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DATA ACQUISITION AND PROCESSING SYSTEM FOR DIAGNOSTICS OF TURBULENT PLASMAS

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ABSTRACT

Digitally implemented spectral analysis techniques enable one to make simultaneous measurements of ω and $\underline{k}$ associated with each of the several waves present in a turbulent plasma and as such possess great potential as plasma - turbulence - diagnostic tool. This report describes a data acquisition and processing system for implementing digital spectral analysis techniques.

The details of instrumentation and implementation of the system are described together with various considerations to obtain desired resolution and accuracies in calculated spectra. Examples of the spectra, obtained using the system, for plasma data are presented.

1. Introduction

The study of instabilities and turbulence in plasmas normally involves analysis of fluctuating plasma data (e.g. density and potential fluctuations). The aim of such an analysis is usually the identification of various waves involved, investigation of the nonlinear interactions between the waves and looking for a possible connection between the waves and anomalous properties displayed by the plasma. The task of the wave identification normally involves detection of the waves in a turbulent or noisy background. A further complication arises because one has to deal with the quantities which are fluctuating both in space as well as time. In order to characterise each wave one must, then be able to measure the amplitude, the frequency ω, the wave number $\underline{k}$ and the coherence for each of the waves which may be simultaneously present in the plasma. Digitally implemented spectral analysis techniques enable one to make simultaneous measurements of ω and $\underline{k}$ associated with each of the several waves present in a turbulent plasma and as such possess great potential as plasma-turbulence diagnostics tool. Smith et al (1974) have demonstrated the usefulness and advantages of these techniques for obtaining the above emntioned (see also Smith & Powers 1973; Powers, 1974) information. In this report a Data acquisition and processing system to implement digital spectral analysis techniques is desribed. Details of the data acquisiton system are given in section 2. Various standard steps involved in the data processing are summarised in section 3. In section 4 some examples of the dispersion and spectral characteristics of plasma, obtained using the data acquisition and processing system are presented. Present capabilities and limitations, and possible future extension of the system are discussed in section 5.

2. Data Acquisition System.

The data acquisition system shown in figure 1 consists of an analog tape recorder a digital tape recorder and an interface between the two. The analog signals from the experimental system are recorded on a 7 track, 7 speed analog tape recorder (AMPEX FR 2000). The tape recorder has a frequency response from 400 Hz to 2 MHz. The next step in the data acquisition is the digitisation of the signals. For the purpose of digitisation, a digitiser module (Datel DAS-16) is incorporated into the system. An external control circuit (interface) controls the digitiser and digitised data is recorded on a digital tape recorder. For this purpose a Dual Memory Buffered Formatter (Pertec F 849 & DB 1024) and a synchronous tape transport (Pertec 6840-9; 9 Track; 75 ips; 800 cpi NRZI) are incorporated in the system. Long lengths (greater than memory length) of data can be written without data loss at maximum throughput rates of 30 Kcps. The data tape thus prepared is processed on IBM 360 computer for data processing and analysis.

Details of the interface developed for the system are shown in block diagram of fig.2. An important consideration in digitisation of the data is the sampling rate, f_s which determines the highest frequency (known as Nyquist frequency $f_N = f_s/2$) about which information can be recovered from the digitised data. The analog signal from analog tape recorder is amplified to appropriate level and fed to a 4-pole-lowpass-butterworth filter. Each filter has a frequency range of 50 KHz but has the facility of resistor tunning to any cut off frequency upto 50 KHz. The cut off frequency of each filter is selected according to the digitisation rate per channel so as to avoid aliasing. Sampling theory dictates that the maximum input frequency must be less than half of the sampling frequency . Aliasing, is the generation of inaccurate digital outputs, and results from the presence of high frequency (greater than $f_s/2$) components in the analog input. To avoid aliasing the maximum input frequency ($f_s/2$) is attenuated below the resolution amplitude of the analog to digital converter, by means of the anti-aliasing filter. The filters used have a 0 dB gain in pass-band and 4-pole - Butterworth design ensures fast roll-off in cut-off region.

The signal is now fed to the digitiser module consisting of a multiplexer, sample and hold, A/D converter (ADC) and programming circuits. As many as 8 channels can be multiplexed both in a sequential as well as random mode. The selected channels are sampled with a fast sample and hold circuit with sampling time 5 μs.

The ADC uses successive approximation method and 8 bit conversion is over in less than 5μs. Thus the whole process of multiplexing sampling and A/D conversion takes just under 10 μs giving throughput conversion rate of 100 KHz.

Fig.3 gives a time sequence diagram for the digitisation and digital recording process. To start the data writing, the interface can either be triggered manually or with a synchronising pulse from the analog recorder. Input threshold of the trigger circuit is adjusted at 2.4 volts, so as to avoid false triggering by stray pick-ups. The circuit incorporates a comparator whose output triggers a mono-shot (MS) to generate a 300 ms delay pulse. The complimentry output of this MS is used as a logic level for writing file mark on the tape. Also at the rising edge of this pulse, a 2μs pulse is generated, which initiates a Write File Mark (WFM) operation on the digital tape recorder. File Mark is thus written prior to each data record written on the digital tape and separates one record from the other. At the falling edge of the 300 ms delay pulse, a pulse forming network (PFN) generates a number of sequential pulses. It changes the WFM logic to Write Data Mode, resets the Formater and generates a second initiate command to strobe the write command lines into the formatter. An OR gate allows either of the two initiate command pulses to strobe the command lines into the formatter. The PFN further generates a pulse to reset the multiplexer to channel I and at the same time sets the logic which initiates the data conversion by enabling one input of the Gate. The other input to the gate is the clock output whose frequency is 24 KHz. A convert command at 24 KHz rate is thus given to the ADC. At the end of each data conversion, a pulse is generated (ANS) which is used to strobe 8 bit (= 1 byte) data out put lines of ADC into the Formatter for subsequent writting on the digital tape. These strobe pulses are also fed to a counter which is used to select data record lengths to be written on the tape. Record lengths of 2^{10}, 2^{11}, 2^{12}, 2^{13}, 2^{14} and 2^{15} bytes can be selected by the use of a single pole 6 way switch. The counter at the end of selected record length resets the logic thereby inhibiting the Gate. The whole process is repeated with a new trigger pulse. The complete data acquisition system is housed in a shielded room and analog signals from experiments are taken there by means of coaxial cables and feed-throughs.

3. Implementation of Digital Spectral Analysis technique for interpretation of Plasma Data.

The data processing, for implementing digital spectral analysis, essentially involves application of Fast Fourier Transform (FFT) algorithms (Cooley & Tukey 1965, Glassman, 1970, Brigham 1974) to the digitally converted data in order to compute standard auto and cross power spectra together with other useful spectral functions e.g. coherence spectra, co - and quad - spectra. A detailed description of procedures involved in calculation of the above mentioned spectral function via FFT is given by Smith, et al, (1974). In the following we summarise the basic ideas.

