A METHOD OF ESTIMATING THE INFLUENCE OF SHIP'S NOISE ON AMBIENT NOISE MEASUREMENTS

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ABSTRACT

Ambient noise measurements are often adversely affected by noise from passing ships. Here, a method is presented which allows the estimation of this influence. The method is especially suitable for shallow water applications. It is based on mode interference. The broad-band ship-generated noise is transmitted to the measuring sensor by modes. Because of the interference of these modes, the spectrogram of the noise exhibits interference patterns. Disturbance of ambient noise measurements occurs whenever interference patterns appear in the spectrogram. The degree of the disturbing effect is specified by a mode interference modulation factor which is defined here. In addition, the number of ships and their distance from the measurement sensor can be estimated from the interference patterns. Measurement results are shown which have been evaluated with this method.

1. INTRODUCTION

Ambient noise measurements are often disturbed by noise from passing ships. This is especially the case in sea areas which carry a large amount of shipping, such as the North Sea and the Baltic.

The aim of this investigation is to identify the disturbances and to estimate the degree of disturbance. Level observations alone are not adequate for solving this problem. In the sea areas mentioned above, which are shallow-water areas, the ambient noise level itself fluctuates considerably [1, 2], so that it is difficult to distinguish between fluctuations in ambient noise level and changes in disturbance level. For this reason, the disturbance is to be characterised in a different way. A method of doing this is presented here. The method is based on mode propagation.

The structure of this paper is as follows: In Chapter 2, some basic matters are discussed. In Chapter 3, the mode interference modulation factor is defined. Chapter 4 deals with the estimation of the number of disturbance sources and their distance from the measurement point. In Chapter 5, measurement results are discussed. Finally, Chapter 6 gives conclusions.

2. BASICS

The acoustic energy emitted by the disturbing ship is carried to the measurement point with the aid of normal modes. This is a well-known fact (e. g. [3], [4], [5]). Because of the mode propagation, the spectrograms (defined in [6], for example) of the measured underwater sound contain interference patterns [7, 8].

The spectrogram is the power P versus frequency f and measurement time t. According to this, the function for the spectrogram can be written as P(t,f). In cases where motion is involved, the time may be replaced by the distance.

An example of a measured interference pattern is shown in the lower part of Fig. 1; the distance is plotted against the frequency. The degree of blackness corresponds to the acoustic intensity. The associated measurement situation is sketched in the upper part of the illustration. If the disturbing source of noise is moving away from the measurement point at constant speed, the modulation of the power in each narrow analysis band (e.g. at frequency F_0) is harmonic.

Because of its orderly structure, this interference pattern is easily distinguished from the ambient noise, and is therefore very suitable for the detection of disturbance sources. This is substantiated by Fig. 2. This illustration shows a longer spectrogram. Here, a frequency band from 0 to 450 Hz is shown. The ordinate scale is not in distance units like the scale in Fig. 1; instead, it is in time units (the usual procedure in spectrograms). The spectrogram contains an interference pattern of a passing ship. Shortly after the starting instant t = 0 of the spectrogram recording, the measured noise had not yet been affected by the ship which would later cause disturbance. No mode interference pattern is apparent yet in this period of time. The pattern does not begin until later; it then becomes more and more pronounced as the distance between the disturbance source and the measurement point becomes smaller. After the closest point of approach (CPA) has been reached, the pattern becomes fainter again.

The clear distinction between spectrogram regions with and without a mode interference pattern, as illustrated in Fig. 2, causes us to make the following statement: whenever interference patterns are present in the spectrogram, it should always be assumed that a source of disturbance is present. The degree of disturbance is to be described by a modulation factor, which is referred to here as the "mode interference modulation factor".

In addition to the degree of acoustic disturbance of the ambient noise measurement, a rough estimate of the number of disturbance sources and their distance from the measurement point is often of interest. Mode interference offers possibilities for this. A glance at the spectrogram in Fig. 2 will verify this. The interference lines which charaterise the fan-like structure of the interference pattern have different gradients. At a given frequency, the absolute value of the gradient of the interference lines increases with the distance between the source and the receiver. This fact forms the basis of the distance estimate.

