Preferred citation: J.R. Parker and J.B.A. Epton. The analysis of disturbances affecting paper machines. In **The role of fundamental research in paper-making**, *Trans. of the VIIth Fund. Res. Symp. Cambridge, 1981*, (Fundamental Research Committee, ed.), pp 785–807, FRC, Manchester, 2018. DOI: 10.15376/frc.1981.2.785.

THE ANALYSIS OF DISTURBANCES AFFECTING PAPER MACHINES

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Abstract

The characteristics of the disturbances affecting the paper web are discussed with particular reference to grammage variation, wet press vibration, and calender barring. Some of the difficulties of investigation are pointed out. It is shown that the usual assumptions of stationarity and linearity may not hold, so that frequency domain analysis must be applied with caution.

The key to any investigation lies in the comparison of corresponding spectral components in signals from different points in the system. Two contrasting approaches are compared and discussed: that adopted in the conventional two channel analysis of random data, and that of considering the interrelationship as a vector function of time. The latter approach, embodied in the Vector Correlator, gives considerable insight into the underlying relationship between the variables. Some practical examples are given.

Introduction

A frequently encountered problem in paper mills is that of characterising a disturbance affecting the uniformity of the paper web, tracing it to its source, and eliminating it. Such work requires, firstly, the use of transducers with which to convert vibration, pressure, opacity variation, roll rotation, and so on, into electrical signals; secondly, a means of analysing the disturbance to reveal its character; and thirdly a means of comparing one signal with another and of confirming the existence of a positive relationship.

This paper is mainly concerned with the characterisation and comparison of signals using frequency domain techniques. Frequency analysis via the Fast Fourier Transform has been thoroughly described elsewhere(8). The problem of comparing one signal with another is a different matter. The authors are not aware of any readily available publication in which the problems of signal comparison in the presence of periodic components is adequately discussed. Some procedures call for the elimination of periodic components before completion of the analysis. Bendat and Piersol(1) give an excellent account of random data analysis, but their approach and methods of testing the significance of inter-relationships presuppose the absence of periodics.

A number of years ago the authors were fortunate enough to devise an instrument known as a Vector Correlator(2) by which the relationship between a pair of signals corresponding to one spectral component from the frequency analysis of the orignal signals could be displayed. This device proved to be an excellent self-teaching aid as well as a powerful, though slow, tool for practical investigations. It allowed an investigator to study, as a function of time, the detailed information that is normally destroyed by averaging within a conventional digital two channel analyser. Thus it offered an alternative to the formal mathematical approach usually adopted in random data analysis. It showed how to make optimum use of the information available in the process signals, and at the same time allowed the significance of a relationship to be assessed either by visual inspection or, if necessary, by the application of elementary statistics. Before considering such approaches in more detail, it is useful to examine the nature of the disturbances likely to be found in the paper web and throughout the paper machine.

Disturbances Affecting the Paper-making Process

The properties of the paper web are determined by the furnish, and by a number of controlling variables that are in principle capable of continuous adjustment whilst the machine is running. These variables include thin stock consistency, slice opening, efflux velocity, machine speed, line loads at the wet presses and calender stacks, and drying cylinder temperature. Ideally all these variables are held constant. In practice however, they may fluctuate about steady mean values with frequencies in some instances as high as 800 Hz. Their fluctuations affect such paper properties as grammage, moisture content, caliper and hence opacity, bulk, roughness and gloss, as well as paper strength characteristics and formation. If sufficiently severe, they may cause production losses.

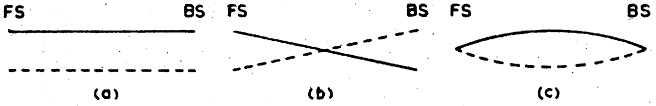


Fig 1—Typical cross machine variations.

In some cases fluctuations in a controlling variable, for example thin stock consistency, may have a uniform effect across the full width of the web Figure 1(a). This effect would be classified, in a two-way variance analysis of grammage(3), as machine direction variation.

However, other modes of variation may be observed. Cross direction headbox vibration causes the grammage at the front side and back side of the machine to vary in antiphase, Figure 1(b), and the vibration of wet press rolls in a rocking mode will cause the moisture content of the web entering the dryers to vary in a similar manner. This type of variation would contribute to the residual variation, usually assumed to be random, estimated by two-way variance analysis.

The intensity of the caliper variations associated with calender barring has been found to vary across the reel as in Figure 1(c) and other more complex patterns of cross direction variation cannot be ruled out.

With respect to time, the controlling variables may fluctuate randomly, or they may have slight, or more commonly, very marked periodic tendencies. In certain cases, the amplitudes of observed fluctuations may vary significantly over periods of minutes or hours, the spectral content may vary, and frequencies of supposed periodics may drift significantly. Usually, disturbances with frequencies below 0.01 Hz are of very low amplitude because they are virtually eliminated by automatic control, by passive control devices, by dead weight loading, or by positive mechanical constraint. At higher frequencies, severe fluctuations may occur within characteristic frequency bands.