3.1 Digital Spectral Analysis Technique.

Let us consider two fluctuating signals g_1 (t) and g_2 (t) representing density or potential fluctuations at two spatial points $\underline{r_1}$ and $\underline{r_2}$ and let $\underline{r_2} - \underline{r_1} = \underline{r}$. In FFT approach to the spectral analysis g_1 and g_2 are first digitised and the digitised data is Fourier transformed using FFT alogorithms. Let G_1 (f) and G_2 (f) represent the fourier transforms corresponding to g_1 (t) and g_2 (t). The auto power spectra of g_1 (t) and g_2 (t), respectively are then given by

$$P_{11}(f) = G_1^*(f)\ G_1(f) \tag{1}$$

$$P_{22}(f) = G_{22}^*(f)\ G_2(f) \tag{2}$$

where the superscript * on a quantity denotes complex conjugate of that quantity. The cross power spectrum is given by

$$P_{12}(f) = G_1^*(f)\ G_2(f) \tag{3}$$

$P_{12}(f)$ is in general complex and can be written as

$$P_{12}(f) = C_{12}(f) + i\ Q_{12}(f) \tag{4}$$

where $C_{12}(f)$ and $Q_{12}(f)$ are the co-spectrum and quad-spectrum respectively. $P_{12}(f)$ can be alternatively written as

$$P_{12}(f) = P_{12}(f) \quad \exp\ (i\ \theta_{12}(f) \tag{5}$$

where $\theta_{12}(f)$ is the phase difference at frequency f and is given by

$$\theta_{12}(f) = \theta_2(f) - \theta_1\ (f) \tag{6}$$

where $\theta_1(f)$ and $\theta_2(f)$ are phases of $G_1(f)$ and $G_2(f)$ respectively. The quantity $\theta_{12}(f)$ can also be written as

$$\theta_{12}(f) = \tan^{-1}\left[\frac{Q_{12}(f)}{C_{12}(f)}\right] \qquad (7)$$

Another function of interest is the coherence function $\gamma_{12}(f)$ which is defined as

$$\gamma_{12}(f) = \frac{|P_{12}(f)|}{[P_{11}(f) \times P_{22}(f)]^{\frac{1}{2}}} \qquad (8)$$

The function $\gamma_{12}(f)$ determines the degree of cross-correlation between g_1 (t) and g_2 (t) at given frequency f. If $\gamma_{12}(f)$ is zero at a particular frequency then $g_1(t)$ and $g_2(t)$ are incoherent at that frequency. If, on the other hand $\gamma_{12}(f) = 1$, the two signals are coherent at that frequency. For intermediate values of $\gamma_{12}(f)$, the signals are partially coherent.

3.2 Interpretation of Plasma Data.

In interpreting the plasma fluctuation data using the techniques outlined above, following steps are followed. Fluctuation data $g_1(t)$, $g_2(t)$ are recorded at two (or more) spatial points. The records are digitised and fourier transforms of the digitised data are calculated using appropriate window to account for the finite duration of the data record. The power spectra $P_{11}(f)$, $P_{22}(f)$ and $P_{12}(f)$ are then calculated from fourier transforms of the data. Also the values of $|P_{12}(f)|$, $\theta_{12}(f)$ and $\gamma_{12}(f)$ are computed. From the peaks in $P_{11}(f)$, $P_{22}(f)$ or $P_{12}(f)$ the spectral bands where wave phenomenon are present are identified. If the coherence value $\gamma_{12}(f)$ at these peaks is reasonably high ($\simeq$0.8 to 0.9) then from the power spectra one can obtain the frequencies and power at each frequency for each of the several waves present. In the region where coherence is poor the results are unreliable. From the phase of the cross-spectrum one can determine values of wave number $\underline{k}(f)$ or for cylindrical geometries, the mode number m(f) corresponding to the coherent waves in following way. The phase spectrum $\theta_{12}(f)$ can be interpreted as the phase shift each frequency component undergoes in travelling a distance $\underline{r}$ between the two spatial points $\underline{r}_1$ and $\underline{r}_2$ and this phase shift can be represented by the dot product of wave number $\underline{k}(f)$ and separation $\underline{r}$. Thus

$$\theta_{12}(f) = \theta_2(f) - \theta_1(f) = \underline{k(f)} \cdot \underline{r} \qquad (9)$$

yields k(f) if r is known. In cylindrical geometry the azimuthal wave number k(f) and azimuthal mode number m(f) are related by the relation $k(f) = m(f)/R$ where R is the radius at which the wave phenomenon is observed. To determine azimuthal mode numbers, the fluctuations are monitored at two spatial points at radius R separated in azimuth by angle ϕ. Then $r = R\phi$ and

$$\theta_{12}(f) = \underline{k(f)} \cdot \underline{r} = \frac{m(f)}{R} R\phi = m(f) \cdot \phi \qquad (10)$$

The associated phase velocity in azimuthal direction can then be expressed

$$V_p = \frac{\omega}{k(f)} = \frac{2\pi f R}{m(f)} = \frac{2\pi f R\phi}{\theta_{12}(f)} \qquad (11)$$

Thus the values of ω, k, V_p and power for each of the several waves present in the plasma can be obtained. Presence of any wave-wave interaction in the plasma can then be detected by looking at frequency and wave matching conditions. Powers (1974) has pointed out the possibility of measuring particle diffusion arising from the waves present in a turbulent plasma using the spectral analysis techniques.

3.3 Resolution and Reliability of the Obtained Spectra.

In the implementation of above mentioned scheme to obtain the spectra, number of intermediate steps are necessary to obtain desired resolution and accuracy in the spectral estimates. For example one has to use proper window to take account of the finite length of the data. Choice of the window is determined by a number of factors extensively discussed in literature (see e.g. Jenkins and Watts. 1968, Smith et al. 1974). The obtained spectra have to be appropriately smoothed to reduce the errors on the estimated spectra to acceptable limits. Length of the data used for the analysis and the number of points used for the spectra smoothing determine the spectral bandwidth and have to be choosen appropriately for desired resolution and accurancies.

The window used in the present processing system is the Hanning window given by

$$W(t) = \tfrac{1}{2} \left(1 - \cos \frac{2\pi t}{T} \right) W_o(t)$$

$$\text{where } W_o(t) = 1 \quad 0 \le t \le T \qquad (12)$$

$$= 0 \quad \text{elsewhere.}$$

and T is the total duration for which the data is recorded.

The choice of this window is dictated by the fact that i) the Hanning window has very low side lobe levels resulting in substantial reduction of leakage problem and consequent improved resolution and ii) it can be easily implemented in terms of simple weighted average in the frequency domain (Smith et al. 1974).

The elementary bandwidth Δf of a digitally computed power spectra is given by $\Delta f = 1/T$ HZ where T is the duration of data in seconds. The spectral estimates with Δf bandwidth, however, have large variances. In order to reduce the statistical errors to acceptable level, the spectra are smoothed. The smoothing procedure adopted in the present system is averaging of the spectra over several adjacent elementary frequency bands. The reduction in variance resulting from such smoothing is accompanied by a loss in frequency resolution. If the averaging is done over 'm' adjecent elementry frequency bands, the spectral bandwidth of the smoothed spectra is given by $\Delta F = m \Delta f$. Thus in deciding the amount of smoothing a compromise has to be made between the reduction in statistical variance and loss of the frequency resolution. Detailed discussion of the quantitative relationship between the amount of smoothing and the variance in the resulting spectra is given by Jenkins and Watts (1968). The variances of various spectra as a function of smoothing parameter 'm' are given in appendix I. One notes that in all cases the variance of the spectral estimates decreases as 'm' increases. The smoothing procedure adopted in the present system gives good spectral resolution provided the length of the data used is large enough to accommodate at least a few periods of the lowest frequency component desired to be resolved. This then dictates the minimum length of data to be used for the analysis. Data lengths smaller than or of the order of one period of the lowest frequency component involved will result in inaccuracies in the calculated spectra. However, in such a situation Maximum Entropy method outlined by Ulrych (1972) can be used to yield accurate spectral estimates.

