A study of cyclic variation in gas velocity and the turbulence structure in spark ignition engines

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APPENDIX  B1

DIGITIZATION AND CALIBRATION

Program

The purpose of such a program is to enable the ICL Computer to read the output data from the ADC of the Hewlett Packard Fourier Analyzer and to reproduce the digitized data, after scaling, into a suitable format for further use in the data analyses programs. The new storing medium is arbitrarily chosen to be punched cards for convenient replacement of damaged cards during data processing. The option of calibrating the recorded signals to their actual values at the output of instruments are also provided at this stage.

Figure (B1) shows an example of the data format on tapes produced by the PUNCH command (via high speed punch) on the ADC.

```
SF -4 0 9 8192 CR LF
( 20) 32767 16384 ......................
( 28) 24523 ............................
```

Fig. (B1) Example of data on output tapes of the Hewlett Packard ADC

where

- CR = Carriage return
- LF = Line feed
- SF = Stands for 'Scale Factor'
- -4 = \( 10^{-4} \) in the expression \( 10^K \).

All data words are multiplied by \( 10^K \). Thus in the above example all data words are multiplied by \( 10^{-4} = 0.0001 \).

- 0 = Is a coordinate code (e.g. rectangular, polar etc...) (for further details see Table  B1).
9 = Frequency Code, which expresses data sampling parameters in terms of SAMPLE MODE and MULTIPLIER switch setting on ADC.

(for further details see Table B2).

8192 = Block Calibrator.

20, 28 = Are the locations of the first data word in each data record (of 8 words) in the data block of the ADC.

32767, ) = Are data words. Data word system is as follows:

16384, ) = 0 stands for 0 and 32767 for -1.

24523 ) = Therefore to convert data words into physical values, use the following formula:

\[
\text{Physical Value} = \frac{\text{Data word}}{32767} \times \frac{\text{Block Calibrator}}{32767} \times 10^K \quad (B1)
\]

Examination of the above mentioned example for paper tape output indicates that appropriate format are required to pick up the values of (K) and the Block Calibrator for scaling the data and to ignore other characters which could not be recognised by the ICL tape reader.

The first part of the program performs the reading and scaling processes, while the second part converts the data into their physical values as given by equation (B1).

Calibration of the recorded signals to their actual values could be carried out at this step using equation (B2).

\[
E_{\text{actual}} = C \cdot E_{\text{recorded}} + D \quad (B2)
\]
where $C$ is the attenuation factor on the recorded signal and $D$ is the biased DC level from the recorded signals.

In fact two versions of this program are available. The first one, calculates the values of $C$ and $D$ from input data giving the values of the calibration voltages and their corresponding digitized values. The latter set of data should be punched on the same tapes of the digitized signals, while the second version of this program could be used for signals with known calibration constants.

Finally, the program calculates the correct engine speed and the sample size of the digitized data as given by the following equations:

\[
\text{rpm} = \frac{1.2 \times 10^8}{NP \times SR} \quad \text{(B3)}
\]

and

\[
SS = \frac{720}{NP} \quad \text{(B4)}
\]

where $NP$ is the number of samples per cycle as obtained from the recorded timing mark

$SR$ is the sampling intervals on the ADC (micro-sec/sample) - (see Table (B 1)).

and $SS$ is the sample size in crank angle degrees.
### TABLE (B1) Frequency Codes of the ADC

<table>
<thead>
<tr>
<th>Freq. Code</th>
<th>$F_{\text{max}}$</th>
<th>$\Delta T$</th>
<th>$\Delta f$</th>
<th>$T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>50 KHz</td>
<td>10 $\mu$sec</td>
<td>100 Hz</td>
<td>10 msec</td>
</tr>
<tr>
<td>46</td>
<td>25 KHz</td>
<td>20 $\mu$sec</td>
<td>50 Hz</td>
<td>20 msec</td>
</tr>
<tr>
<td>45</td>
<td>10 KHz</td>
<td>50 $\mu$sec</td>
<td>10 Hz</td>
<td>50 msec</td>
</tr>
<tr>
<td>44</td>
<td>5 KHz</td>
<td>100 $\mu$sec</td>
<td>1 Hz</td>
<td>100 msec</td>
</tr>
<tr>
<td>43</td>
<td>2.5 KHz</td>
<td>200 $\mu$sec</td>
<td>0.5 Hz</td>
<td>2000 msec</td>
</tr>
<tr>
<td>42</td>
<td>1 KHz</td>
<td>500 $\mu$sec</td>
<td>0.2 Hz</td>
<td>5000 msec</td>
</tr>
<tr>
<td>41</td>
<td>0.5 KHz</td>
<td>1000 $\mu$sec</td>
<td>0.1 Hz</td>
<td>50000 msec</td>
</tr>
<tr>
<td>40</td>
<td>0.25 KHz</td>
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<td>0 Hz</td>
<td>10 sec</td>
</tr>
<tr>
<td>39</td>
<td>0.10 KHz</td>
<td>5000 $\mu$sec</td>
<td>1 Hz</td>
<td>1000 msec</td>
</tr>
<tr>
<td>38</td>
<td>50 Hz</td>
<td>10 msec</td>
<td>100 Hz</td>
<td>1000 sec</td>
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<td>37</td>
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<td>36</td>
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<td>5000 sec</td>
</tr>
<tr>
<td>35</td>
<td>5 Hz</td>
<td>100 msec</td>
<td>0.5 Hz</td>
<td>20000 sec</td>
</tr>
<tr>
<td>34</td>
<td>2.5 Hz</td>
<td>200 msec</td>
<td>0.2 Hz</td>
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<tr>
<td>33</td>
<td>1 Hz</td>
<td>500 msec</td>
<td>0 Hz</td>
<td>10000 sec</td>
</tr>
<tr>
<td>32</td>
<td>0.5 Hz</td>
<td>1000 msec</td>
<td>1 Hz</td>
<td>1000000 sec</td>
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<tr>
<td>31</td>
<td>0.2 Hz</td>
<td>2000 msec</td>
<td>0.5 Hz</td>
<td>2000000 sec</td>
</tr>
</tbody>
</table>

### Frequency Codes of the ADC

<table>
<thead>
<tr>
<th>Freq. Code</th>
<th>$F_{\text{max}}$</th>
<th>$\Delta T$</th>
<th>$\Delta f$</th>
<th>$T$</th>
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</thead>
<tbody>
<tr>
<td>63</td>
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<td>100 Hz</td>
<td>10 msec</td>
</tr>
<tr>
<td>62</td>
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<td>20 $\mu$sec</td>
<td>50 Hz</td>
<td>20 msec</td>
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<tr>
<td>61</td>
<td>20 Hz</td>
<td>100 $\mu$sec</td>
<td>10 Hz</td>
<td>100 msec</td>
</tr>
<tr>
<td>60</td>
<td>10 Hz</td>
<td>1000 $\mu$sec</td>
<td>1 Hz</td>
<td>10000 msec</td>
</tr>
<tr>
<td>59</td>
<td>5 Hz</td>
<td>2000 $\mu$sec</td>
<td>0.5 Hz</td>
<td>2000000 sec</td>
</tr>
<tr>
<td>58</td>
<td>2 Hz</td>
<td>5000 $\mu$sec</td>
<td>0.2 Hz</td>
<td>20000000 sec</td>
</tr>
<tr>
<td>57</td>
<td>1 Hz</td>
<td>10000 $\mu$sec</td>
<td>0 Hz</td>
<td>10000000 sec</td>
</tr>
<tr>
<td>56</td>
<td>0.5 Hz</td>
<td>2000000 $\mu$sec</td>
<td>0.5 Hz</td>
<td>1000000000 sec</td>
</tr>
<tr>
<td>55</td>
<td>0.2 Hz</td>
<td>5000000 $\mu$sec</td>
<td>0.2 Hz</td>
<td>100000000000 sec</td>
</tr>
<tr>
<td>54</td>
<td>0.1 Hz</td>
<td>10000000 $\mu$sec</td>
<td>0 Hz</td>
<td>1000000000000 sec</td>
</tr>
<tr>
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<td>50 Hz</td>
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<td>10 msec</td>
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<tr>
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<td>100 msec</td>
</tr>
<tr>
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<td>2.5 Hz</td>
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<td>0.5 Hz</td>
<td>2000 msec</td>
</tr>
<tr>
<td>48</td>
<td>1 Hz</td>
<td>500 $\mu$sec</td>
<td>0.2 Hz</td>
<td>5000 sec</td>
</tr>
<tr>
<td>47</td>
<td>0.5 Hz</td>
<td>1000 $\mu$sec</td>
<td>0 Hz</td>
<td>10000 msec</td>
</tr>
<tr>
<td>46</td>
<td>0.25 Hz</td>
<td>2000 $\mu$sec</td>
<td>0.5 Hz</td>
<td>200000 sec</td>
</tr>
<tr>
<td>45</td>
<td>0.1 Hz</td>
<td>5000 $\mu$sec</td>
<td>0.2 Hz</td>
<td>500000 sec</td>
</tr>
<tr>
<td>44</td>
<td>50 Hz</td>
<td>10 $\mu$sec</td>
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<td>43</td>
<td>25 Hz</td>
<td>20 $\mu$sec</td>
<td>50 Hz</td>
<td>20 msec</td>
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<tr>
<td>42</td>
<td>10 Hz</td>
<td>50 $\mu$sec</td>
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<td>50 msec</td>
</tr>
<tr>
<td>41</td>
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<td>200 $\mu$sec</td>
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<td>2000 msec</td>
</tr>
<tr>
<td>39</td>
<td>1 Hz</td>
<td>500 $\mu$sec</td>
<td>0.2 Hz</td>
<td>5000 sec</td>
</tr>
<tr>
<td>38</td>
<td>0.5 Hz</td>
<td>1000 $\mu$sec</td>
<td>0 Hz</td>
<td>10000 msec</td>
</tr>
<tr>
<td>37</td>
<td>0.25 Hz</td>
<td>2000 $\mu$sec</td>
<td>0.5 Hz</td>
<td>200000 sec</td>
</tr>
<tr>
<td>36</td>
<td>0.1 Hz</td>
<td>5000 $\mu$sec</td>
<td>0.2 Hz</td>
<td>500000 sec</td>
</tr>
<tr>
<td>Coordinate Code</td>
<td>Time</td>
<td>Frequency</td>
<td>Rectangular</td>
<td>Polar</td>
</tr>
<tr>
<td>-----------------</td>
<td>------</td>
<td>-----------</td>
<td>-------------</td>
<td>-------</td>
</tr>
<tr>
<td>0</td>
<td>X</td>
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</tr>
<tr>
<td>14</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
**INPUT DATA:**

- **NS** Number of individual signals punched on tape.
- **NT** Number of individual tapes for each signal.
- **NC** Control variable calling the calibration subroutine if an input value of 9 is introduced.
- **N1** Number of samples digitized on each tape.
- **N2** Number of calibration voltages.
- **N3** Number of samples digitized from each calibration voltage recorded signal.
- **NI** First sample number on trace (accounts for any shift of the digitized signal).
- **NGRAPH** Control variable calling graph_plotter subroutine if an input value of 9 is introduced.
- **NGP** Number of graph plots required.
- **NX** Control variable for selecting x axis variable according to the type of digitized signal.
  - \(NX = 1\) For crank angles (degrees)
  - \(NX = 2\) For time (sec)
  - \(NX = 3\) For frequencies (Hz)
- **VCV(I)** Actual values of calibration voltages.
- **SR** Sampling interval on the ADC (micro-sec/sample).
- **C** Attenuation factor on recorded signals.
- **D** Biased DC voltages from recorded signals, for known calibration of signals.
- **VARIABLE(I)** A string of alphanumerical characters describing the digitized signals.
- **CR** Compression ratio of engine.
INPUT DATA:

YP  Probe vertical location in combustion chamber.

THETA  Hot wire orientation inside the combustion chamber.

X MIN, X MAX  Maximum and minimum values on x axis.

Y MIN, Y MAX  Maximum and minimum values on y axis.

X INS, Y INS  Length of x and y axis (in inches) - respectively.

OUTPUT DATA:

C  Attenuation factor on recorded signals.

D  Biased DC voltage from recorded signals.

VARIABLE (I)  (As introduced in input data).

RPM  Engine speed.

SS  Sample size (degrees)

A(I)  Actual values of recorded signals.
MASTER DIGITIZATION AND CALIBRATION

**---------------------------------------------------------------------**
** NS = NUMBER OF INDIVIDUAL SIGNALS PUNCHED ON TAPE.**
** NT = NUMBER OF INDIVIDUAL TAPES FOR EACH SIGNAL.**
** NC = CONTROL VARIABLE CALLING CALIBRATION SUBROUTINE IF EQUALS(9)**
** N1 = NUMBER OF POINTS DIGITIZED ON EACH TAPE.**
** N2 = NUMBER OF CALIBRATION VOLTAGES.**
** N3 = NUMBER OF POINTS DIGITIZED FROM EACH CALIBRATION VOLTAGE.**
** NI = FIRST SAMPLE NUMBER ON TRACE (COULD BE NEGATIVE).**
** NAME(X) = NAME OF X- AXIS VARIABLE.**
** NAME(Y) = NAME OF Y AXIS VARIABLE.**
** NX = CONTROL VARIABLE FOR SELECTING THE X-AXIS VARIABLE ACCORDING**
** TO THE TYPE OF DIGITIZED SIGNAL.**
** NX = 1 FOR CRANK ANGLES (DEGREES).**
** NX = 2 FOR TIME (SEC).**
** NX = 3 FOR FREQUENCIES (HZ).**
** NGP = NUMBER OF GRAPH PLOTS REQUIRED FROM EACH SIGNAL.**
** NGP = CONTROL VARIABLE FOR CALLING GRAPH PLOTTER SUBROUTINES**
** IF ITS INPUT VALUE EQUALS 9.**
** VCV(I) = ACTUAL VALUES OF CALIBRATION VOLTAGES.**
** SR = SAMPLING INTERVAL ON THE ADC (MICRO-SEC).**
** C = ATTENUATION FACTOR FOR RECORDED SIGNAL.**
** D = BIASED DC VOLTAGE FOR RECORDED SIGNALS.**
** VARIABLE(I) = A STRING OF ALPHANUMERIC CHARACTERS DESCRIBING THE**
** RECORDER SIGNAL.**

INTEGER SR
COMMON /B1/ N1, IT
COMMON /B2/ C, D, CT, NR, NRP
COMMON /B3/ N2, N3, VCV(5)
COMMON /B4/ NAMEX(3), NAMEY(3), XMIN, YMIN, XMAX, YMAX, XINS, YINS, NX
COMMON /B5/ NP, SR, NI, IG
DIMENSION VARIABLE(4)
NR, NRP = 0
CT = 1073676289.
READ(1,111) NS
DO 500 IS = 1, NS
READ(1,111) NT, NC
IF(NC.EQ.9) GO TO 100
READ(1,333) C,D
READ(1,333) CR
GO TO 200
100 READ(1,11) N2,N3
READ(1,333) (VCV(I),I=1,N2)
CALL CALIBRATION
WRITE(2,999) C,D
200 CONTINUE
IF(N.T. EQ. 0) NNP=NR
IF(N.T. EQ. 0) GO TO 500
DO 400 IT=1,N
READ(1,111) N1,NT,NSR,NGRAPH,NGP,NX,NI
READ(1,444) (VARIABLE(I),I=1,4)
IF(NX. GT. 1) READ(1,333) THETA,YP
SS=720./FLOAT(NP)
RPM=120.*(10.*6)/FLOAT(NP*SR)
MAX FREQ = 10./(FLOAT(SR)*2.)
IF(NX. EQ. 1) WRITE(2,777) (VARIABLE(I),I=1,2),RPM,(VARIABLE(I),I=3
*,4),CR,NSR,SS
IF(NX. EQ. 2) WRITE(2,888)RPM,(VARIABLE (I),I=1,2),CR,YP,THETA,SR,
*MAX FREQ
IF(NX. EQ. 3) WRITE(2,666)RPM,(VARIABLE (I),I=1,2),CR,YP,THETA,SR,
*MAX FREQ
IF(NX. EQ. 4) WRITE(2,555)RPM,(VARIABLE (I),I=1,2),CR,YP,THETA,SR,
*MAX FREQ
CALL TAPE READER
IF(Ngraph.NE.9) GO TO 300
READ(1,444) (NAMEX(I),I=1,3),(NAMEY(I),I=1,3)
IF(NS. EQ. 1) CALL UTOP
DO 300 IG=1,NGP
CALL GRAPH PLOTTING
300 CONTINUE
400 CONTINUE
500 CONTINUE
IF (NGRAPH.EQ.9) CALL UTPCL
111 FORMAT(8I4)
333 FORMAT(6F0.0)
444 FORMAT(4A8)
555 FORMAT(1H1, 'SECOND DERIVATIVE OF AUTO-CORRELATION FUNCTION')
*\' ENGINE SPEED = F3.3, (RPM) = 2A8, COMPRESSION RATIO = ''F2.
*O.1'' PROBE VERTICAL POSITION = F6.3, (MM) CRANK ANGLE = F7.3, (DEGREES) SAMPLING RATE = I3, (MICRO-SEC)/SAMPLE) MAXIMUM
* FREQUENCY = ''F5.2, (KHZ)''/
666 FORMAT(1H1, 'POWER SPECTRAL DENSITY FUNCTION')
*\' ENGINE SPEED = F8.3, (RPM) = 2A8, COMPRESSION RATIO = ''F2.
*O.1'' PROBE VERTICAL POSITION = F6.3, (MM) CRANK ANGLE = F7.3, (DEGREES) SAMPLING RATE = I3, (MICRO-SEC)/SAMPLE) MAXIMUM
* FREQUENCY = ''F5.2, (KHZ)''/
777 FORMAT(1H1, 'DIGITIZED DATA FOR', 2A8/
*\' ENGINE SPEED = F8.3, (RPM) = 2A8, COMPRESSION RATIO = ''F2.
*O.1'' NUMBER OF SAMPLES = I3, SAMPLE SIZE = F7.3, (DEGREES)')
233 FORMAT(1H1, 'AUTO-CORRELATION FUNCTION')
*\' ENGINE SPEED = F3.3, (RPM) = 2A8, COMPRESSION RATIO = ''F2.
*O.1'' PROBE VERTICAL POSITION = F6.3, (MM) CRANK ANGLE = F7.3, (DEGREES) SAMPLING RATE = I3, (MICRO-SEC)/SAMPLE) MAXIMUM
* FREQUENCY = ''F5.2, (KHZ)''/
999 FORMAT(1H1, 'ATTENUATION FACTOR = F8.4,
*BIASED DC VOLTAGE = F8.4)
STOP
SUBROUTINE TAPE READER

C******************************************************************************
INTEGER SR
DIMENSION IA(8)
COMMON /B1/ N1, IT
COMMON /B2/ C, D, CT, NR, NRP
COMMON /B3/ X(3000), A(3000)

C N1 = NUMBER OF POINTS PUNCHED ON THE TAPE.
C N2, N3 ARE NUMBERS USED FOR CALCULATING THE SCALE FACTOR OF DATA
C PUNCHED ON TAPE

N2 = N1/8
N3 = N1/8

IF((NR.EQ.0).AND.((IT.EQ.1).OR.(NRP.EQ.0))) READ(3,111) N2, N3
IF((NR.GT.0).OR.((IT.GT.1).AND.(NRP.GT.0))) READ(3,222) N2, N3
IF (N2.GT.0) SF = FLOAT(10**N2)*N3/CT
IF (N2.LT.0) SF = FLOAT(N3)/(FLOAT(10**ABS(N2))*CT)
DO 100 L = 1, NPP
READ(3,333) (IA(I), I=1,8)
K = (L-1) * 8
DO 100 J = 1, 8
M = J + K
A(M) = C*FLOAT(IA(J))*SF + D
100 CONTINUE
NRP = N1-NPC
IF(NRP.EQ.0) GO TO 200
READ(3,333) (IA(I), I=1, NRP)
M = NPC + J
A(M) = C*FLOAT(IA(J))*SF + D
200 CONTINUE
NCR = INT(FLOAT(N1)/10.)
DO 300 J = 1, NCR
M1 = (J-1) * 10
WRITE(2,444) (A(M1+I), I=1,10), J
300 CONTINUE
111 FORMAT(2X, I7, 14X, I7, /)
222 FORMAT(1X,/, 2X, I7, 14X, I7, /)
333 FORMAT(10X, 3I7, /)
444 FORMAT(2X, 10F7.3, 3I8)
RETURN

END

SUBROUTINE CALIBRATION

C******************************************************************************
INTEGER VRV
DIMENSION VRV(100,5), VRVM(5), N5(5), N6(5), C1(5), D1(5), SF(5)
COMMON /B2/ C, D, CT, NR, NRP
COMMON /B3/ N2, N3, VCV(5)
SC, SD = 0.0
N3C = N3/8
DO 200 J = 1, N2
IF((NR.EQ.0).AND.((IT.EQ.1).OR.(NRP.EQ.0))) READ(3,111) N5(J), N6(J)
IF((NR.GT.0).OR.((IT.GT.1).AND.(NRP.GT.0))) READ(3,222) N5(J), N6(J)
WRITE(2,111) N5(J), N6(J)
SF(J) = FLOAT(10**N5(J))*N6(J)/CT
WRITE(2,444) SF(J)
444 FORMAT (10X,E20.6)
DO 100 IN3 =1,N3C
L = (IN3-1)*8
READ(3,333) (VRV((L+I),J),I=1,8)
WRITE(2,333) (VRV((L+I),J),I=1,8)
100 CONTINUE
NR = N3- (N3C*3)
M1 = N3-NR
IF(NR.EQ.0) GO TO 200
READ(3,333) (VRV((M1+I),J),I=1,NR)
WRITE(2,444) (VCV(I),I=1,N2)
400 CONTINUE
X = 0.0
DO 300 I=1,N3
X = X+FLOAT(VCV(I,,J))
300 CONTINUE
DO 500 I=1,(N2-1)
C1(I) = (VCV(I+1)-VCV(I))/(VRVM(I+1)-VRVM(I))
500 CONTINUE
C = SC/(N2-1)
DO 600 I =1,N2
D1(I) = VCV(I) -C*VRVM(I)
600 CONTINUE
D = SD/N2
111 FORMAT(2X.,17.,14X.,17,/) 
222 FORMAT(1XJ9/ 2X I 
333 FORMAT(10X,8I7,/) 
RETURN 
END

SUBROUTINE GRAPH PLOTTER
**********************************************************************************
COMMON/B4/JAMEX(3),NAMEY(3),XMIN,YMIN,XMAX,YMAX,XINS,YINS,NX
COMMON/B5/NP,SR,NI,IG
COMMON /B6/ X(3000),Y(3000)
IF (NX.EQ.1) CALL ANGLES
IF((NX.EQ.2). OR. (NX.EQ.4)) CALL TIME INTERVALS
IF(NX.EQ.3) CALL FREQUENCIES
CALL UTP4A(XMIN, XMAX,YMIN,YMAX,XINS,YINS,NAMEX,3,NAMEY,3)
CALL GRID(XMIN,XMAX,YMIN,YMAX,XINS,YINS)
CALL UTP4B(X,Y,NP,2)
RETURN 
END

SUBROUTINE ANGLES
**********************************************************************************
C Y(I) = MEASURED ENGINE PERFORMANCE PARAMETER. (E.G. VELO.PRES., TEMP)
COMMON/B5/NP,SR,NI,IG
COMMON /B6/ X(3000),Y(3000)
SS = 720. /NP
DO 10 I=1,NP
X(I) = SS*I
Y(I) = Y((IG-1)*NP +I)
10 CONTINUE
RETURN
SUBROUTINE FREQUENCIES

Y(I) = POWER SPECTRUM VALUES AT DIFFERENT FREQUENCIES.