Let us mention the following boundary conditions for the method proposed here for estimating the influence of disturbance sources on the ambient noise measurement.

The sound propagation channel must be such as to ensure that mode propagation can take place. This is so in shallow water areas especially. The disturbance source should radiate acoustic energy over a wide band of frequencies. This condition is fulfilled for the broad-band cavitation and flow noise produced by moving ships. Here, the frequency band from a few tens of Hz to about 500 Hz is investigated. The underwater sound is to be measured omnidirectionally.

3. DETERMINATION OF THE MODE INTERFERENCE MODULATION FACTOR

The mode interference modulation factor is intended to describe the degree of modulation of a periodogram component. It is thus a measure of the measured time-dependent variation of the power in the narrow analysis bands. To be able to compute the degree of modulation formally, we make the following assumptions. We assume that each periodogram component can be described approximately by a stochastic process Z(t):

$$Z(t) = X(t) \cdot A(t) \qquad (3.1)$$

Equation (3.1) is valid for a fixed frequency. The frequency is suppressed in the notation. According to the function for the power P(t,f) in the spectrogram, our function Z(t) approximates the power P(t, f = const.) at constant frequency.

The product process Z(t) is to consist of a carrier process X(t) and a modulation process A(t), which are both assumed to be stationary.

We shall assume that the carrier process and the modulation process are independent of each other. We shall also assume that short-time power spectra computed one after another are likewise independent of each other.

In the harmonic modulation, the modulation factor is defined as the quotient of the amplitude and mean value; the amplitude is $\sqrt{2}$ times the standard deviation σ .

We shall adopt this definition and describe the mode interference modulation factor M of a periodogram component by:

$$M = \sqrt{2} \cdot \sigma_A / \mu_A \qquad (3.2)$$

where σ_A is the standard deviation of the modulation process and μ_A is its mean value.

Since the product process only (and not the modulation process) is measurable, the quotient σ_A / μ_A cannot be determined directly. For this reason, the modulation process will be described by the obtainable relative standard deviations of the product process Z(t) and of the carrier process X(t). We obtain the following:

$$M = \sqrt{2 \cdot \frac{\left(\frac{\sigma_Z}{\mu_Z}\right)^2 - \left(\frac{\sigma_X}{\mu_X}\right)^2}{1 + \left(\frac{\sigma_X}{\mu_X}\right)^2}} \tag{3.3}$$

We now go over to the discrete case, since discrete periodograms are computed in practice, e. g. with the aid of the fast Fourier Transform. The modulation factor is thus computed for discrete frequency values f_i only. We also assume that, for estimating the modulation factor, only time-intervals of duration T are used in the spectrogram. The position of an interval with respect to time is assigned to the discrete instant t_j. The modulation factor will therefore be symbolised by $M_T(t_j, f_i)$. Averaging in the frequency direction over K modulation factors of adjacent spectrogram-components gives the mean mode interference modulation factor for the instant t_j:

$$\overline{M}_T(t_j) = \frac{1}{K} \sum_{i=l}^{l+K-1} M_T(t_j, f_i) \tag{3.4}$$

where $f_i = i \cdot \Delta f$ and Δf is the frequency resolution cell of the discrete periodogram. During the ambient noise measurement, this mean value $\overline{M}_T$ is continually updated. Depending on the magnitude of $\overline{M}_T$, a decision is then made as to whether the disturbance is too great or is still acceptable.

To estimate the modulation factor in accordance with equation (3.3), we need not only the relative standard deviation $\hat{\sigma}_Z / \hat{\mu}_Z$ (which can be estimated directly from the spectrogram) but also the relative standard deviation σ_X / μ_X for the carrier process. (In the following, estimated values are indicated by a "hat", ^ .)This quotient is generally not known. The required quotient σ_X / μ_X is a constant and can be computed after a special procedure has been applied. This procedure is called "normalisation" [9]. This normalisation is applied to each individual periodogram of the spectrogram before determination of the modulation factor.

