Signature Analysis of Contact Voltage of Resistance Welds

A higher contact voltage decay rate results in longer effective weld time and better weld quality

BY S. P. OWUSU-OFORI AND S. M. WU

ABSTRACT. It has been established that the variation of the contact voltage in the weld zone is closely related to the process quality. The wave form of this voltage is similar to that of the supply voltage, which has been observed to have varied degrees of distortion due to the presence of the odd harmonics of the supply frequency of 60 Hertz.

By mathematical modeling of the contact voltage, the amount of distortion of the welding voltage waveform has been quantified through dispersion analysis. A correlation between the degree of distortion and the weld quality has been established based on the strength of the fundamental supply frequency. Apart from monitoring the peak values of the supply voltage, this work emphasizes the importance of its wave form for a more effective control of the heat produced in the contact zone.

The variation of the contact voltage also shows a deterministic transient and steady state behavior, which has also been used in this work to predict the nugget diameter. A comparison between the developed empirical model and the actual results from experiments shows a good agreement, provided the distortion of the supply voltage is not significant.

Introduction

Conventional quality control procedures are not very reliable because of the speed with which resistance welds are produced. If the process malfunctions, a large number of defective welds can be made before they are detected. With the advent of automation and robotology, there is an increasing need for more reliable equipment and control procedures to ensure the desirable weld quality and consistency. The use of on-line monitoring and control methods seems to provide the answer to the problem of unreliably obtaining the weld quality off-line. However, the search for the operating condition to be monitored is still going on with varied degrees of success.

The commercially available monitors can be divided into two main categories (Ref. 1) — namely, the expansion-based and electrically based systems. The expansion-based systems measure the time taken to achieve a certain predetermined expansion of the weldments parallel to the electrodes during welding; thereafter a decision is made about the weld quality. In certain cases, a correction action is instituted before the completion of the weld. Such monitoring systems fail when narrow workpieces are joined due to the lateral expansion of the weldments.

The electrically based systems make use of the measurable quantities such as the welding current, supply voltage and the contact resistance (Ref. 2-6). These quantities are related to the heat produced in the weld zone during the operation. Hence by controlling these quantities, the welding operation could be controlled to obtain consistently good quality welds.

The minicomputer's fast calculating ability was recently used to monitor the supply voltage and to make decisions on the compensatory actions to cater to the voltage fluctuations (Ref. 7). The supply voltage is normally used to control the timing circuitry, which determines the amount of the current flowing. The contactors are turned on at some specific points on the primary voltage wave-form and turned off at the zero-crossing point (Ref. 7).

The points at which the contactors are turned on and off are very important in controlling the amount of current that is actually employed in the fusion process. It is, therefore, essential that the wave form of the supply voltage be as close as possible to the theoretical line wave form for the efficient performance of the switching circuitry.

When a physical system behaves in a periodic manner, there is always the possibility of the presence of its higher order harmonics. Therefore, the frequencies of the welding voltage can be the funda-

