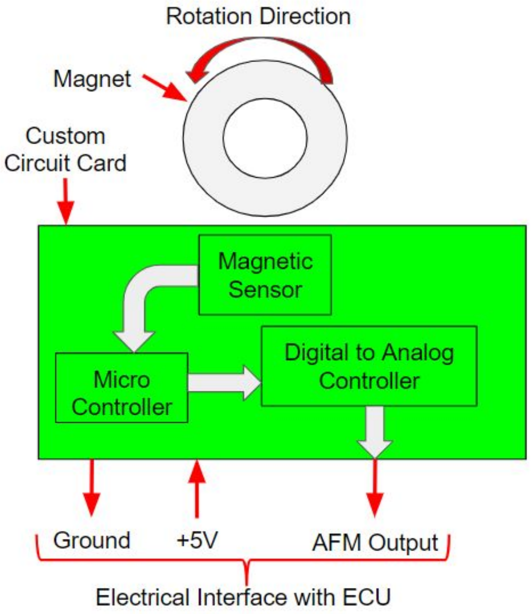


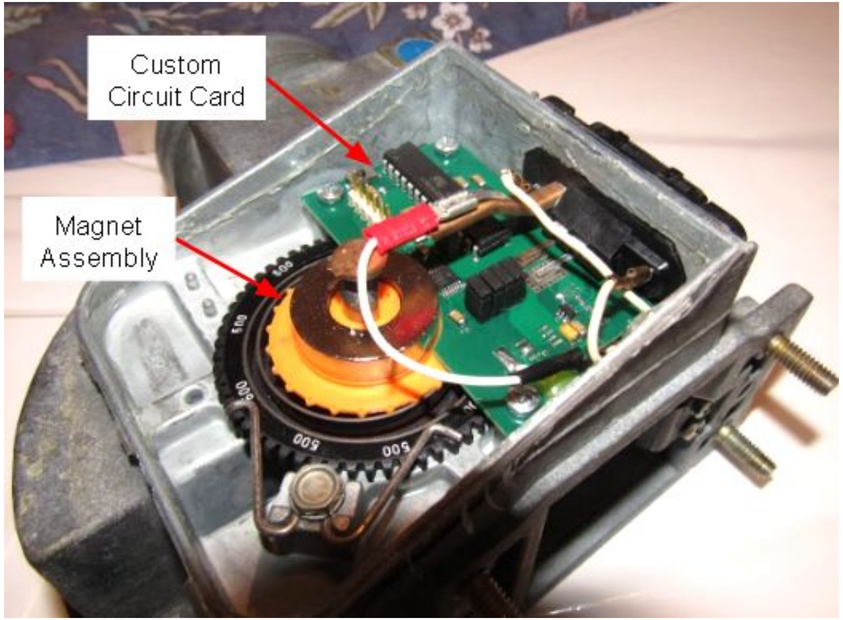
Digitized AFM Design Requirements

- No required modifications to the ECU
  - Work with a +5V input (21mA max current limit draw)
  - Output 0-5V output signal compatible with ECU ADC
- Plug and Play - No wiring modifications required
- No modifications to body of AFM including plastic cover
- No modifications to the spring/pre-tensioning mechanism
- Affordable - Pricing in-line with refurbished OEM unit
- Ability to test for tampering at racing events by tech
- Availability of piece parts/sub-assemblies for repair
- Ruggedized design to meet AFM environments (vibe + thermal)
  - 65C ambient design operating temperature (based on empirical data)

