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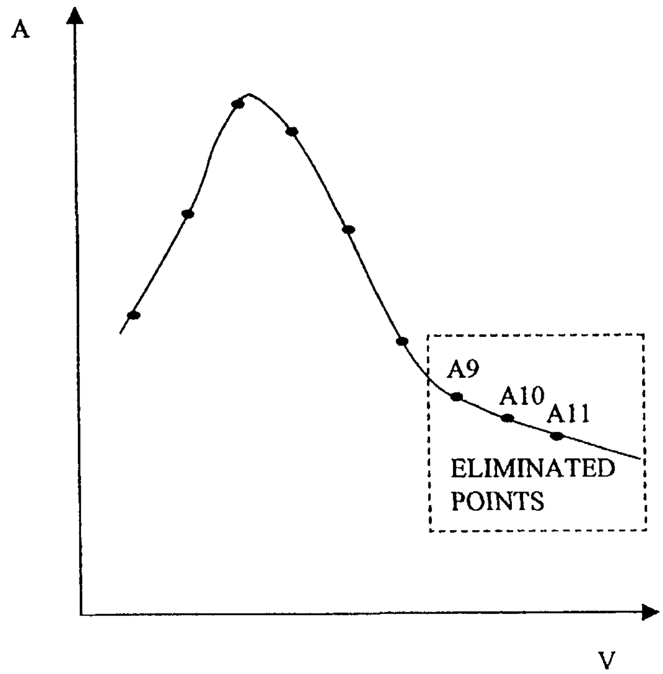
(54) Title: METHOD FOR IMPROVING THE ACCURACY IN THE DETERMINATION OF A WAVEFORM CENTER

(57) Abstract

Prior to performing a centroid calculation on a waveform that is discretely sampled at a limited number of sample points, the last sample point (V_N, A_N) is eliminated if the magnitude of the amplitude at the first sample point (A_1) is greater than the last sample point (A_N), and the difference in magnitude between the first and last sample points (A_1–A_N) is greater than the difference in magnitude between the second to last sample point and the first sample point (A_{N-1}–A_1). The first sample point (V_1, A_1) is eliminated prior to the centroid calculation if the magnitude of the amplitude at the last sample point (A_N) is greater than the first sample point (A_1), and the difference in magnitude between the last and first sample points (A_N–A_1) is greater than the difference in magnitude between the second sample point and the last sample point (A_2–A_N). In a second embodiment of the invention, a first centroid calculation is performed using a set of samples in which one side of the waveform has the lowest amplitude value sample. Sample values on the side of the waveform initially having the lowest amplitude value are then eliminated until the opposing side of the waveform has the lowest amplitude value sample. A second centroid calculation is then performed and the two centroid calculations are averaged together to arrive at an average centroid calculation. In a third embodiment of the invention, the amplitude components of the waveform sample values are normalized to the lowest amplitude value sample point and a first centroid calculation is performed on the normalized waveform. Next, the waveform is normalized to the lowest amplitude value sample point on the other side of the waveform and a second centroid calculation is performed. The two centroid calculations are then averaged to provide an averaged normalized centroid calculation.



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METHOD FOR IMPROVING THE ACCURACY IN THE DETERMINATION OF A WAVEFORM CENTER

Technical Field

The present invention relates to signal processing, and more particularly to the determination of a center value of a waveform.

Background of Invention

Often it is necessary to determine a center value, such as a center wavelength, of a waveform to a high precision. The degree of precision required for different applications varies, but often precision better than 1 part in 300 of the full width at half max (FWHM) of the waveform is required. A simple technique to determine the center of a waveform is to use a centroid (or center of mass) calculation over an area of interest. For a discretely, evenly sampled waveform the basic equation for the calculation of the centroid is:

$$V_C = \frac{\sum_N V_N \cdot A_N}{\sum_N A_N} \qquad (1)$$

where N is the total number of samples for each value (V_N), and A_N is the sampled amplitude. As seen in the above equation each sample point is weighted by the amplitude at that point. This calculation can be performed quickly on a sampled waveform and is therefore useful in real-time computer algorithms. Equation 1 can be used for example to determine the center wavelength (λ_C) of a waveform where a number N of discrete power level (P_N) measurements are taken for each wavelength (λ_N).

The number of sampled points in the calculation is critical when using

Equation 1, ideally the samples should span the entire waveform of interest. However, in practical applications this is not always possible due to factors such as sampling rates and memory requirements. In this case, a fixed number of sample points around the peak value of a waveform can be used. However, the locations of the sampled points will introduce errors in the determination of the waveform center provided the points are not perfectly symmetric around the waveform. Figs. 1-3 illustrate examples of sampled waveforms using a fixed number of points, i.e., seven (7) points. In the example of Fig. 1, the sample points are distributed symmetrically over the waveform. However, in Fig. 2, the sample points are shifted relative to the symmetrical sampling locations in Fig. 1 resulting in an asymmetric distribution of the points over the waveform and consequently an error in the determination of the center due to the weighting of all the points in Equation 1. Fig. 3 illustrates the extreme case, where again seven discrete sample points are shown. The first point will effectively skew the calculation from the correct value. Fig. 4 illustrates the error associated with asymmetric distribution of discrete sample points. In particular, Fig. 4 shows the percent error in the calculation from the FWHM versus the phase difference between the sampled points and the waveform. For a 0-degree phase difference, the peak of the waveform coincides exactly with the center-sampled point. For a 180-degree phase shift, the waveform peak is exactly between two sampled points.

The sample error can be reduced by increasing the number of sample points. However, as indicated above, the number of sample points, and therefore the accuracy of centroid determination, is limited by the sampling rate and the available memory. There therefore exists a need for an improved method of determining a center wavelength of an arbitrary waveform, particularly where the waveform is discretely sampled at a limited number of sample points.

Summary of the Invention

Objects of the present invention include improved accuracy of the centroid calculation of a waveform.

According to a first embodiment of the present invention, a waveform is discretely sampled at a limited number of sample points, each sample point being a set (V_N, A_N) including a sample value (V_N) and an amplitude (A_N), and N being the number of non-eliminated sample points. Prior to performing a centroid calculation on the waveform, the last sample point (V_N, A_N) is eliminated if the magnitude of the amplitude at the first sample point (A_1) is greater than the last sample point (A_N), and the difference in magnitude between the first and last sample points (A_1-A_N) is greater than the difference in magnitude between the second to last sample point and the first sample point (A_{N-1}-A_1). The first sample point (V_1, A_1) is eliminated prior to the centroid calculation if the magnitude of the amplitude at the last sample point (A_N) is greater than the first sample point (A_1), and the difference in magnitude between the last and first sample points (A_N-A_1) is greater than the difference in magnitude between the second sample point and the last sample point (A_2-A_N).

In accordance with a second embodiment of the invention, a first centroid calculation is found using a set of samples in which one side of the waveform has the lowest amplitude value sample. Sample values on the side of the waveform initially having the lowest amplitude value are then eliminated until the opposing side of the waveform has the lowest amplitude value sample. A second centroid calculation is then performed and the two centroid calculations are averaged together to arrive at an average centroid calculation.

In accordance with a third embodiment of the invention, the amplitude components of the waveform sample values are normalized to the lowest amplitude value sample point and a first centroid calculation is performed on the normalized waveform. Next, the waveform is normalized to the lowest amplitude value sample point on the other side of the waveform and a second centroid calculation is performed. The two centroid calculations are then averaged to provide an averaged normalized centroid calculation.

The foregoing and other objects, features and advantages of the present invention will become more apparent in light of the following detailed description of exemplary embodiments thereof, as illustrated in the accompanying drawings.

