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A Superresolution Technique for Antenna Pattern Measurements

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SUMMARY A new superresolution technique is proposed for antenna pattern measurements. Unwanted reflected signals often impinge on the antenna when we measure it outdoors. A time-domain superresolution technique (a MUSIC algorithm) has been proposed to eliminate the unwanted signal for a narrow pass-band antenna. The MUSIC algorithm needs many snapshots to obtain a correlation matrix. This is not preferable for antenna pattern measurements because it takes a long time to obtain the data. In this paper, we propose to reduce a noise component (stochastic quantity) using the FFT and gating techniques before we apply the MUSIC. The new technique needs a few snapshots and saves the measurement time.

key words: *antenna pattern measurements, MUSIC algorithm, fast Fourier transform, gating technique*

1. Introduction

In measurements of gain and radiation pattern for a large aperture antenna, a measurement system must be constructed outdoors to achieve a far-field range. In this case, reflected signals from the ground and other objects often impinge on the antenna, and the measured data are disturbed by them. A recently developed vector network analyzer provides time-domain processing based on the fast Fourier transform (FFT). We can mathematically remove the unwanted responses that appear as ripples in the frequency domain by gating them in the time-domain presentation [1], [2]. However, desired (direct path) and unwanted (e.g. ground path) responses must be clearly separated in the time-domain presentation. Thus, the difficulty often arises in measuring narrow pass-bandwidth antennas. Furthermore, outdoor wideband antenna measurements are not preferable because the wideband radiation may interfere with another radio system, and because the measurement system may be interfered by another radio system.

Superresolution techniques have been proposed for time-domain measurements with a network analyzer [3], and time-domain scattering studies [4]. The authors have proposed antenna gain measurements [5] using a MUSIC algorithm [6], and have shown that we can measure the antenna gain using much narrower frequency bandwidth data in comparison with the conventional FFT based time-domain processing. However, the MUSIC algorithm usually needs many sets of frequency-domain data (snapshots) to estimate a correlation matrix. We used 50 snapshots to obtain the antenna gain [5]. However, it is not preferable to need many snapshots for the antenna pattern measurements because it takes a very long measurement time. It should be noted that we must obtain the response of antenna at each angle of rotation for the antenna pattern measurements. Signal components in the measurements are deterministic quantities, and we need only a single snapshot to estimate the correlation matrix for the signal. The reason why we need many snapshots is because there exists noise which is a stochastic quantity. If the number of snapshots is not enough, we cannot obtain the accurate noise correlation matrix, and the cross term between the signal and noise cannot be ignored.

In this paper, a new superresolution method which employs the MUSIC algorithm accompanied with the FFT and gating techniques. We consider a case where the desired and unwanted responses are closely located in the time domain. Thus, the conventional FFT and gating techniques cannot remove the unwanted signals. In this paper, the FFT and gating are used for reducing the power of random noise. When the noise is reduced substantially, we need only a few snapshots to apply the MUSIC algorithm.

In Sect. 2, we formulate the problem and propose the new method. In Sect. 3, we show the effect of the method using computer simulations. We show experimental results in Sect. 4. Section 5 contains conclusions.

2. Formulation of the New Method

We assume that we have a direct path and a single reflected path. The formulation stated below can be straightforwardly expanded into more complicated multipath environment. We denote propagation

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delays of the direct and reflected responses as t_1 and t_2, respectively. The measured value at frequency of f is given by

$$r(f)=s_1e^{-j2\pi ft_1}+s_2e^{-j2\pi ft_2}+n(f) \quad (1)$$

where s_1 and s_2 denote the signal parameters (amplitude and phase) of the direct path and reflected path, respectively. Also, $n(f)$ denotes a noise component. We assume that s_1 and s_2 are independent of frequency in a narrow frequency band. If s_1 is estimated at each angle of rotation, we can obtain the antenna pattern.

In Eq. (1), $n(f)$ is an only stochastic quantity. It should be noted that $s_1e^{-j2\pi ft_1}$ and $s_2e^{-j2\pi ft_2}$ are transmission coefficients (S_{21}), and then they are deterministic quantities. Were it not for the noise, we would be able to apply the MUSIC algorithm with a single snapshot. This is because we can obtain the correlation matrix using a single snapshot. Thus, if we reduce the noise component drastically, we can apply the MUSIC algorithm with only a few snapshots. Our goal is to apply the MUSIC algorithm using a single snapshot.