Digitized AFM Overview

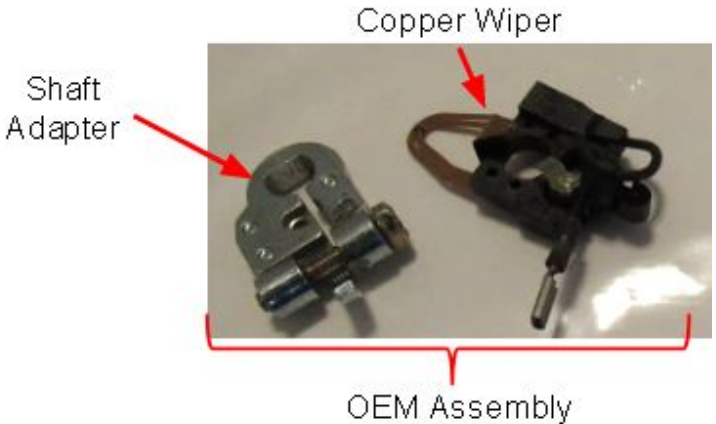
- Contact free sensor utilizes sensor to track the angular displacement of a magnet which rotates with the flap and converts this to a voltage which is sent to the ECU
  - Magnet assembly replaces OEM copper arm assembly
  - Custom circuit card houses magnetic sensor and other components that takes in and outputs the same signals as OEM design
- Magnetic sensing architecture used in automotive sensors such as electronic power steering and transmissions





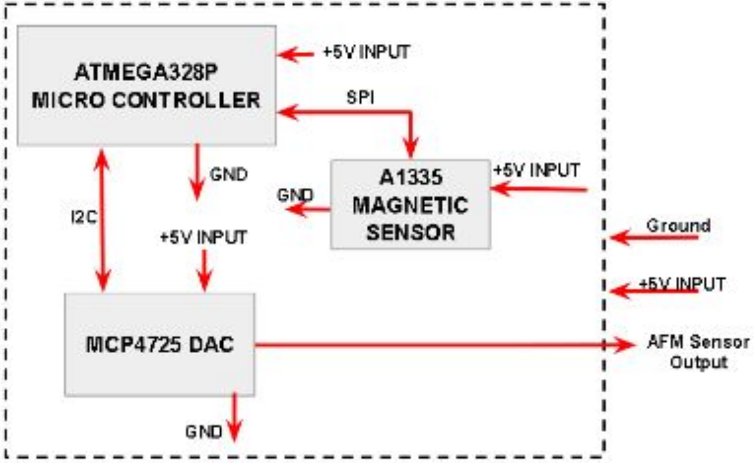
Digitized AFM - Magnet Assembly

- Consists of magnet and shaft adapter
- Magnet
  - SmCo material provides wide temperature range
  - Sized based on commercial availability and matching magnetic strength to magnet sensor requirements
- Bonding Adhesive
  - Recommended by magnet vendors for bonding to SmCo with Nickel finish
- Shaft Adapter
  - FR4 material provides balance between machinable material and good CTE match for magnet
  - D shaped interface locks to shaft
  - Inner bore tightly controlled to align magnet axis to adapter axis during bonding operation
- Assembly weight less than that of equivalent OEM assembly (22.7g vs 23.3g for OEM)

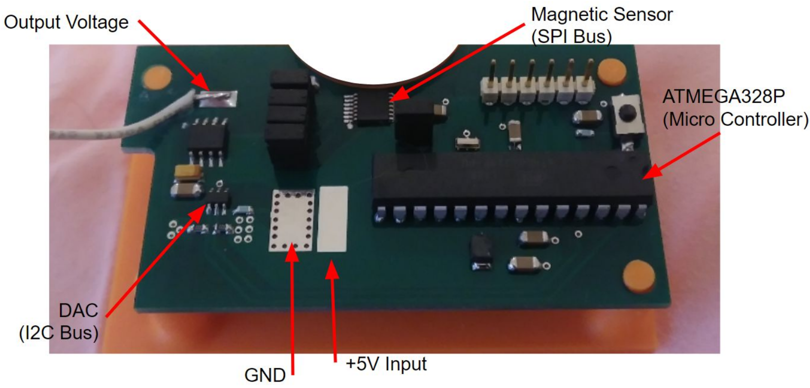


Digitized AFM - CCA Overview

- Custom design consisting of four major components
- FR4 Custom PWB
  - .062” PWB provides all necessary interconnects between components and sensors inputs/outputs
- A1335 Magnetic Sensor
  - Reads angular position of magnet and sends data to Microcontroller through SPI bus
- ATMEGA328P Microcontroller
  - Brain of the system that controls other components and houses Angular position vs Output voltage table
- MCP4725 DAC
  - Receives commands from Microcontroller through I2C bus and outputs voltage to sensor connector