Brief Description of the Drawings

Fig. 1 is a diagram of a discretely sampled waveform wherein the sample values are symmetrically distributed over the waveform;

Fig. 2 is a diagram of the discretely sampled waveform of Fig. 1 wherein the sample values are asymmetrically distributed over the waveform;

Fig. 3 is a diagram of the discretely sampled waveform Fig. 1 wherein the sample values are asymmetrically distributed over the waveform and wherein the peak of the waveform is exactly between two sample points;

Fig. 4 is a diagram showing the percent error in the calculation from the FWHM versus the phase difference between the sample points and the waveform of Figs. 1-3;

Fig. 5 is a diagram of a discretely sampled waveform wherein the sample values are asymmetrically distributed over the waveform, and showing the determination of whether one of the sample points should be eliminated prior to calculating the centroid of the waveform;

Fig. 6 is a flowchart of a subroutine for determining whether one of the sample points should be eliminated prior to calculating the centroid of the waveform of Fig. 5;

Fig. 7 is a diagram showing the percent error in the calculation from the FWHM versus the phase difference between the sample points and the waveform using the flowchart of Fig. 6 for determining the centroid of the waveform;

Fig. 8 is a diagram of a discretely sampled waveform wherein the sample values are asymmetrically distributed over the waveform;

Fig. 9 is a diagram of the discretely sampled waveform of Fig. 8 with the sample having the lowest magnitude amplitude eliminated;

Fig. 10 is a diagram showing the percent error in the calculation from the

FWHM versus the phase difference between the sample points and the waveform wherein the centroid calculations of the diagrams of Fig. 8 and Fig. 9 are averaged to determine a centroid of the waveform in accordance with a second embodiment of the invention;

Fig. 11 is a diagram of a discretely sampled waveform wherein the sample values are asymmetrically distributed over the waveform and wherein the waveform is offset in amplitude;

Fig. 12 is a diagram showing the percent error in the calculation from the FWHM versus the phase difference between the sample points and the waveform of Fig. 11, wherein the waveform is normalized prior to determination of its centroid; and

Fig. 13 is a diagram of a discretely sampled waveform wherein the sample values are asymmetrically distributed over the waveform and wherein a portion of the waveform is not sampled.

Detailed Description of the Invention

The present invention is particularly well suited for determining the center value (centroid) of a waveform. The present invention is particularly suitable for use with a waveform having a generally symmetrical distribution, e.g., a Gaussian or Lorentz relationship. However, the present invention is also suitable for use with waveforms having a generally asymmetrical distribution, such as a Rayleigh function.

The present invention will be described with respect to a waveform where the value of interest is wavelength and the amplitude of interest is the power. However, it will be understood by those skilled in the art that the present inventions may be used with any waveform representing a value and amplitude of interest.

As illustrated in Figs. 3 and 4, with a 180 degree phase shift (the waveform peak is exactly between two sampled points), one of the sample points (in this case the first point) effectively skews the calculation from the correct value. In accordance with a first embodiment of the invention, by eliminating one of the sample points under certain situations, thereby switching between an even and an odd number of sample points, the error in the calculation of center wavelength is significantly reduced.

Fig. 5 illustrates a waveform having an asymmetric distribution of seven sample points. The determination of whether or not a sample point should be eliminated can be performed using the subroutine of Fig. 6. Referring to Figs. 5 and 6, the subroutine is entered in a step 100, and in a step 101, the waveform of interest is sampled and the sample values (V_N, A_N) are stored in memory. In the present example, seven (7) samples are taken of the waveform. However, as described in greater detail herein, any number of samples may be used. Next, a test 105 is performed wherein the amplitude of the first sample (A_1) is compared to the amplitude of the last sample (A_7). If A_1 is less than A_7, steps 110 and 111 are consecutively performed wherein the difference in amplitude between A_1 and A_7 is determined (DA_1) and the difference in amplitude between the amplitude of the second sample (A_2) and A_7 is determined (DA_2). Next a test 115 is performed wherein the magnitude of DA_1 is compared to the magnitude of DA_2. If DA_1 is greater than DA_2, a step 117 is performed wherein the first sample point is eliminated. The centroid calculation of Equation 1 is then performed on the remaining points in step 120. If DA_1 is less than DA_2, the centroid calculation is performed on all of the sample points in step 120. The subroutine then returns to step 101 wherein discrete samples of a new waveform are taken and stored in memory.

If A_1 is greater than A_7,the results of the step 105 are positive, and the discrete samples are skewed to the other side of the waveform. In this case, steps 130 and 131 are performed wherein the difference in amplitude between A_1 and A_7 is determined (DA_3) and the difference in amplitude between the amplitude of the sixth sample (A_6) and A_1 is determined (DA_4). Next a test 135 is performed wherein the magnitude of DA_3 is compared to the magnitude of DA_4. If DA_3 is greater than DA_4, a step 137 is performed wherein the last sample point is eliminated. The centroid calculation of

Equation 1 is then performed on the remaining points in step 120. If DA_3 is less than DA_4, the centroid calculation is performed on all of the sample points in step 120. The subroutine then returns to step 101 wherein discrete samples of a new waveform are taken in stored in memory.

The centroid calculation of Figs. 5 and 6 provides a significant improvement over the prior art. Fig. 7 shows the reduction in centroid calculation error when the centroid is determined in accordance with the first embodiment of the invention. As can be seen from Fig. 7, the maximum percent error in the calculation from the FWHM versus the phase difference between the sampled points and the waveform using the first embodiment of the invention (as illustrated by curve 150) is cut in half with respect to the percent error if the centroid determination in accordance with the first embodiment of the invention is not used (as illustrated by curve 155).

In a second embodiment of the invention, further reduction in the errors associated with a centroid calculation can be achieved by averaging two centroid calculations for a given asymmetrically sampled waveform. Referring to Fig. 8, the first centroid calculation is found using a set of samples in which one side of the waveform has the lowest amplitude value sample. In this case, because of the asymmetry of the discrete samples, the centroid calculated is slightly below the true center. Referring now to Fig. 9, for the same set of samples, sample values on the side of the waveform initially having the lowest amplitude value are eliminated until the opposing side of the waveform has the lowest amplitude value sample. A second centroid calculation is then performed using Equation 1. The two centroid calculations are then averaged together to arrive at an average centroid calculation. Since the centroid calculated for the sample values of Fig. 9 are slightly high, due to the asymmetry, the average of the two centroid calculations greatly reduces the errors in the calculation when the sample points are not exactly symmetrically located around the waveform. Figure 10 shows an example of the reduction in centroid calculation error achieved using this averaging technique. Curve 160 is the percent error using the second embodiment of the invention and curve 165 is the percent error using no correction in accordance with the present invention.

Referring now to Fig. 11, under certain circumstances, the samples may not span the entire waveform, or the amplitude values may not return to zero. In this case, an additional error may be introduced in the centroid calculation associated with the offset of the waveform from zero. In particular, the centroid calculation will be biased towards the centroid of the offset area. For a large offset area, this biasing effect can negate the effects of the waveform shape itself. A third embodiment of the invention is particularly useful for reducing errors in the calculation of the centroid of the waveform of interest, especially when the waveform contains a fixed offset. In accordance with the third embodiment of the invention, the amplitude components of the waveform sample values are normalized to the lowest amplitude value sample point. Fig. 11 shows that an offset sampled waveform is equivalent to the actual waveform of interest on top of a fixed offset, or an offset "box" 170. Elimination of this "box" by normalization of the waveform amplitude to the lowest amplitude value sampled point will minimize the offset associated errors in the calculation. After normalization, a centroid calculation is performed on the normalized waveform. Next, sample values on the side of the waveform initially having the lowest amplitude value are eliminated until the opposing side of the waveform has the new lowest amplitude value sample. The waveform is then normalized to the new lowest amplitude value sample point and a second offset box 175 is eliminated prior to a second centroid calculation being performed. The two centroid calculations are then averaged to provide an averaged normalized centroid calculation. Figure 12 shows an example of the reduction in centroid calculation error achieved with an averaged normalized centroid calculation.