4. Some examples of spectra obtained in plasma experiments using the data acquisition and processing system.

The data acquisition and processing system has been used for obtaining various results from the experiments in laboratory plasmas. Fortran programmes (Appendix II), based on the procedure outlined in the section III have been written, tested and utilised for obtaining these results. For FFT a programme given by Brigham (1974) has been adopted in the present system. In fig.4, we give a series of spectra representing plasma density fluctuations in a crossed electric-magnetic field system where magnetic field is increased from below the threshold of the cross-field instability. A multi-wave spectrum is seen to evolve as the threshold for cross-field modes is exceeded (fig.5(b) - (d)). The peaks are clearly resolved. The spectra have been interpreted in terms of cross-field instability by Saxena and John (1975).

Auto, phase and coherence spectra for low frequency waves observed without (fig.5 (a)) and with a pump wave near lower hybrid (fig. 5 (b)) are shown in fig. 5, while the high frequency pump wave and resulting lower hybrid wave are shown in fig. 6. The coherent waves are marked by the arrows. The results and implications of these spectra in terms of parametric interaction of the waves are discussed elsewhere (Saxena et. al 1977).

5. Discussions:

The highest frequency about which the information can be derived from the fluctuation data using the data acquisition and processing system is determined by the slowest device on the system. The slowest device in the system is the digital tape transport which takes data from the buffered formatter at a constant rate of 60 Kcps, and using a dual buffer memory the maximum rate at which data lengths greater than the memory (1024 bytes) can be transferred with zero data loss turns out to be 30 kcps. However, in small bursts ($\leq$ 1024 bytes) data can be transferred to buffered formatter at a rate upto 1 Mcps, though the data cannot be transferred again until the tape transport has taken the information from the buffer at 60 Kcps.

The multiple speeds of the analog tape recorder help in increasing this limit on the highest frequency which can be handled by the system in following way. A signal having high frequency components can be recorded at a high speed on the tape recorder and played back at a lower speed such that the largest frequency component in the replayed analog signal is compatible with the sampling rate. The speed reduction essentially results in a time stretching of the recorded data and corresponding reduction in the involved frequencies in the replayed signal. Such a time stretching also results in increase in the noise component and appropriate care should be taken about signal levels when attempting to digitise high frequency data in this mode.

Taking into account the maximum speed reduction of 64 (120 ips to $1\frac{7}{8}$ ips) available in the analog tape recorder, the maximum frequency which can in principle, be handled for a single channel data turns out to be 960 KHz and reduces to 480 KHz in the case of two multiplexed channels. However, using one of the tracks of the analog recorder for recording synchronising pulses, each of the data channels can be separately digitised, the simultaniety of the data being assured by starting each digitisation at same place on the tape. Thus maximum frequency which can be handled in the present system is 960 KHz. The ADC incorporated in the system has throughput rates of 100 Kcps and thus if recording system capabilities are suitably modified frequencies upto 2 MHz (the upper cut off for analog tape recorder) can be handled. One way of increasing the high frequency limit without incorporating any additional system is the use of multi-time-delay sampling techniques (Smith et al. 1972).

On one of the tracks of the analog recorder clock pulses can be recorded simultaneously with the data recorded on the other channels. A first digitisation of the data channels can be initiated by the first clock pulse and then subsequent digitisations can be done using succeeding clock pulses to initiate digitisation of the data channels. Thus with multiple scanning of data channels, the effective sampling frequency can be increased manyfolds resulting in an increased value of f_N and hence a higher high frequency capability. The digitised data obtained in multiple scans has to be rearranged using the computer before actual processing. System modifications to incorporate multi-time-delay sampling are in progress. The lower frequency cut-off in the present system is 400 Hz and is determined by the response of the analog tape recorder.

The present system is thus capable of handling plasma turbulence data in the frequency domain of 400 Hz to .96 MHz; with the proposed modification incorporating multi-time-delay sampling, the system will achieve ultimate capability of handling and processing plasma turbulence data upto 2 MHz. This system has been used to study the spectral and dispersion characteristics of the cross-field and the two stream instabilities in collisional plasma subjected to crossed electric and magnetic field (John & Saxena 1975; Saxena & John 1975), parametric interaction of lower hybrid wave with the cross-field instability (Saxena et al. 1977) and suppression of the cross-field modes by injection of cold electrons (Bora et al. 1977).

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REFERENCES

Bora D, Saxena Y.C. and John P.I., 1977, Proc. Symp. Plasma Phys. and Magnetohydrodynamics (BARC, Bombay).

Brigham E.O, 1974, Fast Fourier Transform, Prentice Hall, New Jersey.

Cooley J.W and Tukey J.W., 1965, Math. Comput. 19, 297.

Glassman J.A., 1970 IEEE Trans. Compt. C-19, 105.

Jenkins G.M. and Watts, D.G., 1968, Spectral Analysis, Holder - Day, San Francisco

John P.I. and Saxena Y.C., 1975, Geophys. Res.Letts. 2, 251

Powers E.J., 1974, Nucl. Fus. 14, 749

Saxena Y.C. and John P.I., 1975, Geophys. Res.Letts. 2, 492.

Saxena Y.C., Bora D and John P.I., 1977, Proc. Symp. Plasma Phys. & Magnetohydrodynamics (BARC, Bombay).

Smith D.E., Thomas C.W. and Powers E.J., 1972, IEEE, Trans. Nucl. Sc., NS-19, 784.

Smith D.E. and Powers E.J., 1973, Phys. Fluids, 16, 1373.

Smith D.E., Powers E.J. and Caldwell G.S., 1974, IEEE Trans. Plasma Science, PS-2, 261.

Ulrych T.J., 1972, J. Geophys. Res. 77, 1396.

APPENDIX-I

Formulae for variances of various spectra for smoothing parameter 'm'.

A) CROSS - POWER SPECTRUM

$$\mathrm{Var}\left[|P_{12}(f)|\right] \approx (\tfrac{1}{2}m)\ |P_{12}(f)|^2\left[1 + \frac{1}{|\gamma_{12}(f)|}^{-2}\right]$$

B) COHERENCE SPECTRUM

$$\mathrm{Var}\left[|\gamma_{12}(f)|\right] \approx (\tfrac{1}{2}m)\left[1 - |\gamma_{12}(f)|^2\right]^2$$

C) PHASE SPECTRUM

$$\mathrm{Var}\left[\theta_{12}(f)\right] \approx (\tfrac{1}{2}m)\left[\frac{1}{\left[|\gamma_{12}(f)|\right]^2} - 1\right]$$

