A HORSE POWER MEASUREMENT SYSTEM FOR NEXT GENERATION AIRCRAFT

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ABSTRACT

Understanding the horsepower demands that electrical and hydraulic systems place on an aircraft engine is critical since this directly effects engine performance. The current methods of measuring horsepower have been mainly limited to lower rpm engines and are not suitable for higher rpm jet engines. L-3 Telemetry East has developed instrumentation for the F-22 instrumentation group that is capable of measuring horsepower loads on engine shafts that are rotating at up to 18000RPM. This paper describes the operation of this system.

KEY WORDS

Horse Power, Torque, RPM, Qualification, F-22 Raptor

INTRODUCTION

Engineers have long desired to know the amount of power that auxiliary equipment on aircraft requires during operation. This information is critical because the power to drive these auxiliary devices is taken from the aircraft engines and directly effects the engine performance. As aircraft have become more complicated, the electrical and hydraulic demands have continued to increase. For example, the F-22 Raptor has much larger electrical and hydraulic demands than previous fighter jets such as the F-15 or F-16. Direct measurement of this power is very difficult due to the high rotational speed of the jet engine. Until now, measurement of this diverted power was only possible on low rotational speed systems.

Under contract by Lockheed Martin Aeronautical Systems, L-3 Communications Telemetry-East Division has developed a method of directly measuring the amount of diverted horsepower on high rotational speed systems. This was specifically accomplished on the F-22 Raptor using L-3 Communications HPMS-700 Horsepower Measurement System.

Direct measurement of the horsepower required to run the auxiliary equipment was made by instrumenting the power take off shaft (PTO shaft) of the F-22 Raptor engine. The PTO shaft is the coupling mechanism between the aircraft turbine engine and the auxiliary devices on the aircraft. The HPMS-700 system consists of the instrumented PTO shaft and the stationary unit. Horsepower measurement is made with no direct connection or contact between the PTO shaft and the stationary unit. The system operates from 28V aircraft power and has been fully qualified for engine bay environments. The HPMS-700 system has successfully measured the diverted horsepower of the F-22 Raptor engines during numerous ground and flight tests at Edwards AFB, CA.

REQUIREMENTS

Because failure of the PTO shaft could result in loss of life, the qualification and design requirements for the HPMS system were extensive. The instrumented PTO shaft was required to be acceptance tested and qualified to the original levels. The original PTO shaft manufacturer, Lucas Aerospace, was subcontracted to perform some of the acceptance and qualification testing of the instrumented shaft. The qualification tests were completed with no out of specification conditions found.

The design requirements were:

1) Operation from –45°C to 100°C.
2) Operation from 28V aircraft power.
3) No direct contact between the shaft and other equipment.
4) A maximum height of shaft mounted components of xx inches.
5) Full operation with a 0.5” gap between the shaft and the stationary unit.
6) Torque measurement from –400 Ft-Lbs. to +213 Ft-Lbs.
7) Temperature measurement of the shaft and stationary unit.

The qualification testing required:

1) End to end spin balancing to within 0.025 in-ounces.
2) Static torque test of 11,500 in-Lb.
3) Fatigue cycle test of 7500 ± 2500 RPM for a minimum of 10 million cycles.
4) Maximum over speed testing of > 18,000 RPM for 5 minutes.
5) Dynamic temperature test of > 15,500 RPM from –40°C to 100°C.
6) High altitude operation test at 60,000 ft.
7) Explosive atmosphere test – per MIL-STD-810E, method 511.3, procedure 1.
8) Sinusoidal Vibration tests – sinusoidal cycling at 20 G’s for 39 hours per axis.
9) Random Vibration tests – random cycling from 15 Hz to 2000 Hz at 23.4 G’s for 22 hours per axis.

10) Shock test – 20 G – 11mS sawtooth pulses applied 3 times to each of 6 directions.

11) EMI test – CE102, RE102 and RF level tests per MIL-STD-462D

12) Axial load test – 200lbs axial load applied to the PTO shaft

13) Critical Speed Cycling test – This consisted of varying speeds from 0 to 15,360 RPM and changing speeds from 10,000 RPM to 15,360 RPM for a total of 14 times per cycle. 5333 cycles were performed while changing speeds.