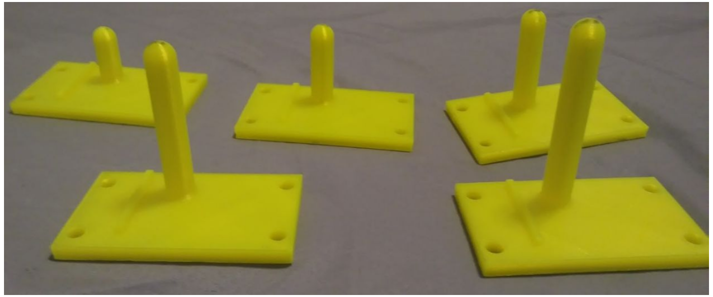


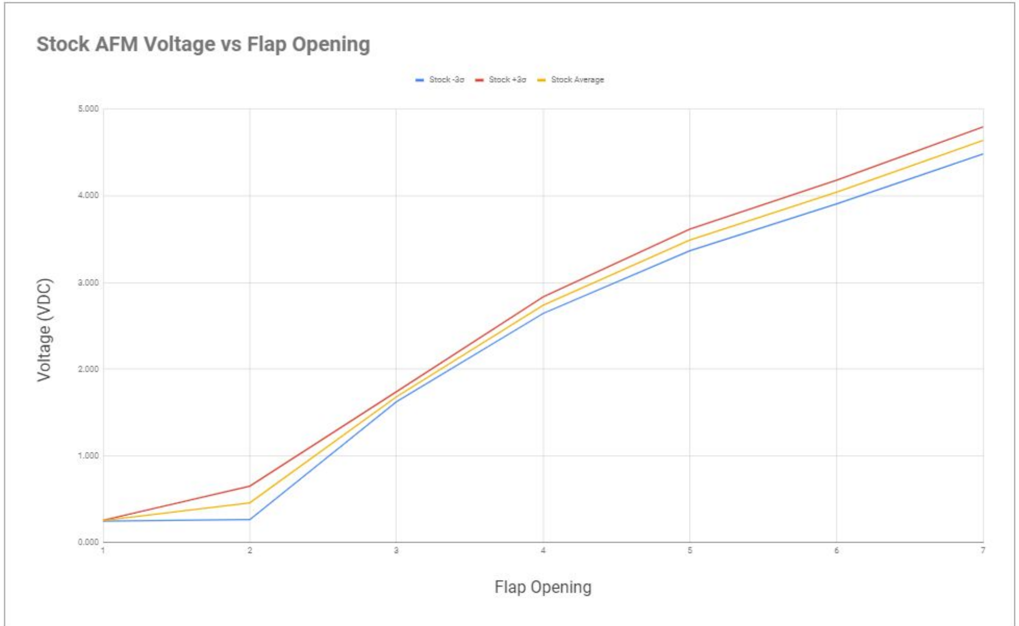
CCA Block Diagram



Characterization of Stock AFMs

- Plan is to utilize this data to help determine proper “curve” for digitized AFM
  - Same/similar setup can be used to verify AFMs at tech inspection
- Currently in process of characterizing stock AFMs being used on active/compliant SE30 cars
  - 4 AFMs currently characterized using regulated power supply to deliver 5VDC
  - Tooling indexes onto front face of AFM to open flap to set value
    - 5 tools result in 5 flap openings with the addition of fully closed and fully open for a total of 7 measurements