COMMON/B5/NP, SR, NI, IG
COMMON/B6/ X(3000), Y(3000)
DF = (10. **6) / (2. * SR * 2048.)
X(1) = I * DF
Y(1) = Y(1 + (IG - 1) * NP)
DO 10 I = 2, NP
X(I) = DF * I + X(1)
Y(I) = Y((2*I-1) + (IG-1) * NP)
10 CONTINUE
RETURN
END

SUBROUTINE TIME INTERVALS

Y(I) = AUTO-CORRELATION FUNCTION OR ITS SECOND DERIVATIVE.

COMMON/B5/NP, SR, NI, IG
COMMON/B6/ X(3000), Y(3000)
X(1) = NI * SR / (10. ** 6)
Y(1) = Y(1 + (IG - 1) * NP)
DO 10 I = 2, NP
X(I) = I * SR / (10. ** 6) + X(1)
Y(I) = Y((IG-1) * NP + I)
10 CONTINUE
RETURN
END

SUBROUTINE GRID (XMIN, XMAX, YMIN, YMAX, XINS, YINS)

DIMENSION X(2), Y(2)
NX = IFIX(XINS)
NY = IFIX(YINS)
X(1) = XMIN
Y(1) = YMIN
Y(2) = YMAX
DX = (XMAX - XMIN) / XINS
DO 1 I = 1, NX
X(1) = X(1) + DX
X(2) = X(1)
1 CALL UTP4B(Y, Y, 2, 3)
X(1) = XMIN
DY = (YMAX - YMIN) / YINS
DO 2 I = 1, NY
Y(1) = Y(1) + DY
Y(2) = Y(1)
2 CALL UTP4B(X, Y, 2, 3)
RETURN
END
FINISH
DIGITIZATION OF CALIBRATED SIGNALS
Program

INPUT DATA:

N CAL A control variable which states the requirement of calibrating the digitized signals using equation (1-2) if an input value of 9 is introduced.

NT Number of individual signals punched on a single tape.

VARIABLE (I)* A descriptive statement about the digitized signal and the test conditions.

NP The number of samples per cycle.

N The total number of samples for each individual signal digitized.

SR The sampling interval on the ADC (micro-sec) (see Table (Bl)).

C Attenuation factor in equation (B2).

D Biased DC voltage in equation (B1).

OUTPUT DATA:

VARIABLE (I)* (As introduced in the input data).

RPM Engine speed.

SS Sample size (degrees).

A(I) Actual values of recorded signals.
**Program N210**

**Input 1 = CRO**

**Input 3 = TRO**

**Output 2 = LPO**

**Output 4 = CPO**

**Trace 0**

**END**

---

**Digitization of Calibrated Signals**

```fortran
INTEGER SR
DIMENSION A(5000), IA(8), VARIABLE(IO)
DATA CT.. C., D/1073676289., 1.0, 0.0/
READ(1, 111) NT, NCAL
IF (NCAL .EQ. 1) READ(1, 222) C, D
DO 4 IT = 1, NT
READ(1, 333) (VARIABLE(I), I = 1, 10)
READ(1, 444) N1, NP, SR
SS = 720. / FLOAT(NP)
RPM = 120. * (0. ** 6) / FLOAT(NP * SR)
WRITE(4, 555) (VARIABLE(I), I = 1, 10), RPM, NP; SS
NPP = N1 / 8
NPC = NPP * 8
IF (NPP .EQ. 0) GO TO 1
IF ((IT .EQ. 1) .OR. (NP .EQ. 0)) READ(3, 666) N2, N3
IF ((IT .GT. 1) .AND. (NP .GT. 0)) READ(3, 777) N2, N3
IF (N2 .EQ. 0) SF = FLOAT(N3) / CT
IF (N2 .GT. 0) SF = FLOAT(10 ** N2) * N3 / CT
IF (N2 .LT. 0) SF = FLOAT(N3) / (10 ** IABS(N2)) * CT
WRITE(2, 1000) N2, N3, SF
WRITE(2, 555) (VARIABLE(I), I = 1, 10), RPM, NP; SS
DO 1 L = 1, NPP
READ(3, 888) (IA(II), II = 1, 8)
K = (L - 1) * 8
DO 1 J = 1, 8
M = J + K
A(M) = C * FLOAT(IA(J)) * SF + D
1 CONTINUE
NRP = N1 - NPC
IF (NRP .EQ. 0) GO TO 2
READ(3, 333) (IA(II), II = 1, NRP)
DO 2 II = 1, NRP
K = NPC + II
A(K) = C * FLOAT(IA(II)) * SF + D
2 CONTINUE
NCR = NINT(FLOAT(N1) / 10.)
IF((NCR * 10.) .LT. N1) NCR = NCR + 1
DO 3 J = 1, NCR
```

---

**END**

---

**Notes:**

- The program initializes variables, reads input values, and performs calculations to digitize calibrated signals.
- It handles cases for different input conditions and outputs results.
M1 = (J-1) *10
WRITE(2,999) (A(M1+I),I=1,10),J
WRITE(4,999) (A(M1+I),I=1,10),J
3 CONTINUE
4 CONTINUE
111 FORMAT(2I3)
222 FORMAT(2F0.0)
333 FORMAT(10A3)
444 FORMAT(3I4)
555 FORMAT(1H1,10X,21H DIGITIZED DATA FOR ,10A8//
*3X,14H ENGINE SPEED =,F7.2,19H NO. OF SAMPLES ,I3,16H SAMPLE $*
*IZE =,F5.2,9H(DEGREES)//
666 FORMAT(2X,I7,14X,I7,/
777 FORMAT(1X,/,2X,I7,14X,I7,/
888 FORMAT(10X,3I7,/
999 FORMAT(2X,10F7.3,I8)
1000 FORMAT(2X,'SCALE FACTORS ARE :'/ 20X,2(I8,2X),E20.5)
STOP
END
FINISH
This program is mainly concerned with the spectral analysis of the turbulence signals as discussed in Chapter 4. The different steps in the program structure could be summarised as follows:

1. Digitization of turbulence signals at the appropriate sampling rates, usually 50 μsec/sample is sufficient which corresponds to a maximum cut off frequency of 10 KHz.

2. Preparation of turbulence signals at a particular crank angle. This step includes the following programming operations:
   a) Isolation of a signal of width Δθ, centred at the crank angle θ₁, i.e. from \[θ - (\frac{Δθ}{2})\] to \[θ + (\frac{Δθ}{2})\].
   b) Addition of previously isolated samples to the present one (note for the first cycle the previous signal represents a clear data block).
   c) Storing of the obtained signal in step (b) into a storing location.
   d) Repetition of steps from (a) to (c) for a (N) number of cycles are given by

\[
\text{Maximum number of analysed cycles (N)} = \frac{\text{(Block size)}}{\text{(Width of individual sample)}}
\]

\text{(B5)}
3. Transformation of the synthesized signal to zero mean value signal. The obtained signal \( u(t) \) in step (2) is transferred into a new time history with zero mean value \( x(t) \) as follows:

\[
x_n(t) = u_n(t) - \bar{x} \tag{B6}
\]

where

\[
\bar{x} = \frac{1}{N} \sum_{n=1}^{N} x_n(t) \tag{B7}
\]

and \( N \) is the number of samples in the data record.

Such a process could be carried out in two ways.

a) **Data record in time domain**

Integrate the signal, then divide the result by the number of samples and subtract the latter value from the original signal.

b) **Data record in frequency domain**

Since the Fourier transform of the signal is an intermediate step in the calculations of the power spectrum function, as will be discussed later, a process of eliminating the DC component of the signal in the frequency domain gets rid of such a mean value.


As discussed in Chapter 4 the auto-correlation function is obtained by the following procedure:
a) Compute the Fourier transform of the time series signal as given by the following equation:

\[ X(n) = \int_{-\infty}^{\infty} x_t(t) e^{-j2\pi nt} \quad (B8) \]

b) Compute the spectrum of original data as given by:

\[ S(n) = \lim_{T \to \infty} \frac{1}{T} X(n) X^*(n) \quad (B9) \]

where

\[ X^*(n) \] is the complex conjugate of \( X(n) \) as given by

\[ X^*(n) = \int_{-\infty}^{\infty} x(t) e^{j2\pi nt} dt \quad (B10) \]

c) Compute the inverse Fourier transform to obtain the auto-correlation function as given by:

\[ R_t(t) = F^{-1} \left[ S(n) \right] \quad (B11) \]

\[ R_t(t) = \int_{-\infty}^{\infty} S(n) e^{j2\pi nt} dn \]

\[ = \int_{-\infty}^{\infty} \lim_{T \to \infty} \frac{1}{T} X(n) X^*(n) e^{j2\pi nt} dn \quad (B12) \]

5. Obtain the auto-correlation coefficient as defined by:

\[ R'_t(t) = \frac{R_t(t)}{2} = \frac{R_t(t)}{R_t(0)} \quad (B13) \]

where \( R(0) \) is the value of auto-correlation function at zero time delay.
\[ R_x(x) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t)x(t+\tau) \, dt \] (B14)

6. Store the auto-correlation coefficient in another data block for further analysis.

7. Obtain the time micro-scale of turbulence by double differentiation of auto-correlation coefficient as given by:

\[ \frac{1}{X^2} = -\frac{1}{2} \left[ \frac{\partial^2 R_x(t)}{\partial t^2} \right] \quad t = 0 \] (B15)

8. Obtain the integral scale of turbulence by integrating the auto-correlation coefficient as given by:

\[ L_t = \int_{0}^{\infty} R^i_x(t) \, dt \quad \text{ (B16)} \]

where the integration process is carried out only for positive values of \( R^i_x(t) \).

9. Obtain the normalised power spectrum function.

This is carried out by taking the Fourier transform of the auto-correlation coefficient after applying a rectangular window of the same width as the original 'cycle sample B' as discussed in Chapter 4.

\[ F(n) = 2 \int_{-\infty}^{\infty} R^i_x(\tau) \cos 2\pi n \tau \, d\tau \quad \text{(B17)} \]

10. Individual cycles analysis.

To obtain the analysis of individual cycles the synthesised data record for \( N \) cycles (step 2) is disintegrated to its constituents and the analysis from (3) to (9) are carried out for each individual cycle.
2.1 Details of the Spectral Analysis Program

(Listing of Instructions on the Hewlett Packard Fourier Analyzer)*

The meanings of each command are given in Table (B3)

a) Preparation of Turbulence Signal

\[ L \quad 1 \quad EN \]
\[ BS \quad 4096 \quad EN \]
\[ CL \quad 1 \quad EN \]
\[ L \quad 2 \quad EN \]
\[ RA \quad EN \]
\[ 0 \quad (N\theta) \quad EN \]
\[ CL \quad 0 \quad (NW) \quad 4096 \quad EN \]
\[ A+ \quad 1 \quad EN \]
\[ 0 \quad (NW) \quad EN \]
\[ x> \quad 1 \quad EN \]
\[ # \quad 2 \quad (NC) \quad EN \]

where \( N\theta \) defines the location of the particular crank angle of interest

\( NW \) the number of samples for the width \( \theta \) of the cycle

\( NC \) is the number of cycles analysed = \( \frac{4096}{NW} \)

Example: For 1000 r.p.m. engine speed, 10° sample width

\[ NW = 33 \text{ samples at } 50 \mu \text{ sec sampling rate.} \]
\[ N = 125 \text{ cycles.} \]

*See Table (B3) for definitions.
b(i)   Transformation of Data to Zero Mean Value by Subtraction of Mean Value

\[
\begin{align*}
L & = 3 \\
x & < 1 \\
$ & = 1 \\
= & 1 \quad 4095 \\
: & 1 \quad 4096 \\
CL & 1 \quad 1 \quad 4096 \\
$ & = 1 \\
* & = 1 \quad -1 \\
A & = 1 \\
\# & = 3 \quad (N1)
\end{align*}
\]

where \((N1)\) is the number of successive processes of subtractions.

b(ii)   Transformation of Data to Zero Mean Value by Eliminating the DC Component in the Frequency Domain

\[
\begin{align*}
x & < 1 \\
F & \\
CL & 0 \quad 1
\end{align*}
\]
Spectrum Analysis

If the method described in (b(i)) is used, the analysis starts with a Fourier transform of the time signal, while for the method described in (b(ii)) the following sequence of commands are used directly:

* - EN
F EN
x > 1 EN
CL 1 1 4096 EN
$ 1 4. EN
: 1 EN
W 1 0 1 EN

* $w_{\text{y}} = 0$ 1 2048 EN
% EN
% EN
W 0 2045 2050 EN

* $(\frac{2}{t^2}) R(t)$ is obtained at this step

x < 1 EN
D EN

* Recognise visually the positive portion of the curve and clear the remaining part

CL 0 N2 4096 EN
$ S 0 EN
x< 1 EN

* Integral time scale is obtained at this step ($L_t$)

CL 0 NW (4096-NW) EN
F EN

* Normalised power spectrum function is obtained at this step
Table (B3) Meanings of Symbols Used in the SPECTRUM ANALYSIS Program

(Hewlett Packard Fourier Analyser Code (142) )

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>L N1</td>
<td>LABEL, this defines a starting statement of a loop in the program.</td>
</tr>
<tr>
<td>≠ N1 N2</td>
<td>COUNT, this determines the number of loops (N2) in the program segment starting at the statement labelled by N1.</td>
</tr>
<tr>
<td>BS</td>
<td>BLOCK SIZE.</td>
</tr>
<tr>
<td>RA</td>
<td>ANALOG IN, this instruction introduces an analog signal to the ADC as soon as a triggering pulse is sensed.</td>
</tr>
<tr>
<td>CL N1 N2 N3</td>
<td>CLEAR, this clears the data from the sample (N2) to the sample (N3) in the data block (N1).</td>
</tr>
<tr>
<td>− N1 N2</td>
<td>SHIFT, this instruction shifts the data in the block (N1) number of samples N2 to the right.</td>
</tr>
<tr>
<td>A + N1</td>
<td>ADDITION, this instruction adds the data in block N1 to that in block (0)*.</td>
</tr>
<tr>
<td>A − N1</td>
<td>SUBTRACTION, this instruction subtracts point by point the data in block N1 from that in block (0).</td>
</tr>
<tr>
<td>(*N1 N2</td>
<td>MULTIPLICATION, this multiplies the data in block N1 by an integer number (N2) (between (-32767) to (+32767)) with the exclusion of 0 value.</td>
</tr>
<tr>
<td>(*N1</td>
<td>BLOCK MULTIPLICATION, this multiplies the data block N1 by block (0).</td>
</tr>
<tr>
<td>* N1 N2 N3</td>
<td>COMPLEX MULTIPLY (N2 + J N3) for data in block N1</td>
</tr>
<tr>
<td>: N1 N2</td>
<td>DIVISION, this divides the data block N1 by the integer number N2.</td>
</tr>
<tr>
<td>: N1</td>
<td>BLOCK DIVISION, this divides block (0) by block N1.</td>
</tr>
</tbody>
</table>
Table (B3) continued.

(*) Block (0) is the first data block in the memory of the Fourier analyser and is usually used as the working data block in any dual operations between two data blocks.

\begin{itemize}
  \item [%Nl] DIFFERENTIATION, this differentiates the data in block Nl (First data point remains constant).
  \item [$Nl$ INTEGRATION, this integrates the data in block Nl.
  \item [W Nl N2 N3 PRINT, this gives a print out (on the teleprinter) of the data words from (N2) to (N3) in the data block (Nl).
  \item [P Nl N2 N3 PUNCH, this produces a punched paper tape for the data words from N2 to N3 in the block Nl.
  \item [F Nl N2 FOURIER TRANSFORM]
    \begin{align}
      & Nl \text{ and N2 are two data blocks} \nonumber \\
      & \text{Forward} \nonumber \\
      & F(m \Delta n) = \frac{1}{N} \sum_{n=0}^{N-1} f(n \Delta t) e^{-j2\pi nm/N} \quad \text{(B18)} \nonumber \\
      & \text{Inverse} \nonumber \\
      & F^{-1}(n \Delta t) = \sum_{m=0}^{N-1} F(m \Delta n) e^{+j2\pi nm/N} \quad \text{(B19)} \nonumber \\
      & \text{where} \nonumber \\
      & \Delta t = \text{time increment, } n = \text{frequency resolution} \nonumber \\
      & N = \text{the total number of points in the time domain.} \nonumber 
    \end{align}
  \item [CR Nl CORRELATE, this performs a cross correlation between the data block Nl and block (0), if Nl is defaulted an auto-correlation of block (0) is obtained.}
\end{itemize}
Table (B3) continued.

\[ X < N1 \quad \text{LOAD, this loads the data in block N1 into block (0).} \]
\[ X > N1 \quad \text{STORE, this stores the data in block (0) into block N1.} \]

END.
**SPECTRAL ANALYSIS**

Program.

Version No. 1

An example of the spectral analysis of turbulence signal at (TDC) compression, using a 'cyclo sample' width of 10 crank angle degrees, a sampling rate of 50/sec/sample, and a data block of 4096 data words.

(Test at 1000 RPM).

```
1 L 1
4 B 4096
7 C 1
10 L 2
13 R
15 = 0 1183
19 C 0 33 4096
24 A+ 1
27 = 0 33
31 X> 1
34 # 2 124 0
39 X< 1
42 F 0
50 C 0 0 2
55 *
57 F
59 X> 1
62 C 1 1 4096
67 § 1
70 : 1
73 W 1 0 1
78 X> 1
81 = 0 2048
85 D
87 %
89 %
91 W 0 2044 2052
96 X< 1
99 § 0
102 W 0 30 37
107 X< 1
110 C 0 33 4063
115 F
117 .
```
Version No. 2

An example of carrying out the spectral analysis of turbulence signals at two crank angles, simultaneously. This version of the program is suitable for high engine speeds, e.g. 2000 RPM. In this case a data block of 2048 words can be used.

```
1 L    1
4 BS   2048
7 CL   2
10 CL  3
13 L   2
16 RA  
18 X>  1
21    0  540
25 CL  0  17  2048
30 A+  2
33    0  17
37 X>  2
40 X<  1
43    0  573
47 CL  0  17  2048
52 A+  3
55    0  17
59 X>  3
62 #   2  120  0
67 X<  2
70 L   3
73 X>  1
76 L   4
79 P   1  0  16
84    1  17
88 #   4  120  0
93 F   
95 CL  0  0  2
100    
102 F  
104 X> 1
107 CL 1  1  2048
112 $   1
115 :   1
```
Version No. 2 continued.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<tr>
<td>118 W</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>123 X&gt;</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>126 ←</td>
<td>0</td>
<td>1024</td>
<td></td>
</tr>
<tr>
<td>130 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>132 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>134 W</td>
<td>0</td>
<td>1022</td>
<td>1027</td>
</tr>
<tr>
<td>139 W</td>
<td>1</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>144 X&lt;</td>
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</tr>
<tr>
<td>147 A+</td>
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<td></td>
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</tr>
<tr>
<td>150 CL</td>
<td>0</td>
<td>33</td>
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<tr>
<td>155 F</td>
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</tr>
<tr>
<td>160 D</td>
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<td></td>
</tr>
<tr>
<td>162 $</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>164 D</td>
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<td></td>
</tr>
<tr>
<td>167 X&lt;</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>169 #</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>172 .</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Version No. 3

An example of a 'data preparation' program for the spectral analysis of turbulence signals at six crank angles simultaneously. This version of the program is suitable for very high engine speeds e.g. 3500 RPM. In this case a data block of 1024 data words can be used.