OPERATION

The basic principal behind the HPMS-700 is that the amount of horsepower a rotating shaft delivers is a function of the applied Torque and the shaft RPM. The HPMS-700 system operates by measuring the torque being applied to the PTO shaft. Strain gauges mounted on the shaft are used to measure the torsional strain on the shaft. The torsional strain is directly proportional to the torque, which is used to determine the horsepower. A detailed derivation of the physics is given in the appendix. Figure 1 shows the block diagram for the HPMS-700 system. Power is coupled to the PTO shaft via a transformer located inside of the stationary unit. Shaft mounted electronics regulate the coupled power and provide the necessary excitation and signal conditioning for the strain gauges. The strain gauge output is amplified, converted to a frequency modulated signal and antenna coupled back to the stationary unit. In addition to the applied torque the shaft temperature is also measured. This signal is also converted to a frequency modulated signal and antenna coupled to the stationary unit. The stationary unit receives the frequency modulated signals, converts them back to voltages, provides additional signal conditioning and outputs voltages that are proportional to the measured torque and shaft temperature. The stationary unit also includes a temperature sensor that monitors the internal temperature of the stationary unit. This is also converted to a voltage and available as an output. The system is capable of measuring the applied torque for either stationary or rotating shafts. Complete operation of the HPMS-700 system is accomplished by applying 28V aircraft power to the stationary unit.

SHAFT MOUNTED ELECTRONICS

Due to the high rotational speed of the shaft, the mounted electronics had to be low mass and able to withstand the high centrifugal force of the high speed rotation. Additionally, after the electronics were mounted the shaft needed to be rebalanced to the original stringent specifications. This required that the final product be small, rugged and not throw the shaft out of balance so badly that it could not be rebalanced to the initial specification. This was accomplished in two parts. First a flexible circuit board was mounted to the shaft with the components then mounted to the circuit board. All components used are surface mount parts with low height and weight. The circuit was then tested and its operation verified. After verification the shaft was wrapped in a high strength, epoxy fiberglass wrap. The shaft was then placed into an oven where the epoxy wrap was cured. The wrap material is fully qualified for use in avionics and is ideally suited to withstand the high centrifugal force of the spinning shaft. The final wrapped shaft was able to be fully qualified to the rigorous tests described above with no out of spec conditions. The completed shaft has no direct contact with other parts, is completely self-contained, requires no batteries or slip rings for power, has a maximum height of 0.25” above the shaft surface and requires no adjustments or maintenance.

STATIONARY UNIT

The stationary unit is used to couple power to the shaft, receive the transmitted signals, perform frequency to voltage conversion and provide additional signal conditioning for the converted signals. As shown in the block diagram the antenna receives both the temperature and torque signals from the shaft using the same antenna. Bandpass filters are used to separate the two signals. The signals are then converted back to a voltage using frequency to voltage converters and gain and offset is applied. The signals are then buffered and available as an output. The unit operates completely on 28V DC power.

CALIBRATION

In order to obtain the highest accuracy, the stationary unit and PTO shaft is fully calibrated from –400 to +213 Ft-Lbs. over the –40°C to +85°C temperature range. To calibrate the system a test station is setup inside an environmental chamber. A precision torque is applied to the PTO shaft at various temperatures and both the shaft and stationary unit outputs are measured. Complete sets of calibration curves are then produced for both the PTO shaft and the stationary outputs. From the calibration curves and the outputs of both the shaft and stationary unit, precision torque measurement is possible.

CONCLUSION

The F22 Raptor Horsepower Measurement Project demonstrated the ability to accurately measure the power load that the auxiliary equipment of the F22 Raptor places on the engines. The measurement was successfully performed on numerous ground and flight tests. This paper defined some of the physical requirements and operating conditions required for the system. Since the qualification and operating requirements for the unit were severe, the approach taken demonstrates a sound solution for any type of torque measurement on a rotating shaft. As aircraft continue to increase in complexity this type of measurement will become increasingly more important.