Grammage Variation

Problems with short term grammage variation usually occur in the range 0.4 - 40 Hz. They are nearly always associated with pressure variations in the headbox, although at low frequencies consistency variation may be involved. Headbox pressure variations arise for a variety of reasons. Pressure fluctuations from pressure screen vanes and asymmetrical fan pump impellers are a common cause of periodic variation in the range 10 - 25 Hz. Both periodic and random variations in pressure may be induced in the headbox or in associated pipework by accelerations imparted to them by mechanical vibrations of the floor and adjacent equipment. Unstable flow in badly designed pipe-work can cause almost periodic variation of the pressure drop usually at frequencies in the 1-10 Hz range. Throughout the frequency range, turbulence in pipework, especially if associated with a hydraulic resonance (standing wave formation) may have marked effects. Mechanical vibrations may be similarly amplified by mechanical resonances. Further amplification is caused by the development of waves in the stock on the wires of fourdrinier machines(4,5). This effect is at a maximum at some frequency in the range 4-40 Hz, dependent on machine speed and wire length.

The investigation of wet end disturbances is complicated by the dependence on air content of the acoustic velocity in thin stock, and also by the existence of parallel paths. Pulsations in the stock as well as vibration of the pipe walls and building structures, may both transmit disturbances to the headbox. Thus there is the possibility not only of interference between the disturbances transmitted by different paths, but also of the variation with time of the phase and amplitude of the resultant signal as the air content of the stock alters.

Wet-Press Vibration and Calender Barring

Wet press rolls are occasionally subject to severe vibrations, usually at frequencies in the range 15-100 Hz. Investigations by time-averaging methods have suggested that the vibrations are mainly associated with the rotation of the rolls themselves or the press felts. It appears that the vibrations are excited by corrugations that develop spontaneously either on the roll faces or in the felts. Any pattern of corrugations may be resolved by Fourier analysis into sets of 1,2,3, etc. corrugations, each uniformly spaced around the circumference of the roll or felt. The frequencies excited by such corrugations must therefore be exact multiples of the rate of rotation of the roll or felt.

The rotation rate of a felt is usually about 1/3 Hz. The 239th, 240th and 241st multiples of the felt rotation could thus excite vibration at 79.7, 80.0 and 80.3 Hz. It may be necessary to distinguish between these and, for example, similarly spaced harmonics that may be generated by another press felt.

The development of corrugations on rolls is essentially a regenerative phenomenon occurring both in wet presses(6) and calender stacks(7). Slight out of roundness of a roll or non-uniformity of a felt may excite vibration at some natural frequency of the system. Such vibration will in turn cause the nip pressure to vary and thus will promote uneven wear of the defective roll or felt. The corrugations which thus form, gradually develop until they encircle the entire circumference. In studying a roll corrugation problem it is helpful to be able to monitor the angular position of any set of corrugations and also to be able to obtain information from which the mode of vibration of the wet press may be deduced.

Calender barring is associated with the vertical vibration of the rolls at frequencies in the range 70 - 800 Hz. It is normally caused either by corrugations on roll faces, or by a regenerative phenomenon in which the caliper variations impressed in the web provide the feedback loop(8). Calender barring may be confused with the effects on the web of rapid moisture control variations induced by wet press vibration at frequencies of about 80 Hz. During calendering, these variations lead to corresponding gloss variations. Calender barring may be investigated by careful comparisons of the gloss variations in the paper with calender roll dimensions. This may be based on laboratory measurements on samples, or on simultaneous recordings of gloss variation and roll rotation in the field. Difficulties may arise if some calender rolls are of very similar diameter. Should it be thought that moisture variation from a press vibration is the cause, then a comparison of the gloss variations and the press vibrations may provide confirmatory evidence.

Investigational Difficulties

On the basis of the above review, the difficulties in investigating disturbances affecting the paper web may be examined as follows:

(a) The super-position of both periodic and random variations, especially as grammage variations in the paper web.

(b) The very close spacing, in terms of frequency, of periodic variations occurring, for example, in press vibrations, or of potential sources of disturbance.

(c) The possible variation of periodic frequencies with time.

(d) The variation with time of distance - velocity lags. These are associated either with the transmission of pulsations through thin stock of varying air content, or with the delay down the machine as a result of speed variations.

(e) Interference between signals propagated through parallel paths, especially if the lag in one path varies with time.

(f) The difficulty in obtaining signals that directly correspond to certain types of sources of disturbance, particularly those associated with turbulance and unstable flow in pipework and elsewhere.