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Version No. 3 continued.

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SPECTRAL ANALYSIS FOR INDIVIDUAL DATA RECORDS.

This program is concerned with investigating the extent of cyclic variations in the turbulence characteristic parameters. Its input data consists of individual cycle samples of turbulence signals isolated at the particular crank angle of interest. The output results of the program can be summarised as follows:

1- Mean square value of the signal for each cycle sample.

2- The Time Micro and Macro scales of turbulence for each cycle sample.

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APPENDIX B3

VELOCITY PREDICTION Program

The main objective of this program is to calculate the gas velocities at different crank angles during the engine cycle. The analysis is usually carried out for a number of consecutive cycles to yield the statistical characteristics of the velocity signal.

The program is fed with a continuous data record of the hot wire anemometer signal digitized as discussed in Appendix B1. This requires a way of recognizing the start and end of each individual cycle on the trace. Moreover, because of the limitations on the storage capacity of the ICL computer, a certain intermediate storing facility for the calculated gas velocities is required for further analysis. Magnetic tapes, paper tapes or cards could be used for such purpose. The latter facility was preferred in view of the reliability of cards and possible replacement of damaged ones. The use of magnetic tapes was also used in an earlier stage of this investigation.

The facilities for analyzing any number of tests are provided, (e.g. probe rotations, different traverses, variable engine speeds or throttle settings). Also, the facilities of using any combinations of output peripherals (line printer, card punch and graph plotter) are also provided, together with a further option of the number of individual cycles produced on each of the above mentioned peripherals.
The required input data for this program could be summarised in the following groups of variables:

1. A complete statement describing the test conditions for any particular experiment considered. This will appear on the heading of output results and do not enter in the program calculations. This group of variables includes: engine speed, throttle setting, engine compression ratio, probe vertical location in the combustion chamber and wires direction relative to probe axes of reference.

2. Another statement about the collected and digitized signal of the hot wire anemometer is also required. This provides the program with the required information about the sampling rate for the digitized data, the number of samples per cycle, the number of complete cycles consisting of the data record, the firing order of the particular cylinder considered (relative to the reference cylinder used for setting the timing mark) and the code number for the anemometer bridge used in collecting the signal.

3. The third group consists of a number of control variables used to select the particular output peripheral on the ICL computer or the combination of more than one peripheral together with a specification of the required number of cycles appearing on each peripheral.
4. The characteristics of the hot wire anemometer used. This includes the values of wire operating resistance and operating temperature, wire cold resistance, lead resistance, the wire length, the wire diameter, the temperature coefficient of resistance for the wire material and the electric resistivity of wire material.

5. A statement about the signal conditioning for both the hot wire anemometer and the pressure transducer. This gives the values for the biased DC level and the attenuation factors on the recorded signals, as discussed in Chapter 4 and in Appendix B1.

6. The sixth group of variables consists of the digitized data for the pressure trace for one engine cycle. A temperature trace is optional and is replaced by introducing the values for the gas temperature during the induction period and making use of polytropic relations.

7. The last group of variables represent the continuous trace of hot wire anemometer signals.
INPUT DATA

NS  Number of individual tests considered.
VC(I)  Coefficients of the dynamic viscosity function.
CPAC(I)  Coefficients of the specific heat at constant pressure function.
N PUNCH  A control variable for producing output results on punched cards.
N GRAPH  A control variable for producing output results on graph plots.
NC  Number of cycles analysed.
NP  Number of samples per cycle.
NEQ  A control variable for selecting the appropriate current equation according to the anemometer system used in collecting the signal.
    NEQ = 1  For DISA Aol system (100Ω top resistance)
    NEQ = 2  For DISA M system (50Ω ""
    NEQ = 3  For DISA M system (5Ω ""
THROTTLING*(I)  Description of throttle setting.
DIRECTION*(I)  Description of wires direction.
YP*  Vertical location of probe inside the combustion chamber.
CR*  Compression ratio of the engine.
RPM*  Engine speed.
AMIN  Minimum crank angle on the x-axis of a graph plot of velocity.
AMAX  Maximum crank angle on the x-axis of a graph plot of velocity.
VMIN  Minimum value of gas velocity on the y-axis.
VMAX  Maximum value of gas velocity on the y-axis.
AINS Length of x-axis of the plot (inches).

VINS Length of y-axis of the plot (inches).

(*) The variables marked with (*) are used to give full description of test conditions which will appear with output results but do not enter in the calculations.

A Biased DC level from the recorded velocity signal (volts).

B Attenuation factor on the recorded signal of gas velocity (-).

SFP Scale factor for the pressure trace (psi/volt).

E Polytropic exponent.

RW Wire operating resistance (ohms).

RC Wire cold resistance (ohms).

RL Probe lead resistance (ohms).

TW Wire operating temperature (°C).

To Reference temperature (°C).

Po Reference pressure (N/m²).

D Wire diameter (m).

Z Wire length (m).

ALPHA Temperature coefficient for wire material (/°C).

BETD Coefficient of electric resistivity for wire material at the reference temperature T₀ (Ω-m).
OUTPUT DATA

CA(I)  Crank angles (degrees).
T(I)  Gas temperature (°C)
P(I)  Gas pressure (N/m²).
CUR(I)  Hot wire current at the crank angle of index I (amps).
BV(I)  Bridge voltage.
H(I)  Heat transfer coefficient (W/m² °C).
VE(I)  Gas velocity (m/sec)
VM(I)  Gas mean velocity averaged over NC number of cycles (m/sec).
LIBRARY (ED, SUBGROUP USUB)
LIBRARY (ED, SUBGROUP GRAP)
LIBRARY (ED, SUBGROUP NAGF)
PROGRAM (N220)
COMPACT
INPUT 1 = CRO
OUTPUT 2 = LPO
OUTPUT 4 = CPO
TRACE 0
END

MASTER VELOCITY PREDICTION

THE USE OF DIFFERENT OUTPUT PREPHIRALS ARE PERMISSIBLE BY ASSIGNING A VALUE OF 9 TO THE CORRESPONDING CONTROL VARIABLE AS FOLLOWING:

NG FOR GRAPH PLOTTER.
NPUNCH FOR CARD PUNCH.
NWR FOR LINE PRINTER.
NCPL NUMBER OF CONSECUTIVE CYCLES PLOTTED.
NCWR NUMBER OF CYCLES PRINTED OUT.
NCYL CONTROL VARIABLE ALLOWING FOR ENGINE FIRING ORDER FOR A FIXED TRIGGER LOCATION.
NEQ SELECTOR FOR USE OF APPROPRIATE BRIDGE EQUATION.
NP NUMBER OF SAMPLES PER CYCLE.
NC NUMBER OF CYCLES ANALYZED.
NAI NUMBER OF FIRST DATA POINT ON THE CYCLE.
DIMENSION CA(400), T(400), P(400), BV(400), VE(400), BETA(400), RG(400), TITLE(6), VM(400)

COMMON/PROP/VC(9), CPAC(9)
READ(1, 1010)NS
READ(1, 1020) (VC(I), I=1,9)
READ(1, 1020) (CPAC(I), I=1,9)
READ(1, 1030) AMIN, AMAX, VMIN, VMAX, AINS, VINS
DO 5000 IS = 1, NS
READ(1, 1010) NG, NPUNCH, NCPL, NCWR, NCYL, NEQ, NP, NC, NAI
READ(1, 1015) NMAX
READ(1, 1030) RW, RC, RL, TW, TO, PO, D, Z, ALPHA, BETO
READ(1, 1030) A, B, SPF, E
READ(1, 1030) RPM, CR, YP
READ(1, 1040) (TITLE(I), I=1,2)
READ(1, 1040) (TITLE(I), I=3,6)
IF(NPUNCH .NE. 9) GO TO 5
IF(IS.EQ.1) WRITE(4,1010) NS
IF(IS.EQ.1) WRITE(4,1050) AMIN, AMAX, VMIN, VMAX, AINS, VINS
WRITE(4,1060) RPM, (TITLE(L), L=1,2), CR, YP, (TITLE(L), L=3,6), NC, NP
WRITE(4,1010) NP, NC
CONTINUE
5 CONTINUE
SS=720. / FLOAT(NP)
NCR=NP/10
IF((NCR*10).LT.NP)NCR=NCR+1
IF((NG.EQ.9).AND.(IS.EQ.1)) CALL UTOPP
40 READ(1, 1050)(P(I), I=1, NP)
NPM=NP/8+1
NPME=7*NP/8
DO10 I=1, NPM
10 SP=SP+P(I)
P(I)=SP/NPM
DO20 I=1, NPM
P(I)=P(I)
20 P(I+NPME)=P(I)
PMN=P(1)
DO30 I=1, NP
IF(P(I).LT.PMN) P(I) = PMN
P(I)=(((P(I)-PMN)*SFP)+14.7)*6895.
T(I)=(TO+273.)*((P(I)/PO)**E)-273.
COEF=1+ALPHA*(T(I)-TO)
RG(I)=RC*COEF
30 BETA(I)=BETO*COEF
MRI=0
DO200 JC=1, NC
IF((NCYL.EQ.0).OR.(JC.NE.1)) GO TO 50
NI=NINT(FLOAT(NP)*FLOAT(NCYL)/8.)
NX=NI+NP
NPP=NX/10
IF((NPP*10).LT.NX)NPP=NPP+1
NPC=NPP*10
MRE=NPC-NI-NP+1
READ(1,1050)(BV(I), I=1, NPC)
DO40 I=NI, NPC
40 BV(M)=A*BV(I)+B
GOTO70
50 NX=NP-MRI
NPP=NX/10
IF((NPP*10).LT.NX)NPP=NPP+1
NPC=NPP*10
MRE=NPC-NX
READ(1,1050)(BV(MRI+I), I=1, NPC)
MI=MRI+1
ME=MRI+NPC
DO60 I=MI, ME
60 BV(I)=A*BV(I)+B
70 CONTINUE
WRITE(2,1010) NCYL, NP, NC, NEQ
WRITE(2,1020) RW, RL, TW, TO, PO, D, Z, ALPHA, BETO
NLAST = NLAST +NPC
J2=0
DO80 I=1, NP
IF(NEQ.EQ.1) CUR = BV(I)/(100.+RL+RW)
IF(NEQ.EQ.2) CUR = BV(I)/(50.+RL+RW)
IF(NEQ.EQ.3) CUR = BV(I)/(5.+RL+RW)
CA(I)=SS*(I+NAI)
CALLDF(T(I),TW,CUR,RW,RO(I),BETA(I),Z,D,ALPHA,P(I),VE(I),H,M)
IF(J2.EQ.51)J2=0
IF(J2.EQ.0) AND (JC.LE.NCWR) WRITE(2,1070) RPM, (TITLE(L), L=1, 2), CR *,YP, (TITLE(L), L=3, 6), JC
J2=J2+1
IF(JC.GT.NCWR) GOTO30
WRITE(2,1030) CA(I), T(I), P(I), BV(I), VE(I), H, M
CONTINUE
DO 85 IM = 1, NP
IF (JC.EQ.1) VM(IM) = 0.0
VM(IM) = VM(IM) + VE(IM)
IF (JC.NE.NC) GO TO 85
VM(IM) = VM(IM) / NC
85 CONTINUE
IF (NG.NE.9) GOTO 90
IF (JC.GT.NCPL) GOTO 90
CALLUTP4A (AMIN, AMAX, VMIN, VMAX, AINS, VINS, 23I) CRANK ANGLE (DEGREES)
*, 3, 16HV (M/SEC), 2
CALLGRID (AMIN, AMAX, VMIN, VMAX, AINS, VINS)
CALLUTP4B (CA, VE, NP, 2)
90 CONTINUE
IF (NPUNCH.NE.9) GOTO 110
DO 100 IX = 1, NCR
MX = (IX - 1) * 10
100 WRITE (4, 1090) (VE(MX + I), I = 1, 10), JC, IX
110 IF (JC.EQ.NC) GO TO 200
DO 120 IR = 1, MRE
L = NP + IR
120 BV(IR) = BV(L)
MRI = MRE
200 CONTINUE
WRITE (2, 990) (VM(IM), IM = 1, NP)
IF (NG.NE.9) GOTO 300
CALLUTP4A (AMIN, AMAX, VMIN, VMAX, AINS, VINS, 23H) CRANK ANGLE (DEGREES)
*, 3, 21HMEAN VELOCITY (M/SEC), 3
CALLGRID (AMIN, AMAX, VMIN, VMAX, AINS, VINS)
CALLUTP4B (CA, VM, NP, 2)
300 CONTINUE
990 FORMAT (10(2X, F8.3))
NXY = (NMAX - NLAST) / 10
IF (NXY.EQ.0) GOTO 5000
DO 4000 IXY = 1, NXY
READ (1, 1050) (BV(I), I = 1, 10)
4000 CONTINUE
NLAST = 0
5000 CONTINUE
1010 FORMAT (2X, 10I3)
1015 FORMAT (2I4)
'020 FORMAT (3E20.12)
030 FORMAT (10F0.0)
040 FORMAT (10A8)
1050 FORMAT (2X, 10F7.3)
1050 FORMAT (2X, 1 ENGINE SPEED = ', F7.2, '(RPM)', 2A8, ' COMPRESSION RATIO = ', F2.0, ': 1/
1 = ', F2.0, ': 1/' PROBE VERTICAL LOCATION = ', F5.2, '(MM)', 4A8/' NUMBER OF CYCLES ANALYZED = ', I3, ' NUMBER OF SAMPLES PER CYCLE = ', I3)
1070 FORMAT (1H1, ' MEASUREMENT OF GAS VELOCITIES INSIDE A COMBUSTION CHAMBER OF A S.I. ENGINE'/
2ENGINE SPEED = ', F7.2, '(RPM)', 2A8, ' COMPRESSION RATIO = ', F2.0, ': 1/
3 = ', F2.0, ': 1/' PROBE VERTICAL LOCATION = ', F5.2, '(MM)
4 = ', F5.2, '(MM)
5 = ', 4A8, ' CYCLE NUMBER = ', I2, '/
6 CRANK ANGLE TEMPERATURE
5E PRESSURE BRIDGE VOLTS VELOCITY H NO. OF I
6TERATIONS '/)
030 FORMAT (12X, F8.4, 5X, 5E14.6, 5X, I4)
1090 FORMAT (2X, 10F7.3, I3, 2X, I3)
CALLUTPC1
STOP
END
SUBROUTINE DF(T0, TW, CUR, RW, RC, BETO, Z, D, ALPHA, P, V, H, M)
CALCULATES GAS VELOCITY FOR A HOT WIRE ANEMOMETER IN AIR USING
DAVIES AND FISCHER EQUATION FOR \( V = \frac{P}{h} \)
PARAMETERS
T0- AMBIENT TEMPERATURE
TW- WIRE OPERATING TEMPERATURE.
CUR- WIRE CURRENT.
RW- WIRE OPERATING RESISTANCE.
RC- WIRE COLD RESISTANCE AT TEMPERATURE TO.
BETO-WIRE RESISTIVITY AT TEMPERATURE TO.
Z- WIRE TOTAL LENGTH.
D- WIRE DIAMETER.
ALPHA- WIRE MATERIAL 1ST TEMPERATURE COEF. OF RESISTANCE.
P- AMBIENT PRESSURE.
V- CALCULATED VELOCITY.
H-- HEAT TRANSFER COEFICIENT.
M- NUMBER OF ITERATION LOOPS COMPLETED IN SUBROUTINE CJMIT.

REAL K1
COMMON/PROP/V(9), CPAC(9)
PI= 3.141592654

\[ V_{TO} = V_T(V_C, 0.00001717, 0.0, T_C, -139.5) \]

\[ CNT0 = CNT(0.02435, 0.0, 0.82, T0) \]

\[ CPCT = CPCT(CPAC, T0, 9) \]

\[ CVTO = CPCT/1.403 \]

\[ RHO = P*28.93/(8314.3*(T0+273.)) \]

\[ CNTI = CNT(0.02435, 0.0, 0.82, T0) \]

CALL HTRANS(H, K1, CUR, RW, RC, TW, T0, BETO, Z, D, ALPHA, M)

IF(H GT 99999999-0) COTO 1

\[ Gl = H*PI*CNT0/(2.6*CVTO*CNTI) \]

\[ G2 = D/VTO \]

\[ FC = ((TW+273.)/(TO+273.))^{0.3} \]

\[ V = (Gl**3)*(G2**2)*FC/RHO \]

RETURN

1 WRITE(2,2) K1

2 FORMAT(29H ITERATION FAILURE IN DF IER=, E12.4)

RETURN

END

SUBROUTINE CJMIT(X, V1, V2, V3, V4, FN, XLI, XRI, EPSI, IEND, IER, M)
SOLVES GENERAL NON-LINEAR EQUATIONS OF THE FORM \( FN(X, A, B, C, D) = 0 \)
BY MUELLERS ITERATION METHOD
PARAMETER FN CALLS AN EXTERNAL FUNCTION SUPPLIED BY THE USER
DESCRIPTION OF PARAMETERS
X- RESULTANT ROOT OF EQUATION \( FN(X, A, B, C, D) = 0 \)
V1-V4 VALUES OF CONSTANTS A, B, C, D
FN- NAME OF EXTERNAL FUNCTION USED
XLIX-INITIAL LEFT BOUND OF THE ROOT X.
XRI-INITIAL RIGHT BOUND OF THE ROOT X
EPS-UPPER BOUND OF THE ERROR OF RESULT X
IEND-MAX NUMBER OF ITERATION STEPS SPECIFIED
IER-RESULTANT ERROR PARAMETER
IER=1 NO CONVERGENCE AFTER IEND ITERATIONS FOLLOWED BY IEND SUCCESSIVE STEPS OF BISECTION.
IER=2 BASIC ASSUMPTION \( FN(XLI) * FN(XRI) \) LESS THAN ZERO IS NOT SATISFIED.
IER=0 NO ERROR
SOLUTION OF EQUATION \( FN(X, A, B, C, D) = 0 \) IS ACHIEVED BY MEANS OF
MUELLERS ITERATION METHOD OF SUCCESSIVE BISECTION AND INVERSE
PARABOLIC INTERPOLATION WHICH STARTS AT THE INITIAL BOUNDS XLIX AND XRI.
CONVERGENCE IS QUADRATIC IF THE DERIVATIVE OF FN AT THE
ROOT X IS NOT EQUAL TO ZERO. ONE ITERATION REQUIRES TWO
EVALUATIONS OF FN(X,A,B,C,D).
FOR REFERENCE SEE G.K.KRISTIANSEN, ZERO OF ARBITRARY FUNCTIONS,BIT,
VOL3(1963), PP205-206.

PREPARE ITERATION
IER=0
XL=XLI
XR=XRI
X=XL
TOL=X
F= FN(TOL,V1,V2,V3,V4)
IF(F) 1,16,1
1 FL=F
X=XR
TOL=X
F= FN(TOL,V1,V2,V3,V4)
IF(F) 2,16,2
2 FR=F
IF(SIGN(1.00,FL)+SIGN(1.00,FR)) 25,3,25
BASIC ASSUMPTION FL*FR LESS THAN 0 SATISFIED.
GENERATE TOLERANCE FOR FUNCTION VALUES.
3 I=0
TOLF= 100.0*EPS
START ITERATION LOOP
4 I=I+1
M= I
START BISECTION LOOP
DO 13 K=1,IEND
X= 0.5*(XL+XR)
TOL=X
F= FN(TOL,V1,V2,V3,V4)
IF(F) 5,16,5
5 IF(SIGN(1.00,F)+SIGN(1.00,FR)) 7,6,7
INTERCHANGE XL AND XR IN ORDER TO GET SAME SIGN IN FL AND FR
6 TOL= XL
XL=XR
XR= TOL
TOL= FL
FL=FR
FR= TOL
7 TOL= F-FL
A= F*TOL
A=A+A
IF(A-FR*(FR-FL)) 8,9,9
8 IF(I-IEND) 7,17,9
9 XR=X
FR=F
TEST ON SATISFACTORY ACCURACY IN BISECTION LOOP
TOL= EPS
A= ABS(XR)
IF(A-1.00) 1',11,10
10 TOL= TOL*A
11 IF(ABS(XR-XL)-TOL) 12,12,13
12 IF(ABS(FR-FL)-TOLF) 14,14,13
CONTINUE
END BISECTION LOOP
COMPUTATION OF ITERATED X-VALUE BY INVERSE PARABOLIC INTERPOLATION

\[
\begin{align*}
A &= \text{FR} - F \\
DX &= (X - XL) \times FL \times (1.00 + F \times (A - \text{TOL}) / (A \times (\text{FR} - FL))) / \text{TOL} \\
XM &= X \\
FM &= F \\
X &= XL - DX \\
\text{TOL} &= \text{X} \\
F &= \text{FN}(\text{TOL}, V1, V2, V3, V4) \\
\text{IF}(F) &= 18, 16, 18 \\
\end{align*}
\]

TEST ON SATISFACTORY ACCURACY IN ITERATION LOOP

\[
\begin{align*}
\text{TOL} &= \text{EPS} \\
A &= \text{ABS}(X) \\
\text{IF}(A - 1.00) &= 20, 20, 19 \\
\text{TOL} &= \text{TOL} \times A \\
\text{IF}(\text{ABS}(\text{EX} - \text{TOL}) &= 21, 21, 22 \\
\text{IF}(\text{ABS}(F) - \text{TOL}) &= 16, 16, 22 \\
\end{align*}
\]

PREPARATION OF NEXT BISECTION LOOP

\[
\begin{align*}
\text{IF}(\text{SIGN}(1.00, F) + \text{SIGN}(1.00, FL)) &= 24, 23, 24 \\
XR &= X \\
FR &= F \\
GOTO &= 4 \\
XL &= X \\
FL &= F \\
XR &= XM \\
PR &= FM \\
\end{align*}
\]

END ITERATION

GOTO 4

ERROR RETURN IN CASE OF WRONG INPUT DATA.

\[
\begin{align*}
\text{IER} &= 2 \\
\text{RETURN} \\
\end{align*}
\]

SUBROUTINE HTRANS(H,K1,CUR,RW,RO,TW,TO,BETO,Z,D,ELP,M)
CALCULATES THE HEAT TRANSFER COEFFICIENT FOR A FINE WIRE IN A CROSS FLOW OF GAS.
H - HEAT TRANSFER COEFFICIENT.
K1 - FUNCTION VARIABLE.
CUR - WIRE CURRENT.
RW - WIRE OPERATING RESISTANCE.
RO - WIRE RESISTANCE AT TEMPERATURE TO.
TW - WIRE OPERATING TEMPERATURE.
TO - REFERENCE AMBIENT TEMPERATURE.
BETO - RESISTIVITY OF WIRE MATERIAL AT TO.
Z - TOTAL WIRE LENGTH.
D - WIRE DIAMETER.
ELP - FIRST TEMPERATURE COEFFICIENT OF RESISTANCE FOR WIRE MATERIAL.
M - NO OF ITERATIONS EXECUTED IN CJMIT.
ADDITIONAL SUBROUTINES REQUIRED-- CJMIT, FK1.