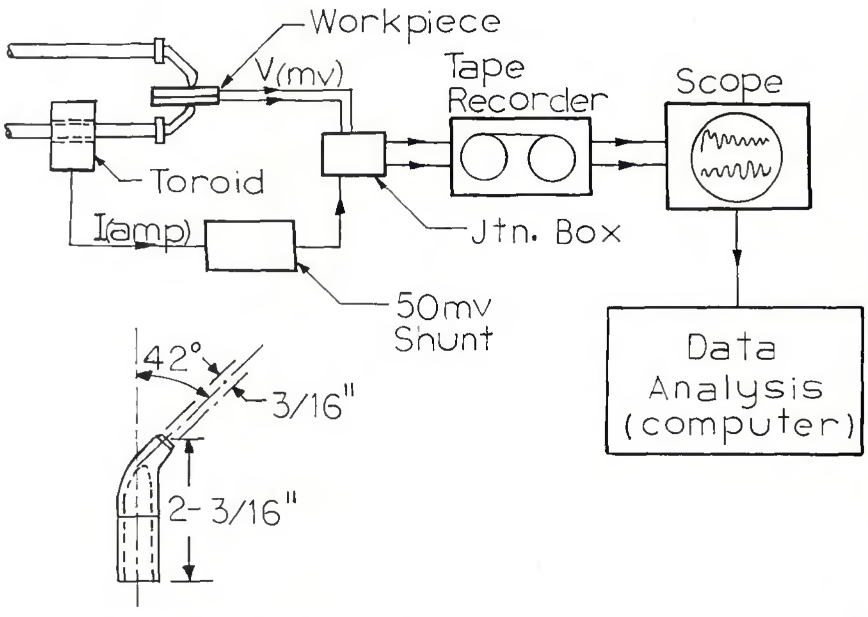

Fig. 1 — Experimental setup and electrode tip geometry

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Table 1—Terminology/Definitions

- A_t — Random disturbance (input) at time t
- A_{t-j} — Random disturbance (input) at previous time t − j, j = 1,2,3,n
- B — Back-shift operator
- C_{1i} — Voltage at start of data collection (i.e., at t = 0) for i^{th} frequency (harmonic)
- C_{2i} — Rate of voltage build-up for i^{th} frequency (harmonic)
- C_{3i} — Magnitude of voltage at steady-state for i^{th} frequency (harmonic)
- C_{2l} — Rate of voltage build-up for 60HZ
- d_i — Weight of root λ_i
- D_i — Dispersion of i^{th} harmonic
- D_n — Nugget diameter
- E — Expectation sign
- f_o — Fundamental frequency of supply voltage (60 Hz)
- g_i, g_r } Factors in equation (A4)
- i — integer
- j — integer
- y — integer
- Y — Constant of proportionality
- m — Order of moving average part of ARMA model
- n — Order of autoregressive part of ARMA model
- NID — Normally and independently distributed
- t_l — Weld time lost in first half of period
- t_2 — Weld time lost in second half of period
- t — time
- T — Period of contact voltage
- $V_{(t)}$ — Voltage at time t (Analog)
- V_t — Voltage at time t (Digitized)
- α_i — Decay rate of voltage for i^{th} frequency (harmonic)
- β — Nugget size factor (= C_{2l}/α_l)
- γ_y — Auto-covariance function of lag y
- δ_y — Kronecker delta
- λ_i — i^{th} Autoregressive root of ARMA model
- ν_j — j^{th} Autogressive root of ARMA model
- ν_i — i^{th} Moving average root of ARMA model
- ν_y — y^{th} Moving average root of ARMA model
- σ^2_a — Variance of random disturbance A_t
- ϕ_i — i^{th} Autoregressive parameter
- ω_l — Angular velocity of 60 Hz frequency
- α_l — Decay rate of voltage for 60 Hz
- θ_i — i^{th} Moving average parameter

mental frequency of 60 Hertz (Hz) and its higher order harmonics. If some of the higher harmonics are superimposed on the 60 Hz signal, the weld current wave form will be distorted and adversely affect the weld quality. Such a distortion could affect the switching circuitry and thus the welding operation.

The objective of this paper is to report the results of investigation on the effects of the wave-form and general characteristics of the welding voltage on the weld quality by use of the contact voltage in the weld zone. The general characteristics of the contact voltage were obtained through deterministic mathematical models. The wave-form of the welding voltage signal was analyzed by use of time series methodology and the dynamic data system (DDS) modeling technique with its concomitant dispersion analysis. The mathematical formulation of the DDS methodology is described in the Appendix.