A further complication occurs when, for example, signals are obtained of the pressure variations at two different points in a stock main. Although the two signals may appear to have a common origin the correlation may fall to zero. This may occur, firstly, if acoustic waves are passing along the pipe in both directions simultaneously, and secondly if there is a cavitating valve between the two points which acts as a source of acoustic noise at the same time as acoustic waves from a second source are being transmitted along the pipe through this valve. The explanation of the fall in the correlation is as follows:

It is possible that at one point (B), the sum, and at the other point (A), the difference of the two acoustic waves may be observed as shown in Fig. 2. At A the observed signal is:

$$A(t) = x(t) - y(t) \qquad (1)$$

and at B

$$B(t) = x(t) + y(t) \qquad (2)$$

where x(t) and y(t) are assumed to be uncorrelated.

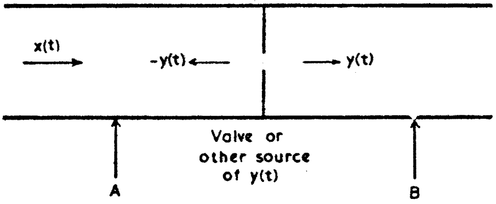


Fig 2—The sum and difference of two signals.

The correlation coefficient between A(t) and B(t) is defined as:

$$r = \frac{\text{Cov (AB)}}{(\text{Var (A)}. \ \text{Var (B)})} \qquad (3)$$

where

$$\begin{aligned} \text{Var(A)} &= \text{Var } (x(t)-y(t)) \\ &= \text{Var}(x(t))-\text{Var}(y(t)) \\ &= S_x^2 - S_y^2 \qquad (4) \end{aligned}$$

where S_x^2 and S_y^2 are the sample variances of x(t) and y(t):

similarly $\text{Var(B)} = S_x^2 + S_y^2$ (5)

The covariance is defined as:

$$\begin{aligned} \text{Cov (AB)} &= \frac{1}{T}\int_0^T (x(t) - y(t)).(x(t) + y(t))\, dt \\ &= \frac{1}{T}\int_0^T (x^2(t) - y^2(t))\, dt \\ &= S_x^2 - S_y^2 \qquad (6) \end{aligned}$$

From 3 and 6

$$r = \frac{S_x^2 - S_y^2}{S_x^2 + S_y^2} \qquad (7)$$

Clearly if the two variances are of similar magnitude the correlation between the signals at A and B is close to zero.

This reduction in the correlation may lead to the false conclusion that the presence of the valve prevents the propagation of the disturbance x(t) to point B. One may encounter this situation whenever one is tracing a transmission path in a system as ill-defined as a paper machine wet-end. This problem can also occur when vibrations are traced through mechanical structures.

Underlying assumptions in frequency and time domain analysis

Time varying signals may either be studied as they stand, or, after transformation, as an assemblage of spectral components estimated by frequency analysis. Analysis in the time domain has advantages, especially if the variations being studied can be linked with some regular or irregular occurrence such as the rotation of a felt or the observation of a discrete pulse at some point in the system. Using such an occurrence as a starting point, readings of the variation it is intended to study may be taken digitally at regular time intervals. If many such sets of readings are taken and the results averaged for each time interval after the starting point, the result will correspond to the mean contribution of the occurrence to the variation in question. This technique, known as Signal Averaging, has been used for example in press rotation studies(9). A disadvantage of the method is that it is not possible, unless special precautions are taken, to estimate the number of averages required to reduce interfering periodics to some level at which they are no longer significant.

In comparison, frequency domain techniques have many advantages, provided that the underlying assumptions are well understood. Therefore before considering these techniques in more detail it is worth considering some of these assumptions.

It is usually assumed that the source of a disturbance and the parameters of the system through which the disturbance is propagated are both stationary. That is to say the characteristics of the source of disturbance do not change with time: their intensities and their spectral characteristics remain constant apart from normal statistical variations.

Similarly it is assumed that such parameters as machine speed and the velocity of sound in thin stock do not vary with time. Moreover the positions of the observation points are assumed to remain fixed in relation to the system and the sources it contains.

Under these conditions the spectral components of any disturbance travel through the system unchanged in frequency, so that in principle, the source of any periodic disturbance may be identified merely by matching spectral components at sufficiently high resolution. As we have seen, these assumptions may not be valid, and it may not be possible in practice to obtain the necessary degree of resolution.

It is generally appreciated that, for linear systems, i.e. systems for which the output is linearly proportional to the corresponding input, sinusoidal disturbances are propagated unchanged in wave-form, though altered in amplitude and phase. Because phase lag and attenuation may both vary with frequency, complex wave-forms may be radically changed in character by transmission, and therefore their relationship to the input wave-form cannot always be established by inspection.