To summarise, the expected value of the power density in the neighbourhood of the individual frequency points f_j of the original periodogram is estimated first. Next, the values of the original periodogram are divided by the estimated expected values. An effect of this normalisation is, for example, that broad-band pink noise turns into white noise (more or less).

Furthermore - and this is important for us - in the unmodulated case all moments for the components of the normalised peridogram can be stated, and thus also the required values μ_x and σ_x of our carrier process.

We expect the mean modulation factor $\overline{M}_T$ for an unmodulated spectrogram to be around zero. In this case especially, it is clear that estimated relative standard deviations $\hat{\sigma}_z / \hat{\mu}_z$ of individual periodogram-components may be smaller than the calculated quotient σ_x / μ_x of the carrier process. The modulation factor according to equation (3.3) would become imaginary. However, this result is not meaningful. For this reason, equation (3.3) is modified somewhat:

$$\hat{M} = \mathrm{sign}\left\{\left(\frac{\hat{\sigma}_z}{\hat{\mu}_z}\right)^2 - \left(\frac{\sigma_x}{\mu_x}\right)^2\right\} \cdot \sqrt{2 \cdot \frac{\left|\left(\frac{\hat{\sigma}_z}{\hat{\mu}_z}\right)^2 - \left(\frac{\sigma_x}{\mu_x}\right)^2\right|}{1 + \left(\frac{\sigma_x}{\mu_x}\right)^2}} \qquad (3.5)$$

In equation (3.5), the radical expression is now unsigned. The sign has been moved to a place in front of the root, and is determined by the operation "sign$\{\bullet\}$". The following applies:

$$\mathrm{sign}\{c\} = \begin{cases} 1, & c > 0 \\ 0, & c = 0 \\ -1, & c < 0 \end{cases} \qquad (3.6)$$

According to equation (3.5), the estimate may yield negative modulation factors. This is unimportant as only the mean value of the modulation factor must be zero or positive.

4. ESTIMATION OF THE NUMBER OF SHIPS AND THEIR DISTANCE

By means of the interference patterns in the spectrogram, it is possible to estimate the number of disturbing ships and to make a rough estimate of the distance. However, this requires the spectrogram to be available in a form which will allow visual evaluation, e. g. as a display on a grey-shade recorder or on a TV screen.

If the ambient noise measurement is being disturbed by more than one ship, the corresponding interference patterns are superimposed on one another. In the spectrogram, this superimposition is clearly recognisable, especially for the practised eye. An example is shown in Fig. 3. There, two principal sources of disturbance are involved. The superimposition is clearly visible in the time interval from 15:10 to 15:17.

The interference pattern in Fig. 2 had shown that the pattern depends on distance. The magnitude of the gradient of the "interference lines" is proportional to the distance between the disturbance source and the measurement point. This fact is used to make a passive estimate of distance. In addition to the modulation factor, we thus also obtain an important parameter for situation assessment in ambient noise measurement.

The method described here works with relatively simple aids. It requires that the sources of disturbance are approximately on a collision course with respect to the measurement point. Since this requirement is only more or less fulfilled in practice, the estimate can only produce rough values for the distance.

Fig. 4 summarises the main steps in the evaluation. In addition to the measured interference pattern, results from the model calculation are required: for the evaluation frequency F_0, we require the interference wavelength IWL (also called the "horizontal interaction distance") Λ of the mode pair which is dominant in the measured interference pattern. Secondly, the frequency-dependent changes of the IWL, $\partial\Lambda/\partial f$, must be determined. These tasks can be performed by computer programs such as those described in [10] or [11] or by much simpler procedures [12].

Two things must be determined from the measured spectrogram - firstly, the number k of interference wavelengths passed through per unit time by the disturbing ship (k does not have to be an integer), and secondly the gradient of the interference lines.