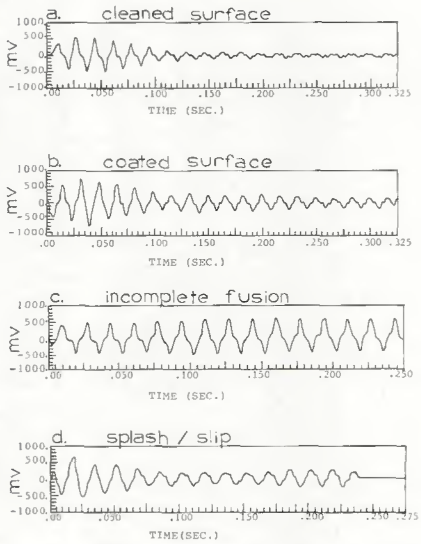

Fig. 2 — Plots of typical contact voltages

Experimental Procedure

The secondary welding current was monitored during the welding operation by means of a commercially available current transformer (toroid) of ratio 24:1, a 50 mV shunt and an FM tape recorder. The voltage drop in the weld was monitored by means of alligator clips connected directly to the weldments and the tape recorder. The analog outputs of the recorder were connected to the A/D input of a digital oscilloscope for digitization and transferred via a modem to a Univac computer to be analyzed. The set-up is as shown in Fig. 1.

Welding conditions were as follows: current — 10,000 A; weld time — 15 cycles; electrode force — 600 lb (2669 N); material — 18 gauge, cold-rolled 1020 carbon steel sheet; electrode — cold formed, single bend copper alloy with 3⁄16 in. (4.8 mm) tip diameter; machine — 20 kVA spot welding unit.

The alligator clips acted as probe points across the welding zone and thus recorded the instantaneous analog voltage drop within this zone during the formation of the weld. This voltage drop was monitored by the digital oscilloscope, which converted the data from its analog form to a digitized form at predetermined sampling intervals. The sampling interval used here was 1 millisecond per point. The digitized data could then be transmitted to the computer for modeling and analysis.

In order to test the generality of the behavior of the contact voltage, surfaces were cleaned with benzene and compared with zinc-phosphated (coated) surfaces. Figures 2A and 2B show two typical contact voltage signals; They suggest that the general behavior is independent of the surface treatment. However, the steady state values can be seen to be higher for the coated surfaces.

Figure 2C shows a situation with incomplete fusion. This type of signal could easily be detected and interpreted as a "sticking" condition. Figure 2D indicates an unstable situation where the contact voltage started to increase again after attaining the steady-state condition. This could be due to either slippage of the weldments or electrodes which will result in a poor quality weld.

Analysis and Discussion of Results

The ultimate aim of these experiments was to obtain the quantitative effects of the contact voltage on the weld quality. This requires that some contact voltage characteristics which influence the weld quality be obtained.

An examination of the contact voltage shows a dominant, deterministic, nondecaying distorted sine wave which settles at a steady value after an initial transient state. The amount of distortion of the wave-form of the contact voltage could affect the weld quality. The degree of distortion and the deterministic behavior are analyzed and their effects on the weld quality are discussed below.

Relationship Between Deterministic Model Parameters and Nugget Diameter

The weld-producing contact voltage signals show a definite relationship with respect to time. A nonlinear least squares technique was used to find the best deterministic model that fits the voltage signals. Referring to the terminology in Table 1, this was found to be of the form:

$$V(t) = \sum_{i=1}^{n} e^{-\alpha_i t}(C_{1i} + C_{2i}t)\sin(\omega_i t - \phi_i) + C_{3i}\sin(\omega_i t - \phi_i) \quad (1)$$

Table 2—Comparison of Predicted and Experimental Results

Predicted values		Estimated values from experiment		
β, mV	Nugget diameter, mm (in.)	β, mV	Nugget diameter, mm	Tensile shear strength, lbf
0.065	2.4 (0.09)	0.072	2.6 (0.10 in)	750[a]
0.079	3.0 (0.12)	0.075	2.6 (0.10 in)	800
0.080	3.0 (0.12)	0.079	2.8 (0.11 in)	825
0.083	3.1 (0.12)	0.082	2.9 (0.12 in)	885
0.084	3.2 (0.13)	0.086	3.0 (0.12 in)	985
0.091	3.4 (0.13)	0.090	3.2 (0.13 in)	1000
0.102	3.8 (0.15)	0.100	3.9 (0.15 in)	1200[b]
0.112	4.2 (0.17)	0.104	4.1 (0.16 in)	1235[b]
0.122	4.6 (0.18)	0.114	4.6 (0.18 in)	1365[b]
—	—	0.120	Splash	[c]