Although the third embodiment of the invention is described herein as eliminating an "offset box", it will be understood by those skilled in the art that the amplitude values of each of the discrete sample points are simply normalized to the value of the smallest magnitude amplitude value. In effect, this smallest value amplitude value is simply subtracted from all of the other amplitude values.

Rather than performing two normalizations of the waveform in accordance with the third embodiment of the invention, either the first embodiment of the invention, wherein sample points are eliminated under certain circumstance, or the second embodiment of the invention, wherein two centroid calculations are averaged, may be used to determine the center value or centroid of the waveform of interest after the initial normalization of the waveform.

The present invention has been described thus far wherein the number and distribution of sample points on either side of a waveform are generally evenly distributed, with an error in the centroid determination of the waveform being introduced by a generally asymmetric distribution of sample points over the waveform of interest. However, under certain circumstances, there may be an extremely skewed distribution of sample points on one side of a waveform as compared to the other. Referring now to Fig. 13, this situation may occur where the sample values do not span the entire waveform or where samples are lost or unusable. Alternatively, if the waveform is extremely asymmetric, the distribution of sample points on the waveform may be extremely skewed. In this case, it may be desirable to delete certain sample values. For example, sample values on both sides of the waveform are compared, and sample values are eliminated on the side of the waveform having the lowest amplitude values until there is only one sample value on one side of the waveform having a smaller amplitude than the smallest amplitude value on the other side of the waveform. In the example of Fig. 13, sample values 9, 10 and 11 are eliminated. After elimination of the sample points, the centroid of the waveform may be determined in accordance with the first, second or third embodiments of the invention as described above. Additionally, as described above with respect to the third embodiment of the invention, all of the sample values may be normalized, either before or after elimination of sample points.

The invention has been described herein as using seven (7) discrete sample points over the waveform. However, it will be understood by those skilled in the art that any number of sample points may be used with the present invention. The greater the number of sample points, the more accurate the centroid determination will be.

Although the invention has been described and illustrated with respect to exemplary embodiments thereof, the foregoing and various other additions and omissions may be made therein and thereto without departing from the spirit and scope of the present invention.

We claim:

CLAIMS:

1. A method for determining the centroid (V_C) of a waveform discretely sampled at a limited number of sample points, wherein each sample point is a set (V_N, A_N) including a sample value (V_N) and an amplitude (A_N), and wherein N is the number of non-eliminated sample points, the method comprising the steps of:

(a) eliminating the last sample point (V_N, A_N) if the magnitude of the amplitude at the first sample point (A_1) is greater than the last sample point (A_N), and the difference in magnitude between the first and last sample points (A_1-A_N) is greater than the difference in magnitude between the second to last sample point and the first sample point (A_{N-1}-A_1);

(b) eliminating the first sample point (V_1, A_1) if the last sample point was not eliminated in the previous step (a), the magnitude of the amplitude at the last sample point (A_N) is greater than the first sample point (A_1), and the difference in magnitude between the last and first sample points (A_N-A_1) is greater than the difference in magnitude between the second sample point and the last sample point (A_2-A_N); and

(c) determining the centroid (V_C) of the waveform using only the remaining sample points in accordance with the following relationship:

$$V_C = \frac{\sum_N V_N \cdot A_N}{\sum_N A_N}.$$

2. The method of claim 1, further including the step of, prior to the step (c), normalizing the amplitude values (A_N) of all of the sample points to the smallest magnitude amplitude value of any of the sample points.

3. The method of claim 1, further including the steps of, prior to the step (a):

(a') selecting the first sample point (V_1,A_1) if the amplitude of the first sample point (A_1) is less than the amplitude of the last sample point (A_N);

(b') eliminating the first sample point if the amplitude of the second sample point (A_2) is less than the amplitude of the last sample point (A_N);

(c') repeating steps (a') and (b') if the first sample point is eliminated in step (b');

(d') selecting the last sample point (V_N,A_N) if the amplitude of the last sample point (A_N) is less than the amplitude of the first sample point (A_1);

(e') eliminating the last sample point if the amplitude of the second to last sample point (A_{N-1}) is less than the amplitude of the first sample point (A_1); and

(f') repeating steps (d') and (e') if the last sample point is eliminated in step (e').

4. The method of claim 3, further including the step of, prior to the step (c) of determining the centroid (V_C) of the waveform, normalizing the amplitude values (A_N) of all of the sample points to the smallest magnitude amplitude value of any of the sample points.

5. A method for determining the centroid (V_C) of a waveform discretely sampled at a limited number of sample points, wherein each sample point is a set (V_N, A_N) including a sample value (V_N) and an amplitude (A_N), and wherein N is the number of non-eliminated sample points, the method comprising the steps of:

(a) determining a first centroid (V_{C1}) of the waveform in accordance with the following relationship:

$$V_{C1} = \frac{\sum_N V_N \cdot A_N}{\sum_N A_N}$$

(b) performing the following steps if the amplitude of the first sample point (A_1) is less than the amplitude of the last sample point (A_N):

(b1) eliminating the first sample point and each successive sample point having an amplitude that is less than the amplitude of the last sample point (A_N);

(b2) determining a second centroid (V_{C2}) of the waveform in accordance with the following relationship:

$$V_{C2} = \frac{\sum_N V_N \cdot A_N}{\sum_N A_N}$$

(b3) determining the centroid (V_C) of the waveform as the average of the first centroid (V_{C1}) and the second centroid (V_{C2});

(c) performing the following steps if the amplitude of the last sample point (A_N) is less than the amplitude of the first sample point (A_1):

(c1) eliminating the last sample point and each previous sample point having an amplitude that is less than the amplitude of the first sample point (A_1);

(c2) determining a second centroid (V_{C2}) of the waveform in accordance with the following relationship:

$$V_{C2} = \frac{\sum_N V_N \cdot A_N}{\sum_N A_N}$$

(c3) determining the centroid (V_C) of the waveform as the average of the first centroid (V_{C1}) and the second centroid (V_{C2}).

6. The method of claim 5, further including the step of, prior to the step (a), normalizing the amplitude values (A_N) of all of the sample points to the smallest magnitude amplitude value of any of the sample points.

7. The method of claim 5, further including the steps of, prior to the step (a):

(a') selecting the first sample point (V_1,A_1) if the amplitude of the first sample point (A_1) is less than the amplitude of the last sample point (A_N);

(b') eliminating the first sample point if the amplitude of the second sample point (A_2) is less than the amplitude of the last sample point (A_N);

(c') repeating steps (a') and (b') if the first sample point is eliminated in step (b');

(d') selecting the last sample point (V_N,A_N) if the amplitude of the last sample point (A_N) is less than the amplitude of the first sample point (A_1);

(e') eliminating the last sample point if the amplitude of the second to last sample point (A_{N-1}) is less than the amplitude of the first sample point (A_1); and

(f') repeating steps (d') and (e') if the last sample point is eliminated in step (e').

8. The method of claim 7, further including the step of, after step (f') and prior to step (a), normalizing the amplitude values (A_N) of all of the sample points to the smallest magnitude amplitude value of any of the sample points.

