AN ABSTRACT OF THE THESIS OF

HASSAN J. EGHBALI for the MASTER OF SCIENCE
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Title: THE IDENTIFICATION OF DUNGENESS CRAB FROM THE POWER SPECTRAL DENSITY FUNCTION OF THEIR ACOUSTIC SIGNATURE

Abstract approved: Redacted for privacy
L. C. Jensen

The power spectral density of the acoustic signature of Dungeness crab was calculated by the use of digital computer. The signal produced by the Dungeness crab was an analog signal. Therefore a conversion of the signal from analog to digital was necessary. This was done by sampling the acoustic signature of the crab at a rate of 100 KHZ, using an EAI-690 computer. The randomness of the crab signature made it necessary to employ statistical methods. The ensemble average of the acoustic signature of the Dungeness crab was used to calculate the mean spectrum for large and small male and female crabs. A significant concentration of energy was shown in the range of 3, 000 to 4, 000 Hertz for large male and female and small male crabs with smaller adjacent side bands. The range of these side bands was 300 to 500

Hertz. The mean spectrum for small female crab has almost constant concentration of energy in the range of 1, 000 to 6, 000 Hertz. The large male crabs also have a very significant concentration of spectral energy in the range of 600 to 1, 000 Hertz.

The Identification of Dungeness Crab from the Power Spectral Density Function of Their Acoustic Signature

by

Hassan J. Eghbali

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Associate Professor of Electrical and Computer Engineering
in charge of major

Redacted for privacy

Head of Department of Electrical and Computer Engineering

Redacted for privacy

Dean of Graduate School

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THE IDENTIFICATION OF DUNGENESS CRAB FROM THE POWER SPECTRAL DENSITY FUNCTION OF THEIR ACOUSTIC SIGNATURE

INTRODUCTION

The purpose of this investigation is to determine whether the acoustic signature of Dungeness crab might provide a method for their location and identification. The commercial fishing for Dungeness crabs is an economically important industry. Therefore, it is important to develop methods for the means of location and identification of Dungeness crab. One important method of identifying a signal is by the use of power spectral density analysis. In this investigation a power spectral density analysis on the acoustic signature of Dungeness crab was performed.

The physical, chemical, and biological response of a system can usually be converted into an electrical signal by using proper equipment to provide fundamental information about the system providing the signal. The simplest but generally not the most effective method of analysis is the direct observation of the signal on an oscilloscope. An important method is the use of power spectral density analysis. The digital computer is an effective tool in finding power spectral density and was used in calculating the power spectral density of the acoustic signature of the Dungeness crab.

Any time varying signal can be analyzed by time series analysis methods. Time series analysis is the analysis of a succession of data values obtained from a physical process. By definition [12] if, as a result of a number of observations of a process made under identical conditions, a number of different values of waveform x(t) is obtained for each of which the relationship between the variable x and the argument t is known only in the probability sense, then the process is called a random or stochastic process. A collection of the waveforms is called an ensemble, and an individual waveform is called a sample function. The data which was obtained from the acoustic signature of Dungeness crabs were random. Therefore, a statistical analysis was required to obtain the desired information for identification purposes. To describe the statistical nature of an observed time series it is necessary to regard it as a random or stochastic process.

Given a record of time series which exhibits random properties, it is not possible to predict future values of the series exactly as would be the case where the signal is deterministic. Since the acoustic signatures of Dungeness crab were random signals, it is necessary to rely heavily on a statistical method of analysis. For a random signal as in the case of acoustic signature of Dungeness crab, it is not possible to define the signal by a mathematical expression, but with proper instrumentation it is possible to obtain an electrical representation of such signals.

DISCRETE TIME SERIES

A discrete time series analysis was used in the identification of acoustic signature of Dungeness crab. In a discrete time series the values are given only at a specific instance of time. A discrete time series can be obtained by sampling a continuous time series at equal intervals of time. In identification of acoustic signature of Dungeness crab the crab signatures were passed through a band pass filter with lower cutoff frequency at 400 Hertz and upper cutoff frequency at 15, 000 Hertz. The crab signals were recorded after filtering. In this case, the recorded crab signals were band limited. Band limited means that the signals contain no frequency components higher than a certain maximum frequency determined by frequency response of the instrument. Therefore, it is possible to determine a sampling interval such that the discrete time series obtained by sampling the continuous time series signal contains all the information in the original series.

The crab signals were recorded by a Sangamo magnetic tape recorder at a speed of 60 ips (inches per second). The time duration of the signals varied from 3 to 30 milliseconds with most of the signal being in the range of 5 to 10 milliseconds. The signal density varied from less than one signal per minute to 10 or more signals per minute. Each crab was monitored for several minutes and the signals recorded which resulted in many more signals than than were desired for analysis. Some of the signals which were observed directly on an oscilloscope are shown on Figures 1, 2, 3, and 4. The first two signals are of the large and small male crab signal respectively and the next two are of the large and small female crab respectively. A large male crab is defined as a legal crab, or one greater than six inches when measured across the back. This same criteria was applied to female crabs. The small crabs used for this investigation were mostly four to five inches across the back with a few between five and six inches.

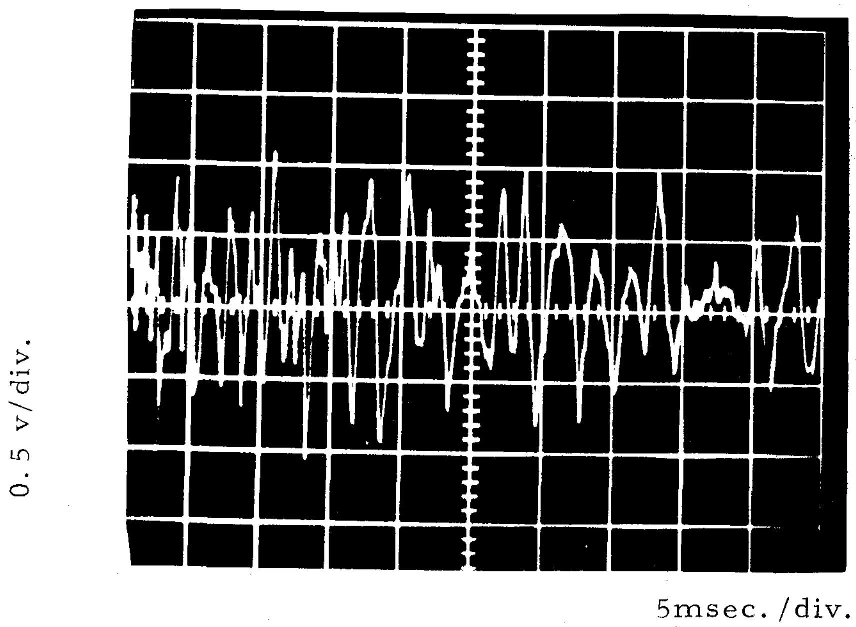


Figure 1. Acoustic signature of large male Dungeness crab.

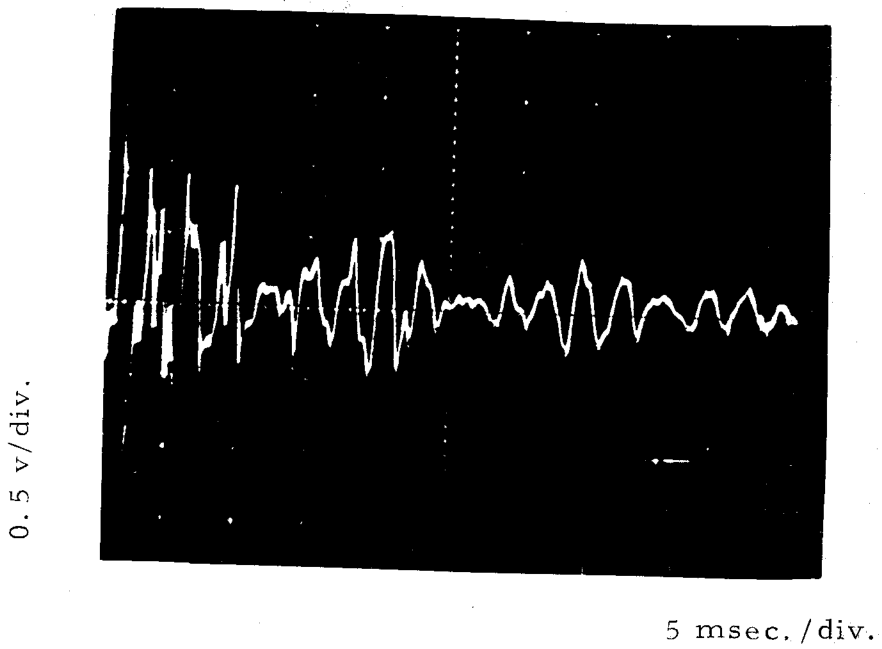
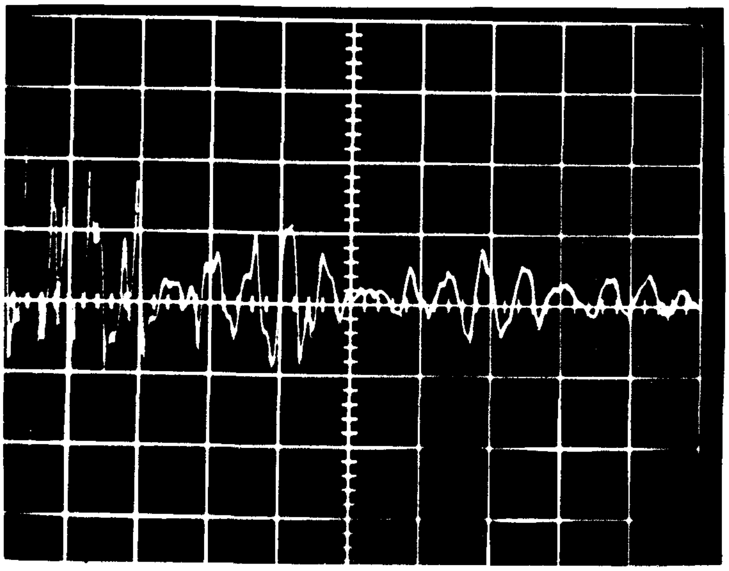


Figure 2. Acoustic signature of small male crab.

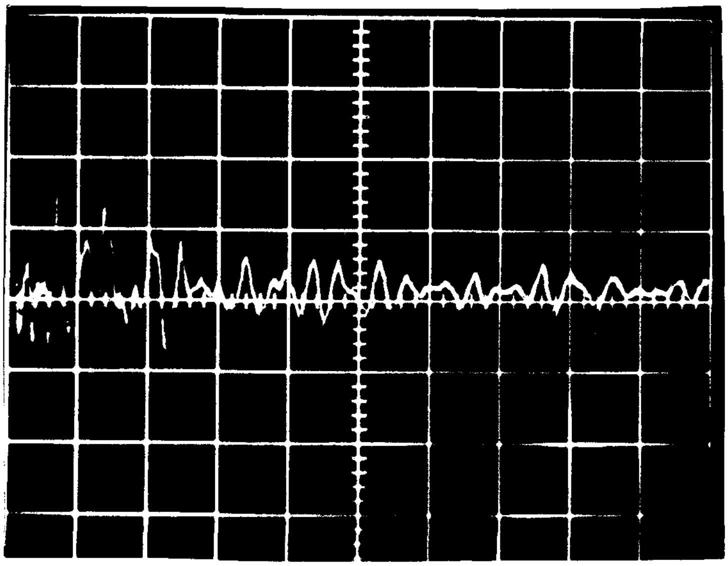
0.5 v/div.



5 msec./div.

Figure 3. Acoustic signature of large female crab.

1 v/div.



5 msec./div.

Figure 4. Acoustic signature of small female crab.