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FIGURE 1

HPX ROTATING SHAFT BLOCK DIAGRAM

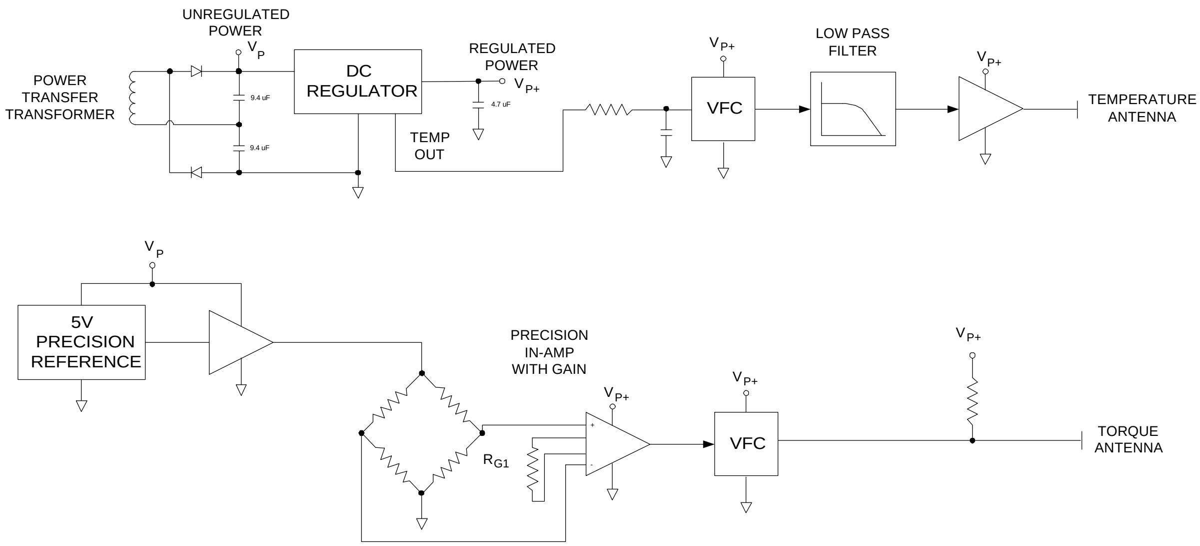

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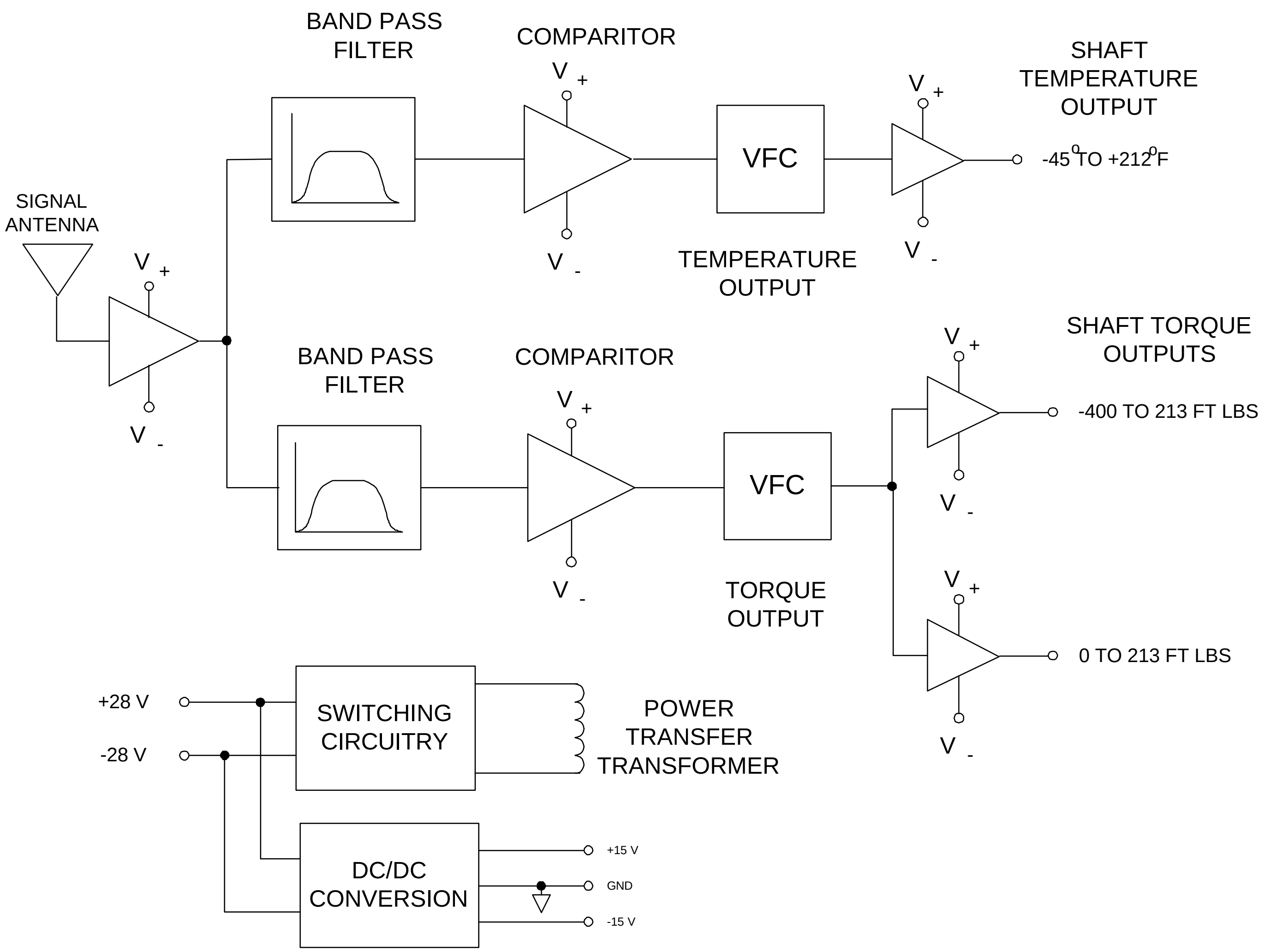
FIGURE 2