The expression $k \cdot \Lambda/T$ represents the speed of approach or departure, v. The distance can be estimated from the determined values according to the following formula:

$$r \approx v \cdot \left[\Lambda \cdot \frac{1}{\frac{\partial\Lambda}{\partial f}} \cdot \frac{\partial t}{\partial f} \right]_{f=F_0} \tag{4.1}$$

In this formula, the interference line gradient $\partial t / \partial f$ is the most important parameter. The other parameters act as scaling factors to some extent.

It is immediately apparent that k can be estimated with sufficient reliability if and only if the interference maxima along the line $f = F_0$ are equidistant. However, this is so only if the speed of approach or departure of the disturbance source (relative to the measurement point) is constant within the evaluation time T.

5. DISCUSSION OF THE MEASUREMENT RESULTS

The evaluation results of many experiments at sea show that the proposed method for estimating the influence of disturbance noise is practicable.

The measured data come from North Sea areas with a water depth of about 43 m. The measurements were performed in the spring of two successive years. An omnidirectional hydrophone was used to receive the sound.

The mean mode interference modulation factor $\overline{M}_T$ was evaluated in the frequency band from 50 Hz to 450 Hz. The duration T of the evaluation interval was fixed at 128 sec. The normalisation produced a computed value of 1.054 for σ_x / μ_x.

All evaluations gave similar results, so we can restrict ourselves here to a discussion of a few examples. In Figs. 5, 6 and 7, the modulation factor $\overline{M}_T$ is plotted against time. The shaded area symmetrical to the modulation factor $\overline{M}_T$ indicates the standard deviation of the K = 401 individual modulation-factors. A new estimation of the modulation factor was carried out every 20 sec, so there is an overlap of 108 periodograms.

The modulation factor $\overline{M}_T$ in Fig. 5 shows the typical variation with time as a ship passes by: at the beginning of the experiment, the disturbing ship is far away and the modulation factor is small. As the distance between the ship and the measurement point decreases, the modulation increases. After the ship has passed the closest point of approach (CPA), the modulation decreases again. The drop in the modulation factor in the region of the CPA is due to the particular form of the interference pattern in this region. A glance at the spectrogram in Fig. 2 which refers to this experiment will make this clear.

At the beginning and end of the experiment, the modulation factor in Fig. 5 stays at a value of about 0.2. However, the passing ship did not have any disturbing influence here. Reduction of the modulation factor to zero was prevented here by slight disturbances of a non-definable type. These disturbances can be recognised in the original plot of the spectrogram. (Owing to the copying process, the grey shades are unfortunately not reproduced very well, so that it is no longer possible to see all of the details in the reproduced spectrograms.)

If sources of disturbance are present, the model is an appropriate one. This has been shown by the measurement results. It has not yet been possible to carry out the test for the case in which disturbance sources are absent, since there were always slight disturbances in the sea areas at all available measurement times.

The noise for Fig. 5 had been measured with a hydrophone situated about 1.5 m above the bottom. Fig. 6 shows an example from a measurement 5 m below the surface of the water. Here too, a ship passed by. The principal difference between the two examples is to be found in the time period after the instant of CPA: the decrease in the modulation factor with time is much steeper in Fig. 6.

Whereas in Fig. 5 the increase and decrease of the modulation factor before and after the CPA are roughly symmetrical, the variation in Fig. 6 is very asymmetrical. This effect was found generally. It is probably due to a strong screening effect produced by the wakes of the ships.

Fig. 7 shows the modulation factor $\bar{M}_T$ as two sources of disturbance pass by. In the first 25 minutes of the experiment, the first disturbance source is dominant, and then the second one is dominant. A corresponding excerpt of the spectrogram for the time period from 10 minutes to 15 minutes after the start of the experiment is shown in Fig. 3.

No representative results can be offered for the distance estimate since the accuracy of the results depends to a very large extent on the amount of practice which the estimator has had - especially in the case of complicated interference patterns. We want to show, by means of an example, that the evaluation method works successfully.