APPENDIX - II

FORTRAN PROGRAMMES FOR DIGITAL SPECTRAL ANALYSIS OF PLASMA DATA

```
C     MAIN PROGRAM FOR CALCULATING POWER SPECTRA.DATA IS READ
C     FROM MAGNETIC TAPE MOUNTED ON UNIT=2.THE DATA TAPE IS
C     PREPARED AFTER UNSCRAMBLING THE DATA FROM DATA TAPE
C     WRITTEN IN LABORATORY.FOR THIS PURPOSE THE PROGRAM'TAPER'
C     IS USED.DATA LENGTH.LE.4096 CAN BE HANDLED.THE LABORATORY
C     DATA IS A RESULT OF DIGITISATION OF TWO MULTIPLEXED DATA
C     CHANNELS........... WRITTEN BY .. Y C SAXENA ...........
      IMPLICIT REAL*8(A-H,O-Z)
      COMPLEX*16 FOURT1(4096),FOURT2(4096),POWER(4096),CROSS(4096)
      EQUIVALENCE (POWER,FOURT1),(CROSS,FOURT2)
      PI=3.14159265D0
      N=4096
      DIVIS=DFLOAT(2*N)
      NCAL=0
      READ(5,40)FD,FR,THETP,NDATA,ISKIP
   40 FORMAT(3F10.4,2I5)
      THETP=THETP*PI/1.8D+2
      DF=FD*FR/DIVIS
      DT=1.0D/FD/FR
      NU=12
  100 IFIL1=0
  600 IFILE=0
  800 IFIL1=IFIL1+1
      IFIL2=IFIL1+ISKIP
 1000 CONTINUE
      READ(2,50,END=10 ) DUMMY
      GO TO 1000
   10 READ(2,50,END=200) (FOURT1(I),I=1,N)
  200 READ(2,50,END=300) DUMMY
  300 IFILE=IFILE+1
      IF(IFILE.NE.IFIL1) GO TO 10
   20 READ(2,50,END=400) (FOURT2(I),I=1,N)
  400 READ(2,50,END=500) DUMMY
  500 IFILE=IFILE+1
      IF(IFILE.NE.IFIL2) GO TO 20
      WRITE(6,30) IFIL1,IFIL2
   30 FORMAT(2I6/)
      WRITE(6,12) NCAL,(FOURT1(I),FOURT2(I),I=1,5)
   12 FORMAT(' DATA SET NUMBER'I4/(1X,10F11.4))
      WRITE(6,6)
      WRITE(6,11)FD,FR,THETP
   11 FORMAT(1X,'DIGITISATION FREQUENCY'E12.4,5X'REDUCTION RATIO'E12.4,
     15X'SEPERATION OF PROBES'E12.4//)
   50 FORMAT(24E15.8)
      CALL FFT2N(FOURT1,N,NU)
      CALL FFT2N(FOURT2,N,NU)
      CALL REFIN(FOURT1,N,DT)
      CALL REFIN(FOURT2,N,DT)
      CALL SPECTR(FOURT1,FOURT2,N,DF,DT)
      CALL SMOOTH(POWER,CROSS,N,C15,DF,IK,THETP,DT)
      WRITE(6,6)
    6 FORMAT(/)
      NCAL=NCAL+1
      IF(NCAL.EQ.NDATA) STOP
      GO TO 800
      END
```

```
C     MAIN PROGRAM FOR CALCULATING POWER SPECTRA.DATA IS READ
C     FROM MAGNETIC TAPE MOUNTED ON UNITTED 2.THE DATA TAPE IS
C     PREPARED AFTER UNSCRAMBLING THE DATA FROM DATA TAPE
C     WRITTEN IN LABORATORY.FOR THIS PURPOSE THE PROGRAM'TAPER'
C     IS USED.DATA LENGTH.LE.4096 CAN BE HANDLED.THE LABORATORY
C     DATA IS A RESULT OF DIGITISATION OF TWO MULTIPLEXED DATA
C     CHANNELS.......... WRITTEN BY .. Y C SAXENA ............
      IMPLICIT REAL*8(A-H,O-Z)
      COMPLEX*16 FOURT1(4096),FOURT2(4096),POWER(4096),CROSS(4096)
      EQUIVALENCE (POWER,FOURT1),(CROSS,FOURT2)
      PI=3.14159265D0
      N=4096
      DIVIS=DFLOAT(2*N)
      NCAL=0
      READ(5,40)FD,FR,THETP,NDATA,ISKIP
   40 FORMAT(3F10.4,2I5)
      THETP=THETP*PI/1.8D+2
      DF=FD*FR/DIVIS
      DT=1.0D0/FD/FR
      NU=12
  100 IFIL1=0
  600 IFILE=0
  800 IFIL1=IFIL1+1
      IFIL2=IFIL1+ISKIP
 1000 CONTINUE
      READ(2,50,END=10 ) DUMMY
      GO TO 1000
   10 READ(2,50,END=200) (FOURT1(I),I=1,N)
  200 READ(2,50,END=300) DUMMY
  300 IFILE=IFILE+1
      IF(IFILE.NE.IFIL1) GO TO 10
   20 READ(2,50,END=400) (FOURT2(I),I=1,N)
  400 READ(2,50,END=500) DUMMY
  500 IFILE=IFILE+1
      IF(IFILE.NE.IFIL2) GO TO 20
      WRITE(6,30) IFIL1,IFIL2
   30 FORMAT(2I6/)
      WRITE(6,12) NCAL,(FOURT1(I),FOURT2(I),I=1,5)
   12 FORMAT(' DATA SET NUMBER'I4/(1X,10E11.4))
      WRITE(6,6)
      WRITE(6,11)FD,FR,THETP
   11 FORMAT(1X,'DIGITISATION FREQUENCY'E12.4,5X'REDUCTION RATIO'E12.4,
     15X'SEPERATION OF PROBES'E12.4//)
   50 FORMAT(24E15.8)
      CALL FFT2N(FOURT1,N,NU)
      CALL FFT2N(FOURT2,N,NU)
      CALL REFIN(FOURT1,N,DT)
      CALL REFIN(FOURT2,N,DT)
      CALL SPECTR(FOURT1,FOURT2,N,DF,DT)
      CALL SMOOTH(POWER,CROSS,N,C15,DF,IK,THETP,DT)
      WRITE(6,6)
    6 FORMAT(/)
      NCAL=NCAL+1
      IF(NCAL.EQ.NDATA) STOP
      GO TO 800
      END
```

```
      SUBROUTINE FFT1(DATA,N,NU)
C   FAST FOURIER TRANSFORM FOR COMPLEX ARRAY 'DATA'
C   OF'N' SAMPLE POINT WHERE N=2**NU
C    TRANSFORM IS RETURNED TO DATA AFTER COMPUTATION
C    PROGRAM REQUIRES EXTERNAL FUNCTION IBITR
C     ADOPTED FROM  ' FAST FOURIER TRANSFORMS BY BRIGHAM'
      IMPLICIT REAL*8(A-H,O-Z)
      COMPLEX*16 DATA(1),T,WK
      TWOPI=6.283185307/DFLOAT(N)
      N2=N/2
      NU1=NU-1
      K=0
      DO100L=1,NU
  102 DO101I=1,N2
      P=DFLOAT(IBITR(K/2**NU1,NU))
      ARG=P*TWOPI
      WK=DCMPLX(DCOS(ARG),DSIN(ARG))
      K1=K+1
      K1N2=K1+N2
      T=DCONJG(WK)*DATA(K1N2)
      DATA(K1N2)=DATA(K1)-T
      DATA(K1)=DATA(K1)+T
  101 K=K+1
      K=K+N2
      IF(K.LT.N) GOTO102
      K=0
      NU1=NU1-1
  100 N2=N2/2
      DO103K=1,N
      I=IBITR(K-1,NU)+1
      IF(I.LE.K)GOTO103
      T=DATA(K)
      DATA(K)=DATA(I)
      DATA(I)=T
  103 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE FFT2N(DATA,N,NU)
C     THIS SUBROUTINE CALCULATES FFT OF A DATA SET OF LENGTH
C     2N BY CONSIDERING THE DATA ARRAY AS A COMPLEX ARRAY OF
C     LENGTH N AND THEN UNSCRAMBLING THE RESULTING TO OBTAIN
C     THE FT OF THE REAL DATA ARRAY OF LENGTH N.SUBROUTINE
C     REQUIRES EXTERNAL SUBROUTINE FFT1.THE FT IS RETURNED TO
C     DATA ARRAY AFTER CALCULATIONS.
C     ADOPTED FROM ' FAST FOURIER TRANSFORMS BY  BRIGHAM'
C     ********* WRITTEN  BY ... V C SAXENA *********
      IMPLICIT REAL*8(A-H,O-Z)
      COMPLEX*16DATA(1)
      CALL FFT1(DATA,N,NU)
      N2=N/2
      PI=3.1415926D+0
      DO20I=2,N2
      AI=I-1
      C I =DCOS(AI*PI/4.096D+3)
      SI=DSQRT(1.D0-C I **2)
      IN=N+2-I
      AIN=IN-1
      CIN=DCOS(AIN*PI/4.096D+03)
      SN=DSQRT(1.D0-CIN**2)
      X1=DREAL(DATA(I))
      X2=  DREAL(DATA(IN))
      Y1=DIMAG(DATA(I))
      Y2=DIMAG(DATA(IN))
      AI=0.5D0*(X1+X2+CI*(Y1+Y2)-SI*(X1-X2))
      BI=0.5D0*(Y1-Y2-CI*(X1-X2)-SI*(Y1+Y2))
      AIN=0.5D0*(X2+X1+CIN*(Y2+Y1)-SN*(X2-X1))
      BIN=0.5D0*(Y2-Y1-CIN*(X2-X1)-SN*(Y2+Y1))
      DATA(IN)=DCMPLX(AIN,BIN)
   20 DATA(I)=DCMPLX(AI,BI)
      RETURN
      END
```

```
      FUNCTION IBITR(J,NU)
      J1=J
      IBITR=0
      DO200I=1,NU
      J2=J1/2
      IBITR=IBITR*2+J1-2*J2
  200 J1=J2
      RETURN
      END



      SUBROUTINE REFIN(FOURT,N,DT)
C     THIS SUBROUTINE IMPLEMENTS THE HANNING WINDOW TO OBTAIN
C     A REFINED ESTIMATE OF THE FOURIER TRANSFORM OF THE DATA.
C     THE WINDOW IS IMPLIMENTED IN TERMS OF WEIGHTED AVERAGES
C     IN FREQUENCY DOMAIN REFINED ESTIMATES ARE RETURNED TO
C     THE ARRAY 'FOURT'
C     .......WRITTEN BY Y C SAXENA........
      IMPLICIT REAL*8(A-H,O-Z)
      COMPLEX*16 FOURT(1),TERM,TEMP
      TEMP=DCONJG(FOURT(2))
      N1=N-1
      DO10I=1,N1
      TERM=(0.5D0*FOURT(I)-(TEMP+FOURT(I+1))*0.25D0)*DT
      TEMP=FOURT(I)
   10 FOURT(I)=TERM