DIGITIZATION PROCESS

In order to calculate the power spectral density of the acoustic signature of the Dungeness crab it was necessary to digitize the analog signals produced by the crab. A hybrid computer (EAI-690) was used for the analog-to-digital conversion of the signal. Since the analog crab signals recorded on magnetic tape contained a significant level of noise and a low density of useful information, it was necessary to arrange a scheme to record only useful signals. All the crab signals were observed on the screen of an oscilloscope and it was found that the noise level did not exceed 0.5 volts. It was also noted that the desired signals ranged from 400 Hertz (cycle per second) to 10,000 Hertz with the speed of magnetic tape at 60 ips. The analog computer was programmed such that a trigger would start the digitization program if the signal level exceeded the observed background noise level twice within a period of 10 milliseconds. Since spurious noise spikes of greater amplitude were observed the double threshold triggering was used to eliminate false triggers caused by the spikes. The analog diagram for an EAI-680 computer and the timing clock are shown in Appendix A. The signals were amplified by using the amplifier of the analog computer and then introduced into two comparators. Comparator 34 shown in Figure A-2 was used to sense a crab signal level of about 1.25 volts and comparator $\phi 4$ was used to sense an end of crab signal any time the signal falls below 2.25 volts level.

During the digitization period the speed of the Sangamo magnetic tape was reduced from 60 ips to 15 ips. Since the Sangamo magnetic tape recorder is an FM-recorder. Therefore any reduction in its speed does not affect the amplitude of the signal. This reduction in the tape speed reduced all the signal frequencies by a factor of four. This change of frequency was taken into consideration in calculating the power density spectrum of the Dungeness crab signal. The digitization program was designed to continuously digitize selected analog signals, convert them to 24-bit words and output a block of 2,048 words to magnetic tape along with necessary identification header information. The EAI-690 computer on which the signals were digitized has memory complexity of 16-bit words. The calculation of power spectrum was done on a CDC-3300 computer which has a memory complexity of 24-bit words. Therefore the conversion from 16-bit words to 24-bit words was necessary. The digital program is shown in Appendix A. This program is written in an in-line assembly language. The flow-chart of operation is also shown in Appendix A. At the beginning of every record, the channel number of the magnetic tape, the crab number and the tape number was recorded. The block diagram of the digitization conversion is shown on Figure 5.

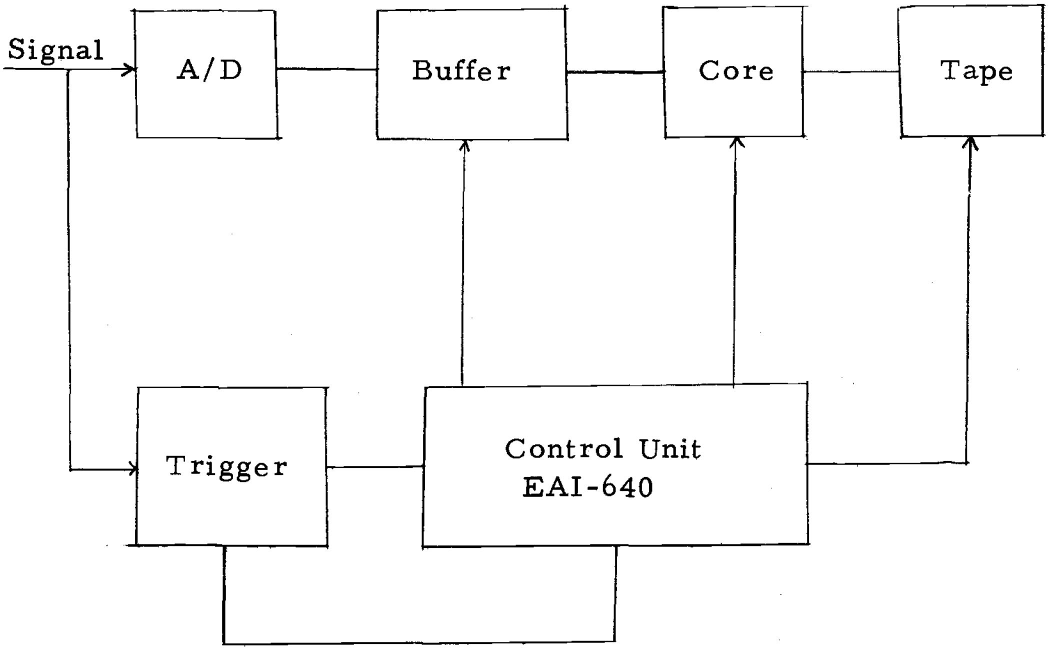


Figure 5. Digital Conversion Block Diagram.

A sample of the outputs after digitization are shown on Figures 6 through 9. Figures 6 and 7 represent the acoustic signature of large and small male crab respectively. Figures 8 and 9 represent the signature of large and small female crab.

FOURIER TRANSFORM

The fourier transform permits the representation of an arbitrary function f(t) by a continuous sum of exponential functions of the form $e^{j\omega t}$, where $j = \sqrt{-1}$. The fourier transform $F(\omega)$ of the function f(t) is the frequency domain representation of f(t). Time domain representation specifies the magnitude of a function at each instant of time, where a frequency domain representation specifies the relative amplitude of the frequency components of the function as well as phase component.

The fourier transform $F(\omega)$ of a signal f(t) in the time domain represents the distribution of the signal strength in the frequency domain and is defined by the following expression:

$$F(\omega) = \int_{-\infty}^{\infty} f(t) \; e^{-j\omega t} \; dt \qquad (1)$$

where $\omega = 2\pi f$ and f is the frequency in Hertz, $-\infty < f < +\infty$ and t is the time. The expression $F(\omega)$ represents the frequency domain function. The inverse fourier transform is given by

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) \; e^{j\omega t} \; d\omega \qquad (2)$$

The analogous discrete fourier transform which applies to sampled versions of the above functions for N samples is

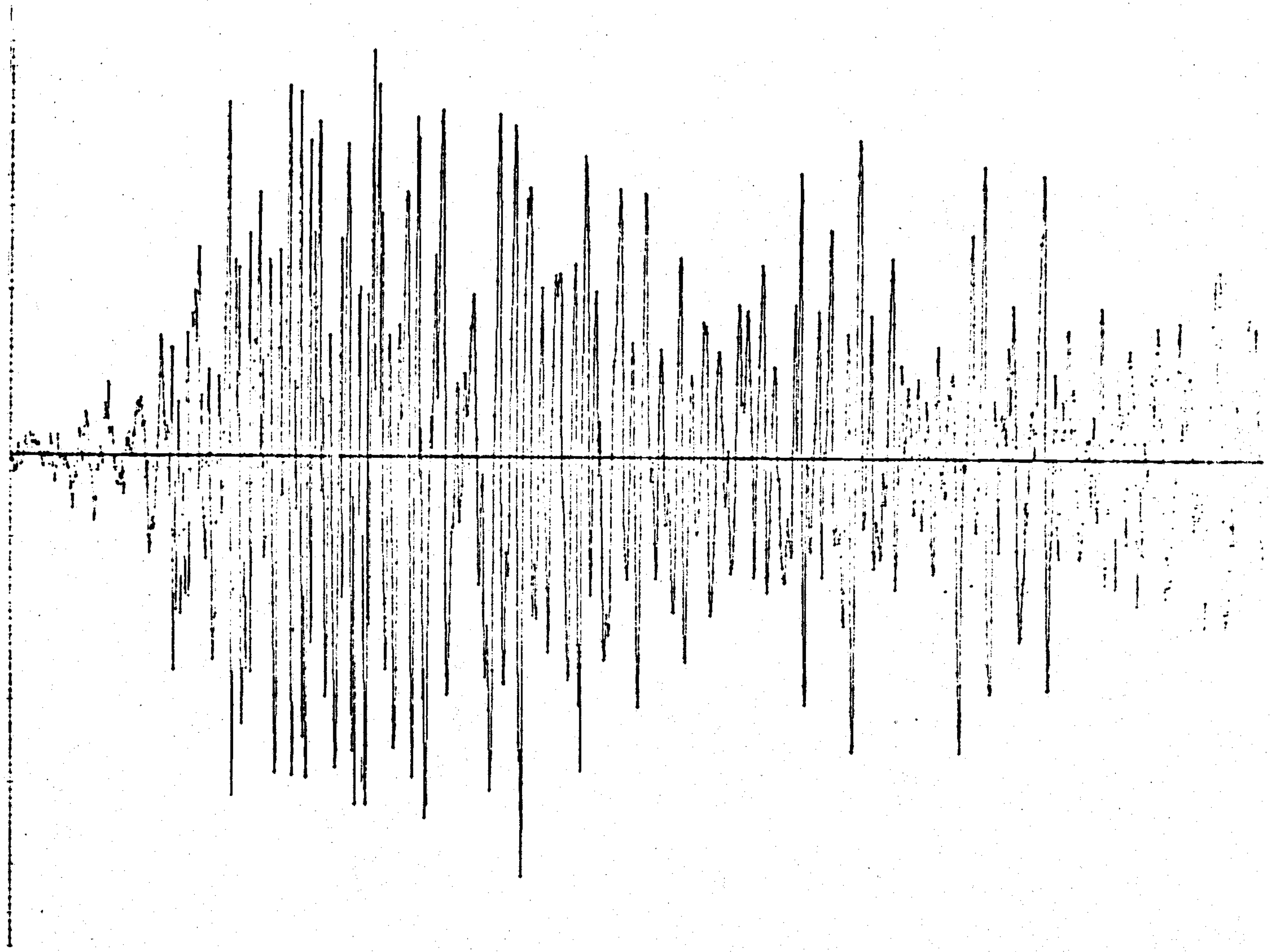


Figure 6. Acoustic signature of large male crab.