FOR REFERENCE SEE INTERNAL REPORT.

REAL K1
DIMENSION FN(20)
EXTERNAL FK1
PI = 3.141592654
A = PI*D/D/4
CNW = 2.23*(T0+273)/(10.**8)*BETO
CNWT = 2.23*(T0+273)/(10.**8)*BETO*(1+ELP*(TW-TO))
G1 = CUR*CUR*R/(A*CNWT*4*(TW-TO))
G2 = 2*CNW*T/(2*CNWT*R)
G3 = (R*W/R)/R
G4 = Z/2
XL = 0.01
XR = 10.**(12.)
EPS = 10.**(-7)
IEND = 100
CALL CJMIT(K1, G1, G2, G3, G4, FK1, XL, XR, EPS, IEND, IER, M)
IF(IER.LT.1) GOTO 1
H = 100000000.0
CUR = F
K1 = IER
RETURN
1 CONTINUE
K1 = ABS(K1)
H = (KNCTA1+CUR*CUR*ELP*RO/Z)/(PI*D)
RETURN
END

FUNCTION VT(CF, VO, TO, TT, TC)
CALCULATES THE DYNAMIC VISCOSITY OF A GAS AT TEMPERATURE TT.

INPUT PARAMETERS.

CF= POLYNOMIAL COEFFICIENTS FOR VISCOSITY FUNCTION VALUES.
VO= VISCOSITY AT REFERENCE TEMPERATURE TO.
TO= REFERENCE TEMPERATURE.
TT= GAS TEMPERATURE.
TC= TEMPERATURE OF GAS AT ITS CRITICAL POINT.

FOR REP. SEE REID AND SHERWOOD, PROPERTIES OF GASES AND LIQUIDS.
CHAPTER 6, PUBLISHERS MC.GRAW-HILL.

DIMENSION CF(9), X(2), F(2)
TR1 = (TO+273)/(TC+273)
TR2 = (TT+273)/(TC+273)
X(1) = 1.33*TR1
X(2) = 1.33*TR2
DO 2 I = 1, 2
F(I) = 0.0
DO 1 J = 1, 9
1 F(I) = F(I)+CF(J)*X(I)J(J-1)
2 CONTINUE
VT = VO*F(2)/F(1)
RETURN
FUNCTION FK1(K1,G1,G2,G3,G4)
EXTERNAL FUNCTION T3 CMIT.
DESCRIBES THE HEAT TRANSFER FROM A HEATED WIRE IN A CROSS FLOW OF GAS.

INPUT PARAMETERS.
K1- ITERATION VARIABLE.
   (ABS(H*PI*2/CNWT-CUR*CUR*ALPHA*RO/(CNWT*Z)))
G1- EQUATION CONSTANT. (CUR*CUR*RH/(A*CNWT*Z*TV-TO))
G2- EQUATION CONSTANT. (2*CNWS*RO/(2*CNWT*RW))
G3- EQUATION CONSTANT. (RW-RG)/RW
G4- EQUATION CONSTANT. (Z/2)

REAL K1,KA,KSA
KA = ABS(K1)
KSA = SQRT(KA)

FK1 = G1*(1-G2*TANH(KSA*G4)/KSA-G3)-KA
RETURN
END

FUNCTION CNT(CNO,TO,P,T)
C INPUT PARAMETERS.
C CNO- THERMAL CONDUCTIVITY AT REFERENCE TEMPERATURE.
C TO- REFERENCE TEMPERATURE.
C P-POWER FOR PARTICULAR GAS UNDER CONSIDERATION.
C FINDS THE THERMAL COND OF A SINGLE GAS AT TEMPERATURE T
C FOR REFERENCE SEE TSEDERBERG, THERMAL CONDUCTIVITY OF GASES AND
C LIQUIDS, CHAPTER 3, PUBLISHERS ARNOLD.
C T= CNO*((TT+273)/(TO+273))**P
RETURN
END

FUNCTION CPT(AC,T,N)
C FINDS THE SPECIFIC HEAT OF A SINGLE GAS AT TEMP T
C BY POLYNOMIAL FIT TO PUBLISHED DATA.
C INPUT PARAMETERS.
C AC- 1-D ARRAY OF LENGTH N CONTAINING THE COEFFICIENTS.
C T-- GAS TEMPERATURE.
C N- ORDER OF POLYNOMIAL +1
C DIMENSION AC(9)
C 10.0
D0 1 I=1,N
CPT= CPT+AC(I)*(T**(I-1))
1 CONTINUE
RETURN
END
This program is responsible for investigating the extent of cyclic variations in mean gas velocity. This causes cyclic variations in the turbulence parameters from one cycle to another which, consequently, affects the propagation of the combustion process and the development of the cylinder pressure.

It consists, therefore, of a complementary part of the statistical analysis of turbulence analysis which will be discussed in Appendix B5. The input data to this program are obviously the output results of the program 'VELOCITY PREDICTION' discussed in Appendix B3.

The calculations are carried out to give the statistical characteristics of the data in terms of: mean values, variance, standard deviations, coefficient of variations and range of variations. (The definitions of different terms are given in Appendix A2). It calculates also the Skewness and Kurtosis factors at each crank angle. These later variables are measures of the degree of symmetry and peakiness in the probability distribution of the data, which will show any deviations from the normal distribution usually assumed.
INPUT DATA

NS  Number of individual tests considered.
TITLE(I)  Description of each individual test condition.
NP  Number of samples per cycle.
NC  Number of cycles analysed.
V(I,J)  Instantaneous mean gas velocity at the crank angle of index I and the cycle number of index J.

OUTPUT DATA

CA(MP)  Crank angle of index (MP).
VM(MP)  Mean velocity over a number of cycles (NC).
V MX(MP), V MN(MP)  Maximum and minimum values of gas velocity for the crank angle of index (MP) over a number of cycles (NC).
MX  The cycle number (index) where the maximum value of velocity occurred.
MN  The cycle number (index) where the minimum value of velocity occurred.
SD(MP)  Standard deviation of the gas velocity at the crank angle of index (MP).
SDM(MP)  Coefficient of variation of gas velocity at the crank angle of index (MP).
SKEW  Skewness factor at the particular crank angle considered.
OUTPUT DATA (continued)

KURT Kurtosis factor at the particular crank angle considered.

CVR Range of variation of gas velocity at any particular crank angle considered.
MASTER STATISTICAL ANALYSIS

REAL KURT

DIMENSION V(400,12), VM(400), VMIN(400), VMX(400), SD(400), SDM(400),
*TITLE(400), CA(400)

DIMENSION X(1800)

CALL UTPOP

READ(1,111) NS
READ(1,444) AMIN, AMAX, VMIN, VMAX, AINS, VINS

DO 10 IS =1, NS

READ(1,333) (TITLE(I), I=1,30)

READ(1,111) NP, NC

DO 1 J = 1, NC

READ(1,444) (V(I,J), I=1, NP)

1 CONTINUE

SS = 720./NP

JV = 0

DO 6 MP = 1, NP

SV = 0.0

DO 2 J = 1, NC

SV = SV+V(MP,J)

VM(MP) = SV/NC

SVS, DV3, DV4 = 0.0

DO 3 J = 1, NC

SVS = SVS+V(MP,J)*V(MP,J)

DV = V(MP,J)-VM(MP)

DV3 = DV*DV*DV+DV3

3 DV4 = DV4+DV3*DV

Y1 = VM(MP)*VM(MP)*NC

VAR = (SVS-Y1)/(NC-1)

SD(MP) = SQRT(VAR)

SDM(MP) = SD(MP)/VM(MP)*100.

SD3 = SD(MP)*VAR

SD4 = VAR*VAR

SKEW = DV3/(SD3*(NC-1))

KURT = DV4/(SD4*(NC-3))

VMN(MP), VMX(MP) = V(MP, 1)

DO 4 J = 1, NC

IF(VMIN(MP), LT. V(MP,J)) GO TO 4

VMN
VMN(MP) = V(MP,J)
MN = J
4 CONTINUE
DO 5 J=1,NC
IF(VMX(MP),GT.V(MP,J)) GO TO 5
VMX(MP) = V(MP,J)
MX = J
5 CONTINUE
CA(MP) = SS*MP
CVR = (VMX(MP)-VMN(MP))/VM(MP)*100.
IF(JW.EQ.50) JW=0
IF(JW.EQ.0) WRITE(2,555) (TITLE(I),I=1,30)
JW = JW+1
WRITE(2,666) CA(MP),VM(MP),VMX(MP),MX,VMN(MP),MN,SD(MP),SDM(MP),
*SKEW,KURT,CVR
6 CONTINUE
CALL MAXIMUM (SDM,MP,SDMX)
CALL MAXIMUM (SD,MP,SD)
CALL UTP4A (CA,AMAX,VMIN,VMAX,AINS,VINS,23H CRANK ANGLE (DEGREES *)3,16HMEAN VEL (M/SEC).2)
CALL GRID (AMIN,AMAX,VMIN,VMAX,AINS,VINS)
CALL UTP4B (CA,VM,MP,2)
CALL UTP4A (AMAX,VMIN,VMAX,AINS,VINS,23H CRANK ANGLE (DEGREES *)3,15HMAX AND MIN VEL,2)
CALL GRID (AMAX,AMIN,VMIN,VMAX,AINS,VINS)
CALL UTP4B (CA,VM,MP,2)
CALL UTP4B (CA,VM,MP,2)
CALL UTP4A (0.0,720.0,0.0,SDMX,8.5,23H CRANK ANGLE (DEGREES),3,24
*HSTANDARD DEVIATION M/SEC.,3)
CALL GRID (0.0,720.0,0.0,SDMX,8.5,0)
CALL UTP4B (CA,SD,MP,2)
CALL UTP4A (0.0,720.0,0.0,SDMX,8.5,23H CRANK ANGLE (DEGREES),3,24
*HOEFF.COEF VAR. S(U5/U*100,3)
CALL GRID (0.0,720.0,0.0,SDMX,8.5,0)
CALL UTP4B (CA,SD,MP,2)
10 CONTINUE
CALL UTPCL
111 FORMAT (2X,6I3)
222 FORMAT (6F0.0)
333 FORMAT (10A8)
444 FORMAT (2X,10F7.3)
555 FORMAT (1H1,1/'STATISTICAL ANALYSIS OF GAS MOTION /
* INSIDE A CYLINDER OF A S.I. ENGINE /*
*'******************************************************
*' */10A8//'1,10A8//
*' */1,10A8//
'C.A. MEAN VEL MAX VEL CY NO MIN VEL CY NO S.D. MEAN S
*D.S. SKEW KURT COEF OF VAR/*
*3X,F8.4,3X,F8.4,3X,F8.4)
STOP
END
SUBROUTINE MAXIMUM (X, NP, XMAX)
DIMENSION X(200)
XMAX = X(1)
DO 1 I = 1, NP
IF(XMAX.GT.X(I)) GO TO 1
XMAX = X(I)
1 CONTINUE
XMAX = (NINT(XMAX/5.)+1.)*5.
RETURN
END

SUBROUTINE GRID(XMIN, XMAX, YMIN, YMAX, XINS, YINS)
C DRAWS A GRID ON A SET OF AXES PROVIDED BY UTP4A IN THE MASTER.
DIMENSION X(2), Y(2)
NX = IFIX(XINS)
NY = IFIX(YINS)
X(1) = XMIN
Y(1) = YMIN
Y(2) = YMAX
DX = (XMAX-XMIN)/XINS
DO 1 I = 1, NX
X(1) = X(1) + DX
X(2) = X(1)
1 CALL UTP4B(X, Y, 2, 3)
X(1) = XMIN
DY = (YMAX-YMIN)/YINS
DO 2 I = 1, NY
Y(1) = Y(1) + DY
Y(2) = Y(1)
2 CALL UTP4B(X, Y, 2, 3)
RETURN
END
FINISH
APPENDIX D5

TURBULENCE ANALYSIS I
Program

The objective of this program is to calculate the characteristics of the turbulence signal at some particular crank angle of interest during the engine cycle. These turbulence characteristics include the following parameters:

a) Fluctuating velocity components, \( (u') \): 

b) Intensities of turbulence, \( \text{Int} = \left( \frac{u'}{U} \right) \times 100 \). 

c) Time micro-scales of turbulence, \( (\lambda_t) \). 

d) Length micro-scales of turbulence, \( (\lambda_y) \). 

e) Length macro-scales of turbulence, \( (L_x) \).

The mean gas velocities and the mean bridge voltages, over the number of cycles considered (\( \bar{U} \) and \( \bar{E} \)), are calculated as intermediate steps in the program and are, therefore, produced on the output results.

It is obvious that this program requires feeding with the output results obtained from the SPECTRAL ANALYSIS program discussed in Appendix B2. This includes the following variables.

a) Values of the mean square of the fluctuating voltage components as given by \( R_t(o) \) equation (B-14) calculated over a large number of cycles.
b) Values of the second derivative of the autocorrelation coefficient at zero time delay.

\[
\left[ \frac{\partial^2 R_t'(t)}{\partial t^2} \right]_{t = 0}
\]

c) Values of the integral time scale

\[ L_t = \int_0^\infty R_t'(dt) \]  \hspace{1cm} (B20)

This program requires also the digitized signal of the mean bridge voltage for a number of consecutive cycles, the characteristics of the hot wire anemometer used in collecting the signal and finally the fluid properties at the different crank angles considered in the program.

A listing of the MASTER segment of the TURBULENCE ANALYSIS I program is given at the end of this appendix.

All the subroutines and functions required for this program are the same as for the VELOCITY PREDICTION program and are not repeated, therefore, in this appendix.
**INPUT DATA**

**AX(I)**  
String of characters used for the graph plot.

**VC(I)**  
Coefficients of the dynamic viscosity function.

**CPAC(I)**  
Coefficients of the specific heat at constant pressure function.

**NS**  
Number of individual tests considered.

**CASE(I)**  
Description of each test condition.

**N CYL**  
Firing order of any particular cylinder, relative to the reference cylinder, used in setting the timing mark.

**NANG(K)**  
Number of crank angles at which turbulence analysis are required.

**NC**  
Number of complete consecutive cycles from the mean bridge voltage trace.

**NP**  
Number of samples per cycle.

**N**  
Total number of samples on the continuous data record of mean bridge voltage.

**NEQ**  
A control variable for the selection of the appropriate anemometer system current equation.

\[\text{NEQ} = 1 \quad \text{For DISA AoI system (100 \Omega top resistance)}\]

\[\text{NEQ} = 2 \quad \text{For DISA M system (50 \Omega)}\]

\[\text{NEQ} = 3 \quad \text{For DISA M system (5 \Omega)}\]

**N GRAPH**  
A control variable for calling the graph plotter section of the program if its input value = 9.

**ANGLE (I,K)**  
Values of crank angles at which turbulence analyses are required.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMS(I,K)</td>
<td>Mean square values of fluctuating voltage components.</td>
</tr>
<tr>
<td>MICRO (I,K)</td>
<td>Second derivative of auto-correlation coefficient at zero time delay.</td>
</tr>
<tr>
<td>MACRO (I,K)</td>
<td>Integral time scale of turbulence = ∫ R'_t (t) dt</td>
</tr>
<tr>
<td>P(I)</td>
<td>Gas pressures (N/m²)</td>
</tr>
<tr>
<td>T(I)</td>
<td>Gas temperatures (°C)</td>
</tr>
<tr>
<td>A</td>
<td>Biased DC level from mean bridge voltage trace.</td>
</tr>
<tr>
<td>B</td>
<td>Attenuation factor on the recorded mean bridge voltage trace.</td>
</tr>
<tr>
<td>G</td>
<td>Attenuation factor on the recorded turbulence signal.</td>
</tr>
<tr>
<td>X(I)</td>
<td>Digitized values of mean bridge voltage.</td>
</tr>
</tbody>
</table>

(RW, RC, RL, TW, TO, PO, D, Z, ALPHA, BETA, These groups of variables have the same meaning as in the VELOCITY PREDICTION program, Appendix B3).

(*) Subscripts I refer to a particular crank angle index and K to the particular test considered.
OUTPUT DATA

ANGLE (J,K)  Values of crank angles at which turbulence analysis are carried out (degrees).

BVM  Mean value of the bridge voltage at a particular crank angle (volts).

INTENSITY (J,K)  Turbulence intensities, (%) .

MICRO (J,K)  Time micro-scale of turbulence (sec).

MICROL (J,K)  Length micro-scale of turbulence (mm).

MACRO (J,K)  Time macro-scale of turbulence (sec).

MACROL (J,K)  Length macro-scale of turbulence (mm).

VMS (J,K)  Mean square value of fluctuating voltage component (volts).

U (J,K)  Fluctuating velocity component (m/sec).

VM (J,K)  Mean gas velocity over a number of cycles (m/sec).

Subscripts,  J the particular crank angle index.

