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Engine Data Measurement System

C. W. Robinson

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ENGINE DATA MEASUREMENT SYSTEM

C. W. Robinson
Combustion Applications Division 8116
Sandia Laboratories, Livermore

ABSTRACT

The data measurement and reduction system for the Pouliot variable displacement engine uses a Hewlett Packard 2114A minicomputer. The raw data are processed to compute the horsepower, air-fuel ratio, equivalence ratio, brake specific fuel consumption, and brake specific emissions of unburned hydrocarbons, oxides of nitrogen, and carbon monoxide. Emissions are checked for consistency by applying the chemical equilibrium theory of Spindt.[1]

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ENGINE DATA MEASUREMENT SYSTEM

Introduction

An HP-2114 minicomputer data acquisition and data reduction system is being used to measure the performance of the Pouliot engine. The system inputs are ten analog voltage signals and fourteen binary voltages. Seventeen output variables include time-averaged horsepower, air-fuel ratio, and brake specific fuel consumption and emissions.

In this document, emissions and other instrumentation are described in the context of their interfaces with the computer. The data input, correction, and reduction scheme is explained, as are the computation of the important outputs and consistency checks.

The flexibility of the system for output of control signals suggests future expansion of the system to include programmed engine cycles. The system could also be adapted to provide optimum control of engine variables to maximize economy and to minimize emissions.

Emissions Instrumentation

Sandia's emissions measurement system was custom made by Beckman Instruments, Incorporated of Fullerton, California. Its six analyzers provide six analog voltages for measurement by the computer.

The Beckman system includes a refrigerated cold trap for removing the water from the exhaust gases, and an extensive set of solenoid valves to route calibration and exhaust gases to the six analyzers:

1. Beckman model 400 flame ionization detector (FID) for measurement of unburned hydrocarbons

2. Beckman model 951 chemi-luminescence device for measurement of oxides of nitrogen

3. Beckman model 864 nondispersive infrared (NDIR) analyzer for measurement of high concentrations of carbon monoxide

4. Beckman model 865 NDIR for measurement of low concentrations of carbon monoxide

5. Beckman model 864 NDIR for measurement of the concentration of CO_2

6. Beckman model 741 paramagnetic analyzer for measurement of the concentration of oxygen in the dry exhaust gas

Each analyzer is set to output a voltage which varies from zero to plus or minus five volts as the analysis varies from zero to full-scale. The three NDIR devices are nonlinear, so the computer must correct the readings. Each NDIR device has three ranges with different nonlinearity functions. The other three devices are linear, but they have as many as seven knob selectable sensitivity ranges.

Other Instrumentation

Instrumentation for torque, RPM, fuel consumption rate, and air intake rate were designed and developed by Sandia staff (F. W. Kent, 8116, and H. E. Schoeppe, E. E. Smith, T. D. Eskridge, R. F. Facer, D. M. Pierce, and L. D. Zirkle, 8166). These signals are processed by custom analog electronics (to provide digital panel meter outputs) before they are fed to the computer.

Torque is measured by a Baldwin-Lima-Hamilton model U-1B load cell attached to a lever arm on the dynamometer, and it is dead-weight calibrated. RPM is measured by a belt-driven generator on the dynamometer. Fuel mass flow rate is given by a Flowtron model 10E meter. The system has been carefully, extensively calibrated by C. A. Hiller, 8321. The air rate measurement system uses a Flow Technology model LFOA-500 system. Later, a more accurate system, using Hastings models AHL-200PX and AHL-50PX will be adopted.

Computer Description

The computer is an HP-2114A, a machine with a sixteen bit word length. There are 8192 words of memory, a paper tape photo-reader, a tape punch, and a Teletype terminal. The peripherals available include:

1. A 25 kHz, sixteen channel analog-to-digital converter
2. Three high accuracy, six digit voltmeters, customized to provide a 30 Hertz sampling rate
3. Sixteen relays for control of the test
4. Two eight bit digital-to-analog converters
5. A sixteen bit transistor-transistor logic level input-output board

Analog Inputs

The ten analog inputs come to the computer's analog-to-digital converter on the channels indicated in Table I.