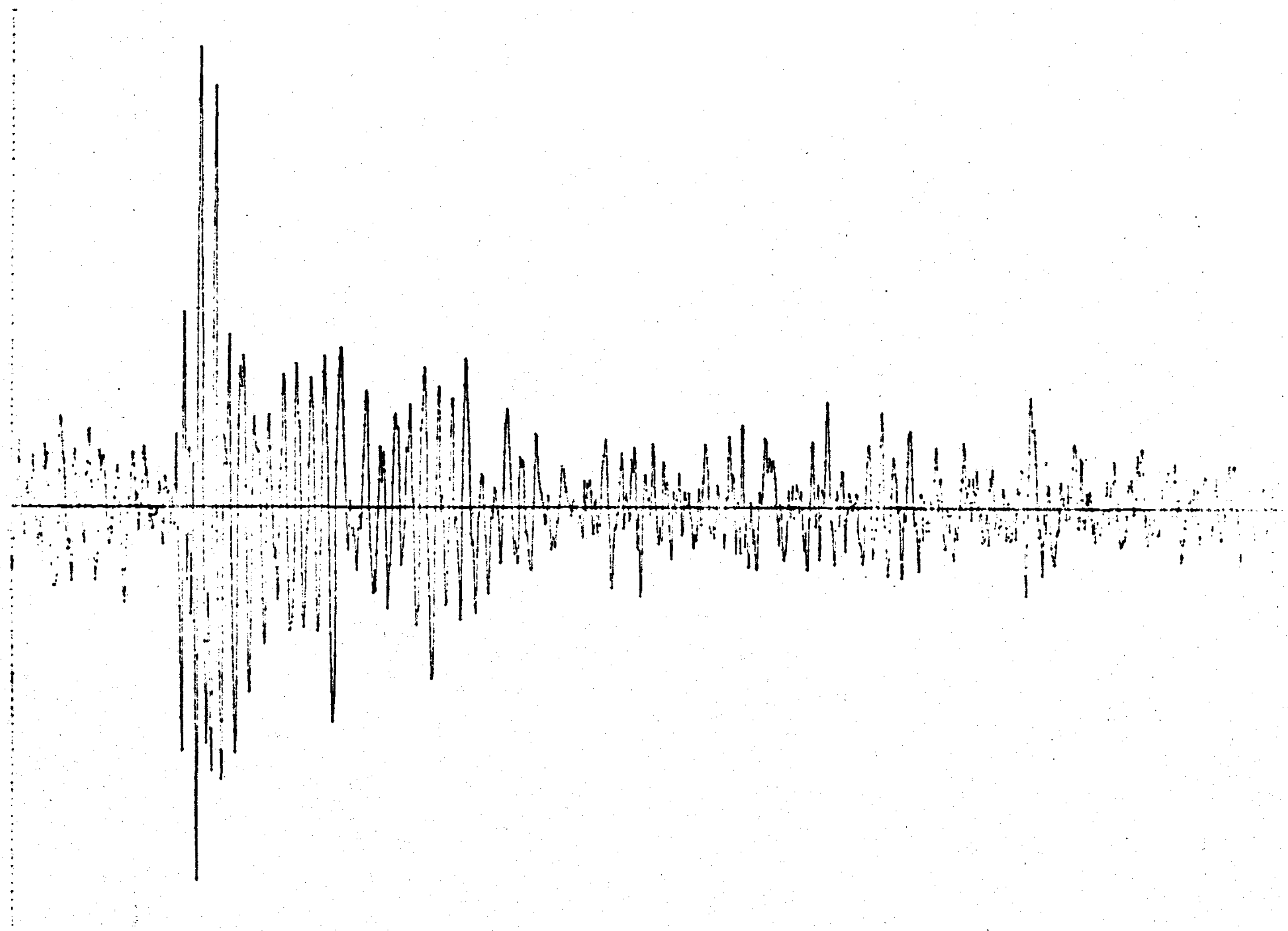


Figure 7. Acoustic signature of small male crab

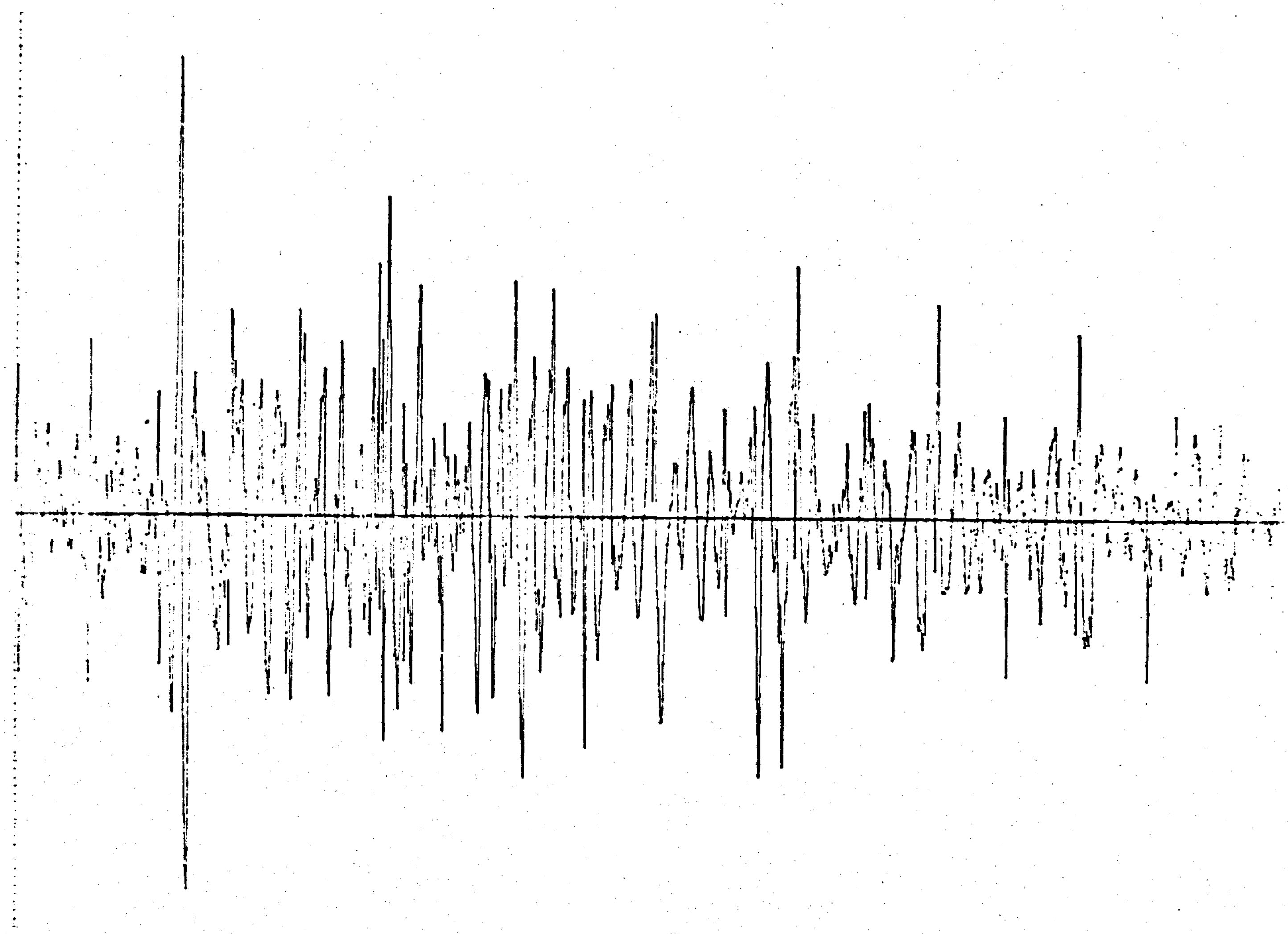


Figure 8. Acoustic signature of large female crab.

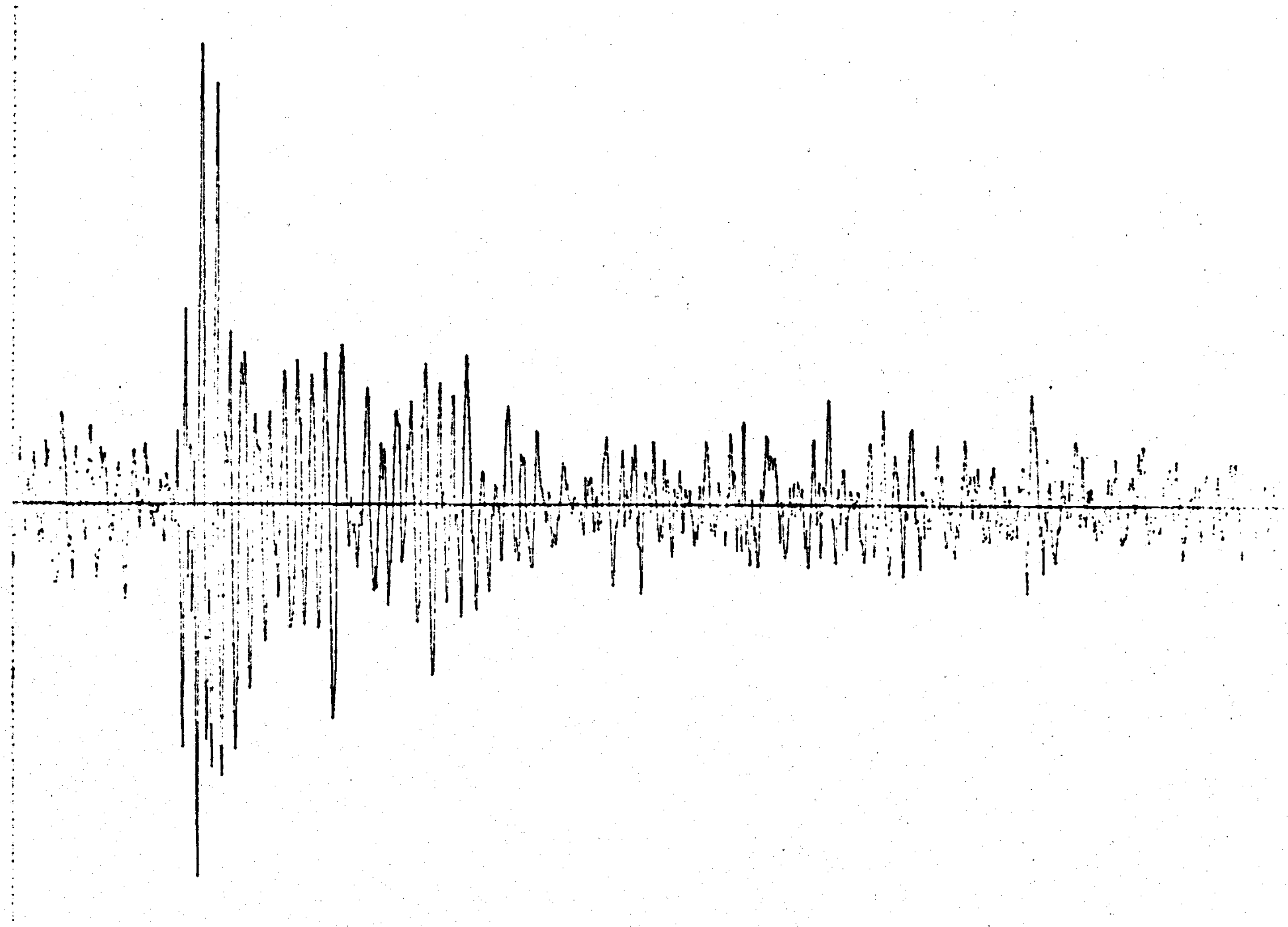


Figure 7. Acoustic signature of small male crab

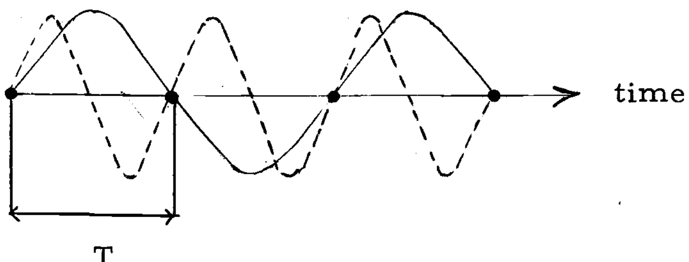
$$F(\omega_n) = \Delta t \sum_{k=0}^{n-1} f(t_k)\ e^{-j\omega_n t k} \qquad (3)$$

for $n = 0, \pm 1, \pm 2, \ldots\ldots\ldots\ldots\ldots, \pm N/_2$ and

$$f(t_k) = \Delta\omega \sum_{n=-N/_2}^{N/_2} F(\omega^n)\ e^{j\omega_n t k} \qquad (4)$$

where $k = 0, 1, 2 \ldots, N-1$ and Δt is a scaling term.

A given signal which has no spectral components beyond a certain frequency f_m (band-limited signal) is uniquely specified by its sample taken at interval of $\frac{1}{2fm}$ seconds. This is known as the Nyquist sampling theorem. The complete signal can be reconstructed from the knowledge of the signal at these instances alone. The sampling of f(t) is performed by multiplying f(t) by a finite train of impulses. The sampling rate should be at least twice the highest frequency represented in the signal, because the high frequency components of a time function can impersonate low frequencies if the sampling rate is too low as shown in the figure below:



Aliasing

This effect is known as ailiasing effect which is a distortion of the signal spectrum caused by the sampling process. Another effect due to sampling is leakage. The problem of leakage is inherent in the fourier analysis of a finite record of data. This record is obtained by looking at the actual signal for a period of T seconds and neglecting everything that occurs before and after this period. This is the same as multiplying the signal by a rectangular data window. Multiplication in time domain is the same as convolution in the frequency domain. Therefore, convolving $F(\omega)$ with a data window in frequency domain results in a series of spurious peaks called side lobes. The idea here is to reduce the amount of leakage through these side lobes. The usual method is to apply a data window to the time series, which has lower side lobes in the frequency domain than the rectangular data window. The sampling frequency as controlled by time made of analog computer (EAI-680) was like 100 KHZ (100, 000 cycles per second) which gives a sampling interval of 10^{-5} second. This sampling frequency was well above the highest frequency of the acoustic signature of the crab.

In the investigation of the acoustic signature of the Dungeness crab the fast fourier transform (FFT) was used to calculate the power spectral density. The fast fourier transform is actually an efficient method for computing discrete fourier transform. The important feature of the FFT as described by Tukey and Cooly [4] and [2] is the reduction of computer time in evaluating the discrete fourier transform. An N point transformation by the direct method requires a time proportional to N^2 where as the fast fourier transform requires a time proportional $N\log_2 N$. The ratio of FFT to direct computing time is $\frac{\log_2 N}{N}$. In the computation of the spectrum of the crab signals N was equal to 2^{11}, therefore the fast fourier transform requires less than $\frac{11}{2048}$ of normal computing time.