      FOURT(N)=0.5D0*(FOURT(N)-DREAL(TEMP))*DT
      RETURN
      END



      SUBROUTINE SPECTR(FOURT1,FOURT2,N,DF,DT)
C     THIS SUBROUTINE CALCULATES AUTO,CO-AND QUARATURE SPECTRA
C     USING FOURIER TRANSFORMS'FOURT1'AND'FOURT2'OF TWO DATA
C     SETS.AUTO SPECTRA ARE RETURNED AS REAL AND IMAGINARY PART
C     OF COMPLEX ARRAY'FOURT1'WHILE CO-AND  QUAD-SPECTRA ARE
C     RETURNED TO COMPLEX ARRAY FOURT2
C     .....WRITTEN BY  Y C SAXENA .........
      IMPLICIT REAL*8(A-H,O-Z)
      COMPLEX*16 FOURT1(1),FOURT2(1),PAWAR
      COMPLEX*16 Z
      CONS=DF*DT*3.14159265D0
      DO10I=1,N
      Z=DCMPLX(0.D0,CONS*DFLOAT(1-I))
      FOURT2(I)=FOURT2(I)*CDEXP(Z)
        PAWAR =DCMPLX(CDABS(FOURT1(I))**2,CDABS(FOURT2(I))**2)
      FOURT2(I)=FOURT2(I)*DCONJG(FOURT1(I))
      FOURT1(I)=PAWAR
   10 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SMOOTH(POWER,CROSS,N,MS,DF,IK,THETP,DT)
C     THIS SUBROUTINE CALCULATES SMOOTHED POWERSPECTRA BY TAKING
C     RUNNING AVERAGE OF'MS'NEIGHBORING POINTS FOR AUTO,CO-AND
C     QUD -SPECTRA.CROSS SPECTRUM,PHASE SPECTRUM AND COHERENCE
C     ALONGWITH THEIR PROBABLE ERRORS ARE CALCULATED AND PRINTED
C     WRITTEN BY Y.C.SAXENA
      IMPLICIT REAL*8(A-H,O-Z)
      COMPLEX*16 POWER(1),CROSS(1),SUMP,SUMC
      FI=0.D0
      DIVID=DFLOAT(MS)
      IDF=2*MS
      CONS=DSQRT(1.D0/DFLOAT(IDF))*1.96D0
      BW=DF*DIVID
      WRITE(6,11)IDF,BW
   11 FORMAT(20X,'DEGREES OF FREEDOM'I5,10X,'BANDWIDTH'E12.4//4X'I'
     1     3X'SPEC1'8X'SPEC2'8X'CROSS SPECTRUM'8X'COSPEC'7X,
     2'QSPEC'7X,'PHASE'8X,'MODE'6X,'COHERENCE'/)
      IK=1
      DO10I=1,N,MS
      IL=I+MS-1
      IF(IL.GT.N)RETURN
      SUMP=DCMPLX(0.D0,0.D0)
      SUMC=DCMPLX(0.D0,0.D0)
      DO15K=I,IL
      SUMP=SUMP+POWER(K)
      SUMC=SUMC+CROSS(K)
   15 CONTINUE
      SUMP=SUMP/DIVID
      SUMC=SUMC/DIVID
      P12=CDABS(SUMC)
      IF(P12.EQ.0.D0) GO TO 50
      PI=3.1415926D00
      COSPEC=DREAL(SUMC)
      QSPEC=DIMAG(SUMC)
      PHASE=DATAN2(QSPEC,COSPEC)
      COHS=P12/DSQRT(DREAL(SUMP)*DIMAG(SUMP))
      COHSQ=COHS*COHS
      CLP12=CONS*DSQRT(1.D0+1.D0/COHSQ)/2.3026D-01
      IF(IK.GT.1)GO TO 108
      PD=P12
      CLPD=CLP12
  108 CLP12=CLP12-CLPD
      P12=DLOG10(P12/PD)*1.D+1
      FMODE=PHASE/THETP
   50 CONTINUE
      WRITE(6,12)IK,SUMP,P12,CLP12,COSPEC,QSPEC,PHASE,FMODE,COHS
   12 FORMAT(I5,9E12.3)
      IK=IK+1
      FI=FI+BW
   10 CONTINUE
      RETURN
      END
```

```
C     PROGRAMME TAPER.THIS PROGRAMME PREPARES A DATA TAPE FOR
C     USE IN DIGITAL SPECTRAL ANALYSIS PROGRAM FROM THE TAPE
C     WRITTEN IN THE LABORATORY AFTER DIGITIGATION OF TWO
C     MULTIPLEXED DATA SETS.THE TAPE ON WHICH UNSCRAMPLED DATA
C     IS WRITTEN IS MOUNTED ON UNIT 3 WHILE TAPE FROM WHICH
C     DATA IS READ IS MOUNTED ON UNIT 2.PROGRAMME USES AN
C     EXTERNAL SUBROUTINE TAPER.
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION Y(8192)
      COMPLEX*16 DATA(8192)
      ID=0
  100    CONTINUE
      CALL TAPRE (DATA,N,FILE,NN,IERR)
      IF(IERR.NE.0)GOTO10
      IF(N.NE.8192)GOTO10
      N1=N-1
      DO15I=1,N1,2
      I1=I+1
      Y(I)=DIMAG(DATA(I))
      Y(I1)=DIMAG(DATA(I1))
      X1=DREAL(DATA(I))
      X2=DREAL(DATA(I1))
      J=I/2+1
   15 DATA(J)=DCMPLX(X1,X2)
      N2=N/2
      DO20J=1,N1,2
      I=N2+J/2+1
      J1=J+1
   20 DATA(I)=DCMPLX(Y(J),Y(J1))
      NI=N2+1
      END FILE 3
      WRITE(3,60)(DATA(I),I=1,N2)
      END FILE 3
      WRITE(3,60)(DATA(I),I=NI,N)
      NL=NI+9
      PRINT25,(DATA(I),I=1,10)
      PRINT25,(DATA(I),I=NI,NL)
   25 FORMAT(1X,10E10.3)
   60 FORMAT (24E15.8)
      END FILE 3
      ID=ID+1
      IF(ID.LT.3) GO TO 100
   10 CONTINUE
      STOP
      END
```

```
      SUBROUTINE TAPRE(DATA,N,FILE,NN,IERR)
C   THIS SUBROUTINE READ DATA FROM A TAPE WRITTEN IN 2'S
C   COMPLEMENTRY FORMAT AND CONVERTS IT INT BCD.DATA IS
C   WRITTEN IN THE BLOCKS OF 512 BYTES EACH.THE PROGRAMME
C   RECORDS INTER BLOCKS GAPS AS WELL AS FILE MARKS AND ALSO
C   CHECKSERRORS ON THE TAPE.AN EXTERNAL SUBROUTINE ASSEMBLE
C   IS USED IN THI SUBROUTINE.PROGRAMME WRITTEN BY STAFF
C   MEMBERS OF COMPUTER CENTRE PRL,AHMEDABAD
      INTEGER A(512),B,FILE
      INTEGER *2 C
      LOGICAL *1 XXY,XX(4),ZZ(2)
      REAL*8 X,Y
      COMPLEX*16 DATA(1)
      EQUIVALENCE (XXY  ,B), (C,ZZ)
      IERR=0
      LL=32
      IA=0
      N=0
      NL=0
      KL=0
      ISKIP=0
      IF=0
      GOTO10
   20 CONTINUE
      J=0
      IF(NN.EQ.0)GOTO100
      ISKIP=ISKIP+1
      IF(ISKIP.LT.NN)GO TO 10
      PRINT6,ISKIP
    6 FORMAT(1X,I6,'FILES SKIPPED ON DATA TAPE'/)
  100 CONTINUE
      IF(ISKIP.EQ.0)ISKIP=1
      FILE=FILE+ISKIP
      PRINT 51,FILE
   51 FORMAT(' FILE NUMBER'I6/)
      IF=1
      N=0
      NL=0
      KL=0
      IA=0
   10 CALL READ(A,IA,IEND)
      IF(IF.EQ.0.AND.IEND.NE.4)GOTO10
      IF(IEND .EQ. 4) GO TO 20
      IF(IEND .NE. 0) GO TO 90
      IF(IA .LE. 0) GO TO 10
      IF(ISKIP.LT.NN)GO TO 10
      IA1=IA-1
      DO60I=1,IA1,2
```

```
      C=0
      B=A(I)
      ZZ(2)=XXY
      LI=C
      IF(C.LT.128) GO TO 160
      LI=LI-255
  160 N=I/2+1+NL
      X=DFLOAT(LI)
      IJ=I+1
      C=0
      B=A(IJ)
      ZZ(2)=XXY
      LI=C
      IF(C.LT.128) GO TO 170
      LI=LI-255
  170 Y=DFLOAT(LI)
      DATA(N)=DCMPLX(X,Y)
   60 CONTINUE
      J=J+1
      IF(IA.LT.512)RETURN
      NL=N
      IF(N.GE.8192) RETURN
      IF(J.LT.LL) GO TO 10
      RETURN
  200 CONTINUE
      PRINT50,LL
   50 FORMAT('  IRG NUMBER EXCEEDED'I6,'  IN PREVIOUS FILE')
      GO TO 10
   90 J=J+1
      PRINT 190,FILE,J
  190 FORMAT('0','PERMANENT READ ERROR IN FILE NO.',I5,  '  RECORD NO.',
     1 I5,'  RECORD IS OMITTED')
      IERR=1
      RETURN
      END
```

```
         ENTRY READ
READ     EQU   *
         USING *,10
         STM   14,12,12(13)
         LR    10,15
         LA    1,PARAMR
         SVC   4
NEW      SVC   6
         L     8,24(13)
         L     8,4(8)
         SR    9,9
         LH    9,LENGTH
         SH    9,RCBR+14
         ST    9,0(8)
         LR    11,9
         L     8,24(13)
         L     9,8(8)
         ST    15,0(8)
         SR    6,6
         CR    15,6
         BNE   BACK1
         L     8,24(13)
         L     8,0(8)
         LA    9,BUFFRN
LOOP     IC    7,0(9)
         STC   7,0(8)
         LA    8,4(8)
         LA    9,1(9)
         BCT   11,LOOP
BACK1    LM    14,15,12(13)
BACK     LM    0,12,20(13)
         MVI   12(13),X'FF'
         BCR   15,14
PARAMR   DC    A(RCBR)
         DC    A(BUFFRN)
         DC    A(COUNTR)
RCBR     DC    X'12'
         DC    39X'00'
COUNTR   DC    X'2000'
LENGTH   DC    H'5000'
BUFFRN   DS    1250F
         END
```