We shall evaluate a part of the experiment which gave the spectra shown in Fig. 2. For this experiment, the model calculation gives an interference wavelength $\Lambda_{1,2} \approx 780$ m and a gradient $\partial\Lambda_{1,2}/\partial f \approx 3.55$ m / Hz, determined at an evaluation frequency $F_0 = 200$ Hz. In the spectrogram, the number of interference wavelengths which have been passed through in 5 minutes is estimated as 3.9. Because the pattern is very complicated, a "ten point divider" is required for this. With the aid of this instrument, the equidistant interference-maxima can be found quickly. The distances estimated after the $\partial t/\partial f$ evaluation are listed for various times in Table I.

TIME SINCE START OF EXPERIMENT (minutes)	ESTIMATED DISTANCE (nautical miles)	DISTANCE MEASURED BY RADAR (nautical miles)
9	3.4	3.55
10	3.0	3.25
11	2.6	2.95
12	2.4	2.55
13	2.1	2.25
14	1.8	1.8
15	1.5	1.5

TABLE I: EXAMPLE OF DISTANCE ESTIMATION

For the sake of comparison, the radar measurements are also listed here. They are not normally available during application of the proposed method. Their purpose here is to act as reference values. The comparison shows that the estimate gives acceptable values.

6. CONCLUSIONS

A method was to be developed with which the influence of disturbing ship's noise on the ambient noise measurement could be estimated. This objective has been achieved by the defining of a mode interference modulation factor. The theoretical model selected for this can be used in practice. This has been demonstrated with the aid of measurement results.

The additional information gained from mode interference, namely information about the distance of the disturbance sources, extends the basis for situation assessment during ambient noise measurement.

The mode interference modulation factor offers the possibility of automating the monitoring of the measurement process; the idea is to use a threshold decision.

In the evaluation of the mode interference modulation factor carried out so far, all periodogram components within a specified frequency band have been taken into account. However, it may be better to evaluate only some of the periodogram components within a specified frequency band, namely those with the largest modulation factors. In this way, frequency bands involving poor propagation behaviour would be excluded from the evaluation process. This would lead to an improvement in the estimation result.

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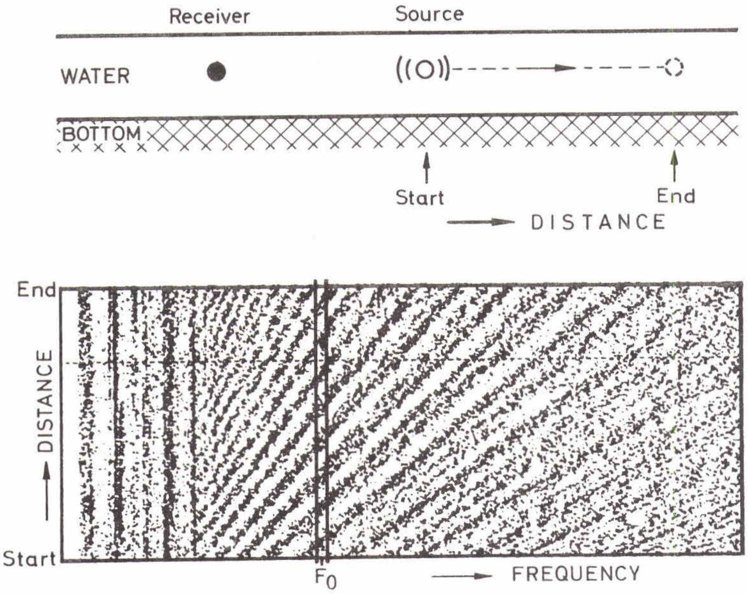
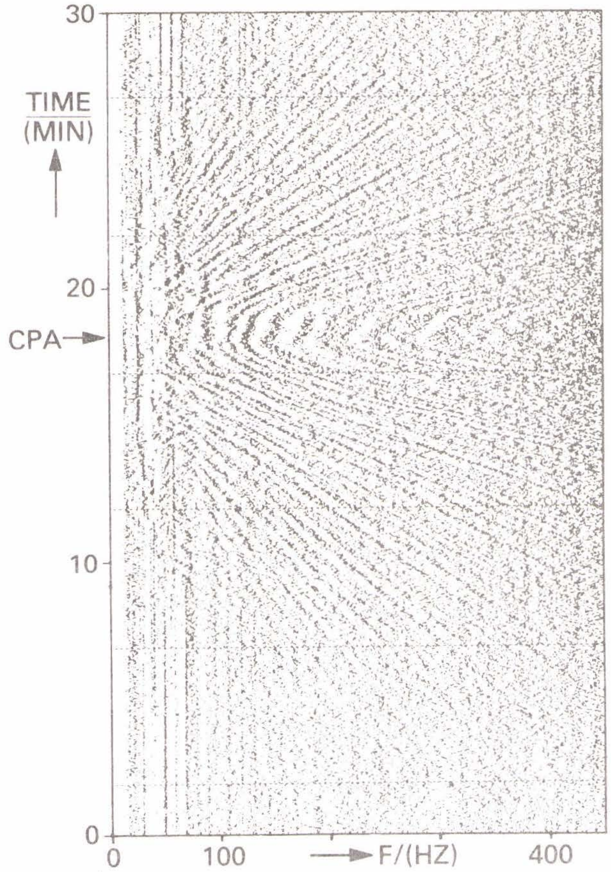