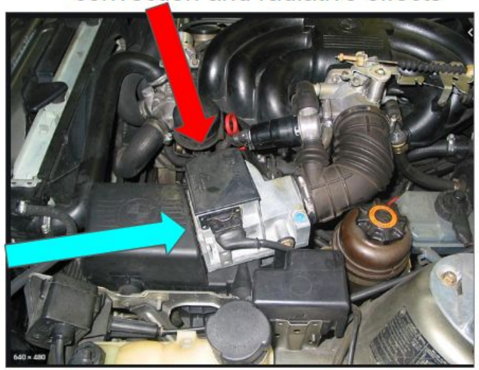




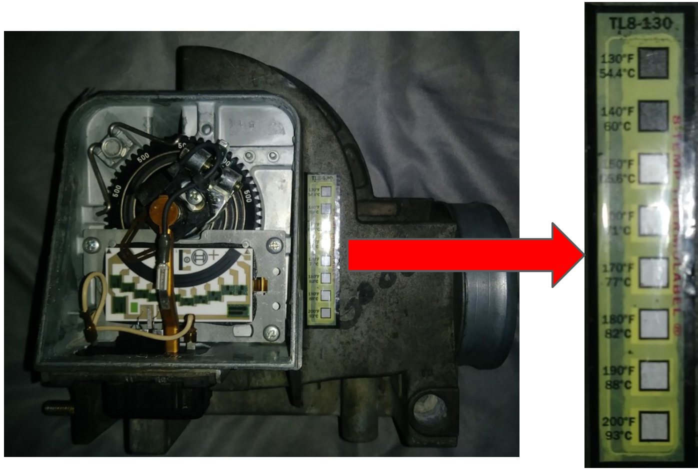
Thermal Analysis (Boundary Conditions)

- AFM is in a unique thermal environment
  - Inside hot engine bay adjacent to radiator but with relatively cooler air always flowing through it
- Utilized 2019 Florida summer race series to gather temperature data
  - Sebring, FL June 22-23 (~94-96°F) - Local Ambient
  - Homestead, Fl August 10-11 (~92-93°F) - Local Ambient
  - Surface temp strips placed on 3 different cars, located on AFM outer surface that faces towards engine bay
  - Hottest temperature recorded was 140°F (60°C)
- Utilizing the 140°F maximum temperature for the electronics internal to the AFM should be conservative as they are not as exposed to the ambient air of the engine bay
  - Offsets the effects of hotter ambient temperature days
- Future data collections will record temperatures of actual digitized AFM both on the inside and outside of AFM
  - Verifies assumptions above

Hot engine bay heats up AFM through convection and radiative effects



“Cool” (relatively) air runs through AFM providing relief to internal components through conduction



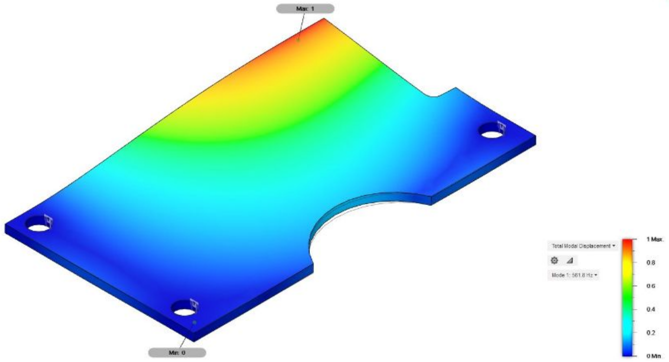
Thermal Analysis (Initial Results)

- Components selected to maximize operating temperature range where available
- Components with highest power dissipations chosen with comencеritive higher maximum temp
  - Magnetic Sensor @ 13mA/5VDC
  - DC-DC Converter
- Special attention paid to those components with lower operating temperature
  - Micro controller modified to minimize power dissipation (only 1mA @ 3.3VDC)
  - Switch is an unpowered component located away from larger power dissipation components
- Positive thermal margin against de-rated component temperatures
  - 80% de-rating typical value used in high reliability military applications