Autocorrelation Function

The autocorrelation function is a measure of the rapidity of variation of a given signal. Given two random variable X_1 and X_2, where X_1 represents the value of the sample functions at time t_1, and X_2 represents the value of the same sample functions at the time $t_1 + \tau$, where τ is time shift. The autocorrelation function is the expected value of the product X_1 and X_2

$$R_x(\tau) \equiv E \left\{ X(t)\ x\ (t+\tau) \right\} \tag{5}$$

R (τ) can also be represented by

$$R_x\ (\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{+T/2} x(t)\, x\ (t+\tau)\ dt \tag{6}$$

POWER SPECTRUM ESTIMATION

The power spectrum (or spectral density) of $S(\omega)$ of process $x(t)$ is defined as the fourier transform of its autocorrelation function

$$S(\omega) = \int_{-\infty}^{\infty} e^{-j\omega\tau} R(\tau)\, d\tau \tag{7}$$

From the inverse fourier transform formula (2) it follows that $R(\tau)$ can be expressed in terms of power spectrum. Therefore

$$R(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S(\omega)\, e^{j\omega\tau}\, d\omega \tag{8}$$

setting $\tau=0$, equation (5) reduces to $R_x(0) = E\left\{x^2(t)\right\}$ and equation (8) becomes

$$R(0) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S(\omega) d(\omega) = E\left\{ \left|x(t)\right|^2 \right\} \tag{9}$$

Therefore, the total area of $\frac{S(\omega)}{2\pi}$ is non-negative and equals the average power of the process $x(t)$. Power density spectrum of a sample function $x(t)$ is also given by

$$S_{XX}(\omega) = \lim_{T\to\infty} \frac{1}{T} \left| X_T(\omega) \right|^2 \tag{10}$$

or

$$S_{XX}(\omega) = \frac{1}{T} \left| \int_{-T/2}^{T/2} x(t)\, e^{-j\omega t}\, dt \right|^2 \tag{11}$$

where τ is the period of the time varying signal x(t) and $\omega = 2\pi f$. Expressing the power spectrum in discrete form equations (10) and (11) become

$$S_{XX}(\omega) = \frac{\Delta}{N} \left| \sum_{t=-n}^{n-1} X_t \; e^{-j\omega_k t\Delta} \right|^2 \tag{12}$$

or

$$S_{XX}(\omega) = \frac{\Delta}{N} \left\{ \left(\sum_{t=-n}^{n-1} X_t \cos\omega t\Delta \right)^2 + \left(\sum_{t=-1}^{n-1} X_t \sin\omega t\Delta \right)^2 \right\} \tag{13}$$

Smoothing the Spectral Estimator

It is necessary to estimate the accuracy of various functions obtained from a finite amount of data. A truncation error arises if the time function x(t) is only known in a finite interval of time. To see the effect of this truncation, a data window will be introduced. It is usually desirable to taper a random signal at each end to enhance certain characteristic of spectral estimates. Tappering is multiplying the time series by a data window, which is equivalent to applying a convolution (see Appendix B) operation to the raw fourier transform. The reason for tappering is to suppress large side lobes obtained with the raw transform. An easy method of smoothing the power spectrum is to use symmetric triangular weighting window as was used in estimating the spectrum of each crab signal. The triangular weighting window is defined as

$$P'_k = \frac{1}{M^2} \sum_{j=-M+1}^{M-1} (M - |j|)\, P_{k+j} \qquad (13)$$

over a span of 2M-1, based on Singleton and Poulter.

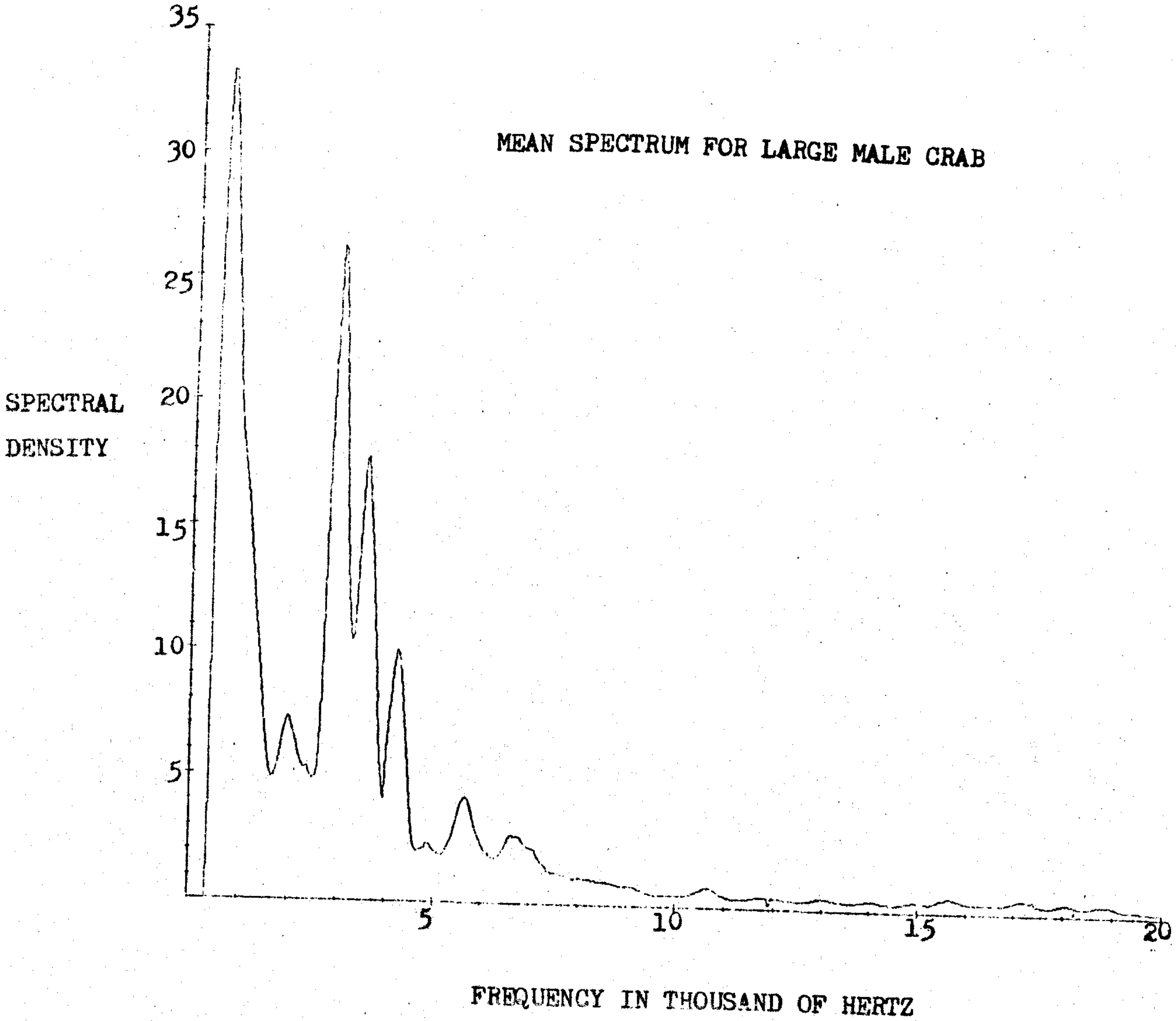
A useful characteristic of spectral window is

$I = \int_{-\infty}^{\infty} w^2(\tau)\, d\tau$ where $w(\tau)$ is the spectral window. $\frac{I}{T}$ provides a measure of reduction in variance of the estimator due to smoothing by the spectral window. Thus to obtain a small variance it is necessary to choose $W(\tau)$ so that I is small. For a given window this can be achieved by making M small. The band width of the spectral density can be calculated by using the following equation

$$b = \frac{1}{\int_{-\infty}^{\infty} w^2(f)\, df} \qquad (14)$$

where b is the band-width and w(f) the spectral window in the frequency domain. In calculating the power spectral density of crab signals the band width for the individual spectrum was 341.747 HZ with truncation point of M=7.

The final step was to find the mean spectral density for a large number of acoustic signatures of Dungeness crab. If the power density spectra of various sample function is found and the average of these spectra obtained the result would be the ensemble or statistical average of the power density spectrum. If the process is not ergodic, then the sample functions are not statistically equivalent and each sample function has a different time autocorrelation and therefore a different power-density spectrum. The question here is that whether we can find the power-density spectra of various sample functions and obtain the average of the power-density spectrum. The answer is that for a general process the ensemble average of the power density spectrum is reasonable method of approach, because it is not known which of the sample functions we are dealing with. This calculation for the average spectrum was done by using a CDC-3300 computer. The mean spectrum was calculated and plotted for approximately 150 to 200 acoustic signatures of large male Dungeness crab. The average spectrum for acoustic signatures of small male and large female Dungeness crab was calculated for about 100 to 150 signals. For small female crab about 100 signals were used to calculate the mean spectrum. The results are shown in Figures 10 through 13. Since all the crab signals were not recorded at the same amplitude level, it was necessary to standardize them. The standardization technique was