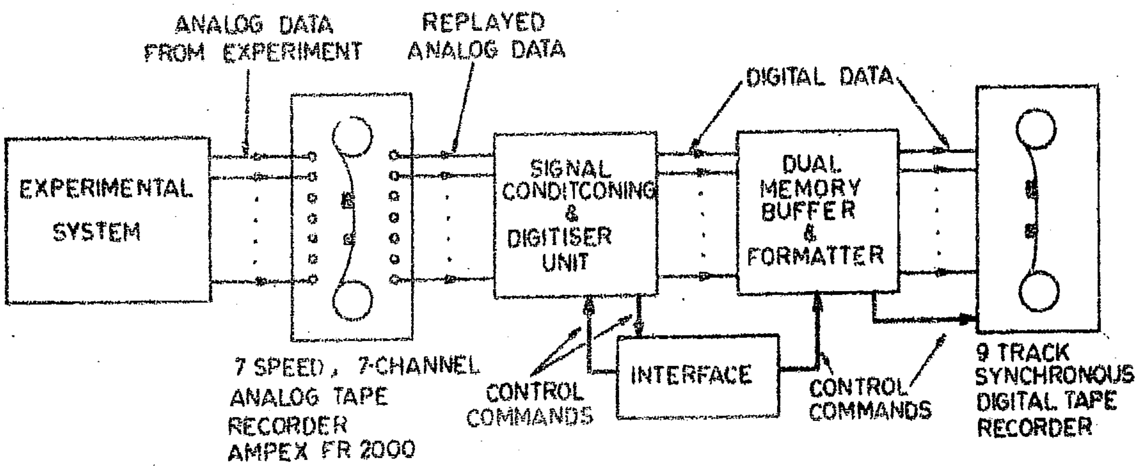

FIG. 1

A block diagram of the Data Acquisition System.