(a) Too low a value for β causes sticking.
(b) A good weld.
(c) Too high a value for β causes splashing (too much heat).

where n = 1, 3, 5, 7, . . . , (2j + 1), j is an integer,

$\omega_i = 2\,\pi n f_o$

and f_o = the fundamental of supply voltage (60 Hz).

The first part of equation (1) represents a transient response while the second portion represents the steady state response. The contact voltage increases in magnitude to a higher level as the current is passed initially. The voltage drops as the weld progresses. This behavior suggests a very high initial contact resistance and a subsequent decrease in the resistance as the welding progresses. The high initial contact resistance is due to two main factors which are:

1. Coating film on the surface.
2. The surface roughness of the weldments.

The first factor has very little or no electrical conductivity and hence a high resistance. Therefore, even though the current may be low at the start of the process, a sharp increase in the contact voltage was observed. Above a certain voltage level, depending on the thickness of any coating or oil films present and the type and extent of the tarnish film, a breakdown of the surface films occurs; this results in an almost entirely metal-to-metal contact at the tips of the asperities in contact.

This type of contact produces a lower resistance to the flow of the current and hence the voltage begins to drop. The voltage continues to drop as long as there are more asperities coming in contact, a consequence of the increase in the real area of contact. The voltage becomes essentially constant when all the asperities have disappeared and there is a constant real area of contact. The actual fusion takes effect at the attainment of the steady state.

The parameter α_1 in the exponent is related to the rate at which the voltage approached its steady value from the highest value. The higher the value of α_1, the faster the attainment of the steady state from the same level. Steady state here refers to the attainment of a constant real area of contact, which is depicted by a constant contact voltage. The bulk of fusion takes place after the steady state is reached and current heats the contacting zone; while in the transient state, part of the current is used to break down the surface film and to remove the surface asperities. All this suggests that, with a higher α_1 value, contact voltage decay will be faster and the weld could be better.

For the same welding conditions and the same sample, it is expected that the process that produces a higher value of α_1 would have better quality welds. However, the value of C_{21}, which is the initial slope of the fundamental frequency, also influences the time taken for the contact voltage to reach its highest value. An increase in C_{21} tends to decrease the time which elapses before the highest voltage point is reached, and hence provides enough time for the actual fusion process (Ref. 10). A new parameter β ($= C_{21}/\alpha_1$) is therefore used as the influencial parameters of the contact voltage. As C_{21} increases, the value of β increases.

It was observed during the modeling procedure that C_{21} and α_1 were highly correlated with a correlation coefficient ranging from 0.85 to 0.98. This means that as C_{21} increases, the value of α_1 also increases. This suggests that the parameter β is property of the surfaces in contact—notably, the surface roughness and oil films.

Table 2 shows the results of the experiments which were performed to ascertain the relationship between β and the nugget size of the weld. The predicted values of β closely agreed with the estimated values. The mathematical relationship between the nugget size (D_n) and β is hence represented by:

$$D_n = Y \cdot \beta \qquad (2)$$

The value of Y is expected to be a function of several variables such as the weld material property and thickness, the electrode material property and tip diameter. This value can be easily established for a particular setting through linear least squares methods. The value of β is also dependent on the welding conditions of current, squeeze time and contact load, which are normally fixed, and such uncontrollable variables as the nature of the surface roughness and surface cleanliness. The uncontrollable variables make β more unpredictable, and hence there is the need to monitor it during the welding process.