9. A method for determining the centroid (V_C) of a waveform discretely sampled at a limited number of sample points, wherein each sample point is a set (V_N, A_N) including a sample value (V_N) and an amplitude (A_N), and wherein N is the number of non-eliminated sample points, the method comprising the steps of:

(a) normalizing the amplitude values (A_N) of all of the sample points to the smallest magnitude amplitude value of any of the sample points;

(b) determining a first centroid (V_{C1}) of the waveform in accordance with the following relationship:

$$V_{C1} = \frac{\sum_N V_N \cdot A_N}{\sum_N A_N}$$

(c) performing the following steps if the amplitude of the first sample point (A_1) is less than the amplitude of the last sample point (A_N):

(c1) eliminating the first sample point and each successive sample point having an amplitude that is less than the amplitude of the last sample point (A_N);

(c2) normalizing the amplitude values (A_N) of all of the sample points to the smallest magnitude amplitude value of any of the sample points;

(c3) determining a second centroid (V_{C2}) of the waveform in accordance with the following relationship:

$$V_{C2} = \frac{\sum_N V_N \cdot A_N}{\sum_N A_N}$$

(c4) determining the centroid (V_C) of the waveform as the average of the first centroid (V_{C1}) and the second centroid (V_{C2});

(d) performing the following steps if the amplitude of the last sample point (A_N) is less than the amplitude of the first sample point (A_1):

(d1) eliminating the last sample point and each previous sample point having an amplitude that is less than the amplitude of the first sample point (A_1);

(d2) normalizing the amplitude values (A_N) of all of the sample points to the smallest magnitude amplitude value of any of the sample points.

(d3) determining a second centroid (V_{C2}) of the waveform in accordance with the following relationship:

$$V_{C2} = \frac{\sum_N V_N \cdot A_N}{\sum_N A_N}$$

(d4) determining the centroid (V_C) of the waveform as the average of the first centroid (V_{C1}) and the second centroid (V_{C2}).

10. The method of claim 9, further including the steps of, prior to the step (a):

(a') selecting the first sample point (V_1,A_1) if the amplitude of the first sample point (A_1) is less than the amplitude of the last sample point (A_N);

(b') eliminating the first sample point if the amplitude of the second sample point (A_2) is less than the amplitude of the last sample point (A_N);

(c') repeating steps (a') and (b') if the first sample point is eliminated in step (b');

(d') selecting the last sample point (V_N,A_N) if the amplitude of the last sample point (A_N) is less than the amplitude of the first sample point (A_1);

(e') eliminating the last sample point if the amplitude of the second to last sample point (A_{N-1}) is less than the amplitude of the first sample point (A_1); and

(f') repeating steps (d') and (e') if the last sample point is eliminated in step (e').