Now, we describe the method to reduce the noise drastically. At first, we obtain the frequency-domain data using measurement equipment such as a network analyzer. We denote the sampling frequency separation as δf. We get the time-domain response by means of the inverse FFT (IFFT). The signal responses concentrate on the time around $t=t_1$ and $t=t_2$. However, the noise component distributes over a whole unambiguous region ($1/\delta f$). δf is determined in such a way that we have $1/\delta f \gg t_2-t_1$. If we extract the time-domain response around the time t_1 and t_2 by the gating technique, the signals are not damaged but the noise component outside the gating filter is suppressed in the time domain. Since $1/\delta f \gg t_2-t_1$, we can reduce the noise drastically. Also, we transform the gated time-domain response into the frequency domain by the FFT. We again have the frequency-domain data given by the same formula as Eq. (1). However, the noise component is reduced compared with the raw data by the above time-domain gating processing.

Reducing the noise by the time-domain gating is similar to that by decimation [7] used for autoregressive spectral estimation. However, the time-domain processing is easier than the decimation to reduce the noise keeping the signal components unchanged. This is because we can see the signal components in the time-domain presentation.

The time-domain gating described above can be used also for removing out-of-range signals, and this effect also improves the resolution. For this purpose, the technique has been used for scattering studies [4], [8].

3. Simulation Results

In order to show the performance of the new superresolution technique, we made computer simulations. We employed a monopole antenna of the length 3 cm and diameter 1 mm for the antenna under test (AUT). We obtained the necessary electric characteristics of the monopole antenna using the moment method. We assumed that two signals (the direct path and reflected path) are incident on the antenna as stated in the previous section, and that we have $t_1=0$ nsec and $t_2=5$ nsec. Also, we assumed that the direct and reflected path outputs (s_1, s_2) from the AUT at the frequency of 2.205 GHz are given by 0.05∠0° and 0.02∠0°, respectively. 2.205 GHz was the first frequency (f_1) in a frequency band when we applied the MUSIC algorithm. The noise component was generated by a white Gaussian random number with mean 0 and variance 10^{-6}.

First, we show the results of the conventional IFFT technique. Figure 1 shows the time-domain

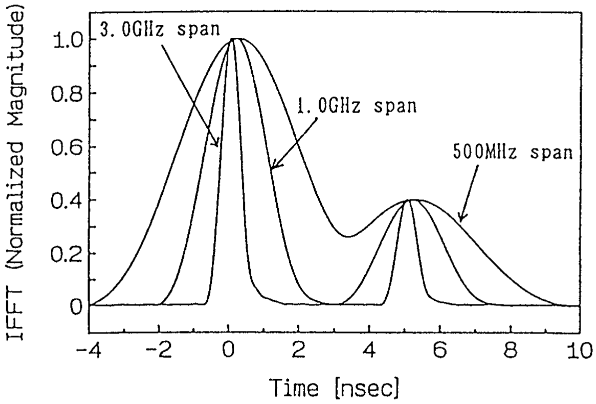


Fig. 1 Time-domain analysis using the IFFT.
500 MHz span: The frequency band is from 2.0 GHz-2.5 GHz.
1.0 GHz span: The frequency band is from 2.0 GHz-3.0 GHz.
3.0 GHz span: The frequency band is from 2.0 GHz-5.0 GHz.

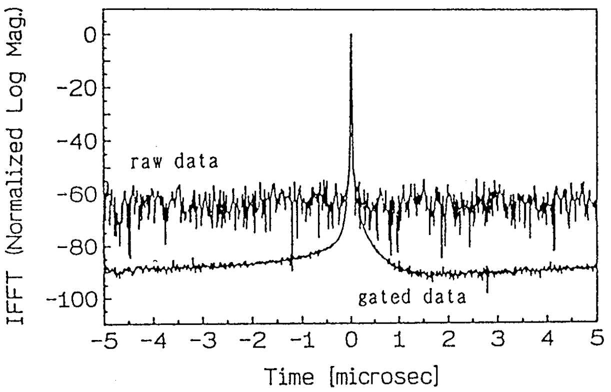


Fig. 2 Time-domain responses of raw data and gated data.
Gate center: 0 nsec.
Gate span: 100 nsec.

analysis calculated by the IFFT. As we see from this figure, the two peaks corresponding to the direct and reflected signals can be detected by 500 MHz bandwidth data. However, since the skirts of each response are overlapped with each other, the gating technique will not work properly. We need at least 1 GHz bandwidth data to apply the gating. It is conjectured that sidelobes for the two responses are overlapped each other for 1 GHz bandwidth data, and that we may have some error when we apply the gating. It is preferable to use about 3 GHz bandwidth data to remove the unwanted reflected signal.