The predicted values of the nugget size using equation (2) have been presented alongside the actual estimated values in Table 2 for comparison. These estimated values from the experiment agree well with the predicted values with Y = 37.66 as obtained by linear least squares methodology.

Relationship Between Stochastic Model Parameters and Weld Quality

The dynamic data system (DDS) modeling technique was used to obtain the adequate discrete stochastic model for the digitized contact voltage signals. The statistically adequate model was found to be ARMA (Ref. 8, 7) in each case with a sampling interval of 1 millisecond. The form of the model is as given below and described further in the Appendix:

$$V_t = \sum_{i=1}^{8} \phi_i V_{t-i} + A_t - \sum_{j=1}^{7} \theta_j A_{t-j}$$

The existing frequencies in the system are obtained from the autoregressive roots (λ_i), while the driving force is given by the moving average roots (ν_i). These roots are given in Tables 3 and 4 together with their dispersions—see Appendix. The dispersion analysis provides information about the relative percentages of the frequencies present in the signal. It can be considered to be a measure of the contribution of the particular frequency in relation to the others in the signal.

It was observed that the closer the

Table 3—ARMA [Ref. 8, 7] Model Parameters for Good Welds

	Example A			Example B		
Roots	Value	Freq., Hz	D_i, %	Value	Freq., Hz	D_i, %
Autoregressive roots:						
λ_1, λ_2	−0.847 ± 0.325i	441.66	0.003	−0.834 ± 0.454i	420.63	0.13
λ_3, λ_4	0.929 ± 0.369i	60.12	99.99	0.938 ± 0.368i	60.14	98.46
λ_5, λ_6	0.421 ± 0.905i	180.71	0.004	0.423 ± 0.905i	180.33	1.27
λ_7, λ_8	−0.354 ± 0.876i	311.12	0.003	−0.306 ± 0.948i	299.68	0.14
Moving average roots:						
ν_1, ν_2	0.633 ± 0.167i			−0.255 ± 0.927i		
ν_3, ν_4	−0.435 ± 0.726i			0.429 ± 0.851i		
ν_5, ν_6	0.356 ± 0.783i			−0.706 ± 0.514i		
ν_7	−0.861			0.847		

dispersion of the fundamental frequency (60 Hz) is to 100%, the better the weld is, if all other conditions remain equal. This observation can be explained by the fact that there is less distortion of the voltage when the other harmonics are less important. A dispersion of less than 95% of the fundamental frequency was observed here to be intolerable, since the other harmonics become more important.

Earlier investigators have observed that the total area under the curve of the electrode-to-electrode voltage against weld time gives an indication of the weld quality. Various controllers have been built based on this observation to compensate for the loss of the supply voltage, the most recent being controlled by a minicomputer (Ref. 7). Hence the nature of the voltage flowing in terms of its wave-form would influence the integration and the decisions made.

The third harmonic increases the number of zero crossings of the voltage within a given period of time. Every zero crossing means that there is no fusion, since there is no current flowing at that particular time. For each half cycle of the fundamental frequency, the current passes through the weldment with a varying amplitude which is not equal to zero and hence produces little or no fusion.