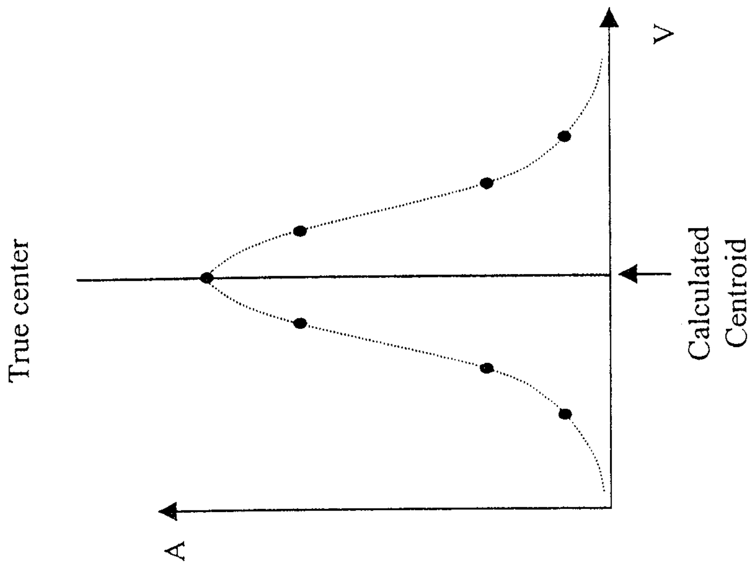

FIG. 1

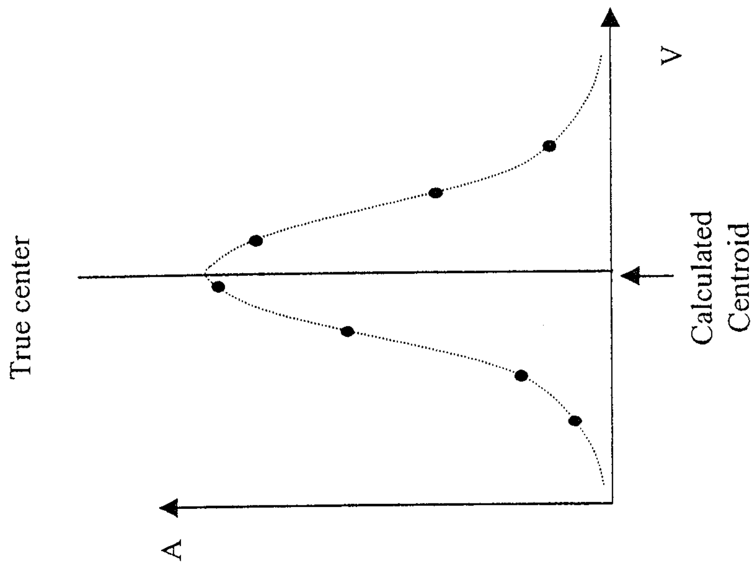

FIG. 2

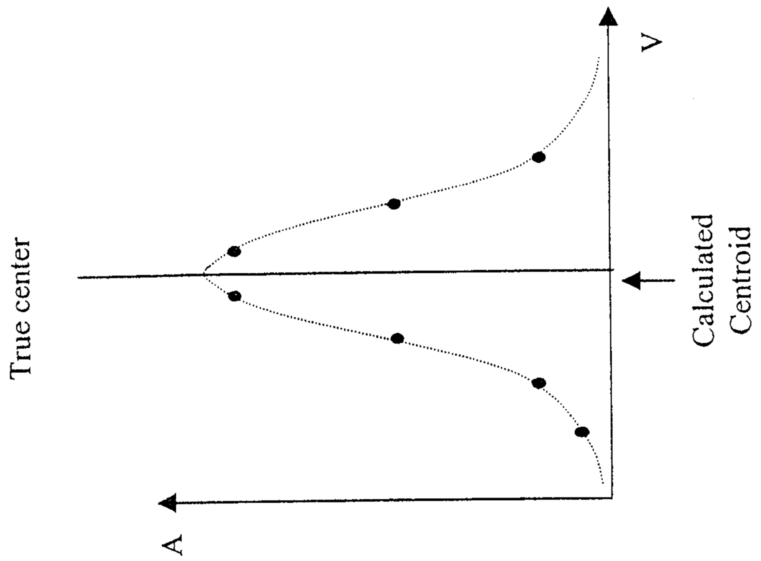

FIG. 3

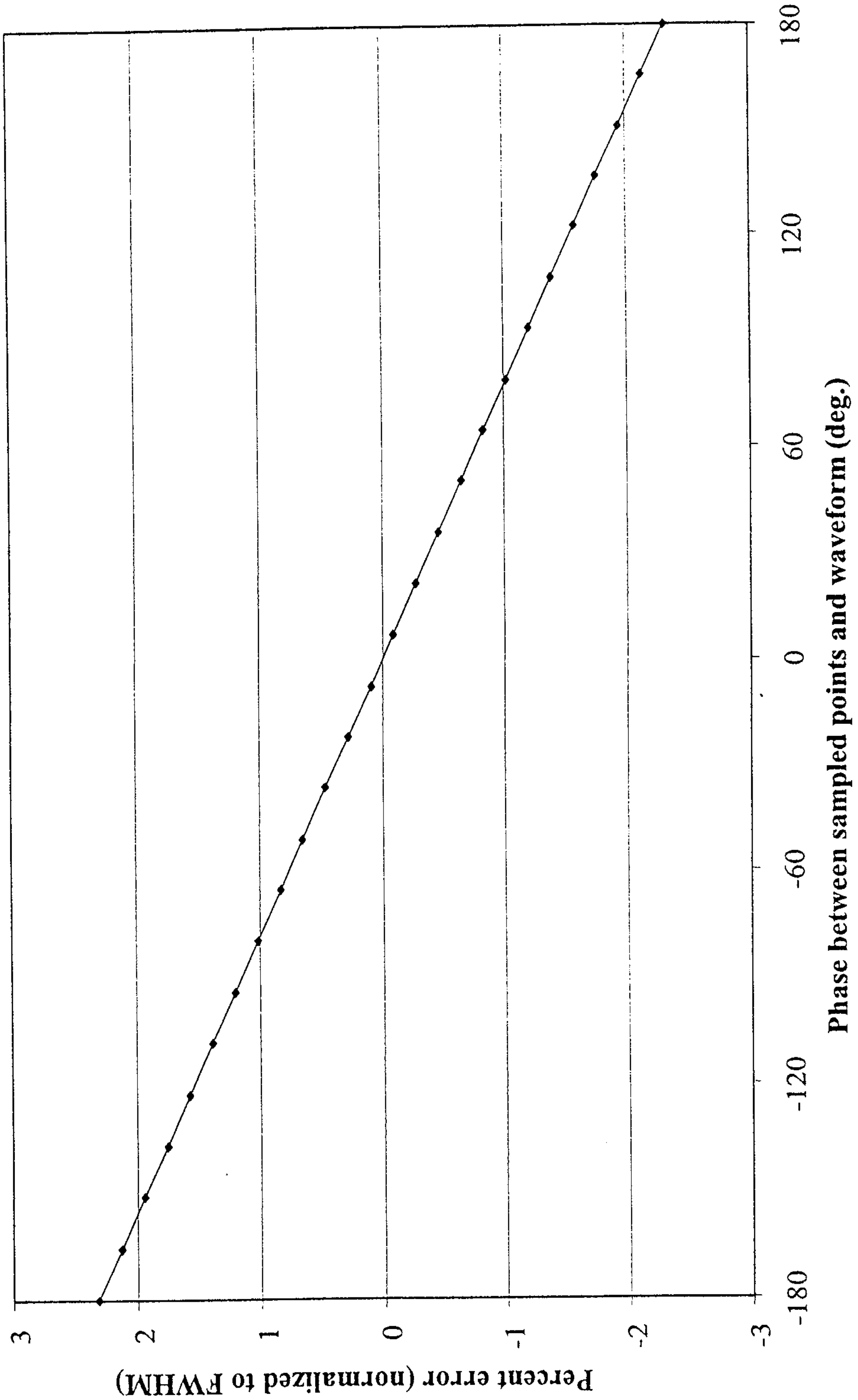
Phase between sampled points and waveform (deg.)
-180
-120
-60
0
60
120
180
Percent error (normalized to FWHM)
3
2
1
0
-1
-2
-3