K the particular test index.
MASTER TURBULENCE ANALYSIS I

REAL INTENSITY(12, 10), MICRO(12, 10), MICROL(12, 10), MACRO(12, 10),
*MACROL(12, 10)

DIMENSION T(12), R(12), BETA(12), RG(12), VM(12, 10),
*ANGLE(12, 10), VMS(12, 10), U(12, 10), X(7500), Y(12), NANG(12)

DIMENSION AX(20), CASE(10), XX(12), YY(12)

COMMON/PROP/VC(9), CPAC(9)

READ(1,1000) (AX(I), I=1,20)
READ(1,666) (VC(I), I=1,9)
READ(1,666) (CPAC(I), I=1,9)
READ(1,111) NS

DO 40 K=1,NS
READ(1,888) (CASE(I), I=1,10)
READ(1,111) NCYL, NANG(K), NC, NP, N, NEQ, NGRAPH
READ(1,222) (RW, RG, RL, TW, TD, PO, DZ, ALPHA, BETO, E
READ(1,222) (ANGLE(I,K), I=1, NANG(K))
READ(1,222) (VMS(I,K), I=1, NANG(K))
READ(1,222) (MICRO(I,K), I=1, NANG(K))
READ(1,222) (MACRO(I,K), I=1, NANG(K))
READ(1,222) (P(I), I=1, NANG(K))
READ(1,222) (T(I), I=1, NANG(K))
READ(1,222) (A, B, C)
READ(1,333) (X(I), I=1, N)
WRITE(2,389) (CASE(I), I=1,10)
WRITE(2,444)

DO 30 J=1, NANG(K)
DO 10 I=1, NANG(K)
BETA(I) = BETO*(1+ALPHA*(T(I)-TO))
RG(I) = RC* (1+ALPHA*(T(I)-TO))

10 CONTINUE

NSHIFT = NINT(FLOAT(NP*NCYL)/3.)
SV, SBV = 0.0
DO 20 I=1, NC
NX = NSHIFT +(I-1)*NP+NINT(ANGLE(J,K)*FLOAT(NP)/720.)
Y1 = (X(NX-1)+X(NX)+X(NX+1))/3.
BV = A*Y1+B
SBV = SBV+BV
IF(NEQ.EQ.1) CUR = BV/(100. +RW+RL)
IF(NEQ.EQ.2) CUR = BV/(50. +RW+RL)
IF(NEQ.EQ.3) CUR = BV/(5.0 +RW+RL)
CALL DF(T(J),TW,CUR,RW,RG(J),BETA(J),Z,D,ALPHA,P(J),VE,H,M)
SV = SV+VE
20 CONTINUE
BVM = SBV/NC
VM(J,K) = SV/NC
VMS(J,K) = VMS(J,K)*G
INTENSITY(J,K) = SQRT(ABS(VMS(J,K)))*6./BVM*100.
U(J,K) = VM(J,K)*INTENSITY(J,K)/100.
MICROL(J,K) & MACRO(J,K) ARE CALCULATED IN (MM)
MICROL(J,K) = MICRO(J,K)*VM(J,K)*5/(10**2)
MACROL(J,K) = MACRO(J,K)*VM(J,K)*(1000)
WRITE(2,555) ANGLE(J,K),BVM,VMS(J,K),VM(J,K),INTENSITY(J,K),U(J,K)
* MACROL(J,K),MICROL(J,K)
30 CONTINUE
40 CONTINUE
IF(NGRAPH .NE. 9) STOP
CALL UTPPOP
VMAX = 40.
SFX = 0.02
CALL UTP4A(80.,380.,0.0,1.0,6.,5.,11HCRAKN ANGLE,2,20HTURBULENCE
*INTENSITY,3)
SFY = 5./VMAX
DO 60 K=1,NS
DO 50 J=1,NANG(K)
XX(J) = ANGLE(J,K)
YY(J) = INTENSITY(J,K)
X(J) = ANGLE(J,K)*SFX-1.6
Y(J) = INTENSITY(J,K)*SFY
CALL UTP3(AX(K),X(J),Y(J),2)
50 CONTINUE
CALL UTP4B(XX,YY,NANG(K),2)
60 CONTINUE
CALL UTP4A(80.,380.,0.0,6.0,6.,6.,11HCRAKN ANGLE,2,19HTURBULENCE
*VELOCITY,3)
DO 80 K=1,NS
DO 70 J=1,NANG(K)
YY(J) = U(J,K)
X(J) = ANGLE(J,K)*SFX-1.6
Y(J) = U(J,K)
CALL UTP3(AX(K),X(J),Y(J),2)
70 CONTINUE
CALL UTP4B(XX,YY,NANG(K),2)
80 CONTINUE
CALL UTP4A(80.,380.,0.0,4.0,6.,5.,11HCRAKN ANGLE,2,24HMICROSCALE OF
* TURBULENCE,3)
SFY = 1.25
DO 100 K=1,NS
DO 90 J=1,NANG(K)
XX(J) = ANGLE(J,K)
YY(J) = MICRO(J,K)
X(J) = ANGLE(J,K)*SFX-1.6
Y(J) = MICRO(J,K)*SFY
CALL UTP3(AX(K),X(J),Y(J),2)
90 CONTINUE
CALL UTP4B(XX,YY,NANG(K),2)
100 CONTINUE
CALL UTP4A(30.,380.,0.0,VMAX,6.,5.,11HCRANK ANGLE,2,20HMEAN VELOC
*Y (M/SEC),3)
SFY = 5./VMAX
DO 120 K = 1, NS
DO110 J = 1,NANG(K)
   XX(J) = ANGLE(J,K)
   YY(J) = VM(J,K)
   X(J) = ANGLE(J,K)*SFX-1.6
   Y(J) = VM(J,K)*SFY
   CALL UTP3(AK(K),X(J),Y(J),2)
110 CONTINUE
CALL UTP4B(XX,YY,NANG(K),2)
120 CONTINUE
CALL UTP4A(80.,380.,0.,2.,6.,5.,11HCRANK ANGLE,2,19HSCALE OF TURBU
*LENCE,3)
SFY = 2.5
DO 140 K = 1, NS
DO130 J = 1,NANG(K)
   XX(J) = ANGLE(J,K)
   YY(J) = MICROL(J,K)
   X(J) = ANGLE(J,K)*SFX-1.6
   Y(J) = MICROL(J,K)*SFY
   CALL UTP3(AK(K),X(J),Y(J),2)
130 CONTINUE
CALL UTP4B(XX,YY,NANG(K),2)
140 CONTINUE
111 FORMAT(10I4)
222 FORMAT(12FO.0)
333 FORMAT(2X,10F7.3)
444 FORMAT(2X,10F7.3)
555 FORMAT(2X,E13.5,2X,E13.5,1X,6(1X,E13.5))
666 FORMAT(3E29.12)
333 FORMAT(10A3)
239 FORMAT(10X,10A8)
999 FORMAT(6FO.0)
1000 FORMAT(20A1)
2000 CONTINUE
CALL UTPCL
STOP
END
APPENDIX B6

TURBULENCE ANALYSIS II

Program

The main operations carried out by this program could be summarised as follows:

1. Calculations of the spatial micro-scale of turbulence from the normalised power spectrum curves as given by

\[ \frac{1}{\lambda_x^2} = \frac{4 \pi^2}{U^2} \int F(n) n^2 \, dn \]  

(B21)

2. Calculations of the macro-scale of turbulence by integrating the positive part of the auto-correlation coefficient curve and by approximating the auto-correlation curve by an exponential function as given by the following relations

\[ L_t = \int R'(t) \, dt \]  

(B20)

\[ L_x = \bar{U} L_t \]  

(B22)

and

\[ R'(t) = e^{-t/L_t} \]  

(B23)

3. Calculations of the percentage of energy content in the signal at different frequencies as given by

\[ \frac{u_1^2}{u^2} = \int F(n) \, dn \]  

(B24)
4. Producing the power spectrum, auto-correlation coefficient and the second derivative of the auto-correlation coefficients in terms of absolute values at different frequencies and time delays, respectively.
**INPUT DATA**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT</td>
<td>Number of individual graphs required with the following sequence</td>
</tr>
<tr>
<td></td>
<td>IT = 1 for normalised power spectrum curve.</td>
</tr>
<tr>
<td></td>
<td>IT = 2 for auto-correlation coefficient curve.</td>
</tr>
<tr>
<td></td>
<td>IT = 3 for the second derivative of auto-correlation coefficient.</td>
</tr>
<tr>
<td>BS</td>
<td>Number of samples in the original data block on the FOURIER ANALYSER.</td>
</tr>
<tr>
<td>U</td>
<td>Mean gas velocity at the particular crank angle of interest.</td>
</tr>
<tr>
<td>VARIABLE(I)</td>
<td>Description of test conditions for each graph.</td>
</tr>
<tr>
<td>NAMEX(I)</td>
<td>The title which appears on the x-axis of a graph.</td>
</tr>
<tr>
<td>NAMEY(I)</td>
<td>The title which appears on the y-axis of a graph.</td>
</tr>
<tr>
<td>N1</td>
<td>Total number of data words on each tape.</td>
</tr>
<tr>
<td>NP</td>
<td>Number of samples per cycle.</td>
</tr>
<tr>
<td>SR</td>
<td>Sampling interval of the digitized data (μ sec/sample).</td>
</tr>
</tbody>
</table>

**OUTPUT DATA**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A(I)</td>
<td>Absolute values of the variable considered.</td>
</tr>
<tr>
<td>MAX</td>
<td>The location of maximum value of ordinates on the tape.</td>
</tr>
<tr>
<td>AMAX</td>
<td>The value of the maximum ordinate on a trace.</td>
</tr>
<tr>
<td>MACROSCLAE</td>
<td>Macro-scale of turbulence.</td>
</tr>
</tbody>
</table>
OUTPUT DATA (continued)

SCALE          Micro-scale of turbulence.
FREQ(I)        Minimum frequency for a certain percentage of
                energy content in the signal.
MASTER TURBULENCE ANALYSIS II

INTEGER SR
REAL MACROSCALE (500)
REAL NAMEX(4), NAMEY(4)
DIMENSION A(2100), IA(3), VARIABLE(10), Z(11)
COMMON/B1/X(1100), Y(1100), FREQ(11), N11, U, BS, FMAX
COMMON/B1/X(1100), Y(2100), FREQ(11), N11, U, BS, FMAX
DATA Z(1), Z(2), Z(3), Z(4), Z(5), Z(6), Z(7), Z(8), Z(9), Z(10), Z(11)/0.0,
     0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0/
READ(1,10) NT
READ(1,20) U, BS, FMAX
CALL UTPOP
DO 1000 IT = 1, NT
READ(1,80) (VARIABLE(I), I = 1, 10)
READ(1,80) (NAMEX(I), I = 1, 4)
READ(1,80) (NAMEY(I), I = 1, 3)
READ(1,70) N1, NP, SR
CT = 32767.0*32767.
SS=720. /FLOAT(NP)
RPM=120. *(10.**6)/FLOAT(NP*SR)
WRITE(2,90) (VARIABLE(I), I = 1, 10), RPM, NP, SS
NPP =N1/3
NPC =NPP *8
IF (((IT.EQ.1) .OR. (NRP.EQ.0)) READ (3,100) N2, N3
IF (((IT.EQ.1) .AND. (NRP.EQ.0)) READ (3,101) N2, N3
WRITE (2,100) N2, N3
IF (N2.GT.0) SF = FLOAT(10**N2)*N3/CT
IF (N2.EQ.0) SF = FLOAT(N3)/CT
IF ((IT.LT.0) SF = FLOAT(N3)/((10.*IABS(N2))*CT)
WRITE (2,500) SF
DO 300 L=1, NPP
READ (3,200) (IA(I), I = 1, 8)
K = (L-1) *8
DO 300 J = 1, 3
H=J+K
A(J) = FLOAT(IA(J)) * SF
300 CONTINUE
NRP = N1 - NPC
IF(NRP.EQ.0) GO TO 75
READ(3,200) (IA(II),II=1,NRP)
DO 75 II =1,NRP
K = NPC +II
A(K) = FLOAT(IA(II))*SF
CONTINUE
75 IF(IT.EQ.1) GO TO 520
IF(IT.NE.3) GO TO 506
DO 505 IF=1,N1
Y(IF) = -A(IF)
CONTINUE
506 IF(IT.NE.2) GO TO 508
DO 507 IF=1,N1
Y(IF) = A(IF)
CONTINUE
507 CALL MAXIMUM (Y,N1,AMAX,MAX)
WRITE(2,10) MAX
WRITE(2,700) AMAX
DO 510 IF=1,N1
X(IF) = FLOAT((IF-MAX)/SR)/(10.**6)
IF(Y(IF).NE.I) GO TO 510
MACROSCALE(IF) = X(IF)/ALOG(ABS(Y(IF)))
CONTINUE
510 WRITE(2,700) (X(II),MACROSCALE(II),II=1,N1)
XMIN = X(1)
XMAX = X(N1)
YMIN = 0.5*AMAX
WRITE(2,700) XMAX
WRITE(2,700) YMIN
WRITE(2,700) (X(II),Y(II),II=1,N1)
CALL UTP4A(XMIN,XMAX,YMIN,AMAX,5.,5.,NAMEX,3,NAMEY,3)
CALL UTP4B(X,Y,N1,2)
GO TO 1000
520 N11 = N1/2
X(1) = 0.0
DO 530 IF =2,N11
DO 540 IF2=1,N1,2
Y(IF) = A(IF2)*+2048/10000.*2.
IF = IF+1
CONTINUE
540 CALL MAXIMUM (Y,N11,YMAX,MAX)
WRITE(2,10) MAX
WRITE(2,700) YMAX
WRITE(2,700) (X(II),Y(II),II=1,N11)
CALL UTP4A( 0.0,5000.,0,YMAX,5.,5.,NAMEX,3,NAMEY,3)
CALL UTP4B(X,Y,N11,2)
CALL ENERGY DISTRIBUTION
CALL UTP4A(0.0,5000.,0.,1.0,5.,5.,16IFREQUENCIES (HZ),2,SHENERGY
**3,1)
CALL UTP4B(FREQ,Z,11,2)
1000 CONTINUE
SUBROUTINE ENERGY DISTRIBUTION

COMMON/B1/X(1100),Y(2100),FREQ(11),N11,U,BF,FMAX
DF=2.*FMAX/BS
AREA,AREA1=0.0
J = 0
DO 1 I=1,(N11-1)
AREA = AREA+(Y(I)+Y(I+1))/2.*DF
AREA1=AREA1+(Y(I)+Y(I+1))*(X(I)**2)*DF/2.
IF(AREA.LE.0.1) FREQ(2) = X(I)
IF(AREA.LE.0.2) FREQ(3) = X(I)
IF(AREA.LE.0.3) FREQ(4) = X(I)
IF(AREA.LE.0.4) FREQ(5) = X(I)
IF(AREA.LE.0.5) FREQ(6) = X(I)
IF(AREA.LE.0.6) FREQ(7) = X(I)
IF(AREA.LE.0.7) FREQ(8) = X(I)
IF(AREA.LE.0.8) FREQ(9) = X(I)
IF(AREA.LE.0.9) FREQ(10)= X(I)
IF(AREA.LE.1.0) FREQ(11)= X(I)
IF(J.GT.100) J = 0
IF(J.EQ.100) WRITE(2,3) X(I),AREA,AREA1
J=J+1
1 CONTINUE
SCALE = SQRT((U**2)*(10.**6)/(39.478416*AREA1))
WRITE(2,2) (FREQ(I),I=2,11)
WRITE(2,4) SCALE
4 FORMAT(2X,'MICRO-SCALE OF TURBULENCE =',F7.4,'(MM)')
2 FORMAT(2X,'MINIMUM FREQUENCIES FOR PERCENTAGES OF TOTAL ENERGY/'
*1 10: 20% 30% 40% 50% 60% 70% 80% 90% 100%'
*10(2X,F8.3))
3 FORMAT(3(2X,F8.4))
RETURN
END
SUBROUTINE MAXIMUM (X,NP,XMAX,J)

DIMENSION X(2100)
XMAX = X(1)
J = 1
DO 1 I=1,NP
IF(XMAX.GT.X(I)) GO TO 1
XMAX = X(I)
J = I
1 CONTINUE
RETURN
END
FINISH
APPENDIX B7
TURBULENCE CYCLIC VARIATION
Program

The main objectives of this program could be outlined as follows:

1. Calculations of the turbulence characteristics for individual cycles at different crank angles during the engine cycle, e.g. fluctuating velocity components, micro-scales, intensities of turbulence and eddy diffusivities.

2. A test on the stationarity of the data at different confidence limits.

3. Estimation of the extent of cyclic variations in turbulence parameters, in terms of their standard deviations, coefficient of variation and ranges of variation.

The input data for such a program are, therefore, the output results of the Spectrum Analysis program for individual cycles (data records) at any particular crank angle of interest during the engine cycle.
### INPUT DATA

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NANG</td>
<td>Number of crank angles during the engine cycle, for which turbulence analysis are carried out.</td>
</tr>
<tr>
<td>NCYC</td>
<td>Number of cycles analysed at each crank angle.</td>
</tr>
<tr>
<td>G</td>
<td>Attenuation factor on the recorded turbulence signal.</td>
</tr>
<tr>
<td>ANGLE(I)</td>
<td>Values of crank angles at which turbulence analysis is carried out.</td>
</tr>
<tr>
<td>N EU(I)</td>
<td>Values of the kinematic viscosity at different crank angles.</td>
</tr>
<tr>
<td>BV(I)</td>
<td>Mean values of the bridge voltage at different crank angles.</td>
</tr>
<tr>
<td>VM(I)</td>
<td>Mean values of gas velocity at different crank angles.</td>
</tr>
<tr>
<td>VMS(I,J)</td>
<td>Mean square values of the fluctuating voltage component at the crank angle index (J) and for the particular cycle number (I).</td>
</tr>
<tr>
<td>MICRO(I,J)</td>
<td>The values of the second derivative of the autocorrelation coefficient at zero time delay for the crank angle of index (J) and the particular cycle number (I).</td>
</tr>
<tr>
<td>MACRO(I,J)</td>
<td>The value of the integral time scale at the crank angle of index (J) and for the cycle number (I).</td>
</tr>
</tbody>
</table>
OUTPUT DATA

The output data of this program are the calculated values of turbulence characteristic parameters for the number of cycles analysed.

These calculated parameters are:

1. Fluctuating velocity component \((u')\).
2. Intensity of turbulence \((\text{Int} = \frac{u'}{U} \cdot 100)\).
3. Micro-scale of turbulence \(\lambda_y\).
4. Macro-scale of turbulence \(\lambda_x\).
5. Micro-eddy diffusivity \(\varepsilon_{\lambda}\).
6. Macro-eddy diffusivity \(\varepsilon_L\).

Meanings of the symbols used for all the output parameters are as follows:

- \(Y(I)\): Value of a particular parameter for the cycle number \(I\).
- \(YM\): Mean value of the parameter \(Y\).
- \(SD\): Standard deviation of the parameter \(Y\).
- \(SDM\): Coefficient of variation of the parameter \(Y = \frac{SD}{YM}\).
- \(ST INDEX\): Stationarity index which provides the number of sign changes for the values of a particular parameter over a number of cycles (NCYC) which is compared with standard values for the "RUN TEST" of stationarity at different confidence limits as given in Table (B4).
TABLE (B4) Test of Stationarity

Percentage Points of Run Distribution (118).

Values of \( r_{n, \alpha} \) such that \[ r_n > r_{n, \alpha} \] where \( n = N/2 \)

<table>
<thead>
<tr>
<th>( n = N/2 )</th>
<th>( \alpha )</th>
<th>( 0.99 )</th>
<th>( 0.975 )</th>
<th>( 0.95 )</th>
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<th>( 0.025 )</th>
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</tr>
</tbody>
</table>
MASTER TURBULENCE CYCLIC VARIATION

REAL MICRO(100,12), MACRO(100,12), NEU(12)
DIMENSION ANGLE(12), BV(12), VM(12), VMS(100,12), X(100), Y(100)
DIMENSION T2(100), T1(100), TITLE(10,12)
READ(1,111) NANG, NCYC
WRITE(2,111) NANG, NCYC
READ(1,222) ANGLE(I), I=1,NANG
READ(1,222) NEU(I), I=1,NANG
READ(1,222) BV(I), I=1,NANG
READ(1,222) VM(I), I=1,NANG
DO 100 J=1,NANG
READ(1,101) TITLE(I, J), I=1,10
READ(1,222) VMS(I, J), I=1,NCYC
WRITE(2,444) VMS(I, J)
READ(1,222) MICRO(I, J), I=1,NCYC
WRITE(2,444) MICRO(I, J)
100 CONTINUE
DO 200 I=1,NCYC
X(I)=FLOAT(I)
DO 250 J=1,NANG
MICRO(I,J)=MICRO(I,J)/(10.**4)
VMS(I,J)=VMS(I,J)*G*G/(10.**5)
250 CONTINUE
CALL UTP4
XMIN=-0.0
XMAX=FLOAT(NCYC)
YMIN=-0.0
YMAX=40.
DO 400 J=1,NANG
WRITE(2,101) TITLE(IW, J), IW=1,10
CALL UTP4A(XMIN, XMAX, YMIN, YMAX, 5., 5., 12, CYCLE NUMBER, 2,
*22HTURBULENCE INTENSITY /3,3)
YM,SYS=0.0
STINDEX =0.0
DO 300 I=1,NCYC
Y(I)=6.*SQRT(VMS(I,J))/BV(J)*100.
YM=YM+Y(I)
SYS=SYS+Y(I)*Y(I)
300 CONTINUE
YM=YM/FLOAT(NYC)
DO 350 I=1,NCYC
DO 350 I=1, NCYC
TE(I)=Y(I)-YM
IF(I.EQ.1) GO TO 350
T =TE(I)/TE(I-1)
IF(T.LT.0.0) STINDEX =STINDEX+1.

350 CONTINUE
YY =YM*YM*FLOAT(NCYC)
VAR =SYS-YY)/FLOAT(NCYC-1)
SD=SQR(T(VAR)
SDM =SD/YM
WRITE(2,555) NCYC
WRITE(2,333) ANGLE(J), YM, VAR, SD, SDM, ST INDEX
WRITE(3,444)(X(I),Y(I),I=1,NCYC)
CALL UTP4B(X, Y, NCYC, 2)

400 CONTINUE
YM=0.2
DO 600 J=1, NANG
WRITE(2,1010) (TITLE(IW, J), IW=1, 10)
CALL UTP4A (XMIN, XMAX, YMIN, YMAX, SY, SY, , 12HCYCLE NUMBER, 2, *16HMICRO-SCALE (MM), 2)
YM, SYS=0.0
STINDEX =0.0
DO 500 I=1, NCYC
Y(I)=VM(J)*0.05/SQRT(MICRO(I, J))
SYS =SYS+Y(I)*Y(I)
YM=YM+Y(I)

500 CONTINUE
YY =YM/FLOAT(NCYC)
DO 550 I=1, NCYC
TE(I)=Y(I)-YM
IF(I.EQ.1) GO TO 550
T =TE(I)/TE(I-1)
IF(T.LT.0.0) STINDEX =STINDEX+1.