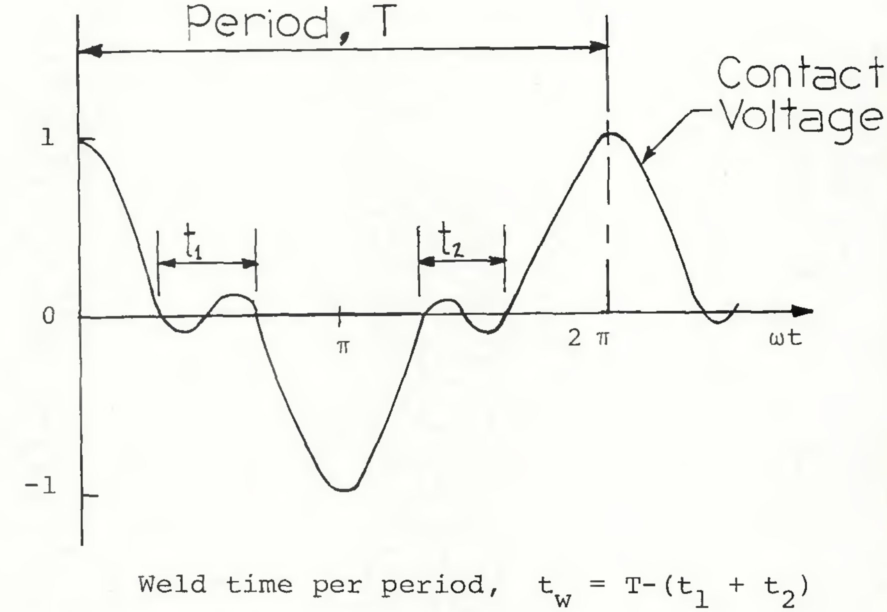

Fig. 3—Sketch showing actual weld time per period

The total amount of fusion, which represents the penetration, is the sum of all the various infinitesimal fusions which are produced by each half cycle of the current. The contact voltage follows the same wave-form as the supply current, and the amount of fusion at a particular half-cycle depends on the amplitude of the contact voltage at the steady condition and the time it takes to go to the zero-crossing point. The increase in the number of the zero-crossings tends to decrease this time. The amplitudes of the smaller cycles near the zero-crossings

Table 4—ARMA [Ref. 8, 7] Model Parameters for Bad Welds

	Example A			Example B		
Roots	Value	Freq., Hz	D_i, (%)	Value	Freq., Hz	D_i, %
Autoregressive roots:						
λ_1, λ_2	−0.856 ± 0.458i	421.82	0.75	−0.848 ± 0.458i	421.12	1.31
λ_3, λ_4	0.939 ± 0.369i	60.14	94.16	0.929 ± 0.368i	60.09	94.59
λ_5, λ_6	0.423 ± 0.905i	180.42	4.52	0.424 ± 0.905i	180.26	1.30
λ_7, λ_8	−0.310 ± 0.932i	301.11	0.57	−0.305 ± 0.878i	303.16	2.72
Moving average roots:						
ν_1, ν_2	−0.126 ± 0.802i			0.470 ± 0.091i		
ν_3, ν_4	0.469 ± 0.772i			−0.711 ± 0.586i		
ν_5, ν_6	−0.679 ± 0.600i			0.390 ± 0.883i		
ν_7	0.812			0.084		

may also not be high enough to produce any fusion which accentuates the loss of valuable weld times.

This situation is depicted in Fig. 3. If the magnitudes of the voltage between t_1 and t_2 are not significant, the actual weld time in one period is seen to be equal to $t = T - (t_1 + t_2)$ which constitutes a loss of valuable weld time.

The loss of the weld time could have an adverse effect on the depth of penetration. An increase in the weld time to offset the loss due to the presence of the other harmonics as indicated by the DDS methodology could remedy the situation. A process control scheme would be needed for the decision making process for the attainment of the required weld quality.

Conclusions

1. A fairly good approximation of the progress of the welding process can be deduced by monitoring and deterministic modeling of the voltage drop within the contact zone. The rate of attainment of the steady-state condition is indicated by β ($= C_{21}/\alpha_1$) which is obtained through the deterministic modeling of the contact voltage. Low values of β could cause incomplete fusion, while higher values indicate improved nugget size up to the limiting value of β where splashing occurs.

2. The monitored contact voltage could be significantly distorted due to the presence of several frequencies superimposed on each other. The distortion of this voltage subsequently affects the continuity of the fusion process due to voltage cancellations at each half cycle; voltage distortion also could affect the switching circuitry of the machine and thus the weld quality.