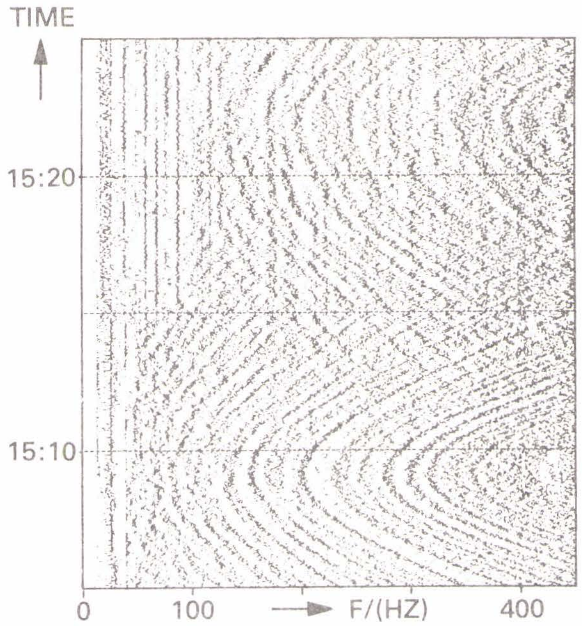
MEASUREMENT OF INTERFERENCE PATTERN

FIG. 1



SPECTROGRAM

FIG. 2



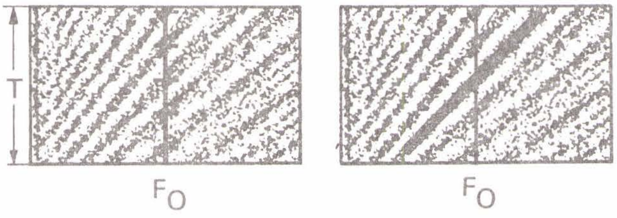
OVERLAPPING INTERFERENCE PATTERNS

FIG. 3

MODEL CALCULATIONS:

- $\Lambda(f)$
- $\partial\Lambda(f)/\partial f$

MEASUREMENT:



$$v \approx \frac{k \cdot \Lambda}{T}$$

$$\partial t/\partial f$$

$$r \approx v \cdot \left[\Lambda \cdot \frac{1}{\frac{\partial \Lambda}{\partial f}} \cdot \frac{\partial t}{\partial f} \right]_{f = F_O}$$