MEAN SPECTRUM FOR LARGE MALE CRAB
SPECTRAL DENSITY
35
30
25
20
15
10
5
5
10
15
20
FREQUENCY IN THOUSAND OF HERTZ

FIG. 12

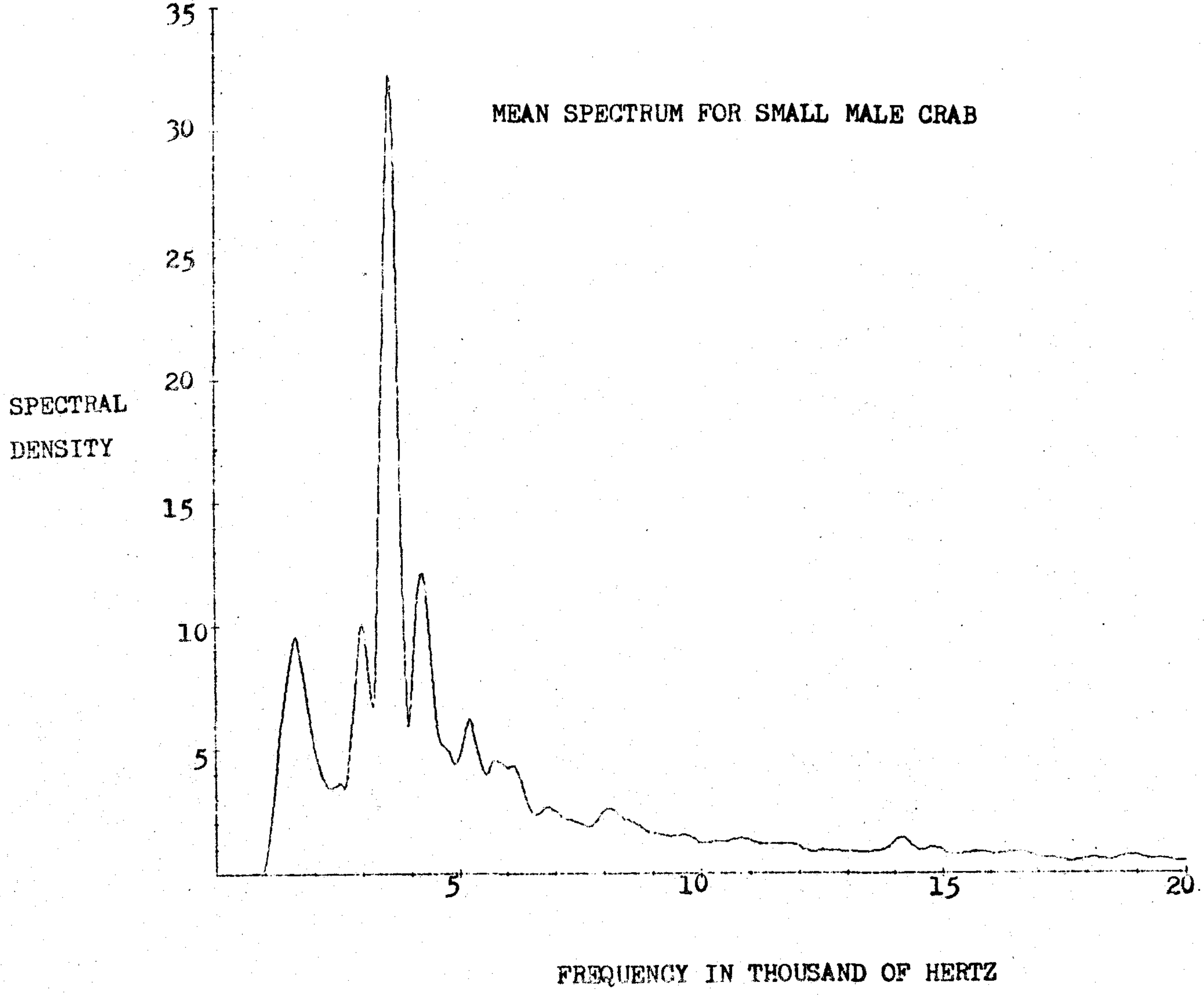

MEAN SPECTRUM FOR SMALL MALE CRAB
SPECTRAL DENSITY
35
30
25
20
15
10
5
5
10
15
20
FREQUENCY IN THOUSAND OF HERTZ

FIG. 11

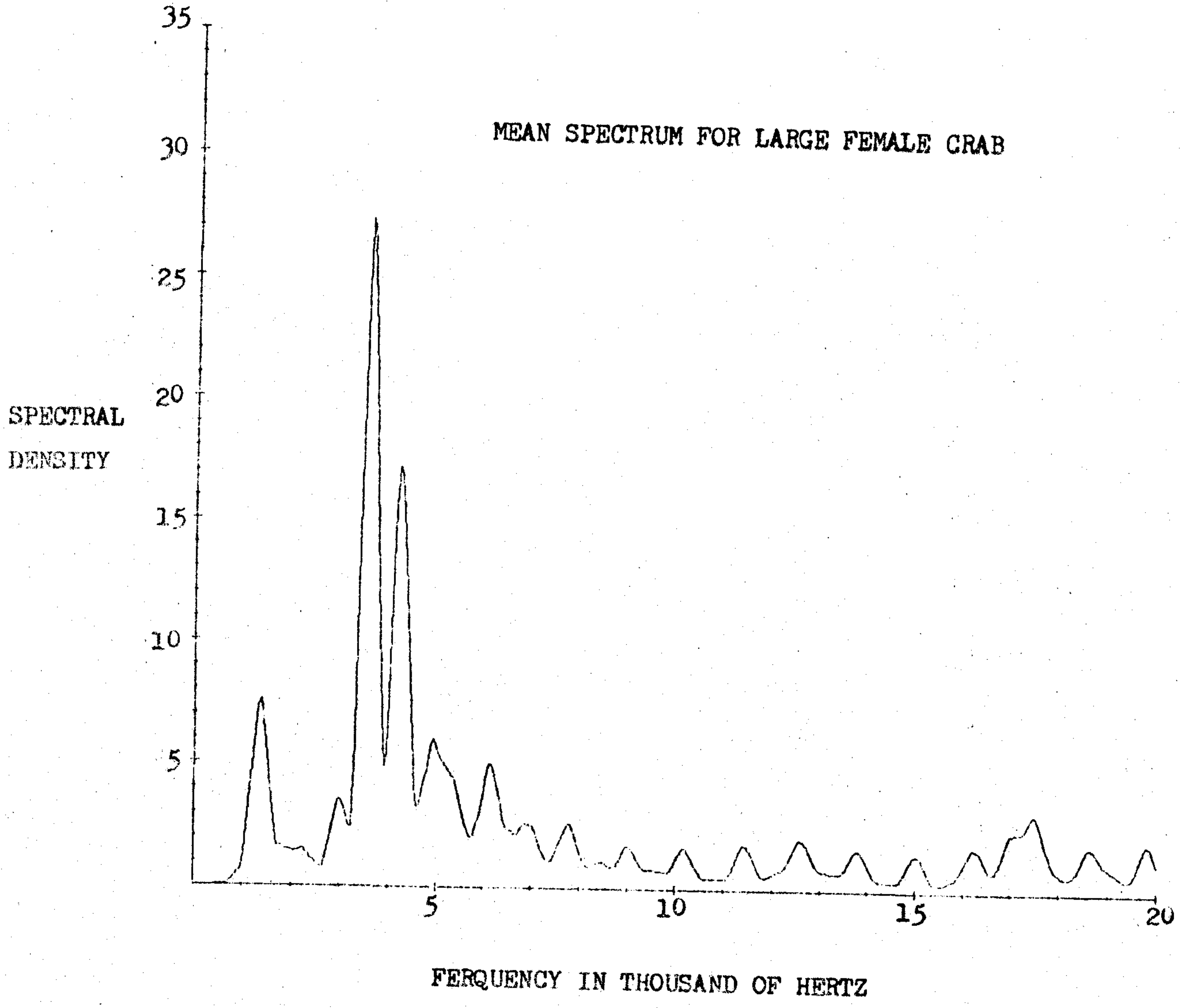

MEAN SPECTRUM FOR LARGE FEMALE CRAB
SPECTRAL
DENSITY
35
30
25
20
15
10
5
5
10
15
20
FERQUENCY IN THOUSAND OF HERTZ

FIG. 13

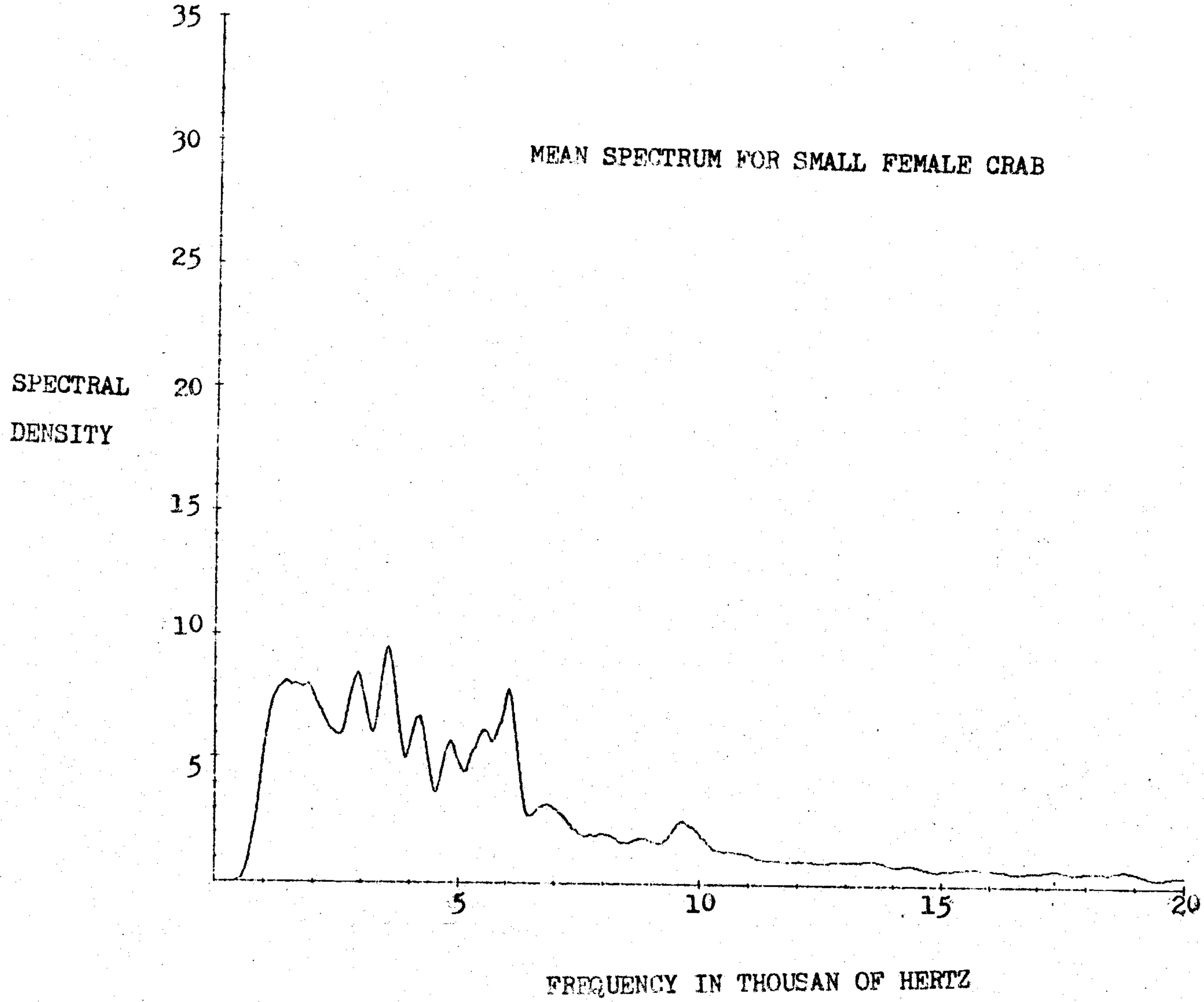

MEAN SPECTRUM FOR SMALL FEMALE CRAB
SPECTRAL DENSITY
35
30
25
20
15
10
5
5
10
15
20
FREQUENCY IN THOUSAN OF HERTZ

FIG. 14

done by subtracting the mean M_x from each sample point X_t and dividing by its standard deviation.

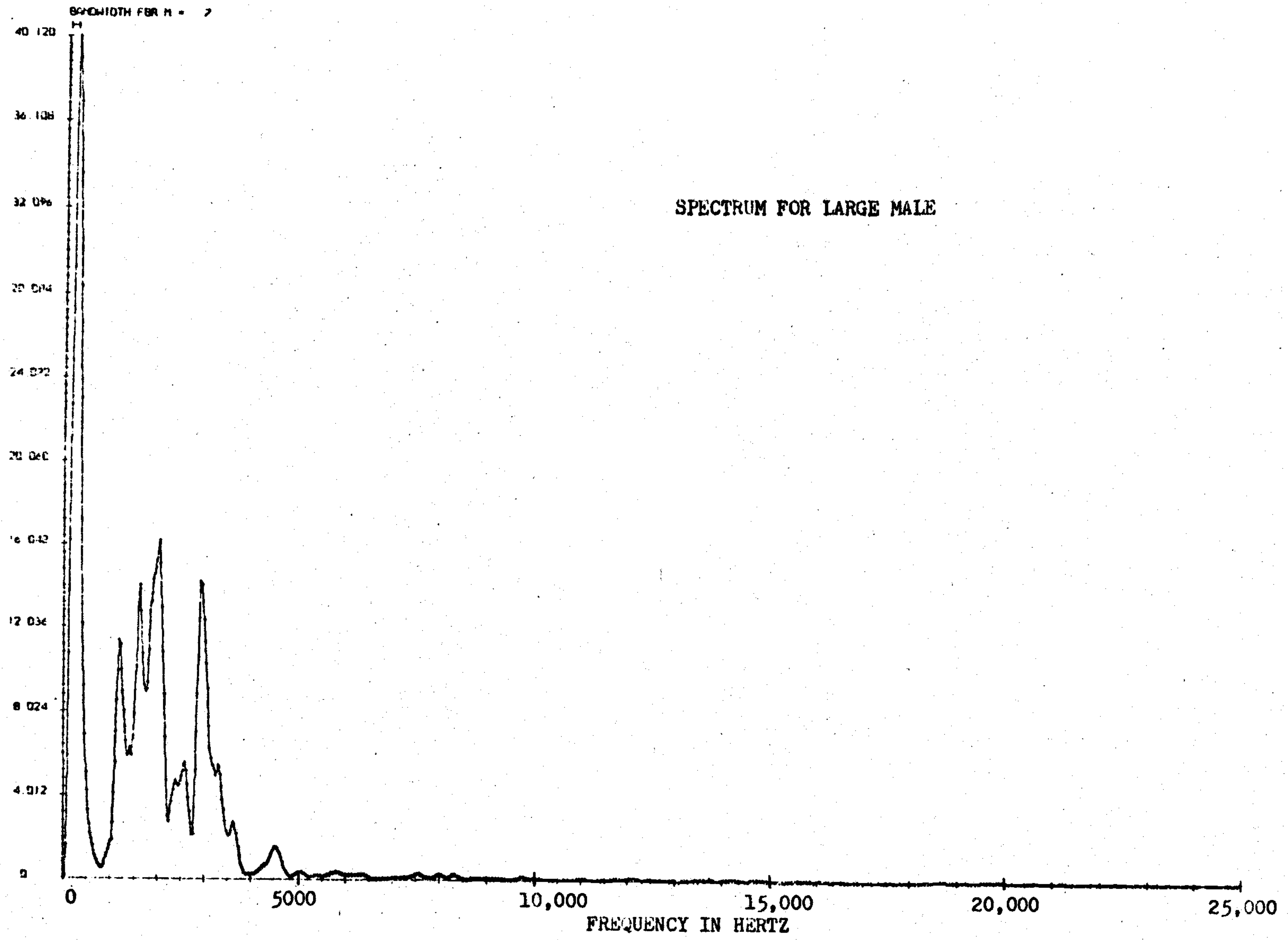

BANDWIDTH FOR M = 2
40 120
36.108
32 096
12 036
8 024
4.012
0
SPECTRUM FOR LARGE MALE
0
5000
10,000
15,000
20,000
25,000
FREQUENCY IN HERTZ