Now, We show simulation results of the MUSIC algorithm accompanied with the FFT and gating techniques. Figure 2 shows the time-domain responses (raw data) given by the IFFT. The frequency band is from 2.20 GHz to 2.28 GHz, and the number of sampling points is 801. Because the bandwidth of the frequency-domain data is narrow (80 MHz), the two responses are not resolved. However, they concentrate on the time around 0 nsec. Since $\delta f=100$ KHz, the noise distributes from -5 μsec to 5 μsec ($1/\delta f=10$ μsec). We see that the noise level ranges from about -80 dB to about -60 dB. We suppressed the noise outside the signal response by the gating technique. The gated response is also shown in Fig. 2 (gated data). We can see that the noise is strongly suppressed outside the signal response.

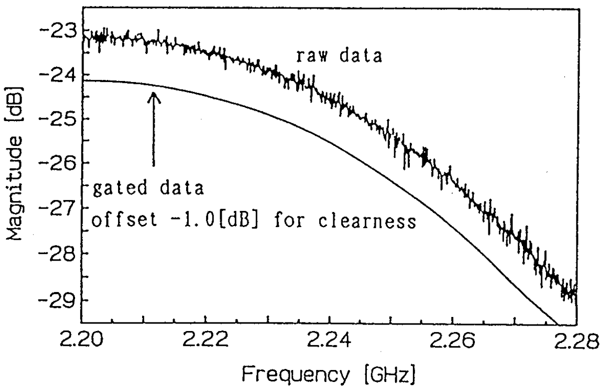
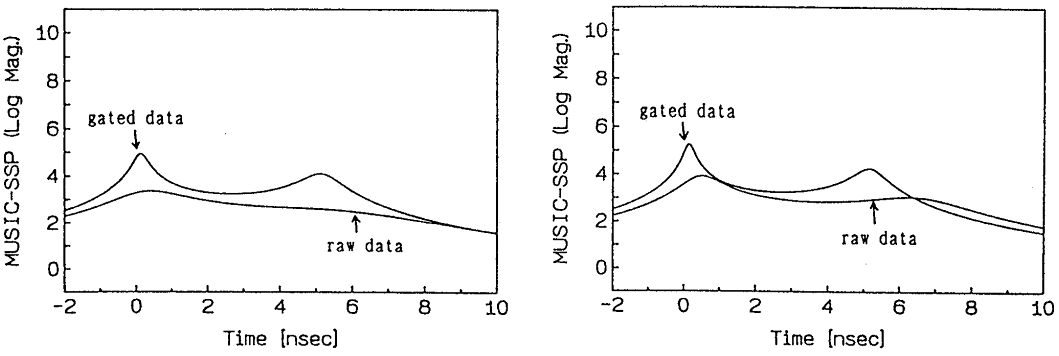


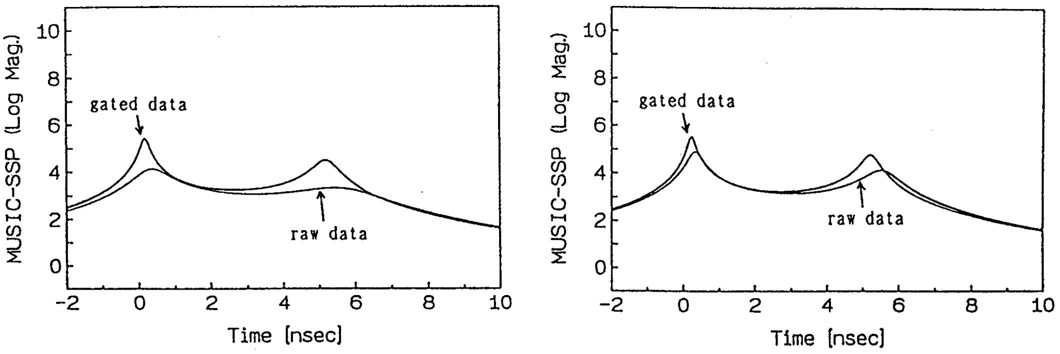
Fig. 3 Effect of gating in the frequency domain.