The A to D is a twelve bit device with a range of -10.24 to +10.24 V and a resolution of 5 mV per bit. Digitization errors are less than 0.1 percent at minimum signal levels. A to D linearity and calibration were verified against an HP-2480 digital voltmeter adjusted by the SLL standards lab.

Table I
Analog Input Channels

Channel	Represents	Voltage Range
0	unburned hydrocarbons	0 to -5
1	RPM	~10 V @ 5300 RPM
2	torque	~8 V @ 180 ft-lbs
3	fuel input rate	~6 V @ 60 lb/hr
4	uncorrected high range CO	0 to -5
5	uncorrected low range CO	0 to -5
6	uncorrected CO_2	0 to -5
7	nitrous oxide	0 to +5
8	air input rate	~6 V @ 900 lb/hr
9	oxygen	0 to -5

The A to D is controlled by a special assembly language subroutine (subroutine DAS) which requires about three milliseconds to return a value. At this (intentionally) slow speed, the system reads a complete data set in 30 ms. Errors due to noise on the inputs are minimized by averaging over several seconds.

Digital Inputs

Engine stroke and the ranges of the nonlinear NDIR analyzers are input digitally with the bit assignments given in Table II. These signals are read only once for each output data set. A very simple assembly language subroutine (STR) reads the values. The computer input register uses inverted logic (1 < 3V; 0 > 4V) so logic voltages are inverted before input to the computer.

Table II
Digital Input Bits

Bit	Description
0-7	Stroke, binary, bit 7 is MSB, ~0.02 inches per bit
8	High level CO, mid-range
9	High level CO, insensitive range
10	Low level CO, mid-range
11	Low level CO, insensitive range
12	CO_2 analyzer, mid-range
13	CO_2 analyzer, insensitive range

Correction of NDIR Inputs

Because the carbon monoxide and carbon dioxide analyzers are nonlinear, the input voltages are converted from meter readings to concentrations through correction functions. These correction functions were provided by Beckman and are confirmed by calibration using standard gases. Each of the three NDIR analyzers has three ranges, so there are nine correction functions. The functions are input by specifying ten equally spaced points on each of the nine curves. The corrected concentrations are determined by linear interpolation between input points.

Brake Specific Emissions Computations

Emissions are converted from the concentrations provided by the Beckman system to grams of emissions per brake-horsepower-hour by following the analysis specified by the EPA regulation CFR 86.777-15.[2] The coefficients are adjusted to account for use of the more accurate FID and for calibration with propane.

Carbon balance is used to convert concentrations into flow rates. The basic equation of gasoline combustion

$$C_x H_{1.85x} + a\,O_2 \rightarrow b\,H_2O + c\,CO_2 + d\,CO + e\,C_aH_{1.85a} + \ldots$$

requires, for carbon conservation

$$x = c + d + ea$$

Since calibration is done with propane, a = 3.

The carbon input rate $\dot{m}_{ci}$ is related to the fuel input rate $\dot{m}_f$ by the mass ratio of carbon in the fuel

$$\dot{m}_{ci} = \frac{12.01x}{12.01x + 1.008 * 1.85 * x}\,\dot{m}_f = 0.866\,\dot{m}_f$$

The carbon output rate is

$$\dot{m}_{co} = 12.01\left([CO] + [CO_2] + 3[HC]\right) * \dot{M}$$

where $\dot{M}$ is the molar rate of total dry exhaust gas production, square brackets denote concentration, and [HC] is the concentration of equivalent propane.

Defining total carbon

$$TC = [CO] + [CO_2] + 3[HC]$$

and equating carbon input and output rates gives

$$\dot{M} = 0.0727\,\dot{m}_f/TC$$

The mass output rate for CO is

$$\dot{m}_{CO} = (12 + 16)[CO]\,\dot{M} = 2.02\,[CO]\,\dot{m}_f/TC$$

The mass output rate for oxides of nitrogen assuming all converts to NO_2 is

$$\dot{m}_{NO_2} = (14 + 2 * 16)[NO]\ \dot{M} = 3.36\ [NO]\ \dot{m}_f/TC$$

Since the FID measures the number of carbon atoms flowing through it

$$\dot{m}_{hc} = 3[HC]\ \dot{m}_f/TC$$

These quantities are divided by the horsepower to obtain the output quantities; grams of emissions per horsepower-hour.