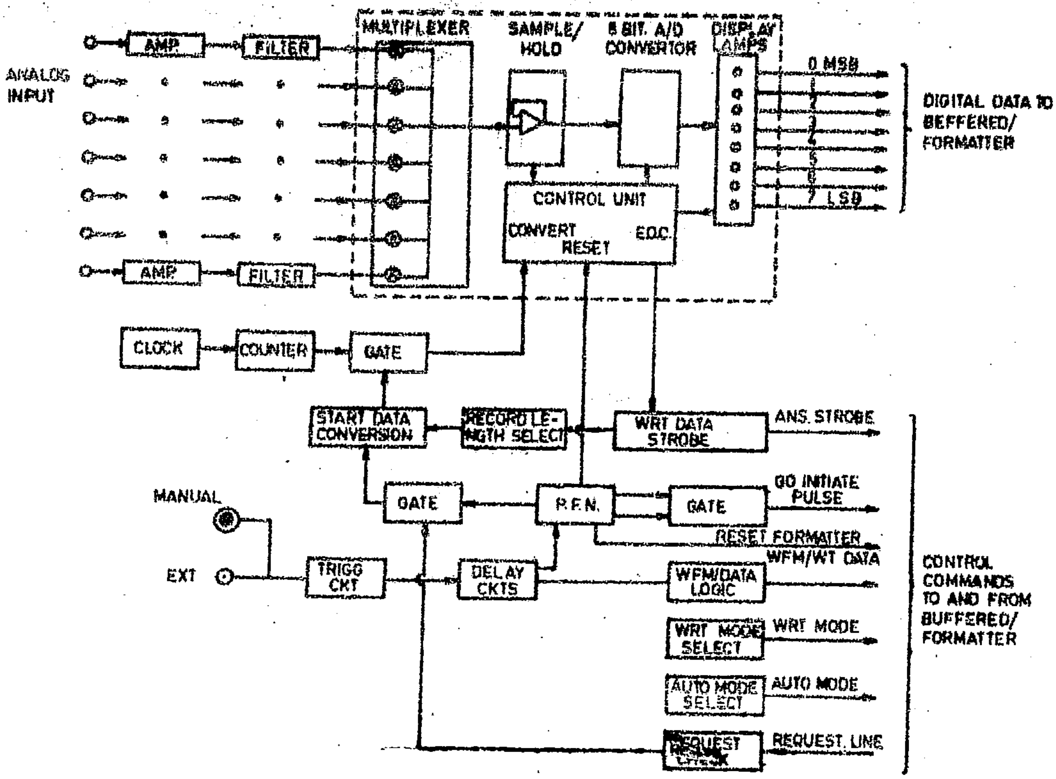

FIG...

Detailed bolck diagram of the interface developed for the data acquisition system.

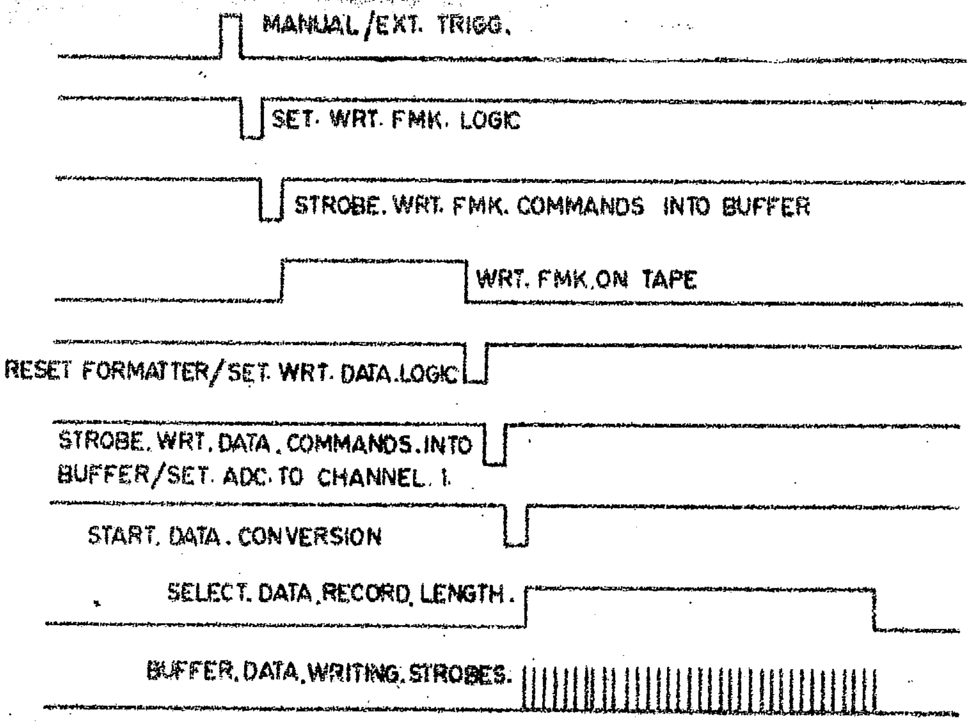

FIG.3

Time sequence of the digitisation procedure adopted in data acquisition system.

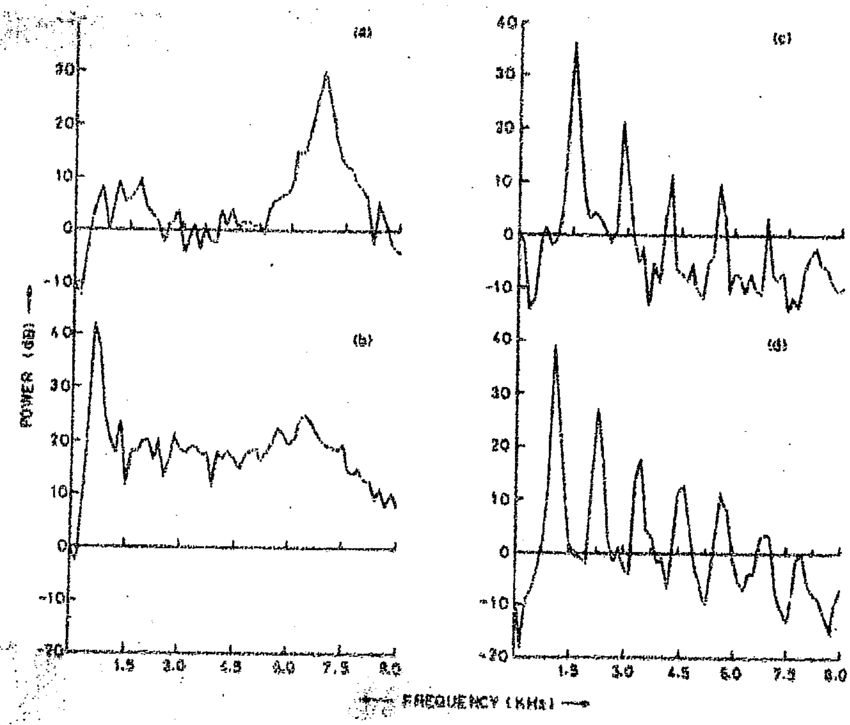

FIG.4

Power spectra for the density fluctuations observed in a collisional magnetoplasma in crossed electric and magnetic field.