In non-linear systems sine waves are distorted by transmission: the fundamental frequency is maintained but harmonics are added. A further characteristic of non-linear systems is the interaction of components of differing frequencies and effects such as modulation and demodulation. Although these are uncommon in paper machine systems they are not entirely unknown. For example, a pair of pressure screens was found to be exciting a strong standing wave in a thin stock main. Since the screens operated at slightly different speeds they beat against each other and the intensity of the standing wave varied with time. It was observed that the mean pressure down stream of the screens varied slowly in sympathy with these beats, presumably because the high frequency flow induced by the standing wave helped clear the rejects from the screen baskets.

Frequency analysis

For investigational purposes analogue methods using single, or multiple, tuned filters have been superceded by digital analysers. These analysers make use of the Fast Fourier Transform algorithm devised by Tukey and others(10). Essentially the first stage is to filter the raw signal to remove from it components with frequencies higher than those to be considered in the analysis. This is necessary to prevent aliasing. The filtered signal is then sampled at regular intervals of time until $N=2^n$ readings have been obtained. Usually there are 512 or 1024 readings in each frame. A FFT is then performed and a frequency spectrum is calculated and displayed. This power spectrum will be in the form of up to N/2 `components´. Each `component´ corresponds to the power in the original signal that would pass through an ideal band-pass filter having a bandwidth of 1/T Hz, where T is the time period over which the N points are collected.

For the purposes of the analysis it is assumed that each `component´ consists of a single periodic. In reality however, each `component´ may be the resultant of a number of unrelated periodics all of slightly differing frequencies. These individual periods will be continually changing phase relative to each other over the duration of the frame period T.

The composite `components´ calculated are usually referred to as spectral components whilst the word `component´ is reserved for individual periodics. To resolve such periodics the original frame period T must be increased. Typically a resolution of 0.04 Hz can be achieved, but when this is done the range of frequencies measured may be limited to about 10 Hz.

If a single frequency spectrum is composed for a random disturbance it will be found that the magnitudes of the individual spectral components of the power spectrum will vary very considerably in magnitude. Statistically, it may be shown that the standard error of any component is equal to its expected mean value. In order to obtain better estimates of individual components it is necessary to average the results of at least 16 and preferably 100 or more individual spectra. Averaging facilities are normally available in digital analysers.

Two channel frequency domain analysers

The purpose of this type of analysis, which is normally carried out digitally, is firstly to decide whether or not two signals fully or partly arise from some common source, and secondly to establish the phase relationship of one signal relative to the other. This phase information may be necessary to deduce the direction of energy flow. In the frequency domain the analysis is carried out by the comparison of corresponding spectral components rather than by considering the signal as a whole.

If two signals are simultaneously sampled over the same period T as described in the previous section, and then analysed via the Fourier Transform, one may obtain not only the power spectrum of each signal but also the phase of each spectral component in relation to the starting point of the sampling period. Because the two signals were sampled simultaneously their relative mean phase over the sampling period may also be obtained. By repeating this procedure of sampling and analysis over further periods of time it is possible to observe how the phase relationship of any pair of components changes with time. It will be appreciated that if the two signals were obtained under stationary conditions and were also derived from a common source, then the phase relationship between them would remain constant.

In practice, in a digital two-channel analyser the cross spectrum would be calculated in addition to the power spectrum and phase of the individual signals. The cross spectrum consists of both real and imaginary parts calculated for each spectral component. Suppose that the signals being analysed are denoted by x(t) and y(t). For any spectral component the real part of the cross spectrum is the average power of the product x(t), y(t) taken over the narrow frequency range corresponding to that component. Similarly, the imaginary part is the average power of the product of $x'(t)$, $y'(t)$ over the same frequency range, where $x'(t)$ is $x(t)$ phase shifted by 90°.

In operation, a two channel analyser would simultaneously sample both signals and compute the power spectrum of each together with the real and imaginary parts of the cross spectrum. These four quantities would be accumulated for each sampling period or frame and the average values computed component by component, over many frames. From these average values for each frequency bin f (the frequency range corresponding to a spectral component from $f - 1/2T$ to $f + 1/2T$ Hz), the rms amplitudes X_{rms} and Y_{rms} are calculated. Similarly, the averages, P and Q of the real and imaginary parts of the cross spectrum are also found. The coherence $g^2(f)$ is then calculated for each of the spectral components from

$$g^2(f) = \frac{P^2 + Q^2}{X^2_{rms} \quad Y^2_{rms}} \qquad (8)$$

Coherence, which may therefore be displayed as a spectrum, resembles the square of a correlation coefficient, r. Whereas the mean correlation coefficient between say, $\cos(\omega t)$ and $\sin(\omega t)$ is zero, the coherence indicates the maximum value that could be obtained between the two wave forms if the relative phase was reduced to zero. Thus the coherence between $\sin(\omega t+\varphi)$ and $\sin(\omega t)$ is always unity regardless of the phase angle φ.