We transformed the gated time-domain data into the frequency domain by the FFT. Figure 3 shows the frequency-domain response (magnitude) of the gated data. The figure shows also the raw data. We can see that although the raw data are disturbed by the noise, the noise is reduced drastically by the gating technique.

Figure 4 shows time-domain responses given by the MUSIC algorithm. Spatial smoothing preprocessing [9] was employed to destroy signal coherence [3]. f_1 and Δf represent the first frequency and frequency increment in the band, respectively. M denotes the number of subarrays used for the spatial smoothing preprocessing. Furthermore, N represents the number of elements in each subarray. We have N eigenvalues and N eigenvectors. Refer to the literature [3] for



(a) 1 snapshot (b) 5 snapshots



(c) 10 snapshots (d) 50 snapshots

Fig. 4 Time-domain responses given by the MUSIC algorithm. $f_1=2.205$ GHz, $\Delta f=2.5$ MHz, $N=20$, $M=10$.

details of those parameters and the time-domain MUSIC algorithm. Peak positions in Fig. 4 indicate time delays. Each peak diverges in an ideal case (no noise or infinite snapshots). Note that the peak value does not indicate the magnitude of signal. Using the delay time estimated by the peak position, we can calculate the magnitude of signal.

We see from Fig. 4 that the new superresolution technique (gated data) can resolve two signals using only a single snapshot. However, the conventional MUSIC algorithm (raw data) needs more snapshots. Although two peaks are barely resolved by the conventional MUSIC using 5 snapshots or 10 snapshots, we need 50 snapshots to resolve them clearly.

70 MHz bandwidth data (2.205 GHz-2.275 GHz) were used for the MUSIC algorithm. It should be noted that we needed slightly wider bandwidth (80 MHz) to reduce the noise by gating. Namely, the data ranging from 2.20 GHz to 2.28 GHz were used for the gating.

Table 1 shows the magnitude of direct path signal estimated by the conventional and proposed MUSIC algorithms. Table 1 shows also the result of the FFT and gating techniques (FFT-GATE). Those values are the magnitude at frequency of 2.205 GHz. Each technique estimates almost exact value (0.05). 3 GHz bandwidth data were used for the FFT and gating. On the other hand, the proposed MUSIC algorithm required only a single snapshot of 80 MHz bandwidth data. From these simulation results, we can say that the proposed MUSIC algorithm is useful for measuring the pattern of narrow pass-bandwidth antenna.

From Table 1, we see that the more snapshots we use, the more accurate estimate value we obtain for the MUSIC algorithm. However, the discrepancies between the estimated values and the true value (0.05) are very small. We can obtain almost the same patterns for those snapshots except the conventional MUSIC algorithm with a single snapshot. Since the conventional MUSIC algorithm using a single snapshot cannot eliminate the unwanted signal, it provides an erroneous pattern.

Table 1 Estimated magnitude of the direct path signal at frequency of 2.205 GHz.

	Magnitude
Conventional MUSIC	
1 snapshot	not resolved
5 snapshots	0.052584
10 snapshots	0.050668
50 snapshots	0.050467
Proposed MUSIC	
1 snapshot	0.048363
5 snapshots	0.048474
10 snapshots	0.048656
50 snapshots	0.049171
FFT-GATE (3.0GHz span)	0.049318

Note that the conventional MUSIC algorithm estimates a more accurate value than the proposed MUSIC algorithm for 10 snapshot and 50 snapshot cases. When we have sufficient snapshots, the conventional MUSIC algorithm can obtain the accurate value. Although the proposed technique reduces the noise dramatically, it cannot be suppressed completely. The noise component in the time gate remains. Although the original noise is white, the residual noise is correlated in the frequency domain because of the time-domain gating (filtering in the time domain). The correlation was ignored when we applied the MUSIC algorithm. Furthermore, although the gate span was sufficiently wide (100 nsec), a portion of signal components were slightly destroyed by the time-domain gating. These are the reasons why the conventional MUSIC algorithm provides a more accurate value than the proposed algorithm for many snapshot case.