FIG. 14

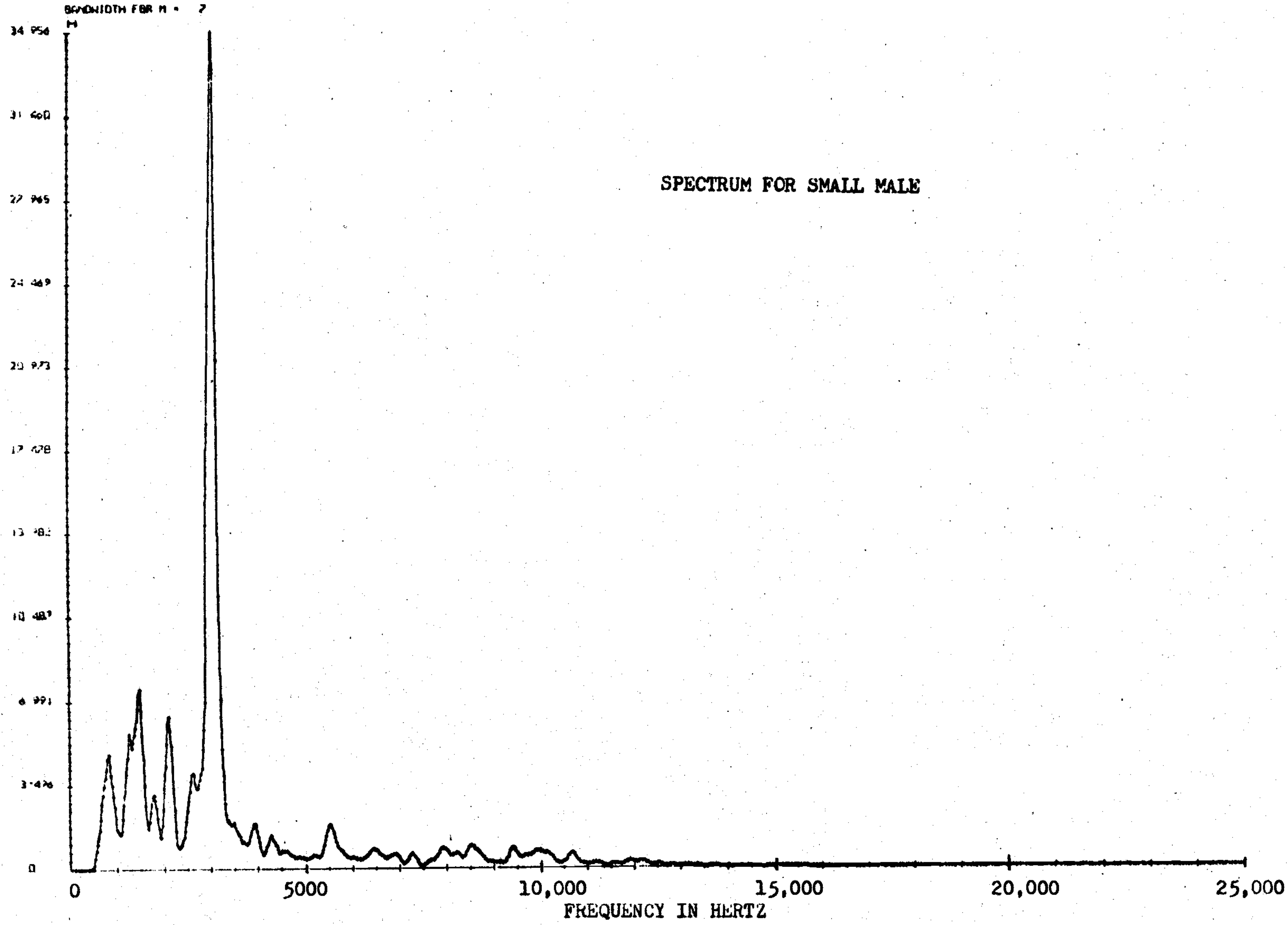

SPECTRUM FOR SMALL MALE
0
5000
10,000
15,000
20,000
25,000
FREQUENCY IN HERTZ

FIG. 15

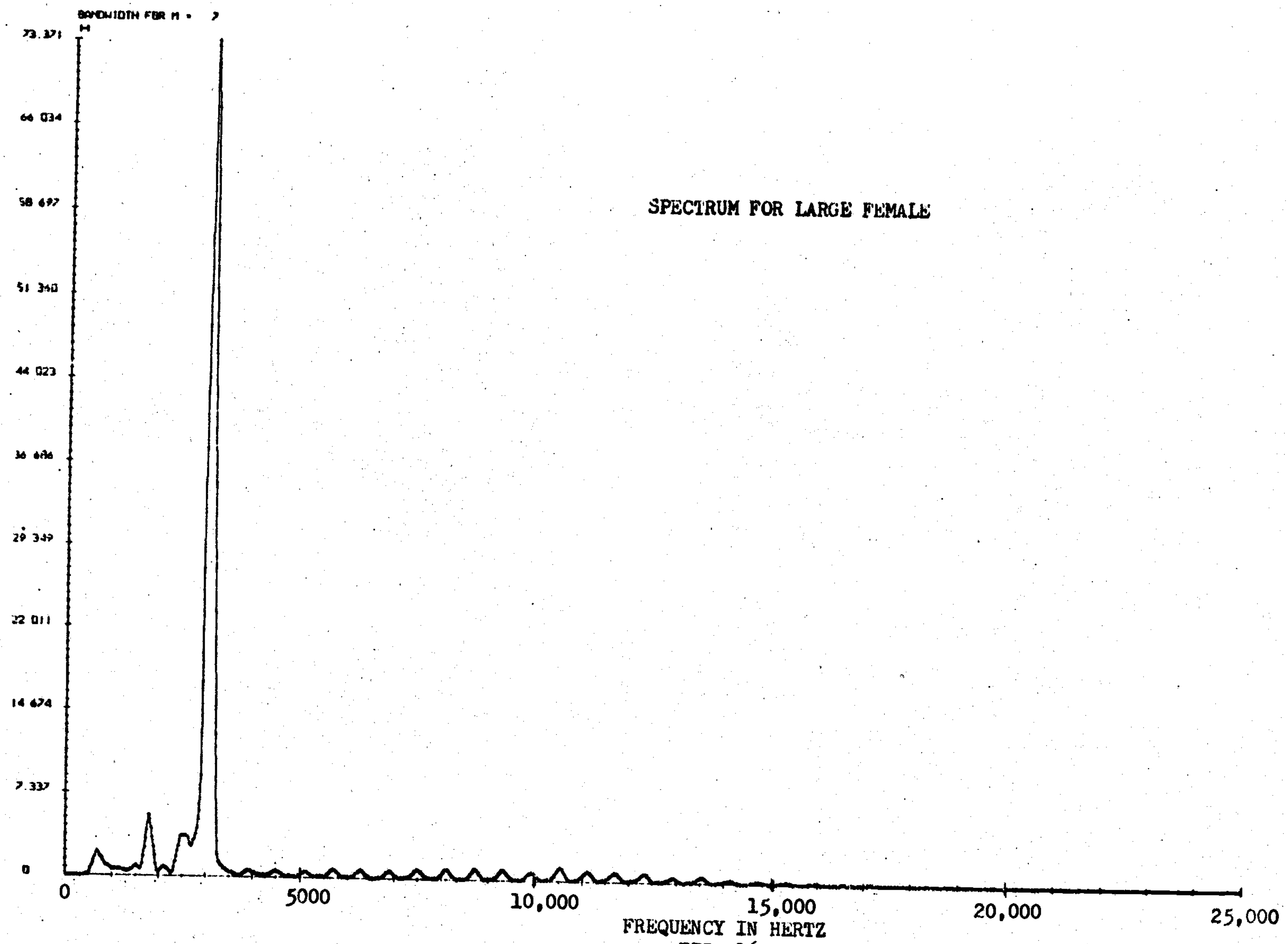

BANDWIDTH FOR M = 7
SPECTRUM FOR LARGE FEMALE
73.371
66.034
58.697
51.360
44.023
36.686
29.349
22.011
14.674
7.337
0
0
5000
10,000
15,000
20,000
25,000
FREQUENCY IN HERTZ

FIG. 16

CONCLUSIONS

Digital spectral analysis is an efficient and useful technique in the identification of the frequency components of animal communication. The speed and accuracy of fast fourier transform enable us to produce analysis similar to a sonogram. In this investigation fast fourier transform was used to obtain the power spectral density of the acoustic signatures of Dungeness crab. Figures 10, 11 and 13 all show a significant concentration of spectral energy in the range of 3, 000 to 4, 000 Hertz with smaller adjacent side hands. These figures indicate that the acoustic signature of large and small male crab and large female crab all contains a significant spectral component in the range of 3, 000 to 4, 000 Hertz which is modulated by some lower frequency component in the range of 300 to 500 Hertz. These figures represent the averages of several hundred signals. Figures 14, 15 and 16 are the spectrum of individual signals. This characteristic also appears in these spectra. It thus appears that this spectrum is characteristic of these three classes of crab and might provide a useful means of identification of these crabs. Figure 13, the spectrum for small females, does not have the significantly large spectral component at 3, 000 to 4, 000 Hertz that is present in the other three classes of crab. However, this sample had a significantly larger percentage of the smaller crabs (about four inches) than did the sample of small male crabs. This size differential might possibly have contributed as much to the spectral differences as did the difference in sex.

In addition to the concentration of spectral energy, at 3, 000 to 4, 000 Hertz, Figure 14 shows that the large male crabs also have a very significant spectral component in the range of 600 to 1, 000 Hertz. Since this spectral component is relatively small in all spectra except for the large males, the presence of this spectral component in the average spectrum in a large sample might indicate the presence of a significant number of large male crabs in the sample.

In this investigation the acoustic signature of crab with unknown periodicies was studied. It appears that it would be possible to use spectral analysis for crab location and identification for commercial purposes, as well as for resource management. The analysis techniques used here are practical and also applicable for other applications. The digital program was designed to continuously digitize any given signal and output to the magnet tape along with any identification header desired.

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APPENDICES

APPENDIX A

Timing on an EAI-680.

The sampling frequency of the digitizing program is controlled by the Analog Mode Control Timer on the patch board of the EAI-680. The time is patched as shown in Figure A-1.