Part #	Ref Des	Description	Qty Req'd/Sensor	Min Temperature (C)	Max Temperature (C)	De-Rated Maximum Temperature (C)	Maximum Expected Temperature (C)	Margin Against De-Rated Maximum Temperature (C)
CSTCC2M00G53A-R0	Y1	2MHz Resonator	1	-40	125	100	60	40
PCA9306DTR2G	U6	I2C Translator	1	-55	125	100	60	40
TPS62203DBVT	U4	DC Converter	1	-40	150	120	60	60
A1335LLETR-T	U3	Magnetic Sensor	1	-40	150	120	60	60
MCP4725A1T-E/CH	U2	DAC	1	-55	125	100	60	40
ATMEGA328P	U1	MicroController	1	-40	125	100	65.5	34.5
434121025816	S1	Switch	1	-40	85	68	60	8
ERJ-3EKF2003V	R5	200k Ohm Resistor	1	-55	155	124	60	64
SG73S1JTTD103J	R1-R4, R6, R7	10k Ohm Resistor	6	-55	155	124	60	64
MLZ2012M100WTD25	L1	10uH Inductor	1	-55	125	100	60	40
SAM11547-ND	J3	8 Position Header	1	-55	125	100	60	40
68705-102HLF	J2	2 Position Header	1	-65	125	100	60	40
SAM9528-ND	J1	6 Position Header	1	-55	125	100	60	40
GRM188D71A106KA73D	C9, C10	10uF Cap	2	-55	125	100	60	40
CGA3E2X7R1E104K080AA	C3-C7, C16-C17	0.1uF Cap	7	-55	125	100	60	40
CL10C101JB81PNC	C2	100pF Cap	1	-55	125	100	60	40
C1608X7S1A475K080AC	C1	4.7uF Cap	1	-55	125	100	60	40

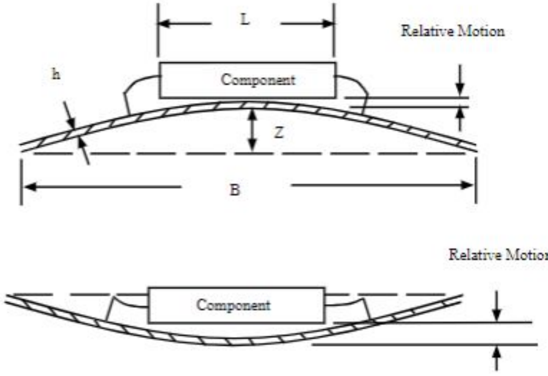
Structural Considerations

- Failure mechanism of interest is the fatigue of the component solder joints
    - Combination of high cycle (vibration) and low cycle (thermal cycling)
- For high cycle fatigue, Steinberg analysis provides method of determining maximum allowable deflection
    - Utilized GM spec for durability of electronic components as source for random vibration environment
        - Provides a random vibration environment for body mounted components with a time of 36hrs to represent 100k miles
        - Placed 20x factor on environment to factor for differences in vehicle dynamics and utilization (race car vs road car)



Circuit Card Modal Analysis Showing 560Hz Mode

Steinberg's Fatigue Limit Equation



Component and Lead Wires undergoing Bending Motion

High Cycle Fatigue Structural Considerations Cont'd

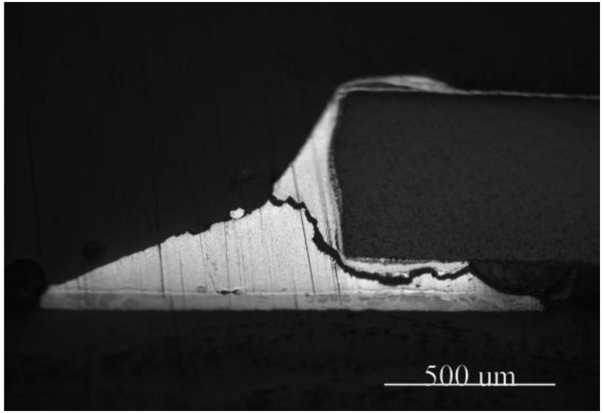
- Limiting component is the microcontroller due to its location on the PWB and overall size
    - 0.01" maximum allowable deflection for 20 million cycles (based on Steinberg analysis)
- Fusion360 FEA tool utilized to determine CCA natural frequency of 560 Hz
    - Used 15 GPa Young's Modulus based on low end empirical data for CCA characterization
    - Incorporated weight of components + PWB into model
- Leveraged GM specification for durability of vehicle electronics components (GMW3172)
    - Random vibration PSD input of 0.1 G^2/Hz for 44 hrs represents ~100k miles
        - Input is for components mounted on engine/transmission (extremely conservative)
        - Assumed out of plane vibe is the driving axis (in-plane results in minimal deflection)
- ~16% of micro controller's life is consumed with random vibration, leaving remaining ~84% for thermal cycling (see following slides)