Note that the symbol $g^2(f)$ is used for coherence instead of the usual symbol $\gamma^2(f)$ used by Bendat & Piersol(1). In practice the coherence measurement $g^2(f)$ is only an estimate of the true population coherence $\gamma^2(f)$ and the actual value of $g^2(f)$ will depend upon the number of frames analysed.

Suppose that the relationship between x(t) and y(t) is such that:

$$y(t) = T.x(t - \tau) + e(t) \qquad (9)$$

where τ is the time delay between y(t) and x(t).

Suppose also that x(t) and e(t) both represent narrow band noise but that e(t) is uncorrelated with x(t). Thus x(t) and y(t) may be thought of as spectral components. If they are subjected to two channel analysis as indicated above, for the kth frame the components of x(t) and y(t) may be regarded as

$$\begin{aligned} x(t)_k &= a_k \cos(\omega t + \theta_k) \\ y(t)_k &= A a_k \cos(\omega t + \theta_k - \varphi) + b_k \cos(\omega t + \theta_k - \beta_k) \end{aligned}$$

Where θ_k and β_k are randomly varying phase angles but $\varphi = \omega\tau$ is constant. a_k and b_k are randomly varying amplitudes of x(t) and e(t) for each frame k such that the mean square values are equal to the variances of x(t) and e(t).

For the k^{th} frame the coherence is calculated from:-

$$\mathrm{var}(x_k) = \frac{1}{T}\int_{kT}^{(k+1)T} x^2(t)_k \, dt = \frac{1}{2} a_k^2$$

$$\mathrm{var}(y_k) = \frac{1}{T}\int_{kT}^{(k+1)T} y^2(t)_k \, dt = \frac{1}{2} A^2 a_k^2 + \frac{1}{2} b_k^2 + \frac{1}{2} A a_k b_k \cos(\varphi - \beta_k)$$

$$\mathrm{Cov}(x_k y_k) = \frac{1}{T}\int_{kT}^{(k+1)T} x(t)_k y(t)_k \, dt = \frac{1}{2} A a_k^2 \cos\varphi + \frac{1}{2} a_k b_k \cos\beta_k$$

$$\mathrm{Cov}(x_k' y_k) = \frac{1}{T}\int_{kT}^{(k+1)T} x'(t)_k y(t)_k \, dt = \frac{1}{2} A a_k^2 \sin\varphi + \frac{1}{2} a_k b_k \sin\beta_k$$

If the above quantities are averaged over K frames then

$$X^2_{rms} = \sum_{k=1}^{K} \frac{1}{2} a_k^2 = S_x^2$$

$$Y^2_{rms} = \sum_{k=1}^{K} \frac{1}{2} A^2 a_k^2 + \frac{1}{2} b_k^2 = A^2 S_x^2 + S_e^2$$

$$P = \sum_{k=1}^{K} \frac{1}{2} A a_k^2 \cos\varphi + \frac{1}{2} a_k b_k \cos\beta_k = A S_x^2 \cos\varphi$$

$$Q = \sum_{k=1}^{K} \frac{1}{2} A a_k^2 \sin\varphi + \frac{1}{2} a_k b_k \sin\beta_k = A S_x^2 \sin\varphi$$

Thus the coherence is given by

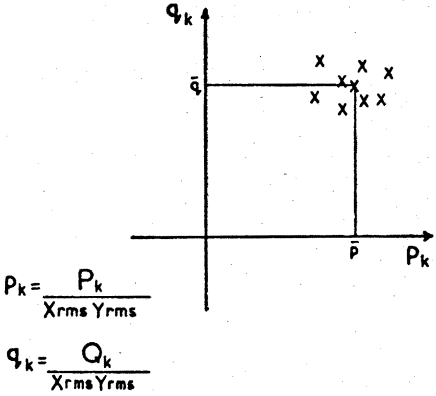
$$g^2 = \frac{P^2 + Q^2}{X^2_{rms}\ Y^2_{rms}}$$

$$g^2 = \frac{A^2 S_x^4}{S_x^2 (A^2 S_x^2 + S^2)}$$

It will be seen that this is identical to the squares of the correlation coefficient between x(t) and y(t) if the time lag τ or phase angle φ is set to zero.

The significance of coherence and its related phase angle may also be explained by means of a plot of the normalised real and imaginary parts of the cross spectrum calculated frame by frame as shown in Figure 3.

For the model defined by equation (9) the individual points will be clustered randomly about point $(\bar{p},\bar{q})$. This point is at a distance g from the origin at which it subtends an angle φ to the horizontal axis. It will be appreciated that the confidence limits for these parameters may be determined from the scatter of the individual observations about $(\bar{p},\bar{q})$. It should also be noted that the order in which the individual points are obtained is ignored. As will be seen later this information which is lost by averaging can give a



$$p_k = \frac{P_k}{X_{rms}\,Y_{rms}}$$

$$q_k = \frac{Q_k}{X_{rms}\,Y_{rms}}$$

Fig 3—Digital analyser vectors for frame k.

valuable insight into the underlying relationship between the two signals.