4. Antenna Pattern Measurements

We carried out antenna pattern measurements. Figure 5 shows a setup of the measurement system. We employed the double ridged guide antenna (EMCO Model 3115) for the AUT. We placed the AUT and metal plate in a radio anechoic chamber. Then, we had an intentional reflected path other than the direct path. The delay difference between the direct and reflected path signals is about 1.4 nsec when the AUT is pointed toward a transmitting antenna. The delay difference can change when the AUT is rotated because the delay time in the antenna is in general dependent on an angle. The frequency-domain data were obtained by the network analyzer system (HP8510B) every 6 degrees of rotation. Figure 6 shows the antenna patterns at frequency of 5.2 GHz. We can see that the measured pattern (raw data with a metal plate) is distorted due to the reflected signal by the metal plate. The distortion is recognized from 0° to 60°.

In Fig. 6, we also show the following results.

(1) The antenna pattern which was obtained by suppressing the reflected signal using the conventional FFT and gating techniques (FFT-GATE). The required frequency bandwidth was 6 GHz (5 GHz -11 GHz). The pattern is drawn by the line --⊖--.

(2) The antenna pattern which was obtained by suppressing the reflected signal using the proposed superresolution technique (the MUSIC algorithm accompanied with the FFT and gating techniques). We used a single snapshot of 800 MHz bandwidth data (5.04 GHz-5.84 GHz, $\delta f = 2$ MHz, 401 data points) to reduce the noise component by gating. As stated previously, the delay difference can change when the AUT is rotated. The gate span (12 nsec) was determined wide

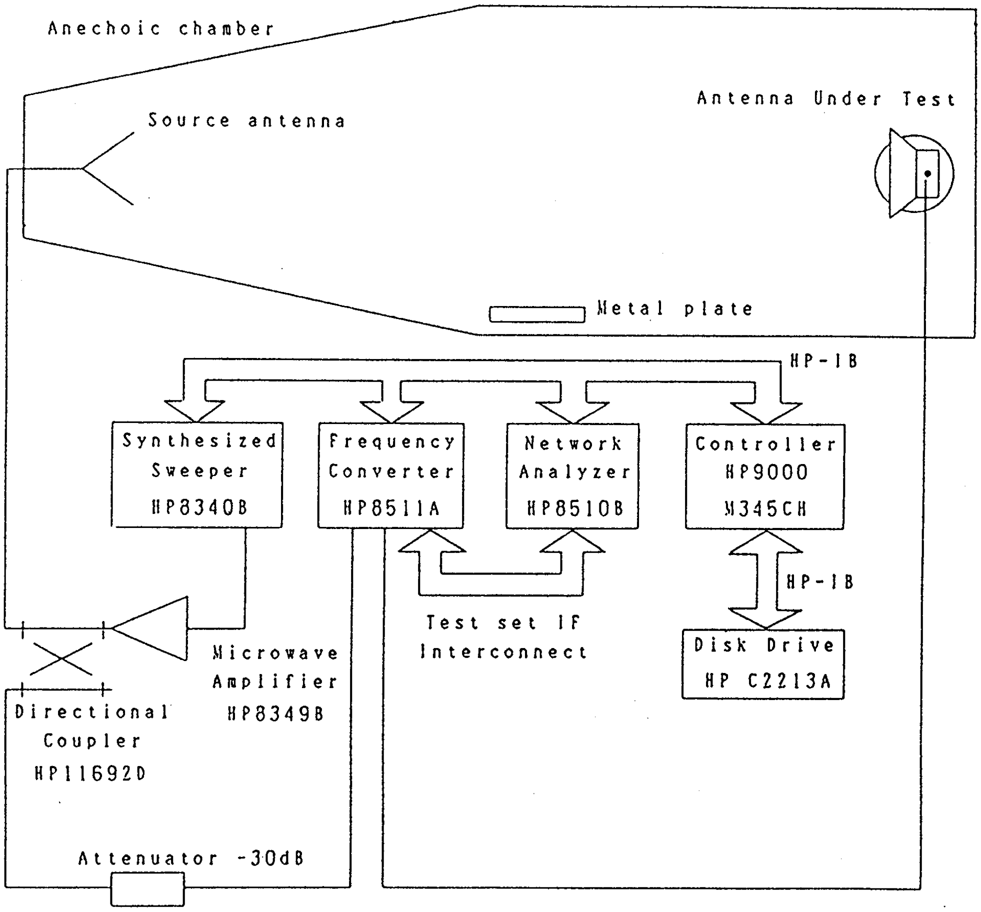


Fig. 5 A setup of the measurement system.