Fn (natural frequency)	561.8	Hz	
PSD Input @ Resonant Frequency	0.1	G^2/Hz	GM 3172 Engine/Transmission Mounted Components
Q	23.70		
Grmspcb	45.73	G	
Estimated Deflection 1σ	0.0014	in	
Estimated Deflection 3σ	0.0043	in	

Micro Controller Fatigue Ratio	0.156
Magnetic Sensor Fatigue Ratio	0.013
DAC Fatigue Ratio	0.107

Low Cycle Fatigue

- The more severe environment for this device is from thermal cycling which stresses the solder joints due to the coefficient of thermal expansion mismatch between the electrical components and PWB
- Steinberg analysis provides estimation of how many thermal cycles a specific design can survive based on some critical parameters
  - Environment - Combination of on/off powered cycles and diurnal cycling
  - Solder Type - Tin/Led Eutectic
  - Component Geometry - Microcontroller in this case due to size
  - CTE of items - Component ~15ppm/C and PWB ~18ppm/C

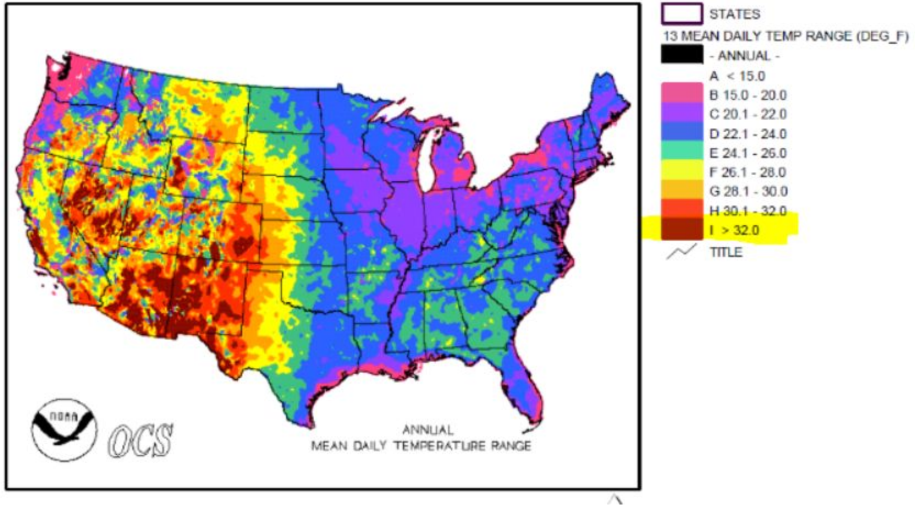


Low Cycle Fatigue Cont'd

	# of On/Off Cycles/Day	2	
	# of Service Years	10	
	# of Total Thermal Cycles from Driving	7300	
	# of Diuarnal Cycles	3650	
	PWB CTE	1.80E-05	ppm/C
	Temperature Delta	60	C
User Inputs	Micro Controller CTE	1.40E-05	ppm/C
	Micro Controller Length	1.37	in
	Micro Controller Thickness	0.014	in
	Micro Controller Width	0.295	in
	Diagonal Half Length	0.670	
	Change in Length	1.61E-04	in
	h	0.080	in
	E	1.60E+07	lb/in^2
	I	5.76E-09	in^4
	P	3.47E-01	lb
	M	1.39E-02	lb*in
	Lead Stress	1.69E+04	lb/in^2
	Avg. Solder Joint Thickness	0.026	in
	Avg. Solder Joint Area	5.31E-04	in^4
	PCB Thickness	0.062	in
	Solder Joint Stress	4.22E+02	lb/in^2
	Cycles to Failure (on/off cycling)	12360	
	Cycles to Failure (diuarnal cycling)	83083	
	Micro Controller LCF Damage Index	0.63	

Assumes you drive the car twice a day, every day for 10 years

Cycle every day for 10 years with a range of 32F



Steinberg Analysis Estimates 63% of life will be exhausted from LCF

Structural Analysis Conclusion

- High and Low cycle fatigue damages are added together to determine the cumulative damage index (CDI)
- A CDI less than 1 indicates the device will survive the analyzed environments without a fatigue failure
- All three major components of the AFM show a CDI of less than 1