3. The contact voltage may be represented by a statistically adequate ARMA model. The characteristics of the adequate model can be used to quantify the distortion effects of the welding voltage due to the presence of the odd harmonics. The amount of distortion is insignificant when the supply voltage frequency of 60 Hertz constitutes 95% to 100% of the existing frequencies in the contact voltage signal. The percentages of the supply voltage components are obtained through dispersion analyses, which are part of the ARMA modeling procedure.

4. The characteristic behavior of the contact voltage and its wave-form dispersion analysis can be incorporated in a monitoring system that can obtain the peak level of the supply voltage. As a result, an effective control procedure can be established for the process through the fast data processing capabilities of modern minicomputers to obtain consistently good quality resistance welds.

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Appendix: Mathematical Formulation

Autoregressive Moving Average Models

The general form of the discrete representation of the contact voltage signal was considered to be an Autoregressive-Moving Average Model, ARMA (n, m) of order n (Ref. 9). This is mathematically written as:

$$V_t = \sum_{i=1}^{n} \phi_i V_{t-i} + A_t - \sum_{j=1}^{m} \theta_j A_{t-j} \qquad \text{(A1)}$$

where ϕ_i's are the autoregressive parameters, θ_i's are the moving average parameters, and A_t is a random variable for a fixed time t or a stochastic process of different values at t (Ref. 8, 9) whose probabilistic behavior is characterized by the distribution property:

$A_t \sim NID\ (0, \sigma_a^2)$

where σ_a^2 is the variance of A_t and NID means Normally and Independently Distributed.

Alternatively,

$E\ (A_t) = 0$

$E\ (A_t \cdot A_{t-y}) = \delta_y \sigma_a^2$

where δ_y is the Kronecker delta function.

$$\delta = \begin{cases} 1 \text{ for } y = 0 \\ 0 \text{ for } y \neq 0 \end{cases}$$

and E is the expectation sign. V_t is the voltage at time t.

Equation (A1) can be factorialized and re-written as:

$$(1 - \lambda_1 B)(1 - \lambda_2 B) \ldots (1 - \lambda_n B) V_t = (1 - \nu_1 B)(1 - \nu_2 B) \ldots (1 - \nu_m B) A_t \qquad \text{(A2)}$$

where λ_i are the autoregressive roots, ν_i are the moving average roots and B in a backshift operator ($B^n V_t = V_{t-n}$)

Dispersion Analysis

The autocovariance function of lag y for the discrete model is defined as:

$\gamma_y = E\ [V_t \cdot V_t - y]$

It can be shown that the autocovariance function is a weighted linear combination of the autoregressive roots (Ref. 9), i.e.:

$$\gamma_y = d_1 \gamma_1^y + d_2 \gamma_2^y + \ldots + d_n \gamma_n^y \qquad \text{(A3)}$$

where d_i is the weight of root λ_i and given by:

$$d_i = \sigma_a^2 g_i \sum_{r=1}^{n} \frac{g_r}{1 - \lambda_i \lambda r} \qquad \text{(A4)}$$

and

$$g_i = \frac{\sum_{y=1}^{m} (1 - \nu_y/\lambda_j)}{\sum_{\substack{y=1 \\ y \neq j}}^{n} (1 - \lambda_y/\lambda_j)} \qquad \text{(A5)}$$

The variance of the series is given by:

$$\lambda_0 = d_1 + d_2 + \ldots + d_n \text{ for } y = 0 \qquad \text{(A6)}$$

The dispersion, D_i, is basically the contribution of the root(s) or ultimately the frequencies in the series and given as:

$$D_i = \frac{d_i}{\lambda_0} \qquad \text{(A7)}$$

A pair of complex conjugate roots provide one frequency and hence when d_i and d_{i+1} are complex conjugates,

$$D_i = \frac{d_i + d_{i+1}}{\lambda_0} \qquad \text{(A8)}$$

By decomposing the signal into its various frequencies and by applying the dispersion analysis method, an order of merit of the existing frequencies can be established as discussed in the paper.