The Vector Correlator

The Vector Correlator is an instrument which was developed specifically for investigating the sources of disturbances and the transmission paths of these disturbances on paper machine systems. It is essentially an instrument which allows the details of the correlation and phase angle between two signals to be studied as a function of time. The Correlator is therefore used to study the relationship between individual spectral components at two points in the system after some form of frequency analysis has been carried out. Since the signals have to be compared on a frequency by frequency basis some form of band pass filtering of the two signals is usually required.

Consider two band limited stationary signals x(t) and y(t) with rms values X_{rms} and Y_{rms} respectively. In the Correlator two functions are calculated p(t) and q(t) which are the normalised in-phase and quadrature cross products between x(t) and y(t) calculated on a continuous basis using

$$p(t) = \frac{1}{k}\int_{-\infty}^{\infty} x(t-\tau).y(t-\tau).h(\tau).d\tau$$

$$q(t) = \frac{1}{k}\int_{-\infty}^{\infty} x'(t-\tau).y(t-\tau).h(\tau).d\tau$$

where $k = X_{rms}.Y_{rms}$, $h(\tau)$ is a weighting function used to smooth the data, and $x'(t)$ is x(t) shifted in phase by 90°. Note that the weighting function must average the data over a period much greater than 1/B where B is the band width of the spectral component being investigated.

The two functions p(t) and q(t) can be considered as the components of a time varying vector which express the normalised correlation and phase between x(t) and y(t) as shown in Figure 4. This vector has magnitude r(t) and phase $\varphi(t)$, and r(t) has a

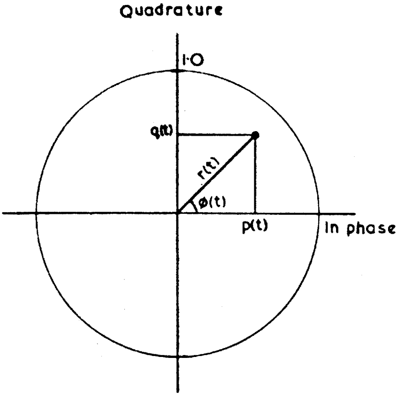


Fig 4—Correlator output vectors.

value between 0 and 1. In the case of the Vector Correlator, if the inputs have the same frequency but arbitrary phase the correlation will always be unity and the arbitrary phase angle displayed. Normally x(t) is chosen to be the suspected source of disturbance and y(t) is the output variation.

Practical examples of signal comparison

The value of the Vector Correlator in investigating disturbances is best demonstrated by considering specific examples and comparing the results with those obtained using a two channel spectrum analyser.

Figure 5 shows the display produced when comparing two sinusoids of the same frequency but arbitrary phase φ. The vector r(t) has unit amplitude. An identical result would be obtained using the two-channel analyser.

If the two signals had slightly differing frequencies then the phase between them would be progressively varying. The displayed vector would therefore steadily rotate around the unit circle at a rate determined by the frequency difference. If the frequency difference were larger then the

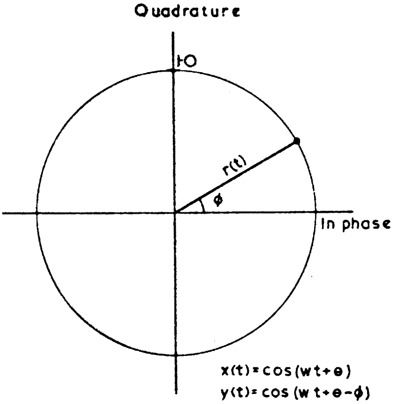


Fig 5—Comparing two sine waves of same frequency.

vector length would be reduced by the action of the weighting function and zero correlation would be approached as the frequency difference increased. The results from the two-channel analyser to two different frequencies would depend upon the resolution selected. If the two periodics were included in the same spectral component then they could not be separated. However, the coherence between the two signals would start at unity and gradually decrease as the number of frames increased due to the progressive phase shift. If the resolution were sufficiently increased then the two periodics could be separated and a zero coherence would be measured.

In cases where frequency components are very close, for example when investigating the contribution due to induction motors, or pumps and vibrating screens etc., it may not be possible to obtain sufficient resolution using an analyser. If say a 25 Hz component was being investigated, then using the Correlator it is not difficult to observe a progressive phase change of say 90^{o} over a 100 second period. This represents a resolution of 0.01% or 0.0025 Hz. If a higher resolution is required it is only necessary to increase the observation time. Using the Correlator it is obvious from the progress with time of the vector that the two signals are of different frequency.