Consistency Computations

Spindt[1] uses the water gas equilibrium constant

$$H_2O + CO \leftrightarrow H_2 + CO_2$$

$$K = \frac{[H_2O][CO]}{[H_2][CO_2]} \doteq 3.5$$

and carbon, hydrogen, and oxygen balance to compute the air-fuel ratio.

Spindt derived and he and Eltinge[3] experimentally confirmed that

$$A/F = F_b\left[11.492\ F_c\left(\frac{1+R/2+Q}{1+R}\right) + \frac{120(1-F_c)}{3.5+R}\right]$$

For Indoline with a carbon-hydrogen ratio of 1:1.85,

$$R = [CO]/[CO_2]$$

$$Q = [O_2]/[CO_2]$$

$$F_b = ([CO] + [CO_2])/([CO] + [CO_2] + 3[HC])$$

$$F_c = 0.866$$

This relationship, at the cost of measurement of $[O_2]$, provides a check involving air, fuel, [CO], $[CO_2]$, and [HC].

Conclusion

The system described here is adequate to the current, immediate needs, which are to record steady-state brake specific economy and emissions maps of the engine averaged over many seconds.

In a few months, we will extend the system to incorporate programmed control of the stroke and the dynamometer braking relationship. This will allow pacing the engine through the EPA cycles. The system could also be adapted to control spark advance, carburetor throttling, and other engine parameters to optimize economy and minimize emissions.