HPX STATIONARY UNIT
BLOCK DIAGRAM



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APPENDIX A

This appendix shows how the output of a strain gauge is directly proportional to the torque being applied to a shaft. We begin by showing that the output of a full element strain gauge is proportional to the applied strain.

$$1A)\qquad E_o = \frac{E_i * F}{2}$$

Where : Eo = Output voltage from the strain Gauge (Volts)
Ei = Excitation Voltage (Volts)
F = Gauge Factor (Dimensionless)
ε = Strain (In/In = Dimensionless)

Next we use Hooke's Law which states that the torsional stress is proportional to the torsional strain.

$$2A)\qquad s = \frac{G * e}{2}$$

Where: σ = Torsional Stress (Lbs/In^2)
G = Torsional Modulus of Elasticity (Lbs/In^2)
ε = Torsional Strain (In/In = Dimensionless)

Using the following formula we see that the torsional stress is also proportional to the torque.

$$3A)\qquad s = \frac{T * C}{J}$$

Where: σ = Torsional Stress (Lbs/In^2)
T = Torque (In–Lb)
C = Radius of shaft (In)
J = Moment of Inertia (In^4)

Substituting 2 into 3 and solving for strain we see that the torque and strain are proportional.

$$4A)\qquad e = \frac{T * C}{J * G}$$

Taking this one step further we substitute equation 1 into equation 4 and solve for torque. We end up with the final equation that relates the strain gauge output voltage to applied torque.

$$5A)\qquad T = \frac{E_0 * 2 * G * J}{E_i * F * T * C}$$

APPENDIX B

In this appendix we show how Horsepower and Torque relate. First we start with some basic definitions. Equations 1B and 2B show some useful definitions for work and horsepower. Equation 3B shows the relationship between torque and horsepower.

$$1B) \qquad HORSEPOWER = \frac{WORK}{TIME}$$

Using the above equations we need to change rpm to radians per second. This is easy given the

$$2B) \qquad WORK = TORQUE * RADIANS$$

relationship between radians and revolutions as shown in 4B.

$$3B) \qquad HORSEPOWER = \frac{550 FT - LBS}{SEC}$$

$$4B) \qquad 2p \ Radians = 1 \, \mathrm{Re}\, volution$$

Next we convert revolutions per minute to revolutions per second as shown in 5B.

$$5B) \qquad \frac{\mathrm{Re}\, volution}{Second} = \frac{RPM}{60}$$

Putting all this together we get the relationship between torque, horsepower and rpm as shown in equation 6B.

$$6B) \qquad Horsepower = \frac{Torque * 2 * p * RPM}{60 * 550}$$

$$Horsepower = \frac{Torque * RPM}{5252}$$

Or