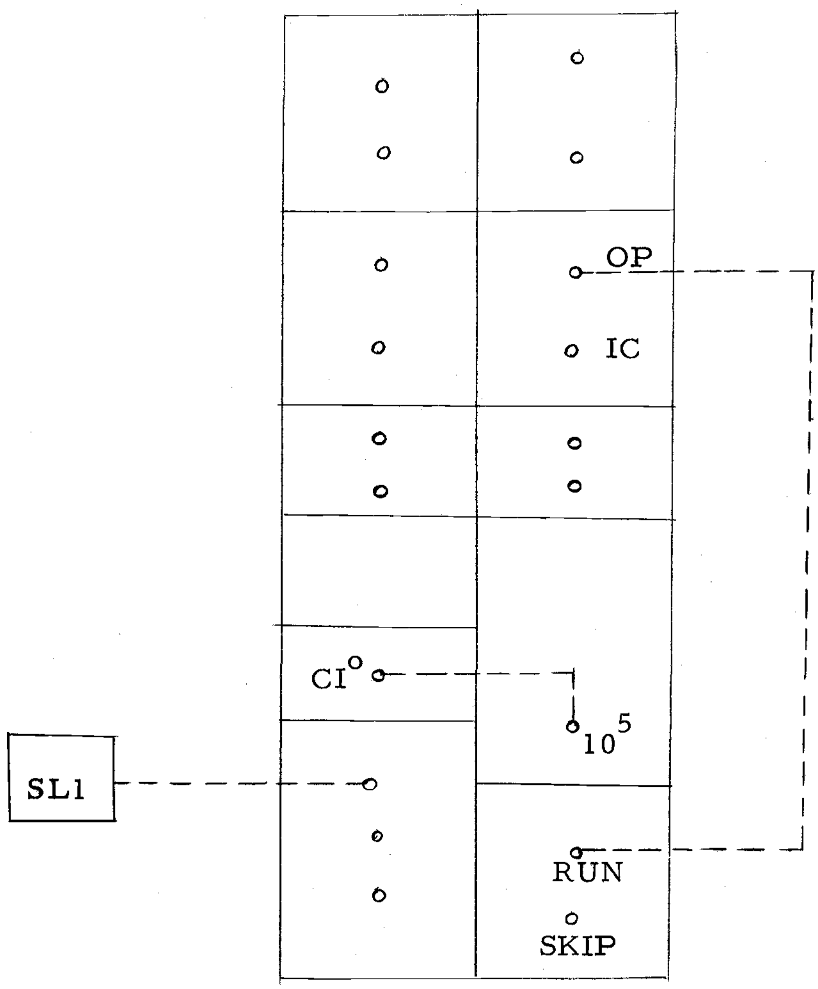


Figure A-1. Mode control timer.

The Analog computer diagram for sensing the acoustic signature of Dungeness crab is shown on Figure A-2. The following are the definitions of the symbols used in Figure A-2.

PBi: represent push button i on the EAI-680 analog computer patch board.

FFi: represent flip-flop i. Where the flip-flop of an EAI-680 computer is an RS (set-reset) flip-flop. The characteristic of an RS flip-flop can best be shown by a truth table:

R	S	Q^1	Q^{n+1}
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	0

where Q^n is the present state of the flip-flop and Q^{n+1} is the next state representation of flip-flop. The two are related as

$$Q^{n+1} = S + R'Q$$

where + mean a logical sum (OR) and R' represents the negation of R.

SLi: represent sense line i.

ADC: represent the analog to digital converter.

DAC: represent the digital to analog converter.

The operation of the digitization program is shown on the following pages.

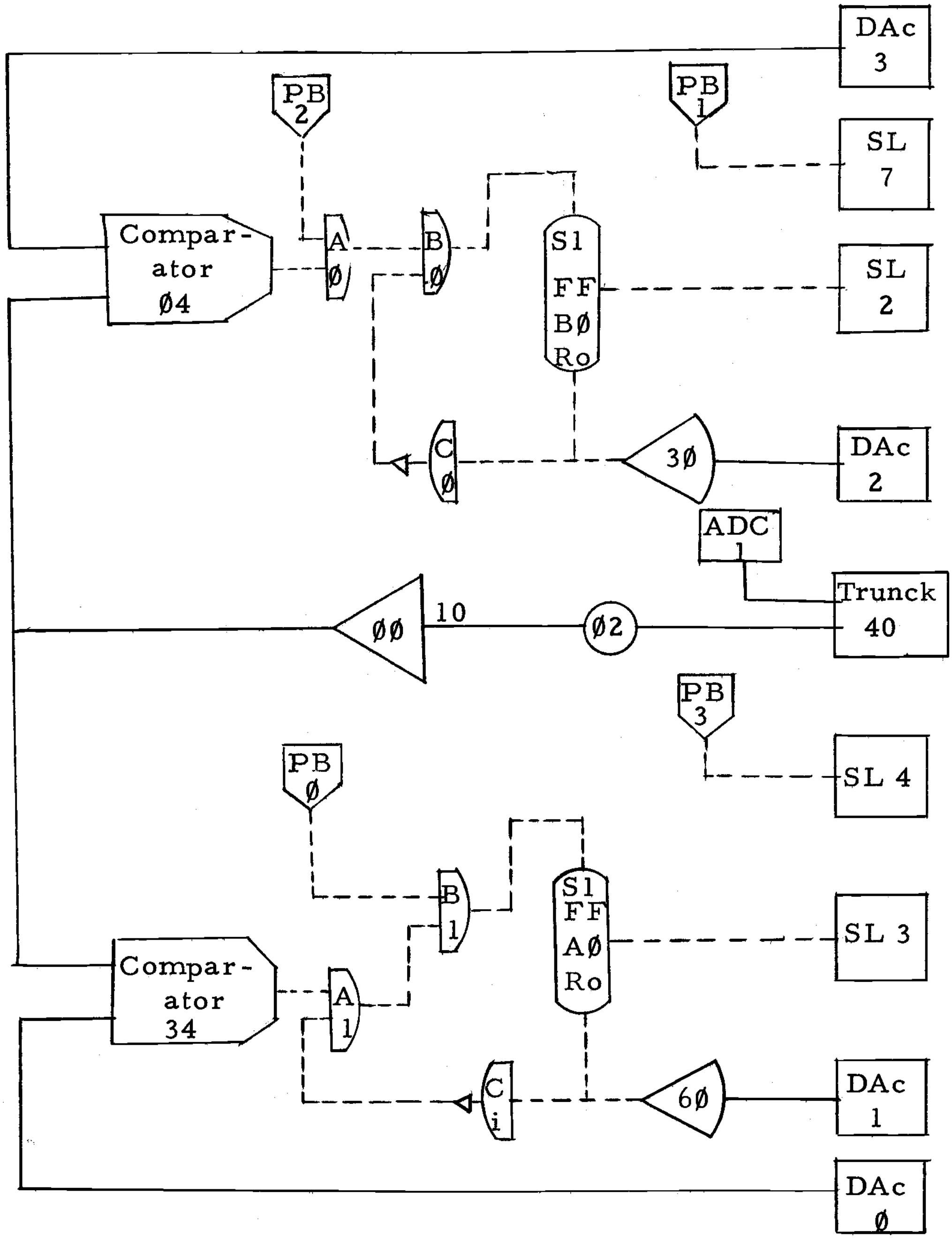


Figure A-2. Analog computer diagram for triggering and sensing a signal.

OPERATING PROCEDURE

Operating procedure on an EAI-690 hybrid computer for digitizing the acoustic signature of Dungeness crab is as follows:

1. Set digital clock rate control on an EAI-680 to 10^5 and set the timer to A=1, B=9 and C=0.

2. Set the EAI-640 density to medium.

3. Load the main program.

4. Load the subroutine for positioning the magnetic tape.

5. Remove monitor tap from tape unit and load private tape.

6. Set tape density to low.

7. If this is a new tape and recording is to begin at the beginning of the magnetic tape, push sense switch A on the EAI-640 console. Sense switch A will cause the program to by-pass the tape positioning routine. This routine moves the tape until a double end of file mark is encountered, then moves it back past the last one.

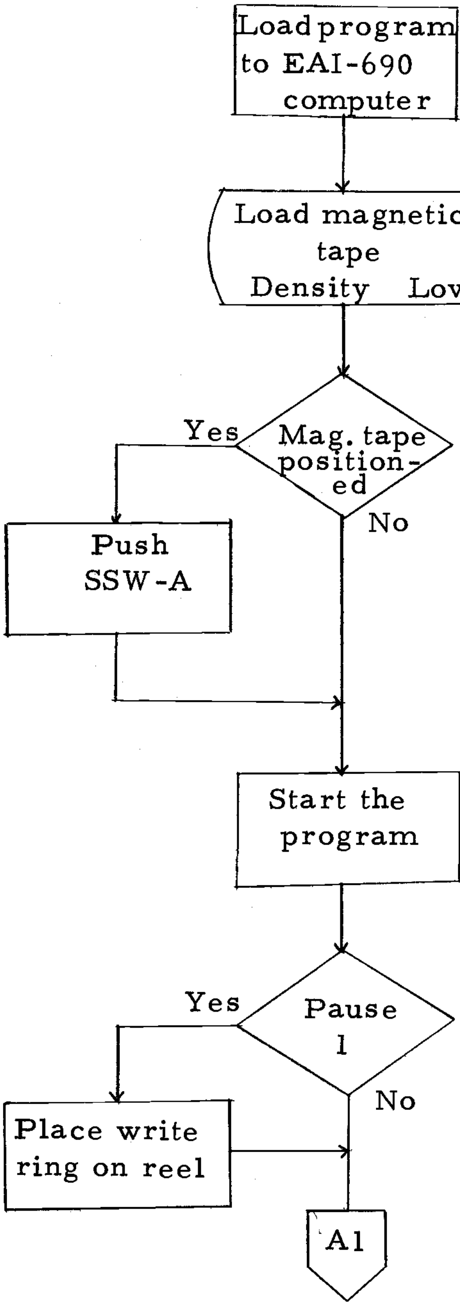
8. Put signal in Trunck "40" of the analog computer EAI-680.

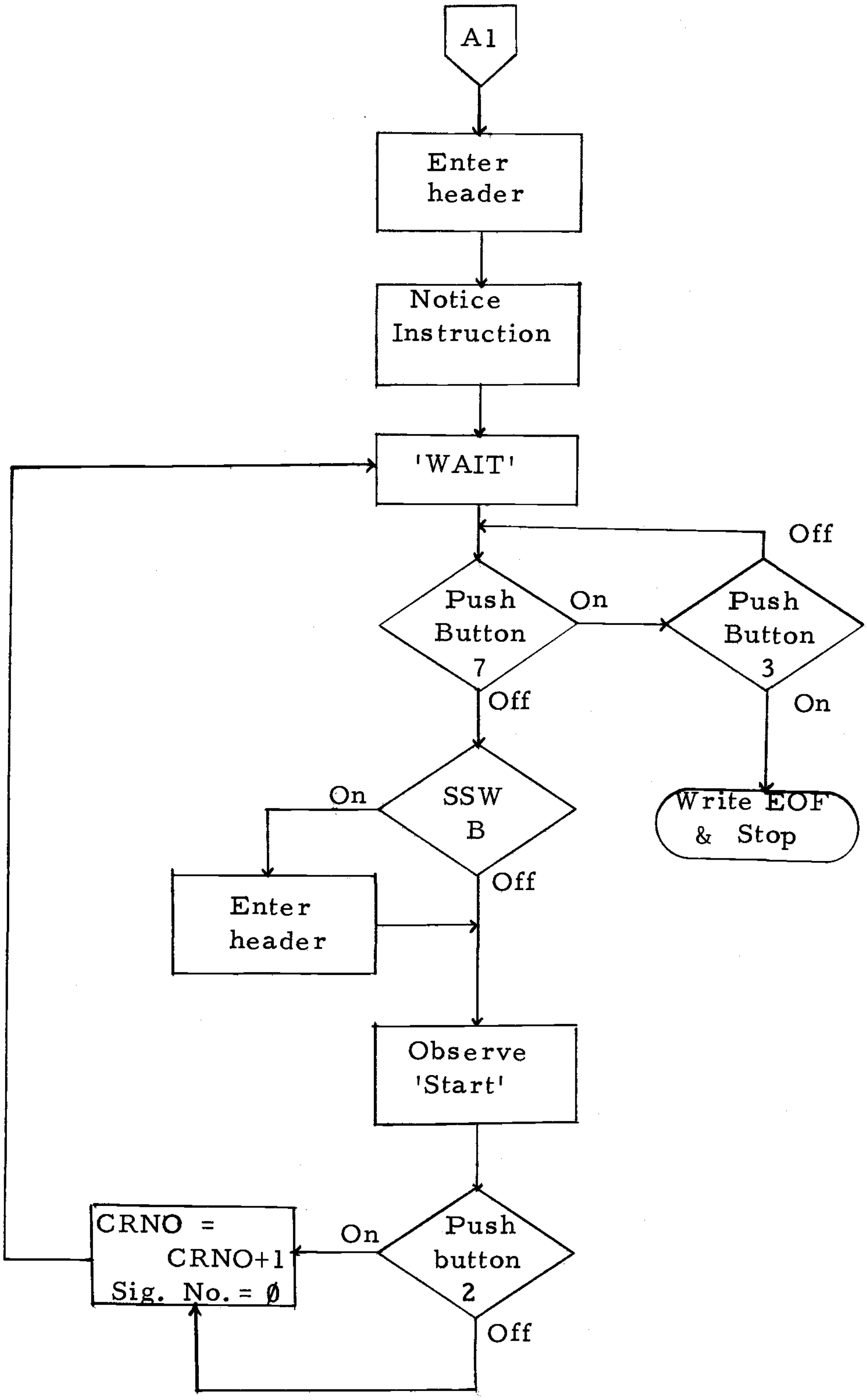
9. Set toggle switch on EAI-640 to $1ØØØ_8$.