APPENDIX

Program

```
FTN,B
      PROGRAM BSFD
      DIMENSION Q(10,9)
    3 WRITE(2,100)
  100 FORMAT("BSFC AND HP COMPUTED FROM TORQUE,RPM,FUEL RATE")
      WRITE(2,301)
  301 FORMAT("EMISSIONS PER CFR 86.777-15")
      WRITE(2,202)
  202 FORMAT("INPUT AIR LB/HR AND OXYGEN PROPORTION PER VOLT")
      READ(1,*) HA,HB
      WRITE(2,203)
      H1=20.
      H2=20.
      H3=20.
  203 FORMAT("INPUT TABLES TO CORRECT COHI, COLO, CO2 AT READER")
       DO 8 I=1,9
      DO 7 J=1,10
      READ(5,*) Q(J,I)
    7 CONTINUE
    8 CONTINUE
      WRITE(2,204)
  204 FORMAT("INPUT CO VALUE FOR SHIFT TO HIGH RANGE NDIR")
      READ(1,*)BP
      WRITE(2,207)
  207 FORMAT("INPUT NUMBER OF READINGS TO AVERAGE")
      READ(1,*) L
    2 WRITE(2,101)
  101 FORMAT("INPUT RPM,FT-LB,LB/HR,INCHES PER VOLT OR BIT")
      READ(1,*)A,B,C,D
      WRITE(2,102)
  102 FORMAT("RECORD DATE AND TEST DESCRIPTION")
      READ(1,*) J
   77 WRITE(2,201)
  201 FORMAT("INPUT NOX, HC PER VOLT")
      READ(1,*) E,FF
      WRITE(2,105)
  105 FORMAT(1X,6HSTROKE,2X,3HRPM,3X,6HTORQUE,3X,4HFUEL,5X,2H
     1HC,3X,4HCOHI,3X,4HCOLO,4X,3HCO2,3X,2HNO)
      WRITE(2,106)
      WRITE(2,155)
  155 FORMAT(5X,2HHP,9X,4HBSFC,8X,4HBSHC,8X,4HBSCO,8X,4HBSNO)
  106 FORMAT(3X,3HAIR,4X,8HAIR-FUEL,3X,6HOXYGEN,5X,3HCAF,5X,
```

```
     13HCER)
    1 CALL STR(I4)
      S=D*FLOAT(IAND(I4,377B))
      J1=IAND(I4,1400B)/400B
      J2=IAND(I4,6000B)/2000B
      J3 =IAND(I4,30000B)/10000B
      N1=J1+1
      N2=J2+4
      N3=J3+7
      R=0.
      T=0.
      F=0.
      CO2=0.
      FNO=0.
      HC=0.
      COHI=0.
      COLO=0.
      AIR=0.
      OX=0.
      DO 400 KK=1,L
      CALL DAS(1,I1)
      VOLTS=FLOAT(IAND(I1,177760B))*.0003125
      R=R+A*VOLTS
      CALL DAS(2,I2)
      VOLTS=FLOAT(IAND(I2,177760B))*.0003125
      T=T+B*VOLTS
      CALL DAS(3,I3)
      VOLTS=FLOAT(IAND(I3,177760B))*.0003125
      F=F+C*VOLTS
      CALL DAS(4,I4)
      VOLTS=FLOAT(IAND(I4,177760B))*.0003125
      FNO=FNO+E*VOLTS
      CALL DAS(0,I0)
      VOLTS=FLOAT(IAND(I0,177760B))*.0003125
      HC=HC-FF*VOLTS
      CALL DAS(5,I5)
      VOLTS=FLOAT(IAND(I5,177760B))*.0003125
      COHI=COHI-H1*VOLTS
      CALL DAS(6,I6)
      VOLTS=FLOAT(IAND(I6,177760B))*.0003125
      COLO=COLO-H2*VOLTS
      CALL DAS(7,I7)
      VOLTS=FLOAT(IAND(I7,177760B))*.0003125
      CO2=CO2-H3*VOLTS
      CALL DAS(8,I8)
      VOLTS=FLOAT(IAND(I8,177760B))*.0003125
      AIR=AIR+HA*VOLTS
      CALL DAS(9,I9)
      VOLTS=FLOAT(IAND(I9,177760B))*.0003125
      OX=OX-HB*VOLTS
  400 CONTINUE
      FL=FLOAT(L)
      R=R/FL
      T=T/FL
      F=F/FL
      COHI=COHI/FL
      COLO=COLO/FL
      FNO=FNO/FL
      HC=HC/FL
      CO2=CO2/FL
```

```
      AIR=AIR/FL
      OX=OX/FL
      JCOHI=IFIX(COHI/10.)
      JCOLO=IFIX(COLO/10.)
      JCO2=IFIX(CO2/10.)
      KCOHI=JCOHI+1
      KCOLO=JCOLO+1
      KCO2=JCO2+1
            REMHI=COHI-10.*FLOAT(JCOHI)
      REMLO=COLO-10.*FLOAT(JCOLO)
      REMC2=CO2-10.*FLOAT(JCO2)
      IF(JCOHI)800,800,801
  800 CCOHI=REMHI*Q(1,N1)/10.
      GO TO 802
  801 CCOHI=Q(JCOHI,N1)+REMHI*(Q(KCOHI,N1)-Q(JCOHI,N1))/10.
  802 IF(JCOLO)803,803,804
  803 CCOLO=REMLO*Q(1,N2)/10.
      GO TO 805
  804 CCOLO=Q(JCOLO,N2)+REMLO*(Q(JCOLO,N2)-Q(JCOLO,N2))/10.
  805 IF(JCO2)806,806,807
  806 CCO2=REMC2*Q(1,N3)/10.
      GO TO 808
  807 CCO2=Q(JCO2,N3)+REMC2*(Q(KCO2,N3)-Q(JCO2,N3))/10.
  808 HP=2.*3.1415927*R*T/33000.
      BSF=F/HP
      AF=AIR/F
      WRITE(2,104)S,R,T,F,HC,COHI,COLO,CO2,FNO
  104 FORMAT(3X,F4.2,3X,F4.0,1X,F6.2,2X,F5.1,F7.4,2X,F5.1,2X,
     1F5.1,2X,F5.1,F7.4)
      IF(BP-CCOLO)600,601,601
  600 CCO=CCOHI
      GO TO 602
  601 CCO=CCOLO
  602 TC=CCO+CCO2+3.*HC
      BSHC=3.*HC*453.6*F/(TC*HP)
      BSCO=CCO*453.6*F*2.02/(TC*HP)
      RR=CCO/CCO2
      QQ=OX/CCO2
      BB=(CCO+CCO2)/(CCO+CCO2+3.*HC)
      SS=(1.+.5*RR+QQ)/(1.+RR)
      UU =16.1/(3.5+RR)
      CAF=BB*(SS*9.95+UU)
      CER=CAF/14.48
      BSNO=FNO*453.6*F*3.32/(TC*HP)
      WRITE(2,161)AIR,AF,OX,CAF,CER
      WRITE(2,150)HP,BSF,BSHC,BSCO,BSNO
  150 FORMAT(5(2X,F10.4))
  161 FORMAT(5(2X,F10.4))
      READ(1,*) J
      IF(J-77)701,700,701
  700 GOTO 77
  701 GO TO 1
    4 END
      END$
```

```
ASMB,R,B,L,T
        NAM DAS
        ENT DAS
        EXT .ENTR
I       BSS 1
V       BSS 1
DAS     NOP
        JSB .ENTR
        DEF I
        LDA =B140000
        CLC 22B
        OTA 22B
        LDA =B100000
        ADA I,I
        OTA 22B
        STC 22B,C
        SFS 22B
        JMP *-1
        LIA 22B
        STA V,I
        JMP DAS,I
        END DAS
```

```
ASMB,R,B,L,T
        NAM STR
        ENT STR
        EXT .ENTR
S       BSS 1
STR     NOP
        JSB .ENTR
        DEF S
        LIA 21B
        STA S,I
        JMP STR,I
        END STR
```