FIG. 4

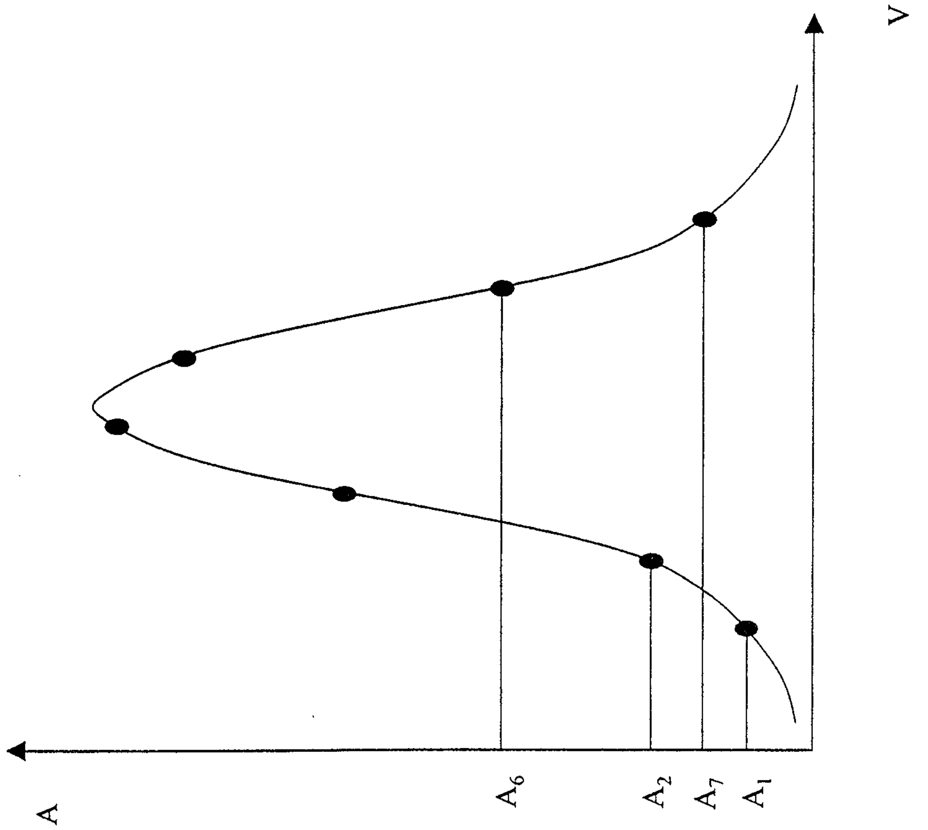

FIG. 5

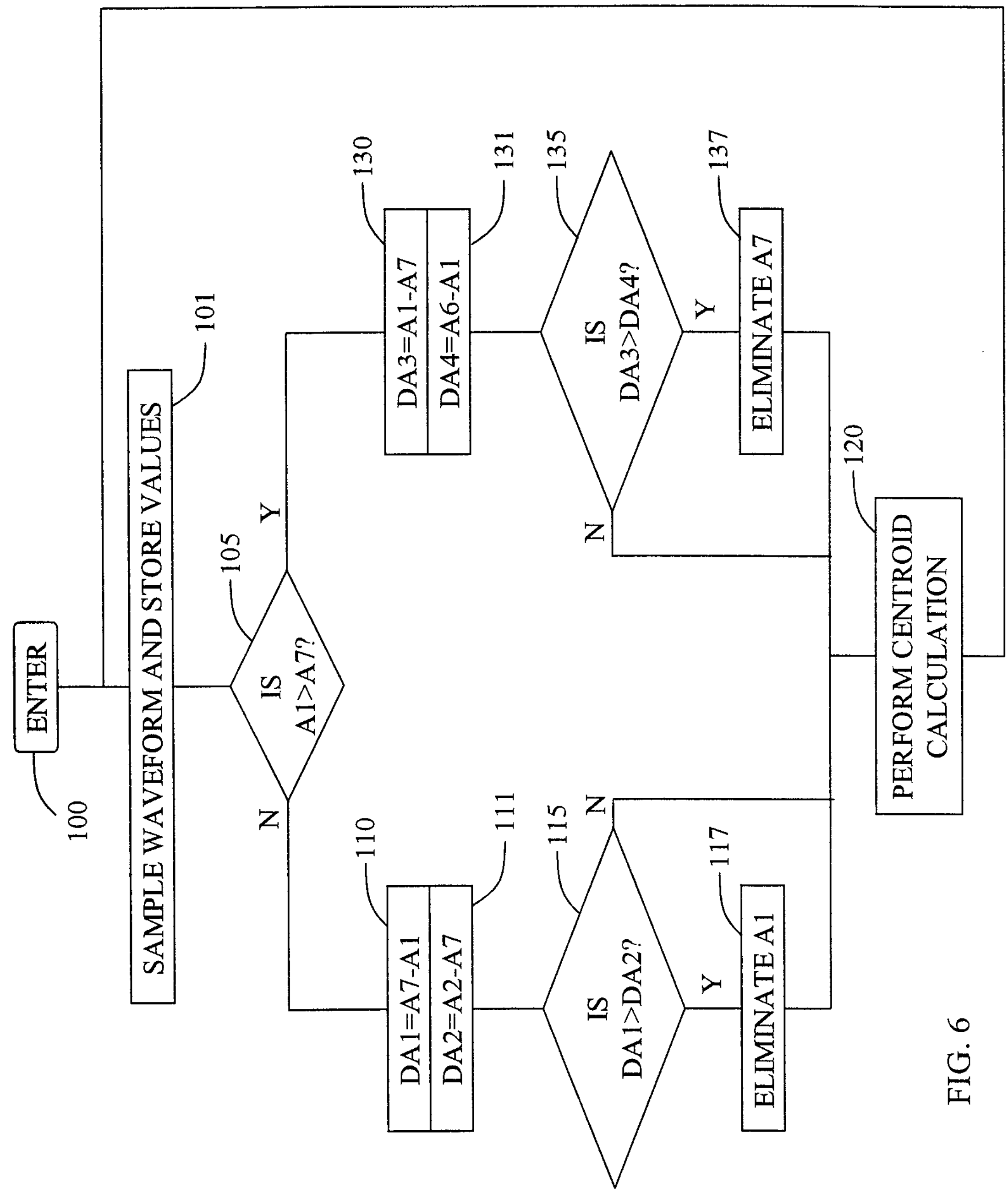
ENTER
100
SAMPLE WAVEFORM AND STORE VALUES
101
IS A1>A7?
105
Y
N
DA3=A1-A7
DA4=A6-A1
130
131
IS DA3>DA4?
135
Y
N
ELIMINATE A7
137
DA1=A7-A1
DA2=A2-A7
110
111
IS DA1>DA2?
115
Y
N
ELIMINATE A1
117
PERFORM CENTROID CALCULATION
120

FIG. 6

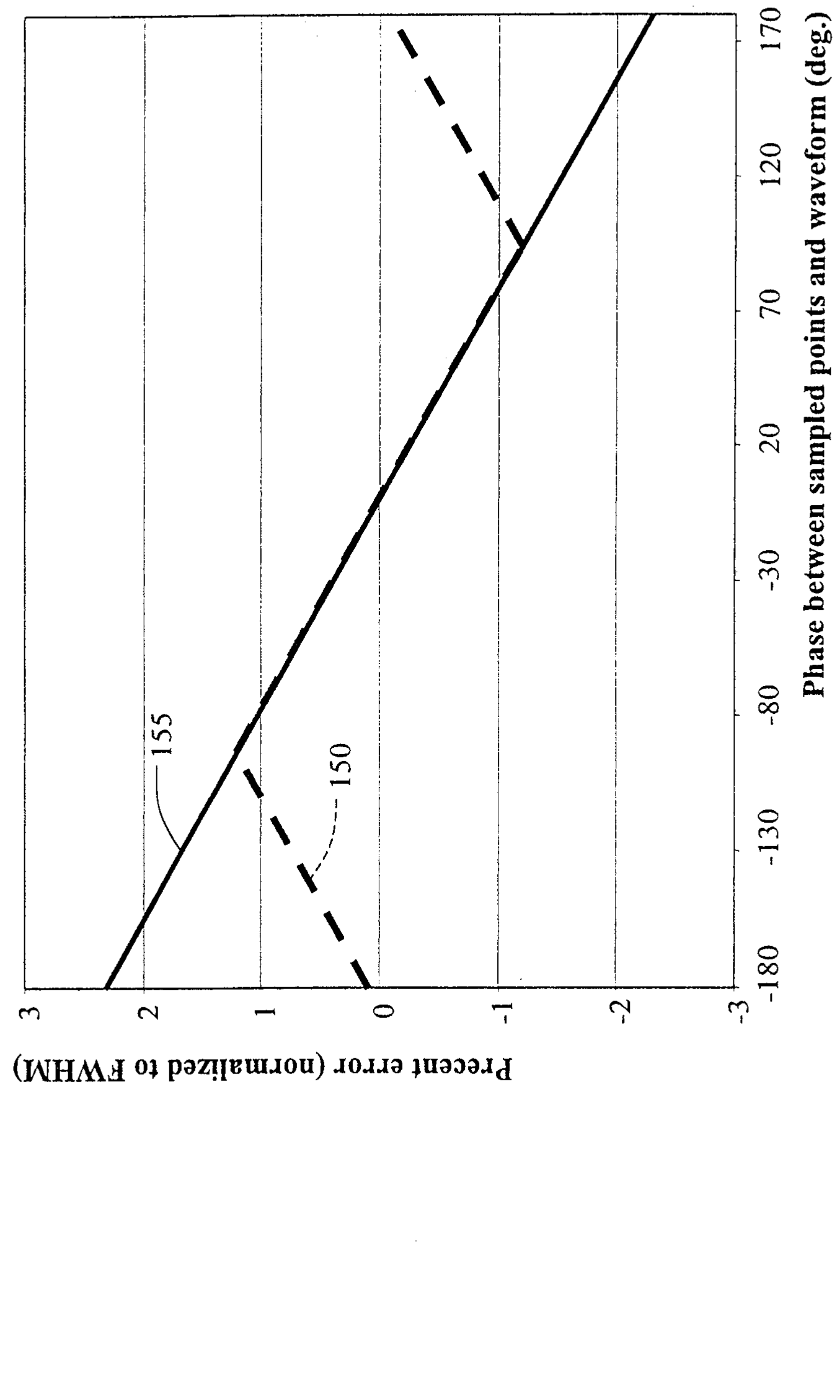
Phase between sampled points and waveform (deg.)
Precent error (normalized to FWHM)
-180
-130
-80
-30
20
70
120
170
3
2
1
0
-1
-2
-3
155
150