10. RESET and push the program counter button.

12. Push run to start the program and follow the operations flow-chart.

Flow chart of digitization operation on an EAI-690 is shown below:




A1
Enter header
Notice Instruction
'WAIT'
Off
Push Button 7
On
Push Button 3
Off
On
Write EOF & Stop
SSW B
On
Off
Enter header
Observe 'Start'
CRNO = CRNO+1
Sig. No. = ∅
On
Push button 2
Off

```
CC THIS PROGRAM WILL DIGITIZE SELECTED SIGNALS USING ADC NUMBER 1
CC LOAD DIGITAL TAPE, SET AT LOW DENSITY, AND PUSH SENSE SWITCH A
CC IF THE TAPE DOES NOT NEED TO BE POSITIONED.
 COMMON LORE(2060)
 INTEGER WEND,WP,BEGLO,FLAG,TPNO,CHNO,CRNO,SIGNO,DATE,ENDLO
CC WEND IS END OF WHEEL, WP IS WHEEL POINTER, BEGLO IS FIRST LOCATION
CC AFTER WHEEL, ENDLO ISTHE LAST MEMORY LOCATION, TPNO IS TAPE NUMBER
CC CHNO IS CHANNEL NO., CRNO IS CRAB NUMBER, AND SIGNO IS SIGNAL NO.
110 ADR LORE+200
120 ADR LORE+2048
CC INITIALIZE ADDRESSING LABELS
 LA  .110
 STA WEND
 STA BEGLO
 LA  .120
 STA ENDLO
CC SET TIME AND CLEAR LOGIC.
 OCT 026740
 OCT 003050
 OCT 003051
 LA  /'1400
 OCT 003052
 LA  /'2000
 OCT 3047
 LA  /'400
 OCT 3052
 TYPE 100
100 FORMAT(60H TYPE SIGNAL DETECT AND END OF CRAB REF. VOLTAGES'/)
CC REFERENCE VOLTAGES MUST BE IN SCALED FRACTION.
 CALL QINS(2,1,REF1)
 TYPE 212
 CALL QINS(2,1,REF2)
 TYPE 102
 CALL QOUTS(2,2,REF1,REF2)
102 FORMAT(20H REFERENCES ARE'/)
 OCT 05061
```

```
 TYPE 212
 LA   REF1
 OCT Ø314Ø
 LA   REF2
 OCT Ø3143
 OCT Ø4Ø14
 13   /'ØØ4ØØØ
 OCT Ø274Ø7
 OCT Ø25ØØ1
CC IF THIS PAUSE OCCURS, THE MAG TAPE IS NOT WRITE ENABLED.
 OCT 236ØØ
 SKU
 J    .195
  CALL POSIT(LNU)
195 TYPE 2ØØ
2ØØ FORMAT(7ØH TYPE DATE, TAPE NO., CHANNEL NO., AND CRAB NO.'/)
CC ALL INPUTS MUST BE IN I5 FORMAT NOT TO EXCEED 32767.
 ACCEPT 21Ø,DATE
 TYPE 212
 ACCEPT 21Ø,TPNO
 TYPE 212
 ACCEPT 21Ø,CHNO
 TYPE 212
 ACCEPT 21Ø,CRNO
212 FORMAT(1ØH NEXT'/)
21Ø FORMAT (I6)
 TYPE 22Ø
22Ø FORMAT(7ØH PUSH SSW B IF THE HEADER MUST BE ALTERED')
 TYPE 221
221 FORMAT(7ØH PUSHBUTTON 1 WILL START THE PROGRAM, AND PUSHBUTTON 2')
 TYPE 222
222 FORMAT(5ØH WILL WRITE AN END OF FILE AND STOP.')
CC CARE MUST BE TAKEN TO TURN PUSH BUTTON 1 OFF AS SOON AS THE PROGRAM STARTS.
225 TYPE 23Ø,DATE,TPNO
23Ø FORMAT(1ØH DATE IS',I8,3ØH, TAPE NO. IS',I6)
 TYPE 231,CHNO,CRNO
```

```
231 FORMAT(30H CHANNEL NO. IS',I6,30H, AND THE CRAB NO. IS',I6)
 SIGNO=0
 TYPE 240
240 FORMAT(10H WAIT'/)
 OCT 4047
 OCT 4044
 OCT 27400
 OCT 27400
245 OCT 26740
 OCT 4047
 SKP
 J   .255
 OCT 26740
 OCT 4044
 SKN
 J   .245
 LA  /'10005
 OCT 5014
 LA  /'10006
 OCT 5014
 STOP
255 OCT 023500
 J   .260
 TYPE 200
 ACCEPT 210,DATE
 TYPE 212
  ACCEPT 210,TPNO
 TYPE 212
 ACCEPT 210, CHNO
 TYPE 212
 ACCEPT 210,CRNO
260 TYPE 270
270  FORMAT(10H START')
 LA  /'1
 OCT 5064
 OCT 2065
```

```
CC THIS IS THE BEGINNING OF THE DIGITIZING SECTION.
28Ø FLAG=-1
CC INITIALIZE WHEEL INDEX.
 LA  /2ØØ
 TCA
 OCT Ø264ØØ
 STA LSET
 OCT 265ØØ
CC RESET SIGNAL DETECT AND END OF CRAB FLIP FLOPS
 LA  /'44ØØØ
 OCT 3141
 OCT 3142
 OCT Ø274ØØ
 OCT 2674Ø
 OCT 3142
 OCT 3141
CC WAIT FOR TIMING PULSE HERE.
285 OCT 4Ø41
 OCT 2674Ø
 OCT 4Ø41
 SKN
 J   *-2
CC START CONVERSION
 OCT Ø5Ø65
 OCT Ø22ØØ1
 J   .29Ø
 LA  LSET
 OCT 265ØØ
 LA  /'1
 STA FLAG
 J   .3ØØ
29Ø OCT 4Ø42
 OCT 2674Ø
 OCT 4Ø42
 SKP
 J   .36Ø
```

```
300 OCT 26740
 OCT 4043
 SKP
  J   .310
305 OCT 2065
 STA WEND,3
 J   .285
310 LA  FLAG
 SKP
 J   .305
 OCT 26500
 STA WP
 LA  /1847
 TCA
 OCT 26400
 OCT 26500
 OCT 26740
 OCT 2065
 STA BEGLO,2
CC WAIT FOR  TIMING PULSE.
320 OCT 4041
 OCT 26740
 OCT 4041
 SKN
 J   *-2
CC START CONVERSION
 OCT 05065
CC TEST FOR OVERFLOW
 OCT 26500
 SKP
 J   .500
 OCT 26500
 OCT 2065
 STA ENDLO,3
 OCT 22001
 J   .320
```

```
 OCT 4042
 OCT 26740
 OCT 4042
 SKP
 J   .360
CC START TO UNSCRAMBLE WHEEL
 LA  WP
 OCT 26440
 STA INDEX1
 LUF=WEND-1
340 WP=WEND-200
 INDEX2=-200
 LA  LUF,2
 OCT 26500
350 LA  WP,2
 OCT 26500
 STA WP,2
  07  WP
 OCT 27400
 07  INDEX2
 J   .350
 07  INDEX1
 J   .340
CC OUTPUT SECTION
 LA  /2048
 TCA
 OCT 26400
 OCT 26500
 LA  /'20012
 OCT 5014
 LA  DATE
 L   .525
 LA  TPNO
 L   .525
 LA  CHNO
 L   .525
```

```
 LA   CRNO
 L    .525
 LA   SIGNO
 L    .525
 LA   /'2ØØ12
 OCT    5Ø14
41Ø LA  ENDLO,3
 L    .525
 OCT 22ØØ1
 J    .41Ø
 SIGNO=SIGNO+1
 J    .28Ø
36Ø CRNO=CRNO+1
 SIGNO=Ø
 LA   /'1ØØØ5
 OCT 5Ø14
 J    .225
5ØØ TYPE 5Ø1
5Ø1 FORMAT(1ØH OVERFLOW')
525 OCT 274ØØ
 SKP
 S    /'1
 OCT 26157
 OCT Ø3Ø14
 OCT 261Ø3
 OCT Ø3Ø14
 OCT 261Ø6
 OCT 3Ø14
 OCT 261Ø6
 OCT 3Ø14
 J    .525,2
 STOP
 END
```

```
CC THIS ROUTINE WILL POSITION THE MAG TAPE BETWEEN THE TWO EOF'S
CC OF A DOUBLE EOF MARK     JULY 15,1971
 SUBROUTINE POSIT(HI)
1 KF=Ø
2 J    .4
3 IF(KS.LT.1Ø) GO TO 1
 KF=KF+1
 IF (KF.LT.2) GO TO 2
 LA   /'1ØØØ1
 OCT 5Ø14
 RETURN
4 LA   /'3ØØØØ
 OCT 5Ø14
 LA   /'2ØØØ2
 OCT Ø5Ø14
6 OCT 4Ø14
 OCT 26243
 OCT 241ØØ
 J    .5
 OCT 2Ø14
 J    .6
5 OCT 26241
 OCT 241ØØ
 J    .7
 OCT 2674Ø
 STA KS
 J    .3
7 LA   /1Ø
 STA KS
 J    .3
 END
```

APPENDIX B

CONVOLUTION

Convolution is one of the most powerful tools in frequency analysis. Given two functions $f_1(t)$ and $f_2(t)$, the convolution f(t) of the functions $f_1(t)$ and $f_2(t)$ is given by

$$f(t) = \int_{-\infty}^{\infty} f_1(T)\, f_2\,(t-T)\, dT \qquad (1\text{-B})$$

The above convolution integral is also expressed symbolically as

$$f(t) = f_1(t) * f_2(5)$$

Equation 1A is a time convolution and convolution in time domain is equal to multiplication in frequency domain. Therefore

$$\int_{-\infty}^{\infty} f_1(T)\, f_2\,(t-T)\, d\,T \leftrightarrow F_1(\omega)\, F_2(\omega) \qquad (2\text{-B})$$

where $F_1(\omega)$ and $F_2(\omega)$ are the fourier transform of the function $f_1(t)$ and $f_2(t)$, respectively.

APPENDIX C

The power spectral calculation was done by using a CDC-3300 package program at Oregon State University called ARAND. The procedure was as follows:

The times series $x(t)$ was segmented into K segments each of length M. The length of the segments was extended to length $L = 2^p$ by adding zeros to it. The Fourier coefficients of the k^{th} tapered segment is

$$A_k(n) = \sum_{j=0}^{L-1} W(j/M) \cdot x_K(j) \exp(-i2\pi nj/L)$$

$$= \sum_{j=0}^{M-1} W(j/M) \cdot x_K(j) \exp(-i2\pi nj/L)$$

for $n = 0, 1, \ldots, L/2$. $W(j/M)$ is the particular data window. In finding the power spectral density of the crab signature a raised cosine (Tukey) data window was used. The raised cosine data window is defined by

$$W(\tau) = \begin{cases} \frac{1}{2}(1 + \cos \pi \tau) & \text{for} \quad |\tau| \leq 1 \\ 0 & \text{for} \quad |\tau| > 1 \end{cases} .$$

Then the power spectral density was calculated using the following formula

$$P(f_n) = \frac{1}{K} \sum_{K=1}^{K} \frac{2}{U} |A_K(n)|^2$$

where $f_n = \frac{n}{L}$ for $n = 0, 1, \ldots, L/2$ and

$$U = \sum_{j=0}^{M-1} W^2 (j/M) .$$

The power spectral estimate $P(f_n)$ was then smoothed by using a triangular window.