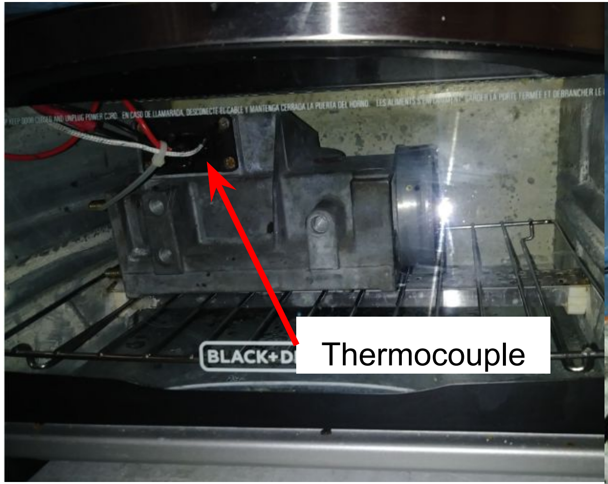
Micro Controller	
Thermal Fatigue	0.61
Random Vibration Fatigue	0.156
Total	0.761

Magnetic Sensor	
Thermal Fatigue	0.32
Random Vibration Fatigue	0.013
Total	0.332

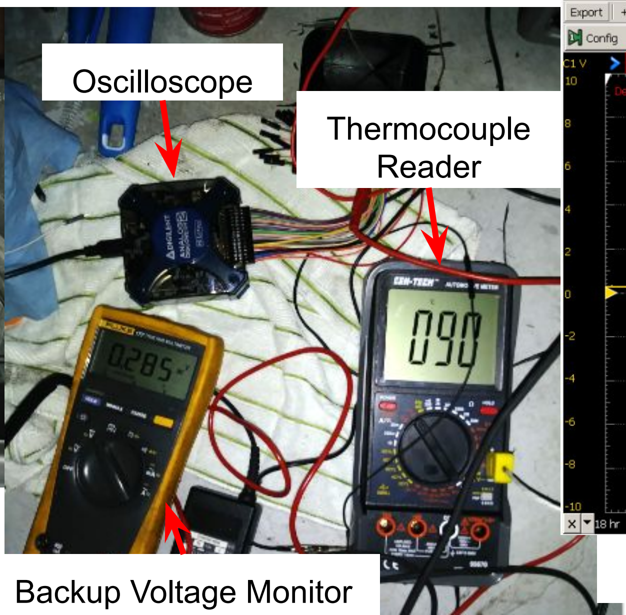
DAC	
Thermal Fatigue	0.26
Random Vibration Fatigue	0.107
Total	0.371

Temperature Testing

- Temp testing performed to characterize sensor's operation at temperature
  - 90°C (194°F) for 24hrs chosen to bound, with margin, any operational case
  - Test performed with flap closed, position where sensor is most susceptible to errors (lowest magnetic strength)
  - Recording voltage output at 200hz, temperature controlled by oven (no record but periodical check)
- Testing showed consistent sensor operation over 24hrs with no dropouts
- Sensor showed a 1% change (lower voltage as temp increases) in voltage output over a 70C swing