FIG. 7

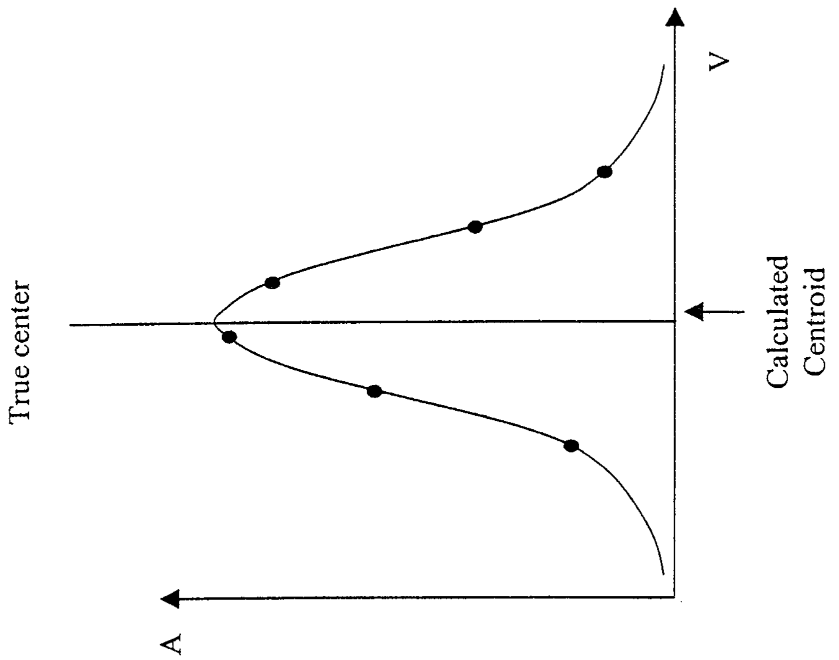
True center
V
A
Calculated
Centroid

FIG. 9

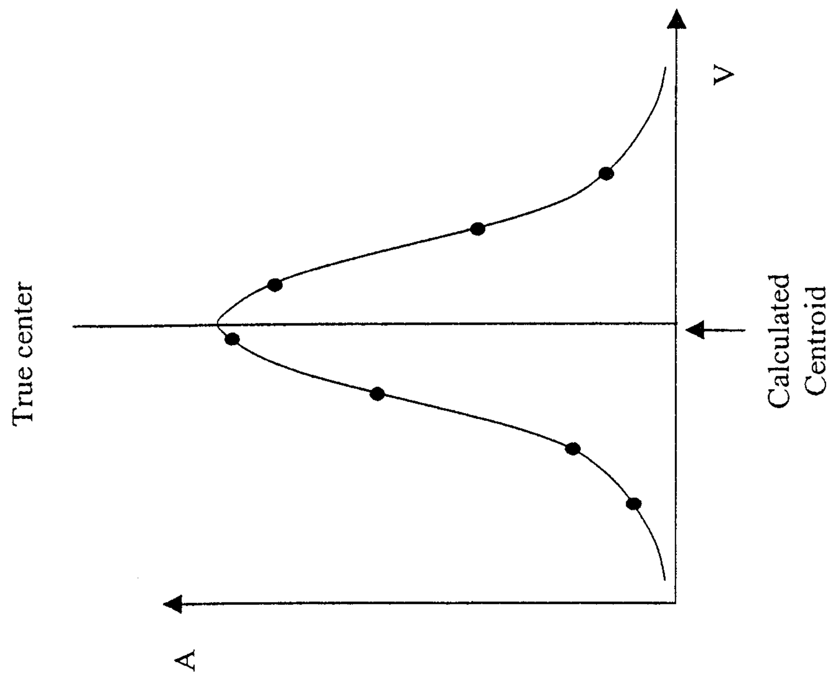
True center
V
A
Calculated
Centroid

FIG. 8

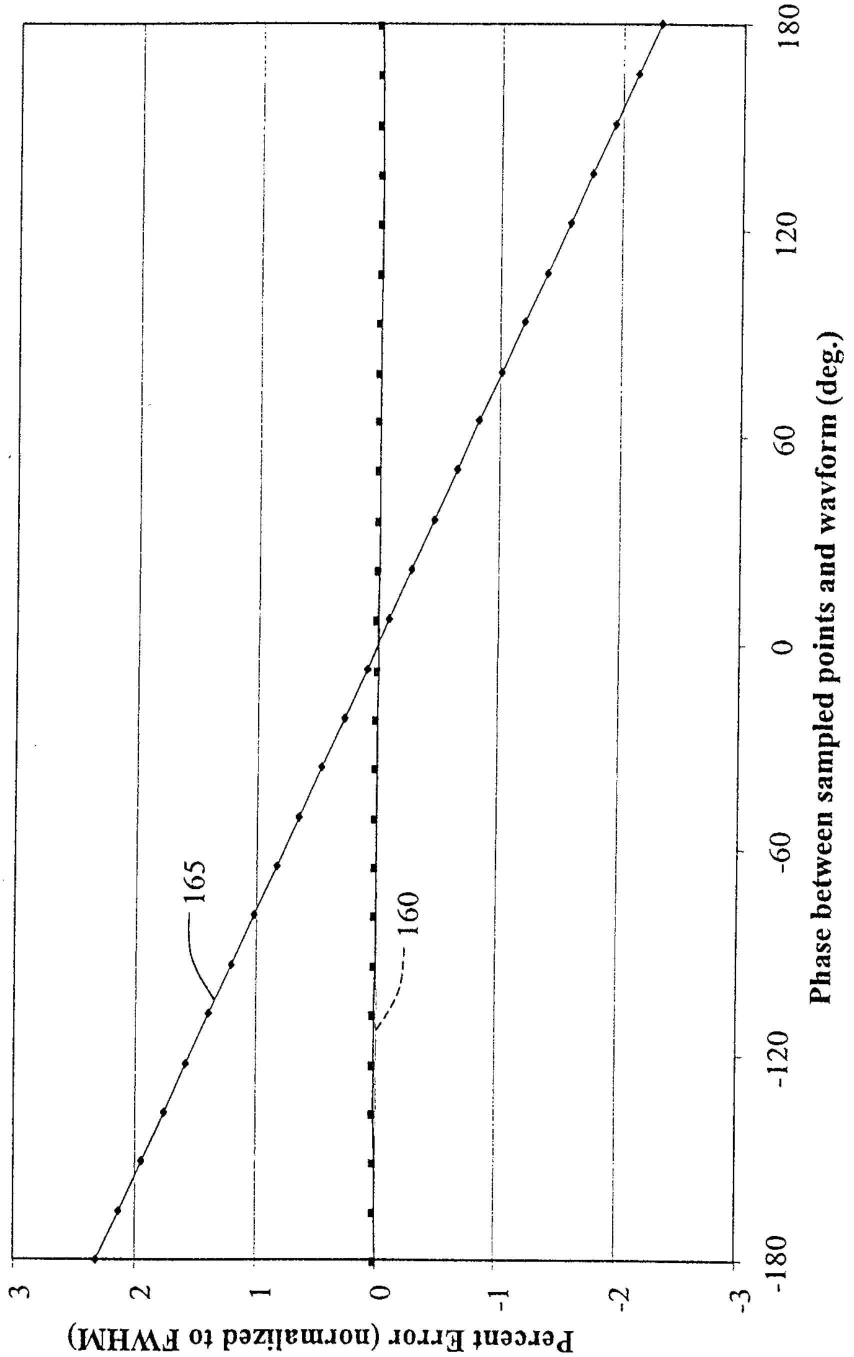
Percent Error (normalized to FWHM)
3
2
1
0
-1
-2
-3
Phase between sampled points and wavform (deg.)
-180
-120
-60
0
60
120
180
165
160