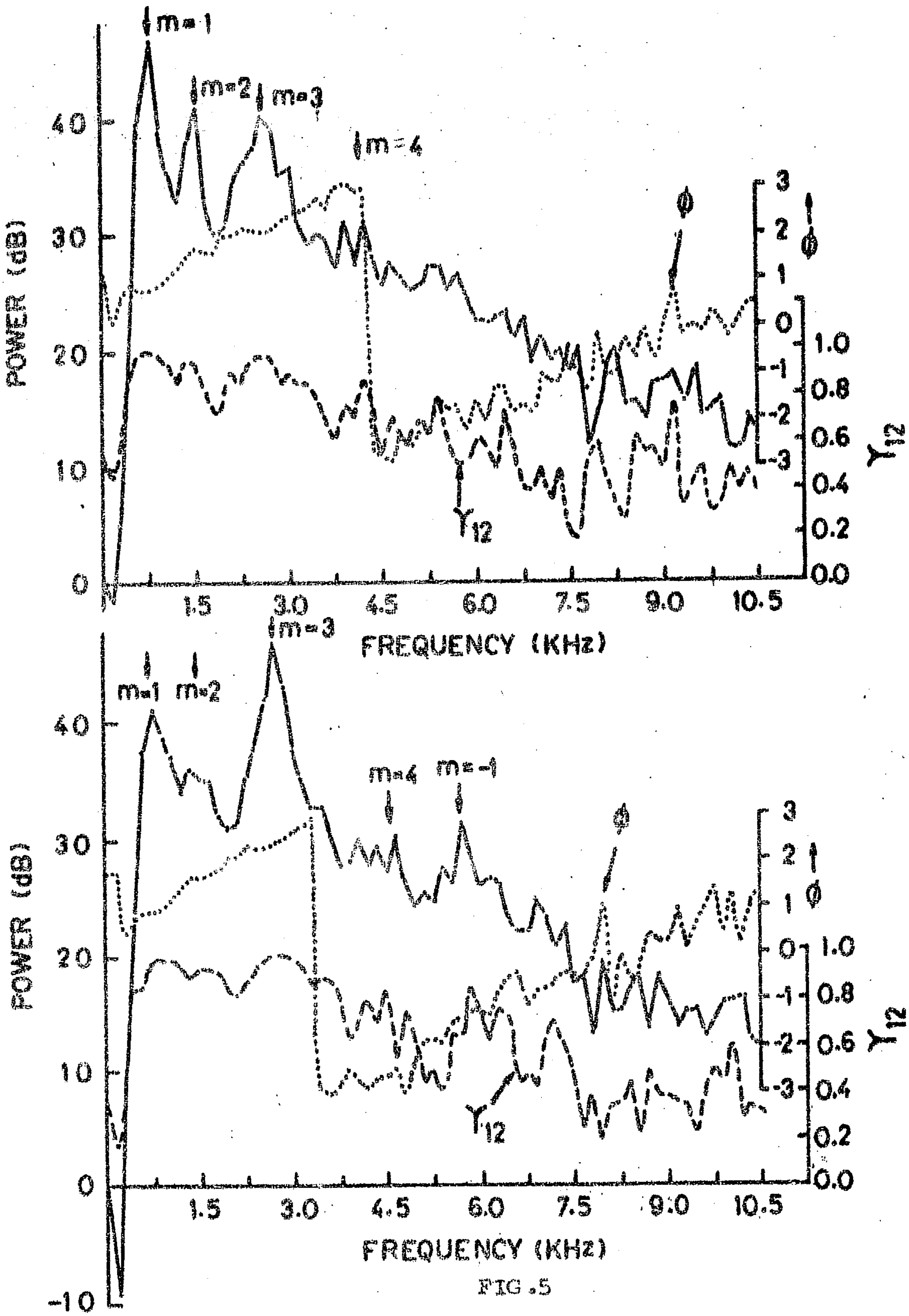

FIG.5

Power spectra of low frequency density fluctuation (a) without and (b) with a high frequency pump wave in collisional magnetoplasma.

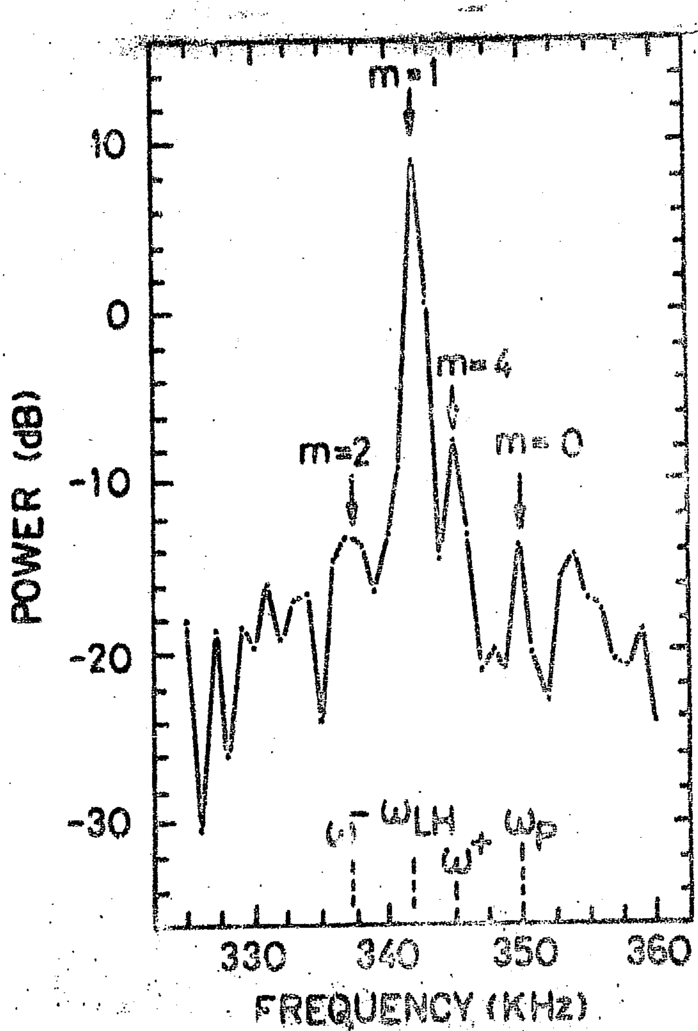

FIG.6

Excitation of lower hybrid wave in a collisional magneto-plasma by a high frequency pump wave.