550 CONTINUE
YY =YM*YM*FLOAT(NCYC)
VAR =SYS-YY)/FLOAT(NCYC-1)
SD=SQR(T(VAR)
SDM =SD/YM
WRITE(2,666) NCYC
WRITE(2,333) ANGLE(J), YM, VAR, SD, SDM, ST INDEX
CALL UTP4B(X, Y, NCYC, 2)
WRITE(2,444)(X(I),Y(I),I=1,NCYC)

600 CONTINUE
YM=0.5
DO 800 J=1, NANG
WRITE(2,1010) (TITLE(IW, J), IW=1, 10)
CALL UTP4A (XMIN, XMAX, YMIN, YMAX, SY, SY, , 12HCYCLE NUMBER, 2, *15HFLUCT VEL M/SEC, 2)
YM, SYS=0.0
STINDEX =0.0
DO 700 I=1, NCYC
Y(I)=6.*SQR(T(VMS(I, J)))*VM(J)/BV(J)
YM=YM+Y(I)
SYS =SYS+Y(I)*Y(I)

700 CONTINUE
YM = YM / FLOAT(NCYC)
DO 750 I = 1, NCYC
TE(I) = Y(I) - YM
IF(I .EQ. 1) GO TO 750
T = TE(I) / TE(I-1)
IF(T .LT. 0.0) STINDEX = STINDEX + 1.
750 CONTINUE
YY = YM * YM * FLOAT(NCYC)
VAR = (SYS - YY) / FLOAT(NCYC - 1)
SD = SQRT(VAR)
SDM = SD / YM
WRITE(2, 777) NCYC
WRITE(2, 333) ANGLE(J), YM, VAR, SD, SDM, ST INDEX
WRITE(2, 444) (X(I), Y(I), I = 1, NCYC)
CALL UTP4B(X, Y, NCYC, 2)
800 CONTINUE
YM = YM = 0.0001
DO 1000 J = 1, NANG
WRITE(2, 1010) (TITLE(IW, J), IW = 1, 10)
CALL UTP4A(XMIN, XMAX, YM, YMIN, YMAX, 5., 5., 12HCYCLE NUMBER, 2,
*22HMICRO EDDY DIFFUSIVITY, 3)
YM, SYS = 0.0
STINDEX = 0.0
DO 900 I = 1, NCYC
Y(I) = SQRT(VMS(I, J) / MICRO(I, J)) * 3. / ((10. ** 4) * BV(J))
SYS = SYS + Y(I) * Y(I)
YM = YM + Y(I)
900 CONTINUE
YM = YM / FLOAT(NCYC)
DO 950 I = 1, NCYC
TE(I) = Y(I) - YM
IF(I .EQ. 1) GO TO 950
T = TE(I) / TE(I-1)
IF(T .LT. 0.0) STINDEX = STINDEX + 1.
950 CONTINUE
YY = YM * YM * FLOAT(NCYC)
VAR = (SYS - YY) / FLOAT(NCYC - 1)
SD = SQRT(VAR)
SDM = SD / YM
CALL UTP4B(X, Y, NCYC, 2)
WRITE(2, 888) NCYC
WRITE(2, 333) ANGLE(J), YM, VAR, SD, SDM, ST INDEX
WRITE(2, 444) (X(I), Y(I), I = 1, NCYC)
1000 CONTINUE
DO 1400 J = 1, NANG
WRITE(2, 1010) (TITLE(IW, J), IW = 1, 10)
STINDEX, STINDEX1 = 0.0
YM, SYS = 0.0
YM1, SYS1 = 0.0
DO 1100 I = 1, NCYC
U = 6. * SQRT(VMS(I, J)) * VM(J) / BV(J)
Y(I) = VM(J) * MACRO(I, J) * 1000.
Y(I) = Y(I) * U / (10 ** 3)
SYS = SYS + Y(I) * Y(I)
SYS1 = SYS1 + Y1(I) * Y1(I)
YM = YM + Y(I)
YM1 = YM1 + Y1(I)

1100 CONTINUE
YM = YM / FLOAT(NCYC)
YM1 = YM1 / FLOAT(NCYC)
DO 1150 I = 1, NCYC
TE(I) = Y1(I) - YM
IF (I, EQ. 1) GO TO 1150
T = TE(I) / TE(I - 1)
IF (T .LT. 0.0) STINDEX = STINDEX + 1.
1150 CONTINUE
DO 1350 I = 1, NCYC
TE(I) = Y1(I) - YM1
IF (I, EQ. 1) GO TO 1350
T = TE(I) / TE(I - 1)
IF (T .LT. 0.0) STINDEX = STINDEX1 + 1.
1350 CONTINUE
YY = YM * YM * FLOAT(NCYC)
VAR = (SYS - YY) / FLOAT(NCYC - 1)
SD = SQRT(VAR)
SDM = SD / YM
YY = YM1 * YM1 * FLOAT(NCYC)
VAR1 = (SYS1 - YY) / FLOAT(NCYC - 1)
SD1 = SQRT(VAR1)
SDM1 = SD1 / YM1
YM1 = 0.0
YMAX = 1.
WRITE (2, 887) NCYC
WRITE (2, 333) ANGLE(J), YM, VAR, SD, SDM, ST INDEX
WRITE (2, 444) (X(I), Y(I), I = 1, NCYC)
CALL UTP4A(XMIN, XMAX, YM1, YMAX, 5., 5., 12HCYCLE NUMBER, 2)
CALL UTP4B(X, Y, NCYC, 2)
YMAX = 0.0004
WRITE (2, 889) NCYC
WRITE (2, 333) ANGLE(J), YM1, VAR1, SD1, SDM1, ST INDEX1
WRITE (2, 444) (X(I), Y1(I), I = 1, NCYC)
CALL UTP4A(XMIN, XMAX, YM1, YMAX, 5., 5., 12HCYCLE NUMBER, 2)
CALL UTP4B(X, Y1, NCYC, 2)
1400 CONTINUE
111 FORMAT (10I3)
122 FORMAT (1DF0.0)
333 FORMAT (2X, 'STARK ANGLE ' , F3.1 , ' MEAN VALUE =', E14.6, 'VARIANCE ', 
* '14.6', 'STANDARD DEVIATION =', E14.6/ 'COEFFICIENT OF VARIATION =', 
* '14.6', 'STATIONARY INDEX =', F4.0)
444 FORMAT (16(2X, E14.6))
555 FORMAT (2X, 'TURBULENCE INTENSITIES FOR A NUMBER OF CYCLES NC=', I4)
666 FORMAT (2X, 'MICRO-SCALE OF TURBULENCE FOR A NUMBER OF CYCLES NC=', I4)
777 FORMAT (2X, 'FLUCTUATING VEL. COMPONENT FOR A NUMBER OF CYCLES NC=', I4)
77. FORMAT(2X, 'MACRO EDDY DIFFUSIVITY FOR A NUMBER OF CYCLES NC=', I4)
833 FORMAT(2X, 'MICRO EDDY DIFFUSIVITY FOR A NUMBER OF CYCLES NC=', I4)
392 FORMAT(20A1)
337 FORMAT(2X, 'MACRO-SCALE OF TURBULENCE FOR A NUMBER OF CYCLES NC=', I4)
1010 FORMAT(10A8)
CALL UTPCL
STOP
END
FINISH
APPENDIX  B8

PIPE FLOW CORRELATION

Program

The main objectives of this program could be divided into two items:

1. Establishment of the best relationship between the ratio of Eulerian/Lagrangian scales and other fluid properties such as fluctuating velocity components or the turbulence Reynolds numbers, $Re_\lambda$ and $Re_L$.

2. Estimation of the coefficient of correlation between the measured values of eddy diffusivities and the predictions from pipe flow empirical relations.

The main operation in the program consists, therefore, of iteration procedures to establish the best values in an assumed model of relations as given by:

\[
\frac{L_L}{L_x} = a_1 + b_1 Re_L \tag{B25}
\]

\[
\frac{L_L}{L_x} = a_2 + b_2 Re_\lambda \tag{B26}
\]

\[
\frac{L_L}{L_x} = a_3 + b_3 u' \tag{B27}
\]

The values of the constants $a_1$ and $b_1$ are calculated by a least square errors regression between $(\frac{L_L}{L_x})$ and $Re_L$, $Re_\lambda$ or $u'$. The values of $a_2$ and $b_2$ are obtained in a similar way.
INPUT DATA

NC  Number of correlation models investigated.
N   Number of experimental points used for establishing the correlation.
NE  Maximum number of iteration loops in the program.
CASE(I) Description of the particular model equation.
ERE Initial value of Reynolds number exponent.
DERE Increment in Reynolds number exponent.
EU  Initial value of fluctuating velocity-component exponent.
DEU Increment in fluctuating velocity component exponent.
U(I) Values of the fluctuating velocity components for different experimental points.
RE(I) Values of the turbulence Reynolds number Re_L or Re.
EDI(I) Eddy diffusivities based on Eulerian scales.

\[ \xi_{\lambda} = u' \cdot \lambda_y \]  \hspace{1cm}  \text{(B28)}
\[ \xi_{L} = u' \cdot L_x \]  \hspace{1cm}  \text{(B29)}

EDM(I) Values of eddy diffusivities obtained from pipe flow data at comparable fluid conditions.

OUTPUT DATA

E  Exponent of the Reynolds number of fluctuating velocity component.
A,B  Constants in equations (B25) - (B27).
X(I) Values of Re_L(I) or U_E(I).
**OUTPUT DATA** (continued)

<table>
<thead>
<tr>
<th>Y(I)</th>
<th>Values of ( \text{ED}_1(I) / \text{ED}_N(I) ).</th>
</tr>
</thead>
<tbody>
<tr>
<td>YC(I)</td>
<td>Values of ((\text{corrected eddy diffusivity} / \text{ED}_N(I))), (\text{corrected eddy diffusivity} = \text{ED}_1.\frac{L}{L_x}). \hspace{1cm} (B30)</td>
</tr>
<tr>
<td>R</td>
<td>Coefficient of correlation between (\frac{L}{L_x}) and (R_E) or (\frac{L}{L_x}) and (U^E).</td>
</tr>
<tr>
<td>ER</td>
<td>Square root of the summation of errors between (Y(I)) and (YC(I)).</td>
</tr>
</tbody>
</table>
**MASTER PIPE FLOW CORRELATION**

```
C

DIMENSION ED1(200), EDM(200), U(200), RE(200), CASE(10)
COMMON /B1/ X(200), Y(200), YC(200), A, B, N
READ(1, 111) NC
DO 400 L=1, NC
READ(1, 666) (CASE(I), I = 1, 9)
READ(1, 111) N, NE
READ(1, 222) ERE, DERE, EU, DEU
READ(1, 222) (U(I), I = 1, N)
READ(1, 222) (RE(I), I = 1, N)
READ(1, 222) (ED1(I), I = 1, N)
READ(1, 222) (EDM(I), I = 1, N)

DO 300 K=1, 2
IF(K.EQ.1) E=ERE
IF(K.EQ.1) DE=DERE
IF(K.EQ.2) E=EU
IF(K.EQ.2) DE=DEU
DO 200 J=1, NE
IF(E.EQ.0.0) GO TO 150
DO 100 I=1, N
Y(I)=EDM(I)/ED1(I)
IF(K.EQ.1) X(I)=RE(I)**E
IF(K.EQ.2) X(I)=U(I)**E

100 CONTINUE
CALL LEAST SQUARES
WRITE(2, 666) (CASE(I), I = 1, 9)
IF(K.EQ.1) WRITE(2, 333) A, B, E
IF(K.EQ.2) WRITE(2, 444) A, B, E
WRITE(2, 555) (X(I), Y(I), YC(I), I = 1, N)
150 CONTINUE
E=E-DE
200 CONTINUE
300 CONTINUE
400 CONTINUE
111 FORMAT (5I3)
222 FORMAT (12F9.0)
333 FORMAT (2X, 'CORRELATION BASED ON REYNOLDS NUMBER'/'*
  5X, 'X=', E14.6, ', '+'', E14.6, 'RE**', F5.3)
444 FORMAT (2X, 'CORRELATION BASED ON THE FLUCTUATING VELOCITY (U)'/'*
  5X, 'X=', E14.6, ', '+'', E14.6, 'U **', F5.3)
```
SUBROUTINE LEAST SQUARES

** **********
COMMON /B1/ X(200), Y(200), YC(200), A, B, N
SX, SX2, SY, SXY = 0.0
DO 1 I = 1, N
SX = SX + X(I)
SX2 = SX2 + X(I) * X(I)
SY = SY + Y(I)
SXY = SXY + X(I) * Y(I)
1 CONTINUE
D = SX2 * FLOAT(N) - (SX * SX)
A = (SX * SX2 - SX * SXY) / D
B = (FLOAT(N) * SXY - SX * SY) / D
ERS = 0.0
DO 2 I = 1, N
YC(I) = A + B * X(I)
ERS = ERS + ABS(YC(I) - Y(I)) ** 2.
2 CONTINUE
ER = SQRT (ERS)
WRITE (2, 111) ER
CALL COEFF OF CORR

111 FORMAT (2X, 'LEAST SQUARE ERROR = ', E20.6)
RETURN
END

SUBROUTINE COEFF OF CORR

** **********
COMMON /B1/ X(200), Y(200), YC(200), A, B, N
SX, SY, SX2, SY2, SXY = 0.0
DO 100 I = 1, N
SX = SX + X(I)
SY = SY + Y(I)
SX2 = SX2 + X(I) * X(I)
SY2 = SY2 + Y(I) * Y(I)
SXY = SXY + X(I) * Y(I)
100 CONTINUE
CXX = SX2 - (SX * SX / FLOAT(N))
CYY = SY2 - (SY * SY / FLOAT(N))
CXY = SXY - (SX * SY / FLOAT(N))
B = CXX * CXY
R = CXY / SQRT (B)
WRITE (2, 111) CXX, CYY, CXY, B, R

111 FORMAT (2X, 'VALUES OF CXX, CYY, CXY, B, R ARE : ', 5(2X, E14.6))
RETURN
END
FINISH
APPENDIX B9

EDDY DIFFUSIVITY
Program

This program is concerned with comparing the variations in eddy diffusivities with different expressions proposed for the friction factor in pipe flow and flow over flat plates. These expressions are given by the following relations:

\[
\begin{align*}
\frac{f}{D} &= \frac{0.02296}{Re} \quad \text{Flat plate} \\
\frac{f}{D} &= \frac{0.0262}{Re} \\
\frac{f}{D} &= \frac{0.148257}{Re} \\
\frac{f}{D} &= \frac{0.139}{Re} \\
\text{Flat plate Data} & \\
\text{Data} & \\
\text{Pipe Flow} & \\
\text{Data} & \\
\end{align*}
\]

where \( Re_D = U_D/\nu \)

The definition of different terms are given in Chapter 7. The eddy diffusivities were calculated from the Spalding expression given by

\[
\varepsilon_m = 0.0407 \left( e^C - 1 - C - \frac{C^2}{2} - \frac{C^3}{6} \right)
\]

where \( C = 0.407 U^+ \)

The input data for this program is some values of gas velocities between 0.5 and 5 m/sec and the kinematic viscosity of gas at TDC, while the output results consist of sets of graphs showing the relations between the following variables:
1. Eddy diffusivity versus non-dimensional velocity $U^+$.  
2. Eddy diffusivity versus friction factor.  
3. Eddy diffusivity versus Reynolds number.  
4. Friction factor versus Reynolds number.
REAL NEU(10)
DIMENSION RE(100), CF(100), UP(100), ED(100)
READ(1,222) N, N1, N2
READ(1,111) (NEU(I), I=1,N1)
READ(1,111) X, U
CALL UTPOP
DO 300 J=1,N1
  DO 250 K1=1,4
    DO 200 K=1,4
      WRITE(2,222) N, N1, N2, J, K, K1
      WRITE(2,444) NEU(J), X
      U = 0.5
      DO 100 I=1,N
         RE(I) = X*U/NEU(J)
         IF(K.EQ.1) CF(I) = 0.02296/(RE(I)**0.139)
         IF(K.EQ.2) CF(I) = 0.0262/(RE(I)**0.14857)
         IF(K.EQ.3) CF(I) = 0.046/(RE(I)**0.2)
         IF(K.EQ.4) CF(I) = 0.0014+0.125/(RE(I)**0.32)
         UP(I) = 1/((CF(I)*0.5)**0.5)
         ED(I) = 0.407*(EXP(C)-1.-C-(C*C)/2.-(C*C*C)/6.)*NEU(J)
      WRITE(2,333) U, RE(I), CF(I), UP(I), ED(I)
    U = U + 0.5
    CONTINUE
  IF(K1 .NE. 1) GO TO 110
    XMIN = 15000.
    XMAX = 160000.
    YMIN = 0.004
    YMAX = 0.008
  IF(K.EQ.1) CALL UTPOP(XMIN, XMAX, YMIN, YMAX, 6., 6., 15REYNOLDS NUMBER
* R, 2, 15FRICTION FACTOR, 2)
  CALL UTPOP(RE, CF, N, 2)
110 CONTINUE
IF(K1 .NE. 2) GO TO 120
XMIN = 15.
XMAX = 24.
YMIN=0.00005
YMAX=0.0011
IF(K.EQ.1) CALL UTP4A(XMIN,XMAX,YMIN,YMAX,6.,6.,21,HEDDY_DIFFUSIVITY)
*FUSIVITY ( ),3)
CALL UTP4B(UP,ED,N,2)
120 CONTINUE
IF(K1.NE.3) GO TO 130
XMIN=0.004
XMAX=0.008
YMIN=0.00005
YMAX=0.0011
IF(K.EQ.1) CALL UTP4A(XMIN,XMAX,YMIN,YMAX,6.,6.,15,HEDDY_DIFFUSIVITY)
*R,2,HEDDY_DIFFUSIVITY ( ),3)
CALL UTP4B(CF,ED,N,2)
130 CONTINUE
IF(K1.NE.4) GO TO 140
XMIN=15000.
XMAX=160000.
YMIN=0.00005
YMAX=0.0011
IF(K.EQ.1) CALL UTP4A(XMIN,XMAX,YMIN,YMAX,6.,6.,15,HEDDY_DIFFUSIVITY)
*R,2,HEDDY_DIFFUSIVITY ( ),3)
CALL UTP4B(RE,ED,N,2)
140 CONTINUE
200 CONTINUE
250 CONTINUE
300 CONTINUE
111 FORMAT(6F0.0)
222 FORMAT(10I3)
333 FORMAT(5(2X,E14.6))
444 FORMAT(2X,'CASE NO: NEU ='.E14.6,'CHARACTERISTIC LENGTH =',E14.6)
CALL UTPCL
STOP
END
FINISH
This program is concerned with comparing the measured turbulence characteristics inside the combustion chambers of engines with predictions of the semi-empirical relations established from the experimental data of pipe flow. It also serves the purpose of correcting the measured turbulence parameters for the effect of finite wire length assuming exponential correlation functions. Plotting facilities of these turbulence parameters for different tests are also provided.

The theoretical analysis of the correlation with pipe flow was discussed in Chapter 7 and it is sufficient here to discuss the INPUT/OUTPUT DATA manipulated by the program. Obviously the INPUT DATA are the results of the turbulence analysis at different crank angles in the cycle as discussed earlier in Appendix B5. These include the following data:

1. Variations of gas mean velocities with crank angles.
2. Variations of fluctuating velocity components with crank angles.
3. Variations of micro-scales with crank angles.
4. Variations of macro-scales with crank angles.
5. Values of dynamic and kinematic viscosities at different crank angles in the cycle.
6. Cylinder diameter and hot wire length.
The output results of the program could be summarised as follows:

i) The variation of corrected turbulence intensities and fluctuating velocity components with crank angles.

ii) The variation of the ratio $u''/u^*$ with crank angles.

iii) Values of turbulence Reynolds number $Re_L$ and $Re_\lambda$ for different crank angles.

iv) Values of micro- and macro-eddy diffusivities as given by:

$$\varepsilon_{\text{micro}} = u' \left( \frac{L_L}{\lambda_y} \right) \frac{L_y}{y^+}$$  \hspace{1cm} (B34)

and

$$\varepsilon_{\text{macro}} = u' \left( \frac{L_{x+}}{L_x} \right) \frac{L_x}{x^+}$$  \hspace{1cm} (B35)

v) Predicted values of eddy diffusivities from pipe flow data.

Graph plots showing the variation of turbulence characteristics with crank angle as well as general plots of eddy diffusivities versus Reynolds numbers $Re_L$ and $Re_\lambda$ and the friction factor are provided. Moreover a comparison between measured and predicted eddy diffusivities is also provided.
INPUT DATA

NS  Number of experiments considered.

$A_1, A_2, B_1, B_2$  Constants in equations of the ratio between Lagrangian and Eulerian scales $L_x/L_x$ and $L_y/L_y$

\[
\frac{L_x}{L_x} = A_1 + B_1 \frac{E_1}{\text{Re}_L} \quad (B36)
\]

\[
\frac{L_y}{L_y} = A_2 + B_2 \frac{E_2}{\text{Re}_L} \quad (B37)
\]

LW  Length of hot wire (m).

Lx  Engine cylinder diameter (m)

CASE(J, K)*  Description of test conditions.

NANG(K)  Number of crank angles considered in test number (K).

ANGLE(J, K)  Values of crank angles considered in the test number (K), (degrees).

VM(J, K)  Values of mean velocities for test number (K), (m/sec).

INTENSITY(J, K)  Values of turbulence intensities for test number (K). (\%)

U(J, K)  Values of fluctuating velocity components for the test number (K), (m/sec).

MICRO(J, K)  Values of time micro-scales for the test number (K), (sec).

MICROL(J, K)  Values of spatial micro-scales for the test number (K), (mm).

MACRO(J, K)  Values of the spatial macro-scales of turbulence for the test number (K), (mm).

NEU (J, K)  Values of the kinematic viscosity for the test number (K).