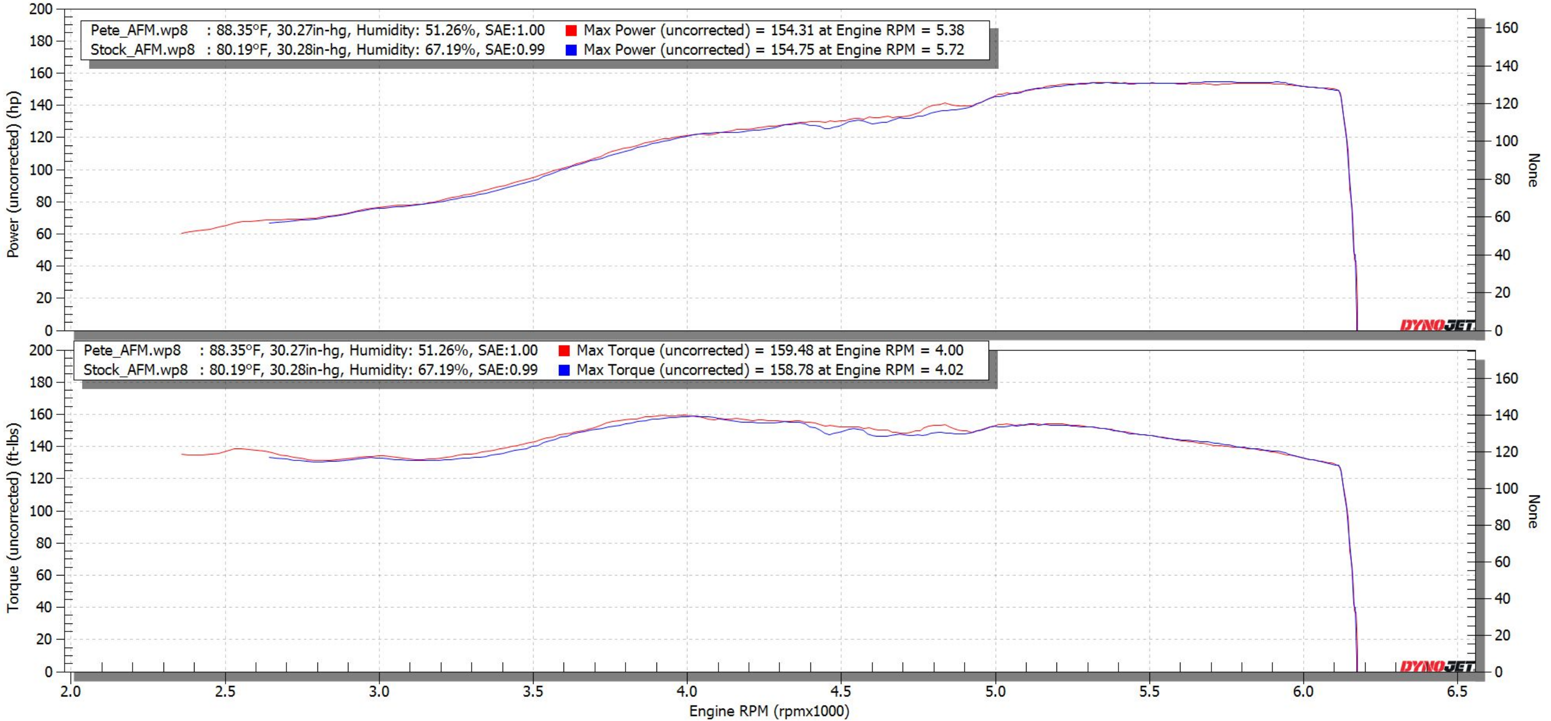
Sensor in Oven with plastic cap removed to expose electronics to ambient temp



Output Voltage Recording Showing hours 18-23

Dyno Testing

- Dyno test performed on 3/14/2020 with Tom Panzarella's car (#88)
    - Runs made with a stock AFM and a modified AFM
- Results show a near identical peak HP trace (>5kRPM)
- Modified AFM shows a slight advantage in 4.4-4.5kRPM against this particular stock AFM



Conclusion

- Significant time and effort put into designing a robust digitized AFM design
- 14 units built to date with different levels of run time
  - 2 complete NASA SE30 seasons over 8+ different cars;
  - 2 installed onto “daily” driver E30s 750+ issue free miles
  - Champcar VIR 8+7 hour Enduro 12/2021
  - Champcar VIR 12 hour Enduro (Car spun rod bearing 8 hours in) 3/2022
  - NASA SoCal 3 hour Enduro 3/2022 (3 AFMs across 3 different cars)
  - 50+ dyno runs to verify consistency and to compare against stock units
  - 2 units built for Porsche 944 and 911 testing
- Have only had a single issue with early unit traced back to damage occurred in shipping
  - Link To Root cause analysis
- Measurement of stick AFMs show a large variance in their output curve which manifests in significant dyno results
  - Meaningful gains to be had for those who have time/money to hunt down golden stock units
  - Digitized AFM has the ability to reduce the power spread in SE30 field