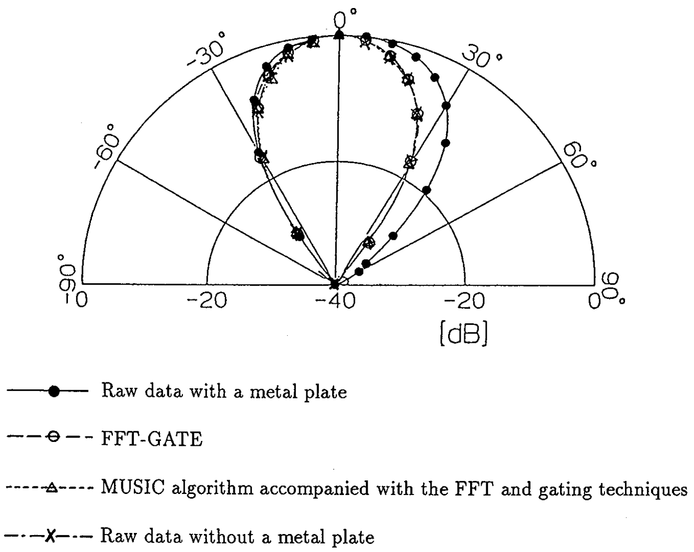


Fig. 6 Antenna patterns.

enough to cover the change. We employed the spatial smoothing preprocessing to destroy the signal coherence. The parameters used for the MUSIC are as follows: $f_1=5.2$ GHz, $\Delta f=6$ MHz, $N=46$, $M=23$. The pattern is drawn by the line - - -△- - -.

(3) The antenna pattern without the metal plate. This is the actual pattern of the AUT. The pattern is drawn by the line —·—×—·—.

From Fig. 6, we see that these three patterns ((1)-(3)) coincide with each other very well. It is seen that if we employ the proposed superresolution technique, we can obtain the antenna pattern using a single snapshot of 800 MHz bandwidth data for this case. Compared with 6 GHz bandwidth data required by the conventional FFT and gating techniques, we can say that the superresolution technique can obtain the antenna pattern using much narrower frequency bandwidth data. Furthermore, we need only a single snapshot, and then the superresolution technique proposed in this paper saves the measurement time.

5. Conclusions

In this paper, we have proposed antenna pattern measurements using the MUSIC algorithm accompanied with the FFT and gating techniques. From the computer simulation results and experimental results, it has been shown that the new superresolution technique needs fewer snapshots than the conventional MUSIC, and that the technique is useful for the pattern measurement of narrow pass-bandwidth antennas. The superresolution technique saves the measurement time.

As stated in Sect. 2, the gating technique removes also out-of-range signals and improves the resolution.

The technique will be useful also for microwave/millimeterwave circuit measurements.

The narrower the gate span (the width of gate in the time domain) is, the more the noise is reduced. However, the too narrow gate span destroys the signals and impedes the proper work of the MUSIC algorithm. The gate span was determined sufficiently wide in this paper. Thus, the effect of the narrow gate span was not clearly seen in this paper. The optimum value of gate span should be studied further in future. Furthermore, as stated in Sect. 3, the noise is correlated after the time-domain gating. If we use generalized eigenvalues and eigenvectors which are obtained taking the noise correlation into account [6], we will be able to estimate a more accurate value. This should be also studied in future.

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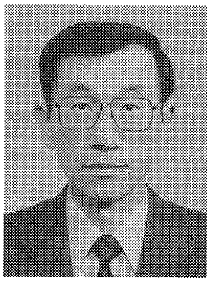

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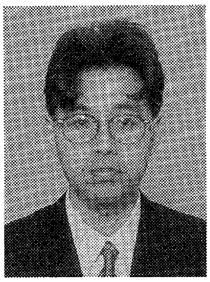

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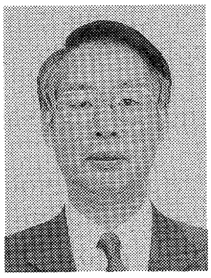

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