AX(I)  A string of alphanumerical characters used for identifying individual tests.
* The index J defines the particular crank angle in the test number (K).

**OUTPUT DATA**

<table>
<thead>
<tr>
<th>UC(J,K)</th>
<th>Values of the fluctuating velocity components after correction for the effect of finite wire length on measurements.</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTENSITY(J,K)</td>
<td>Corrected values of turbulence intensities.</td>
</tr>
<tr>
<td>REO(J,K)</td>
<td>Reynolds number based on gas mean velocity and cylinder diameter.</td>
</tr>
<tr>
<td>RE(J,K)</td>
<td>Reynolds number of turbulence ( R_{0,\lambda} = \frac{u' \lambda \gamma}{\nu} )</td>
</tr>
<tr>
<td>REI(J,K)</td>
<td>Reynolds number of turbulence ( R_{e,\lambda} = \frac{u' \lambda \gamma}{\nu} )</td>
</tr>
<tr>
<td>REOL(J,K)</td>
<td>Reynolds number based on boundary layer thickness over a flat plate under similar flow conditions in engine.</td>
</tr>
<tr>
<td>DELTA(J,K)</td>
<td>Boundary layer thickness, (mm).</td>
</tr>
<tr>
<td>UR(J,K)</td>
<td>Values of friction velocities (( u^* )) (m/sec).</td>
</tr>
<tr>
<td>UP(J,K)</td>
<td>Values of the non-dimensional velocity ( U^+ = \frac{U}{u^*} )</td>
</tr>
<tr>
<td>EPS(J,K)</td>
<td>Rate of energy dissipation.</td>
</tr>
<tr>
<td>RATIO(J,K)</td>
<td>Ratio between fluctuating velocity components and friction velocities = ( u'/u^* ).</td>
</tr>
<tr>
<td>ED(J,K)</td>
<td>Eddy diffusivities based on micro-scales of turbulence.</td>
</tr>
</tbody>
</table>
### OUTPUT DATA (continued)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDI(J,K)</td>
<td>Eddy diffusivities based on macro-scales of turbulence.</td>
</tr>
<tr>
<td>EDM(J,K)</td>
<td>Eddy diffusivities calculated from Spalding's expression for pipe flow. (B32)</td>
</tr>
<tr>
<td>CF (J,K)</td>
<td>Values of the friction factor.</td>
</tr>
</tbody>
</table>
REAL MICRO(12,20), MICROL(12,20), INTENSITY(12,20), NEU(12,20)
REAL MEU(12,20), MACRO(12,20), INT(12,20), LX, LW
DIMENSION ED(12,20), CF(12,20), UT(12,20), CASE(12,20)
DIMENSION UP(12,20), ED1(12,20), EDM(12,20), RE1(12,20),
*RED1(12,20), DELTA(12,20), RATIO(12,20), EPS(12,20), RE(12,20), X(20),
*Y(12), XX(12), YY(12), NANG(20), AX(20), UC(12,12)

ANGLE = CRANK ANGLE DEGREES.
VM = GAS MEAN VELOCITY.
MICRO = MICRO SCALE OF TURBULENCE.
MACRO = MACRO SCALE OF TURBULENCE.
NEU = KINEMATIC VISCOSITY.
A, B, E ARE THE CONSTANTS AND EXPONENT VALUES FOR THE RATIO BETWEEN
THE LAGRANGIAN AND EULERIAN SCALES OF TURBULENCE.
U' = MEASURED FLUCTUATING VELOCITY COMPONENTS.
UC' = CORRECTED FLUCTUATING VELOCITY COMPONENTS FOR THE EFFECT
OF WIRE LENGTH ON TURBULENCE MEASUREMENTS.
LX = CYLINDER DIAMETER.
LW = LENGTH OF WIRE (MM).
RE = TURBULENT REYNOLDS NUMBER BASED ON MICRO-SCALE.
RE1 = TURBULENT REYNOLDS NUMBER BASED ON MACRO-SCALE.
REQ = REYNOLDS NUMBER BASED ON MEAN VELOCITY AND CYLINDER DIAMETER
EPS = RATE OF ENERGY DISSIPATION BY SMALL SCALE EDDIES.
ED = MICRO-EDDY DIFFUSIVITY.
ED1 = MACRO-EDDY DIFFUSIVITY.
EDM = SPALDING EXPRESSION FOR EDDY DIFFUSIVITY.
READ(1,333) (AX(I), I=1,20)
READ(1,111) NS
READ(1,222) A1,A2,B1,B2,E1,E2,LX,LW
DO 1000 K=1,NS
READ(1,9000) (CASE(J,K), J=1,9)
READ(1,111) NANG(K)
READ(1,222) (ANGLE(J,K), J=1,NANG(K))
READ(1,222) (VM(J,K), J=1,NANG(K))
READ(1,222) (INTENSITY(J,K), J=1,NANG(K))
READ(1,222) (U(J,K), J=1,NANG(K))
READ(1,222) (MICRO(J,K), J=1,NANG(K))
READ(1,222) (MICROL(J,K), J=1,NANG(K))
READ(1,222) (MACRO(J,K), J=1,NANG(K))
READ(1,222) (NEU(J,K), J=1,NANG(K))

1000 CONTINUE

DO 500 K=1,NS
DO 400 J=1,NANG(K)
EPS(J,K) = 15.*((10.*6)*NEU(J,K)*((U(J,K)/MICR(J,K))**2)
SCALE=MACRO(J,K)
CX=LW*SCALE
CX1=CX/(SQRT(2.*(1./EXP(CX)-1.+CX)))
UC(J,K)=CX1*U(J,K)
WRITE(2,555) RA, SCALE, CX, CX1, U(J,K), UC(J,K)
RE(J,K)=UC(J,K)*MICR(J,K)/(NEU(J,K)*10.**3)
RE1(J,K)=UC(J,K)*MACRO(J,K)/(NEU(J,K)*10.**3)
R0D(J,K)=UX*VM(J,K)/NEU(J,K)
DELTA(J,K) = 0.1285*UX/(R0D(J,K)**0.148257)
REDJ (J,K)= VM(J,K)*DELTA(J,K)/NEU(J,K)
INTENSITY(J,K)=INTENSITY(J,K)*UC(J,K)/U(J,K)
RA1=A1+B1*(RE(J,K)**6)
RA2=A2+B2*(RE(J,K)**6)
ED(J,K)=MICR(J,K)*UC(J,K)/(10.**3)*RA1
ED1(J,K)=UC(J,K)*MACRO(J,K)/(10.**3)*RA2
CF(J,K)=0.0262/(RED(J,K)**0.148257)
UP(J,K)=1/(CF(J,K)*0.5)**0.5
UR(J,K)=VM(J,K)/UP(J,K)
RATIO(J,K)=UC(J,K)/UR(J,K)
C=UP(J,K)*0.407
EDM(J,K) = 0.0407*(EXP(C)-1.-C-(C*C)/2.-C*C*C/6.)*NEU(J,K)
400 CONTINUE

WRITE(2,9000) (CASE(J,K), J=1,9)
WRITE(2,444) K, IC, NANG(K), NC, NS
WRITE(2,1001)
WRITE(2,555) (ANGLE(J,K), J=1,NANG(K))
WRITE(2,1002)
WRITE(2,555) ( VM(J,K), J=1,NANG(K))
WRITE(2,1003)
WRITE(2,555) (INTENSITY(J,K), J=1,NANG(K))
WRITE(2,1004)
WRITE(2,555) (U(J,K), J=1,NANG(K))
WRITE(2,555) (UC(J,K), J=1,NANG(K))
WRITE(2,1005)
WRITE(2,555) (MICR(J,K), J=1,NANG(K))
WRITE(2,1006)
WRITE(2,555) (MICR(J,K), J=1,NANG(K))
WRITE(2,1007)
WRITE(2,555) (MACR0(J,K), J=1,NANG(K))
WRITE(2,1008)
WRITE(2,555) (RE(J,K), J=1,NANG(K))
WRITE(2,555) (RE1(J,K), J=1,NANG(K))
WRITE(2,1009)
WRITE(2,555) (RED(J,K), J=1,NANG(K))
WRITE(2,1010)
WRITE(2,555) (RED1(J,K), J=1,NANG(K))
WRITE(2,1012)
WRITE(2,555) (DELTA(J,K), J=1,NANG(K))
WRITE(2,1013)
WRITE(2,555) (UR(J,K), J=1,NANG(K))
WRITE(2,555) (UP(J,K), J=1,NANG(K))
WRITE(2,1014)
WRITE(2,555) (EPS(J,K), J=1,NANG(K))
WRITE(2,1015)
WRITE(2,555) (RATIO(J,K),J=1,NANG(K))
WRITE(2,1016)
WRITE(2,555) (ED(J,K),J=1,NANG(K))
WRITE(2,555) (ED1(J,K),J=1,NANG(K))
WRITE(2,555) (EDM(J,K),J=1,NANG(K))
WRITE(2,1017)
WRITE(2,555) (CF(J,K),J=1,NANG(K))
500 CONTINUE
2000 CONTINUE

C

*******PLOTTING OF TURBULENCE CHARACTERISTIC PARAMETERS*******
CALL UTP4A(80.,380.,0.0,YMAX,6.,5.,11HCRANK ANGLE,2,19HRATE OF DIS*
*SIPATION,3)
DO 40 K=1,NS
DO 30 J =1,NANG(K)
XX(J) =ANGLE(J,K)
YY(J) =EPS(J,K)
X(J) = ANGLE(J,K)*SFY-1.6
Y(J) = EPS(J,K)*SFY
CALL UTP3(AX(K),X(J),Y(J),2)
30 CONTINUE
CALL UTP4B(XX,YY,NANG(K),2)
40 CONTINUE
CALL UTP4A(80.,380.,0.0,YMAX,6.,5.,11HCRANK ANGLE,2,20HTURBULENCE*
*INTENSITY,3)
SFY = 5./VMAX
DO 50 K=1,NS
DO 50 J =1,NANG(K)
XX(J) =ANGLE(J,K)
YY(J) = INTENSITY(J,K)
X(J) = ANGLE(J,K)*SFY-1.6
Y(J) = INTENSITY(J,K)*SFY
CALL UTP3(AX(K),X(J),Y(J),2)
50 CONTINUE
CALL UTP4B(XX,YY,NANG(K),2)
60 CONTINUE
CALL UTP4A(80.,380.,0.0,6.0,6.0,6.,11HCRANK ANGLE,2,19HTURBULENT*
*VELOCITY,3)
DO 80 K=1,NS
DO 70 J =1,NANG(K)
XX(J) =ANGLE(J,K)
YY(J) = U(J,K)
X(J) = ANGLE(J,K)*SFY-1.6
Y(J) = U(J,K)
CALL UTP3(AX(K),X(J),Y(J),2)
70 CONTINUE
CALL UTP4B(XX,YY,NANG(K),2)
80 CONTINUE
CALL UTP4A(80.,380.,0.0,4.,6.,5.,11HCRANK ANGLE,2,24HMICROSscale OF*
*TURBULENCE,3)
SFY = 1.25
DO 100 K=1, NS
DO 90 J =1, NANG(K)
XX(J) = ANGLE(J, K)
YY(J) = MICRO(J, K)
X(J) = ANGLE(J, K)*SFX-1.6
Y(J) = MICRO(J, K)*SFY
CALL UTP3(AX(K), X(J), Y(J), 2)
90 CONTINUE
CALL UTP4B(XX, YY, NANG(K), 2)
100 CONTINUE
CALL UTP4A(80., 380., 0., 0., VMAX, 6., 5., 11, CRANK ANGLE, 2, 2OHMEAN VEL/CT
*Y (M/SEC), 3)
SFY = 5./VMAX
DO 120 K=1, NS
DO 110 J =1, NANG(K)
XX(J) = ANGLE(J, K)
YY(J) = VM(J, K)
X(J) = ANGLE(J, K)*SFX-1.6
Y(J) = VM(J, K)*SFY
CALL UTP3(AX(K), X(J), Y(J), 2)
110 CONTINUE
CALL UTP4B(XX, YY, NANG(K), 2)
120 CONTINUE
CALL UTP4A(80., 380., 0., 3., 6., 6., 11, CRANK ANGLE, 2, 19, HS CALE OF TURBU
*LENGTH, 3)
SFY = 2.
DO 140 K=1, NS
DO 130 J =1, NANG(K)
XX(J) = ANGLE(J, K)
YY(J) = MICROL(J, K)
X(J) = ANGLE(J, K)*SFX-1.6
Y(J) = MICROL(J, K)*SFY
CALL UTP3(AX(K), X(J), Y(J), 2)
130 CONTINUE
CALL UTP4B(XX, YY, NANG(K), 2)
140 CONTINUE
200 CONTINUE

C

******** CORRELATION PLOTS ********

VMAX = 50.
XMIN = 400.
XMAX = 4000.
YMAX = 8.
YMIN = 0.0
CFY = 5./(YMAX-YMIN)
CFX = 5./(XMAX-XMIN)
CALL UTP4A(XMIN, XMAX, YMIN, YMAX, 5., 5., 21, HREYNOLDS NUMBER (RE ), 3, 23
*HFLUCT. VEL/FRICITION VEL, 3)
DO 3000 K=1, NS
DO 3000 J=1, NANG(K)
IF(ANGLE(J,K) .LT. 250) GO TO 3000
Z = CFX*(REJ(J, K)-XMIN)
H = CFY*(RATIO(J, K)-YMIN)
CALL UTP3(AX(K), Z, H, 2)
3000 CONTINUE
XMAX = 120000
XMIN = 1000
YMIN = 0.0
CFY = 5.0/(YMAX - YMIN)
CFX = 5.0/(XMAX - XMIN)
CALL UTP4A(XMIN, XMAX, YMIN, YMAX, 5., 5., 21) HREYNOLDS NUMBER (REX), 3, 23
*HPLUCT. VEL/FRICITION VEL, 3
DO 3100 K = 1, NS
DO 3100 J = 1, NANG(K)
IF (ANGLE(J, K).LT. 250) GO TO 3100
Z = CFX*(REO(J, K) - XMIN)
H = CFY*(RATIO(J, K) - YMIN)
CALL UTP3(AX(K), Z, H, 2)
3100 CONTINUE
XMAX = 120000
XMIN = 1000
YMAX = 0.0
CFY = 5.0/(YMAX - YMIN)
CFX = 5.0/(XMAX - XMIN)
CALL UTP4A(XMIN, XMAX, YMIN, YMAX, 5., 5., 21) HREYNOLDS NUMBER (REX), 3, 20
*HITURBULENCE INTENSITY, 3
DO 3200 K = 1, NS
DO 3200 J = 1, NANG(K)
IF (ANGLE(J, K).LT. 250) GO TO 3200
Z = CFX*(REO(J, K) - XMIN)
H = CFY*(INTENSITY(J, K) - YMIN)
CALL UTP3(AX(K), Z, H, 2)
3200 CONTINUE
XMIN = 400.
XMAX = 4000.
YMAX = 40.
CFY = 5.0/(YMAX - YMIN)
CFX = 5.0/(XMAX - XMIN)
CALL UTP4A(XMIN, XMAX, YMIN, YMAX, 5., 5., 21) HREYNOLDS NUMBER (REX), 3, 20
*HITURBULENCE INTENSITY, 3
DO 3300 K = 1, NS
DO 3300 J = 1, NANG(K)
IF (ANGLE(J, K).LT. 250) GO TO 3300
Z = CFX*(REO(J, K) - XMIN)
H = CFY*(INTENSITY(J, K) - YMIN)
CALL UTP3(AX(K), Z, H, 2)
3300 CONTINUE
XMAX = 120000
XMIN = 1000
YMAX = 0.0004
YMIN = 0.0
CFX = 5.0/(XMAX - XMIN)
CFY = 5.0/(YMAX - YMIN)
CALL UTP4A(XMIN, XMAX, YMIN, YMAX, 5., 5., 21) HREYNOLDS NUMBER (REX), 3, 15
*HITURBULENCE INTENSITY, 3
DO 3400 K = 1, NS
DO 3400 J = 1, NANG(K)
IF (ANGLE(J, K).LT. 250) GO TO 3400
Z = CFX*(REO(J, K) - XMIN)
H = CFY*(ED(J, K) - YMIN)
CALL UTP3(AX(K), Z, H, 2)

3400 CONTINUE
XMIN = 400.
XMAX = 4000.
YMIN = 0.0
CFY = 5.0/(YMAX - YMIN)
CFX = 5.0/(XMAX - XMIN)
CALL UTP4A(XMIN, XMAX, YMIN, YMAX, 5., 5., 21HREYNOLDS NUMBER (RE ), 3, 15
*HMICRO-ED. DIFF. , 2)
DO 3500 K = 1, NS
DO 3500 J = 1, NANG(K)
IF (ANGLE(J, K) .LT. 250) GO TO 3500
Z = CFX * (REO1(J, K) - XMIN)
H = CFY * (ED1(J, K) - YMIN)
CALL UTP3(AX(K), Z, H, 2)

3500 CONTINUE
YMAX = 0.002
YMIN = 0.0
XMAX = 120000
XMIN = 1000
CFX = 5.0/(XMAX - XMIN)
CFY = 5.0/(YMAX - YMIN)
CALL UTP4A(XMIN, XMAX, YMIN, YMAX, 5., 5., 21HREYNOLDS NUMBER (RE ), 3, 15
*HMACRO-ED. DIFF. , 2)
DO 3800 K = 1, NS
DO 3800 J = 1, NANG(K)
IF (ANGLE(J, K) .LT. 250) GO TO 3800
Z = CFX * (REO1(J, K) - XMIN)
H = CFY * (ED1(J, K) - YMIN)
CALL UTP3(AX(K), Z, H, 2)

3800 CONTINUE
YMAX = 0.007
YMIN = 0.004
YMIN = 0.0
YMAX = 0.002
CFX = 5.0/(YMAX - YMIN)
CFX = 5.0/(XMAX - XMIN)
CALL UTP4A(XMIN, XMAX, YMIN, YMAX, 5., 5., 17HOEFF OF FRICTION, 3, 15HMAC
*RO-ED. DIFF. , 2)
DO 4100 K = 1, NS
DO 4100 J = 1, NANG(K)
IF (ANGLE(J, K) .LT. 250) GO TO 4100
Z = CFX * (CF(J, K) - XMIN)
H = CFY * (ED1(J, K) - YMIN)
CALL UTP3(AX(K), Z, H, 2)

4100 CONTINUE
YMAX=0.0004
CFY = 5./(YMAX-YMIN)
CALL UTP4A(XMIN,XMAX,YMIN,YMAX,5.,5.,17HCOEFF OF FRICTION,3,15HMIC
*RO-ED. DIFF.,2)
DO 3600 K=1,NS
DO 3600 J=1,NANG(K)
IF(ANGLE(J,K).LT.250) GO TO 3600
Z =CFX*(CF(J,K)-XMIN)
H=CFY*(ED(J,K)-YMIN)
CALL UTP3(AK(Z,H,2)
3600 CONTINUE
XMIN,YMIN=0.0
XMAX=0.001
CFX =5. /(XMAX-XMIN)
CALL UTP4A(XMIN,XMAX,YMIN,YMAX,5.,5.,17HSPALDING ED. DIFF,3,15HMIC
*RO-ED. DIFF.,2)
DO 3700 K=1,NS
DO 3700 J=1,NANG(K)
Z =CFX*(EDM(J,K)-XMIN)
H=CFY*(EDK(J,K)-YMIN)
CALL UTP3(AK(Z,H,2)
3700 CONTINUE
YMAX=0.002
CFY = 5./(YMAX-YMIN)
CALL UTP4A(XMIN,XMAX,YMIN,YMAX,5.,5.,17HSPALDING ED. DIFF,3,15HMIC
*RO-ED. DIFF.,2)
DO 4000 K=1,NS
DO 4000 J=1,NANG(K)
IF(ANGLE(J,K).LT.250) GO TO 4000
Z =CFX*(EDM(J,K)-XMIN)
H=CFY*(EDK(J,K)-YMIN)
CALL UTP3(AK(Z,H,2)
4000 CONTINUE
CALL UTPCL
111 FORMAT(10I3)
222 FORMAT(12F0.0)
220 FORMAT(6F0.0)
333 FORMAT(20A1)
444 FORMAT(2X,10I3)
555 FORMAT(2X,9E12.4)
1001 FORMAT(2X,'CRANK ANGLES ')
1002 FORMAT(2X,'MEAN VELOCITY:')
1003 FORMAT(2X,'TURBULENCE INTENSITY ')
1004 FORMAT(2X,'FLUCTUATING VELOCITY COMPONENT U:')
1005 FORMAT(2X,'TIME MICRO-SCALE:')
1006 FORMAT(2X,'MICRO-SCALE ('HM:')
1007 FORMAT(2X,'MACRO-SCALE ('MM:])
1008 FORMAT(2X,'REYNOLDS NUMBER ')
1009 FORMAT(2X,'REYNOLDS NUMBER ')
1010 FORMAT(2X,'REYNOLDS NUMBER ')
1012 FORMAT(2X,'BOUNDARY LAYER THICKNESS (CM):')
1013 FORMAT(2X,'FRICTION VELOCITY (UR): ')
1014 FORMAT(2X,'RATE OF ENERGY DISSIPATION:')
1015 FORMAT(2X,'FLUCTUATING VEL./FRICTION VEL.: ')
1016 FORMAT(2X,'EDDY DIFFUSIVITY:')
1017 FORMAT(2X,'COEFFICIENT OF FRICTION: ')
9000 FORMAT(2X,9A3)
STOP
END
FINISH
APPENDIX B11

ISOTROPIC PORT AREA

Program

This program is concerned with calculating the variation of isotropic port area with valve lift. It enables a comparison between the effect of different valve shapes on restricting the port area of the combustion chamber. The isotropic area is calculated by the following equation:

\[
\frac{\dot{m}}{A^*} = \left[ \frac{P_c}{P_o} \right]^{\frac{1}{\gamma}} \sqrt{\frac{2 \gamma}{\gamma - 1} \frac{P_o}{S_o} \left[ 1 - \left( \frac{P_c}{P_o} \right)^{\frac{\gamma - 1}{\gamma}} \right]} \tag{B38}
\]

The input data for this program consists of the variation of pressure drop across the port with the rate of mass flow across the port. The latter variable is calculated from the measured pressure drop across a metering orifice in the blowing rig circuit and the calibration of this orifice.