If two signals are compared which are identical in frequency but this frequency is subject to random drifts, for example as the load on a motor varies, then the Correlator display again gives an insight into this situation. Assuming that the other properties of the system are stationary then the varying frequency will cause a varying phase shift through the system. As the Correlator only measures relative phase, then the frequency drift is of no consequence, but the random phase variations are displayed as shown in Figure 6. If, over a considerable time, the mean frequency is constant then the phase will only be perturbed about some mean value. It will not progressively vary as in the case of two periodics of different frequency. Since a two-channel analyser measures absolute frequency then a signal containing a varying frequency could be spread into 2 or more spectral components and the time varying phase would lead to a fall in coherence giving little insight into the type of variation being studied.

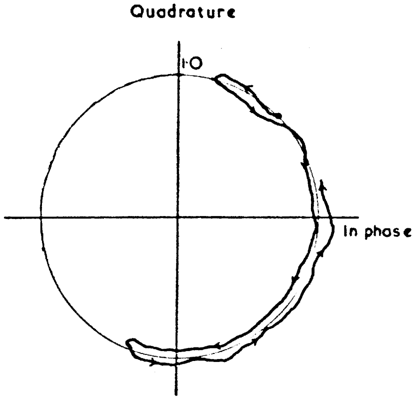


Fig 6—The effects of slow frequency drifts.

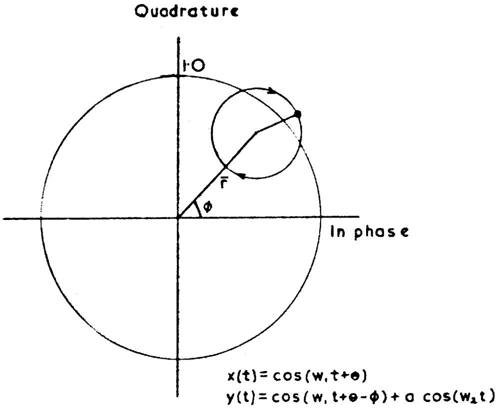


Fig 7—The presence of an additional sinusoidal component.

In many cases a signal may contain two sine waves of slightly different frequency, only one of which will be identical to some source under investigation. In this case the Correlator display would be as shown in Figure 7. The second unrelated component is seen as a vector added to the mean correlation coefficient r and rotating at a rate determined by the frequency difference. As the frequency difference increases, or if the weighting function averaging time is increased, the second vector amplitude approaches zero. The analyser results would again depend on resolution. if the components were too close to resolve, then again a coherence less than unity would be observed with little indication as to why. Often there are several close periodics in the signal y(t) and the resultant pattern is the sum of several vectors, one stationary and the others rotating at the difference frequencies between each periodic and the frequency of x(t).

If the signal y(t) consists of the signal x(t) plus random noise then the display has the form shown in Figure 8 where the varying vector has random amplitude and phase. Again the situation is clear from the display. By increasing the averaging time, the noise vector decreases to zero and slow phase variations or rotations of the correlation vector may readily be observed.

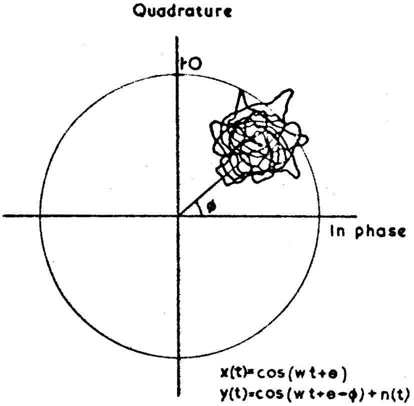


Fig 8—The present of additional random noise.

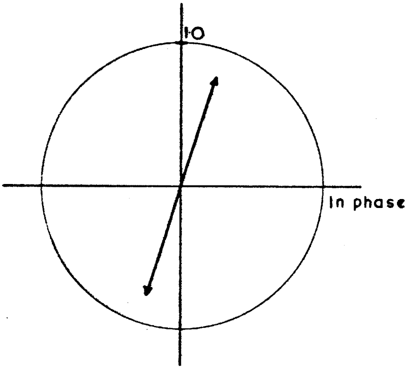


Fig 9—The sum and difference of two unrelated sine waves.

In the case where two signals are compared which are the sum and difference of two band-limited and uncorrelated sources (as in equations (1) and (2)), the Correlator display would be as shown in Fig. 9. In this case the phase rapidly swings by 180° due to the change in phase of the two beats between the components. When investigated using the analyser this situation would indicate no coherence between the two signals as described earlier.