FIG. 4

ESTIMATING THE DISTANCE

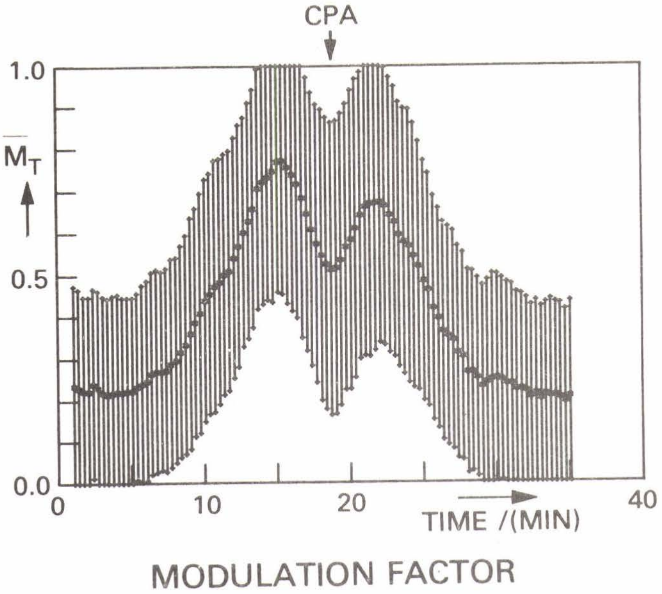


FIG. 5

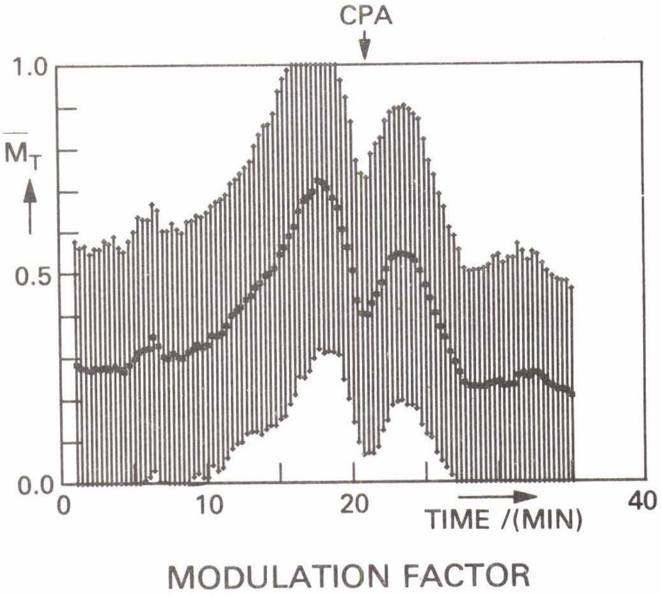


FIG. 6

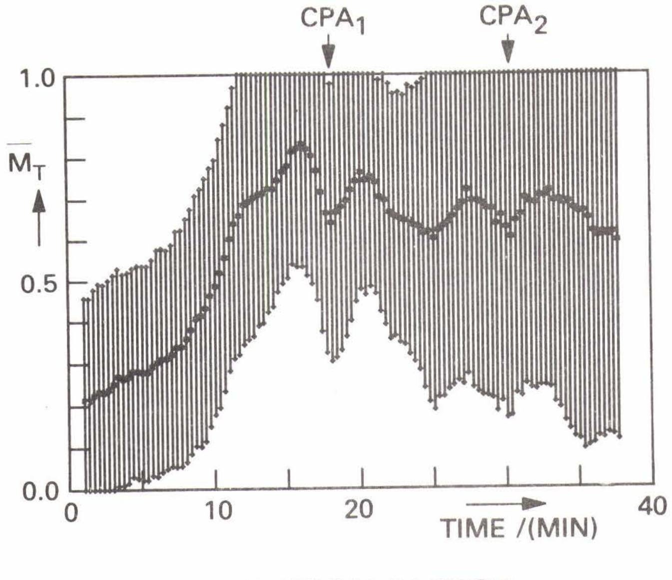


FIG. 7