INPUT DATA

NC  Number of experiments.
N   Number of experimental data points at each valve lift.
PVALVE  Pressure drop across the port (inches H_2O).
PRIG  Pressure drop across the blowing rig metering orifice (inches H_2O).
LIFT  Valve lift.
TITLE(I)  Description of experimental conditions.
<table>
<thead>
<tr>
<th>OUTPUT DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMEAN</td>
</tr>
<tr>
<td>DM(I)</td>
</tr>
<tr>
<td>A(I)</td>
</tr>
</tbody>
</table>
PROGRAM(N300)
COMPACT
INPUT 1 - CHO
OUTPUT 2 - LPO
TRACE 2
END

MASTER ISOTROPIC PORT AREA
*****************************

THIS PROGRAM CALCULATES THE ISOTROPIC PORT AREA IN (MT*?)
AND PRINTS OUT, AS WELL AS, THE MEAN VALUE FOR THE NUMBER OF EXPERIMENTAL POINTS CONSIDERED.

PVALVE = THE PRESSURE DROP ACROSS THE INLET PORT.
PRIG = THE PRESSURE DROP ACROSS THE ORIFICE OF THE BLOWING RIG.
REAL LIFT

DIMENSION Q(20), Ql (20), H(20), PRIG(20) PVALVE(20), P1(20), P2(20), *V2(20), DM(20), A(20), TITLE(10), COMP(20)
E1=1.4235714
E2=1.7142357
CT=0.000472
READ 1,111) NC
READ 1,222) (I), I=1,16)
READ 1,222) (H(I), I=1,16)
DO 500 J=1,NC
READ 1,555) (TITLE(I), I=1,5)
READ 1,222) LIFT
READ 1,111) N
READ 1,222) (PVALVE(I), I=1,N)
READ 1,222) (PRIG(I), I=1,N)
DO 100 I=1,N
PRIG(I)=PRIG(I)*2.54
PVALVE(I)=PVALVE(I)*2.54
P1(I)=93.*PRIG(I)
P2(I)=93.*PVALVE(I)
V2(I)=SQRT(P2(I)*2.44)
R=1.-P2(I)/101300.
COMP(I)=SQRT((R**E1)-(R**E2))*3.5/(1-R))
V2(I)=V2(I)*COMP(I)

100 CONTINUE
AVERAGE =0.0
DO 400 J=1,N
DO 300 I=1,16
DP=PRIG(J)-H(I)
IF (DP)150,200,300
150 Q1(J)=1(I-1)+(PRIG(J)-H(I-1))*(Q(I)-Q(I-1)).(H(I)-H(I-1))
GO TO 250
200 Q1(J)=Q(I)
250 DM(J)=Q1(J)-CT
A(J)=V2(J)/V2(J)
AVERAGE =AVERAGE +A(J)
GO TO 400
300 CONTINUE
400 CONTINUE
AVERAGE =AVERAGE/N
WRITE(2, 333)(TITLE(L), L=1, 5), LIFT, AMEAN
WRITE(2, 444)(DM(I), A(I), PRIG(I), PVALVE(I), P1(I), P2(I), COMP(I), I=1, *N)
500 CONTINUE
111 FORMAT(5I3)
222 FORMAT(10F0.0)
333 FORMAT(2X, 5A8, /'VALVE LIFT=', F8.4, 'MM', 'MEAN ISOTROPIC AREA =', E20 *
*6)
444 FORMAT(7(1X, E13.4))
555 FORMAT(5A8)
STOP
END
FINISH
This program is concerned with verifying the assumptions used in developing the theoretical model of cyclic variation as discussed in Chapter 8. The program compares the theoretical predictions of the model for cyclic variations in the burning times with their measured values. The former values are calculated using measured gas velocities and their cyclic variations, while the experimental values of burning times and their variations were represented by values of the angle of occurrence of maximum cylinder pressure for Barton's data (10) and with burning times for Winsor's data (23).

The output results of these analyses consist of the ratio between the predictions of the theoretical model and the experimental values of burning times and the standard variation of these ratios relative to their mean value. The input/output data for this program could be summarised as follows:

**INPUT DATA**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>Gas velocity at the time of ignition.</td>
</tr>
<tr>
<td>S(U)</td>
<td>Standard deviation of gas velocity.</td>
</tr>
<tr>
<td>THETA</td>
<td>Characteristic parameter representing the burning time, e.g. angle of occurrence of maximum pressure.</td>
</tr>
<tr>
<td>SIGMA</td>
<td>Standard deviation of the burning time or the corresponding parameter used.</td>
</tr>
</tbody>
</table>
**INPUT DATA (continued)**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF</td>
<td>Air/fuel ratio</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
</tr>
<tr>
<td>SL</td>
<td>Laminar flame speed</td>
</tr>
<tr>
<td>RPM</td>
<td>Engine speed</td>
</tr>
</tbody>
</table>

**OUTPUT DATA**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST</td>
<td>Theoretical prediction of variations in burning time assuming a constant value of the critical flame kernel radius.</td>
</tr>
<tr>
<td>SST'r</td>
<td>Theoretical prediction of variations in burning time assuming a critical radius of the flame kernel of some multiple ratio of small scale eddies.</td>
</tr>
<tr>
<td>RATIO, RATIO 1</td>
<td>Ratio between theoretical and experimental values of variations in burning time assuming a constant value of the critical radius and a radius of some multiple ratio of small scale eddies respectively.</td>
</tr>
<tr>
<td>YM, YMI</td>
<td>Mean values of RATIO and RATIO 1 over the total number of experimental points respectively.</td>
</tr>
<tr>
<td>SD, SD1</td>
<td>Standard deviation in RATIO and RATIO 1 respectively.</td>
</tr>
<tr>
<td>SDM, SDM1</td>
<td>Coefficient of variation of RATIO and RATIO 1 respectively.</td>
</tr>
</tbody>
</table>

\[
SDM = \frac{SD}{YM} \\
SDM1 = \frac{SD1}{YM}
\]
**MASTER MODEL OF CYCLIC VARIATION**

```
REAL NEU, MEU  
DIMENSION X(100), X1(100), X2(100), Y(100), VC(9)  
READ(1,444) (VC(I), I=1,9)  
A1 = 0.0165649  
A = 0.65938047  
D = 0.0968375  
DO 200 J=1,6  
WRITE(2,666)  
READ(1,111) NP  
SY, SY1, SYS, SYS1 = 0.0  
DO 100 I=1, NP  
READ(1,222) U, SU, THETA, STHETA, AF, T, P, RPM  
U=U*0.3048  
SU=SU*0.3048  
IF((J.EQ.3).OR.(J.EQ.4)) GO TO 10  
IF((J.EQ.2).OR.(J.EQ.4).OR.(J.EQ.6)) CF=CF/4(323./T)**0.1  
UP=1/SQRT(CF*0.5)  
CF=CF/0.046/(RE**0.2)  
IF((J.EQ.2).OR.(J.EQ.4).OR.(J.EQ.6)) CF=CF/4(323./T)**0.1  
UP=1/SQRT(CF*0.5)  
C=UP*0.407  
SUP=A*((D/NEU)**0.1)/(U**0.9)*SU  
EPS=NEU*0.0407*(EXP(C)-1-C-(C*C)/2.-t*(C*C))/6.)  
DEPS=NEU*A1*(EXP(C)-1-UP-(UP*UP)/2.)  
EDT=EPS+NEU  
SEPS=DEPS+SUP  
DEPSU=SEPS/SU  
YH=EDT/DEPS  
XH=YH-U  
IF(J.GT.2) READ(1,222) SL  
IF(J.GT.2) GO TO 20  
HAF=(16.25-0.22*((AF-14.35)**2.))  
SL=(T**1.4)/(P**0.4)*HAFT  
20 CONTINUE  
SST=(NEU**0.25)*(T**0.66)*(AF**0.33)*SEPS/(4*SL*(EDT**1.25))  
SSTT=SST*XH  
COEF=SST/SEPS  
COEF1=SSTT/SEPS  
SST1=STHETA/(6.*RPM)  
IF((J.EQ.3).OR.(J.EQ.4)) SST1=STHETA  
RATIO=SST/SST1  
RATIO1=SSTT/SST1  
WRITE(2,555)  
WRITE(2,333) U, RE, UP, EPS, SST1, SST, SSTT, RATIO, RATIO1  
WRITE(2,777)  
WRITE(2,333) U, YH, XH, COEF, COEF1, SEPS, DEPS, DEPSU
```
SY = SY + RATIO
SY1 = SY1 + RATIO1
SYS = SYS + RATIO * RATIO
SYS1 = SYS1 + RATIO1 * RATIO1
X(I) = SST
X1(I) = SSTR
Y(I) = SSTR1
100 CONTINUE
N = NP
YM = SY / FLOAT(NP)
YM1 = SY1 / FLOAT(NP)
YY = YM * YM * FLOAT(NP)
YY1 = YM1 * YM1 * FLOAT(NP)
VAR = (SYS - YY) / FLOAT(NP)
VAR1 = (SYS1 - YY1) / FLOAT(NP)
SD = SQRT(VAR)
SDM = SD / YM
SD1 = SQRT(VAR1)
SDM1 = SD1 / YM1
WRITE (2, 333) YM, SD, SDM
WRITE (2, 333) YM1, SD1, SDM1
200 CONTINUE
111 FORMAT (10I3)
222 FORMAT (10F0.0)
333 FORMAT (9(1X, E12.5))
444 FORMAT (3E20.12)
555 FORMAT (1X, 'VELOCITY RE NO. U+ EDDY DIF
* S(0-PHAX) S(ST) S(ST*) RATIO RATIO*')
666 FORMAT (4OX, 'MODEL OF CYCLIC VARIATIONS')
777 FORMAT (2X, 'VELOCITY YH XH COEF COEF1 SEPS
* DEFSU DEFSU*')
STOP
END
FUNCTION VT(CF, VO, TC, TT, TC)
DIMENSION CF(9), X(2), F(2)
TR1 = (TO+273) / (TC+273)
TR2 = (TT+273) / (TC+273)
X(1) = 1.33 * TR1
X(2) = 1.33 * TR2
DO 2 I = 1, 2
   F(I) = 0.0
   DO 1 J = 1, 9
      F(I) = F(I) + CF(J) * (X(I)**(J-1))
1 CONTINUE
VT = VO * F(2) / F(1)
RETURN
END
FINISH
APPENDIX B13

Miscellaneous Programs used in the Data Acquisition System

B13-1 TEMPERATURE COEFFICIENT Program

This program is concerned with calculating the correct value of the temperature coefficient of resistance \( \alpha \) for the wire material by a least square error linear regression.

The input data are the measured values of: wire resistance at various temperatures during the heating up and cooling down processes, the wire cold resistance and the lead resistance.

The output data are the calculated value of \( \alpha \) as given by:

\[
\alpha = \frac{\left[ (R_{H}/R_{C}) - 1 \right]}{\Delta T} \tag{B40}
\]

Denoting \( \left[ (R_{H}/R_{C}) - 1 \right] \) as \( x \) and \( \Delta T \) as \( y \) the least square line approximating the set of points \( (x_1, y_1), (x_2, y_2), \ldots \) \( (x_N, y_N) \) has the equation

\[
Y = a_0 + a_1 x \tag{B41}
\]

where \( a_0 \) and \( a_1 \) are given by the following relations

\[
a_0 = \frac{(\Sigma Y)(\Sigma x^2) - (\Sigma x)(\Sigma xy)}{N \Sigma x^2 - (\Sigma x)^2} \tag{B42}
\]

and

\[
a_1 = \frac{N \Sigma xy - (\Sigma x)(\Sigma y)}{N \Sigma x^2 - (\Sigma x)^2} \tag{B43}
\]
The value of the temperature coefficient \( \alpha \) is given therefore by the calculated value of \( a_1 \) while \( a_0 \) equals zero for the straight line passing through the origin.

The output results are usually obtained as a graph showing the experimental results and the calculated value of \( \alpha \).
C

MASTER TEMPERATURE COEFFICIENT

DIMENSION R(100),T(100),ALPHA(100)

CALL UTOPP

READ(1,222) NS
DO 200 K=1,NS
READ(1,222) N
READ(1,111) RL
READ(1,111) (T(I),I=1,N)
READ(1,111) (L(I),I=1,N)
DO 200 J=1,(N-1)
M = N-J+1
RC =R(M)-RL
TC =T(M)
SALPHA = 0
DO 100 I=1,(N-J)
CT(I) = (T(I)-TC)*.55555
Y(I) = ((R(I)-RL)/(RC-RL)) 1.
ALPHA(I) = Y(I)/CT(I)
SALPHA = SALPHA+ALPHA(I)

100 CONTINUE

L = N-J
CALL LEAST SQUARE
SALPHA = SALPHA/(N-J)
TC =T(1)+32*0.55555
WRITE(2,333) RC,TC,SALPHA,A,B
WRITE(2,444) (DT(I),ALPHA(I),I=1,(N-J),}
WRITE(2,444) (DT(I), Y(I),I=1,(N-J),}
CLS =0.0
CMX =0.0
YMAX=0.3
XMAX = 300.
CALL UTP4A(XHIN,XMAX,YHIN,YMAX,5.,5.0,1.015-(TII-TC) ( ),2,911(MY/RC)-1,2)
CFX = 5./(XMAX-XHIN)
CFY = 5./(YMAX-YHIN)
J 250 IP =1,112
XX =FX*(DT(IP)-XHIN)
YY = SFY*(Y(IP)-YMIN)
CALL UTP3(1H*,XX,YY,2)

111 FORMAT(10F0.0)
222 FORMAT(10I3)
333 FORMAT(2X, 'RC=', F8.3, 'CHMS TC=', F8.3, ' OC MEAN VALUE OF ALPHA = *
      DT *ALPHA DT *ALPHA DT */)
444 FORMAT(2X, 6(1X, F7.3, 1X, F9.7))
555 FORMAT(5(1X, F7.3, 1X, F7.6))

SUBROUTINE LEAST SQUARE

111 FORMAT(10F0.0)

CALL UTP3
STOP
END
FINISH
B13-2  - CYLINDER-TO-CYLINDER VARIATION Program

This program is concerned with estimating the extent of cylinder-to-cylinder variations in the turbulent field characteristics. It consists of a simplified version of the general program (STATISTICAL ANALYSIS) discussed in Appendix B4.

The input data for this program are the variation of turbulence characteristic parameters with crank angles for different cylinders. These data are usually obtained from the output results of the TURBULENCE ANALYSIS I program discussed in Appendix B5.
MASTER CYLINDER TO CYLINDER VARIATIONS

COMMON /B1/X(12,10),CA(10),NANG,NC
READ(1,111) NC,NANG,NS
READ(1,222) C
READ(1,222) (CA(I),I=1,NANG)
DO 10 IS=1,NS
  DO 1 J=1,NC READ(1,222)(X(I,J),I=1,,NANG)
1 CONTINUE
IF((IS.EQ.1).OR.(IS.EQ.4)) GO TO 3
  DO 2 J=1,NC
    DO 2 I=1,NANG
      X(I,J)=X(I,J)*G
2 CONTINUE
3 CONTINUE
CALL STATISTICAL ANALYSIS
10 CONTINUE
111 FORMAT(10I3)
222 FORMAT(10F0.0)
STOP
END

SUBROUTINE STATISTICAL ANALYSIS
DIMENSION SD(10),SDM(10),SKEW(10),VMN(10),VMX(10),CVR(10),VM(10)
REAL KURT(10)
COMMON /B1/V(12,10),CA(10),NANG,NC
DO 4 J=1,NANG
  SV=0.0
  DO 5 I=I,NC
    SV =V+V(J,I)
5 VM(J) = SV/NC
  SSV,DV3,DV4 =0.0
  DO 1 I=I,NC
    SSV = SSV+V(J,I)*V(J,I)
    DV =V(J,I)-VM(J)
    DV3 = DV*DV+DV*DV
    DV4 = DV*DV
1 CONTINUE
  Y = VM(J)*V(J,1)*NC
  VAR = (SSV-Y)/(NC-1)
  SD(J) = SQRT(VAR)
  SDM(J) = SD(J)/VM(J)
  SD3 = SD(J)*VAR
  SD4 = VAR*VAR
  SKEW(J)= DV3/(SD3*(NC-1))
  KURT(J) = DV4/(SD4*(NC-3))
  VMN(J),VMX(J)=V(J,1)
  DO 2 I=1,NC
    IF(VMN(J).LT.V(J,I)) GO TO 2
    VMN(J) = V(J,I)
2 MN =I
2 CONTINUE
  DO 3 I=1,NC
    IF(VMX(J).GT.V(J,I)) GO TO 3
    VMX(J) = V(J,I)
3 MX =I
3 CONTINUE
CVR(J) = (VMX(J) - VMN(J)) / VM(J) * 100.
WRITE(2,333) CA(J), VM(J), VMX(J), VMN(J), CVR(J), SD(J), SDM(J), SKEW(J)
* , KURT(J)
CONTINUE
333 FORMAT (9(1X,E12.4))
RETURN
END
FINISH
The main purpose of this program is to generate some tabulated data required for the SPECTRAL ANALYSIS program. It calculates the exact sample number of a data block for any crank angle during the cycle, the required shift of the signal in the data block and the maximum number of cycle samples in the block.

It calculates also the sample size (crank angle degrees) and the exact value of engine speed for the particular test considered.

The input data for this program could be summarised as follows:

1. The minimum and maximum values of engine speeds in the Table.
2. The width of cycle sample (crank angle degrees).
3. The sampling rate on the ADC (μ sec/sample).
4. The size of the data block used in storing the digitized data.
MASTER TABULATED DATA

*     *     *     *

FOR CALCULATING THE CORRECT ENGINE SPEED AND THE SAMPLE NUMBER
FOR THE AUTO-CORRELATION AND POWER SPECTRUM ANALYSIS

INTEGER SR
DIMENSION ANGLE(100), NA(100), ND(100)
MAX RPM =3900.
MIN RPM =500.
DO 1200 IT=1, NT
READ(1,111) NANGLE, NT, NS, SR, NB
111 FORMAT(4I4)
READ(1,113) (ANGLE(I), I=1,NANGLE)
113 FORMAT(12F0.0)
DO 1100 IM=6,10,2
J=0
NSI = 120.* (10.***6)/(MAX RPM * FLOAT(SR))
DO 1000 NP=NSI, NS,5
RPM=120.* (10.***6)/FLOAT(NP*SR)
IF(RPM.LT.MIN RPM) GO TO 1100
SS=720./NP.
X = FLOAT(NP)/SS
NW= NINT(X)
NW2= NINT(X/2.)
NCOUNT = NINT( FLOAT(NB)/X)
NDI=NB-NW
IF(J.EQ.18) J=0
IF(J.GT.0) GO TO 800
WRITE(2,222) SR, IW
WRITE(2,333) (ANGLE(I), I=1,NANGLE)
WRITE(2,444)
800 CONTINUE
DO 900 I=1,NANGLE
NA(I) = NINT(ANGLE(I)/SS)
ND(I) =NA(I) NW2
900 CONTINUE
WRITE(2,555) NP, RPM, SS, (NA(I), I=1,NANGLE), NW,NDI
WRITE(2,666) (ND(I), I=1,NANGLE), NCOUNT
J=J+1
1000 CONTINUE
1100 CONTINUE
1200 CONTINUE

222 FORMAT(11H1,30X,61H TABULATED DATA FOR CALCULATING THE CORRECT ENGINE RPM)//, 30X, 71H AND SAMPLE NUMBER FOR THE AUTO-CORRELATION AND POWER SPECTRUM ANALYSIS/,, 20X, 16HSAMPLING RATE = ,I5 ,27H(MICRO-SEC.), CHUNK WIDTH = ,I4, 9H(DEGREES))

333 FORMAT(120H*****************************************************************************************************/
X*********************************************************************************************************************/
X4X, 2HNP, 4X, 3HRPM, 2X, 11HSAMPLE SIZE, 21X, 32HSAMPLE NUMBER/SAMPLE DIFFERENCE, 20X, 25X 12(2X, F4.0))

555 FORMAT(2X, I4, 2X, F5.1, 2X, F6.3, 3X, 12(2X, I4), 2X, 11HCLEAR FROM , I2, 4H TO , I4)

444 FORMAT(120H*****************************************************************************************************/
X*********************************************************************************************************************/
X
STOP
END
FINISH