It can be seen from the examples that the value of coherence obtained using a two-channel analyser can be strongly influenced if there are interfering periodics present which fall into the same spectral component. The theory developed for the two channel analysis and the coherence calculations assumes that the data is random and that successive values of p_k and q_k (see Figure 3) are randomly distributed about some mean value. If interfering periodics are present then the successive (p_k, q_k) values will not be random and may have slow systematic movements.

The difficulty may be avoided if frames are started at random intervals of time that are many times greater than the rotation rates of the vectors indicating the frequency difference. By this means the phase of the interfering periodics may be randomised and the confidence limits for the amplitude of each component calculated on the assumption of a normal distribution of the individual values about the centre of gravity. The usual practice of starting each frame as soon as the last one has been processed must be treated with caution.

The investigation of wet press vibration

The problem of assigning wet press vibrations to a particular roll or felt may be attempted by using synchronised Fourier analysis(6) which is a variant of two-channel analysis. This technique has an advantage over the synchronised averaging since it is possible to test the significance of the individual spectral components and to reconstruct the original wave form should that be necessary for the significant harmonics.

A trigger signal is obtained to indicate the commencement of each rotation of the suspected roll or felt, and is used to initiate the sampling of the vibration signal. Sampling is arranged so that 2^n uniformly spaced readings are obtained in one revolution. This method of sampling ensures that the spectral components correspond precisely to the harmonics of the rotation rate. If many sets of readings are analysed to obtain the amplitude and phase of each component in relation to the trigger mark, then a diagram similar to Figure 3 may be plotted. To assess the significance of any particular component one must bear in mind that the interfering disturbances from other rolls or felts will be periodic and random frame sampling must be used.

The correlation of grammage variations in the web

When investigating wet-end disturbances a great deal can be learnt about the nature of the problem from the measurement of the grammage variations at the two sides of the web. For these purposes the instantaneous light transmission through the web may be measured at the dry end using two detectors. A two-channel analyser can then be used to compute the spectra for the two signals and the phase and coherence between them. Coherence is a measure of how well the two signals are correlated and it is therefore possible to compute from the two spectra a new spectrum showing the correlated components and a second spectrum showing the uncorrelated components. The phase spectrum then relates to the new correlated spectrum.

In general it is usually found in any investigation that the total of the uncorrelated components exceeds the total of the correlated components and that the uncorrelated spectrum is flat. This indicates that there is a considerable degree of random variation both within the headbox and on the wire. In contrast the correlated spectrum usually contains peaks due to periodics or quasi-periodics which are disturbances to the system. Any disturbance which generates pressure pulsations in the approach flow will usually be correlated and in phase as will disturbances caused by machine direction headbox vibration. Cross direction headbox vibration will also appear in the correlated spectrum but will be in antiphase. Any periodic components which are uncorrelated must affect one side of the machine and not the other and so must be due to local effects occurring after the approach flow (such as vibration of the walls of the headbox, for example).

By varying the separation of the two dry-end observation points and studying how the correlated and uncorrelated spectra are modified, it is possible to investigate the large scale turbulence and the general performance of the headbox.

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Transcription of Discussion

Discussion following paper given by Dr.J. R. Parker

Dr. H.V. Paulapuro, Jaako Pöyry International Oy, Finland

You have presented a method which is applicable to cases where a stationary time series is assumed. How does your analysis cope with non-stationary time series, where there is a trend present for example?

Dr. J.R. Parker

There are two aspects of stationarity: that of the system and that of the source. Only one is normally discussed and that is the stationarity of the source. Stationarity means, of course, that the statistics of the signal do not vary with time. To overcome this problem, one merely reduces the observation times until the conditions of stationarity are satisifed.

The Vector Correlator makes this aspect of non-stationarity particularly obvious. The method of deriving and displaying the correlation on this instrument shows the properties of non-stationarity as an oscillating vector which moves radially in and out from the centre of the display.

Mr. P.T. Herdman, Wiggins Teape R and D, UK

(This question was written.)

I am very impressed by your work in this field and as you know I am the proud possessor of one of your Vector Correlators.

My question regards the solution of practical paper-making problems in the real world. My personal experience is that an intelligently used two-channel spectrum analyser successfully solves some 95% of real problems of short term stability within a reasonably short space of time, say about 1 to 2 man-days per problem.

A Vector Correlator on the other hand solves some 99% of real problems but takes some 10 man-days per problem, mainly because it is not possible to solve the problems in real-time so readily. Is this a fair reflection of your experience or do I need more intensive training on the use of a Vector Correlator?

Dr. J.R. Parker (written reply)

In principle I agree that the two-channel analyser is the tool to use at the onset of an investigation. It can cover the ground more quickly than the Vector Correlator. But where its results do not make sense, or need to be confirmed, then the Vector Correlator can be very valuable. The Correlator is also an excellent teaching aid: I imagine that the experience you have had with the instrument has given you valuable insights into the results given by your two-channel analyser.