Typical Run

```
BSFC AND HP COMPUTED FROM TORQUE,RPM,FUEL RATE
EMISSIONS PER CFR 86.777-15
INPUT AIR LB/HR AND OXYGEN PROPORTION PER VOLT
335.,.05
INPUT TABLES TO CORRECT COHI, COLO, CO2 AT READER
INPUT CO VALUE FOR SHIFT TO HIGH RANGE NDIR
-1.
INPUT NUMBER OF READINGS TO AVERAGE
300
INPUT RPM,FT-LB,LB/HR,INCHES PER VOLT OR BIT
526.3,22.5,9.81,.021
RECORD DATE AND TEST DESCRIPTION
CONTINUING ABOVE
INPUT NOX, HC PER VOLT
.002,.0006668
 STROKE   RPM    TORQUE    FUEL      HC    COHI    COLO     CO2    NO
   AIR     AIR-FUEL   OXYGEN      CAF      CER
     HP           BSFC          BSHC          BSCO          BSNO
   3.49    1034   99.54     9.6   .0010   28.6      .0    88.3   .0036
    165.2221       17.2537         .0124      14.7121        1.0160
     19.5920         .4888        3.9799      22.2429       15.8326
RUN 16
   3.51    1538   94.99    14.1   .0010   63.9      .1    84.8   .0030
    238.2353       16.9440         .0154      14.1646         .9782
     27.8214         .5054        3.9126      72.2292       12.7849
RERUN ON 16; RUN 16A
   3.51    1539   95.71    14.0   .0010   63.0      .1    85.0   .0031
    238.0735       16.9453         .0150      14.1677         .9784
     28.0521         .5008        3.8829      69.7848       13.1648
RUN 17
   3.53    2018   90.67    17.6   .0010   66.3      .1    85.9   .0025
    283.9515       16.1496         .0092      13.7668         .9507
     34.8440         .5046        3.7955      74.9324       10.6254
RUN 19
   4.28    1059  114.28    10.8   .0010   35.5      .1    88.8   .0033
    188.8061       17.4477         .0098      14.4504         .9980
     23.0472         .4695        3.7273      28.1348       13.5103
ABOVE WAS 17; NOW 19
   4.28    1510  107.87    15.0   .0010   60.4      .1    86.4   .0025
    258.7988       17.2444         .0109      14.0244         .9685
     31.0160         .4839        3.7100      61.3759       10.2123
 RUN 20
   4.28    2003   92.34    17.0   .0010   52.2      .1    87.2   .0027
    260.3396       15.3379         .0113      14.2261         .9825
     35.2095         .4821        3.7474      49.3272       11.2280
ENGINE OFF
   4.28     17.    -.34      .7   .0010   10.9     -.0    18.7   .0000
      6.3315        8.6555         .1027      54.4426        3.7599
     -.0011     -680.3271   -38412.906  -64126.890  -1190.4182
TEMP=79, RH=33
```

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2. Code of Federal Regulations, Title 40, Protection of Environment, Parts 70 to 99, as of July 1, 1975, CFR 86.777-15, US Government Printing Office, 1975.

3. L. Eltinge, "Fuel-Air Ratio and Distribution from Exhaust Gas Composition", SAE-680114, pp 425-450.

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