FIG. 10

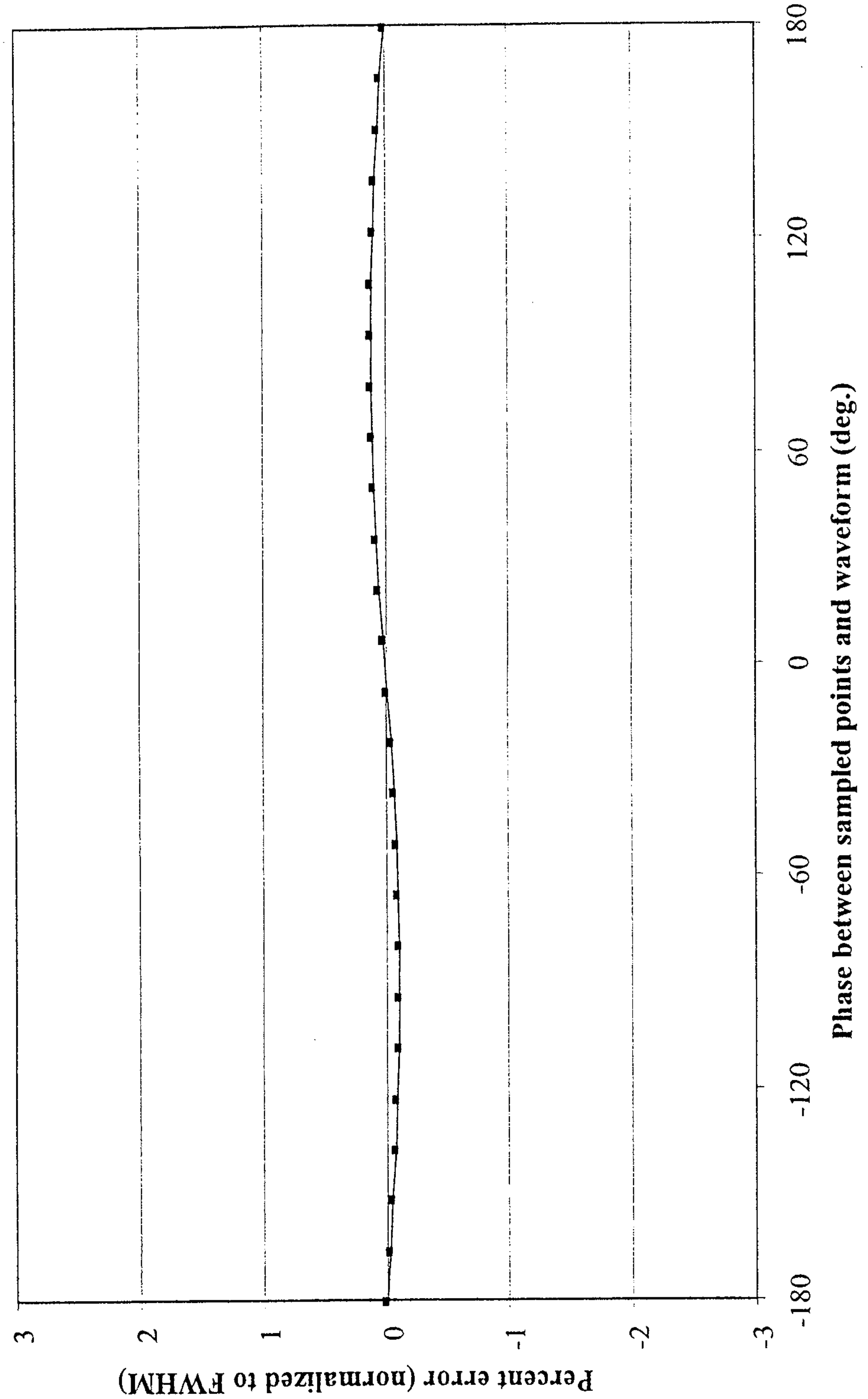
Percent error (normalized to FWHM)
3
2
1
0
-1
-2
-3
-180
-120
-60
0
60
120
180
Phase between sampled points and waveform (deg.)

FIG. 12

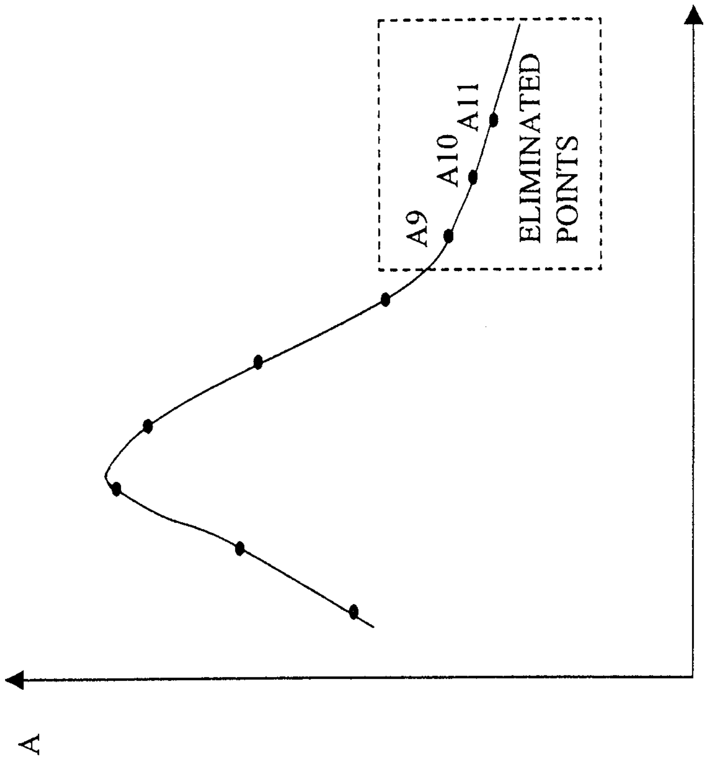
A9
A10
A11
ELIMINATED POINTS
V
A

FIG. 13

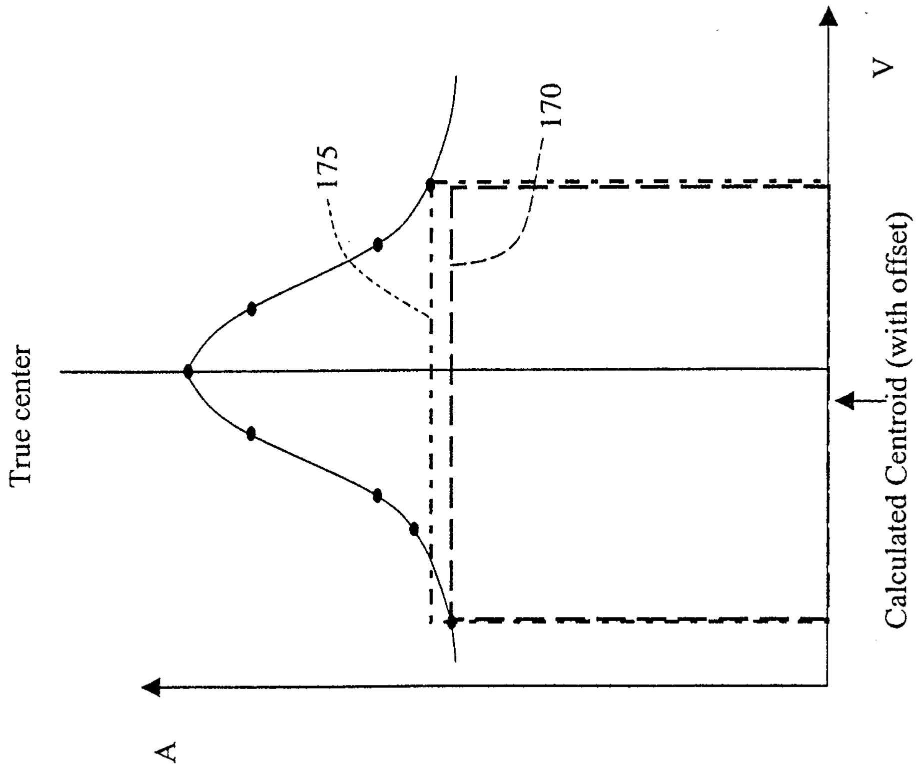
True center
175
170
V
A
Calculated Centroid (with offset)

FIG. 11

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/11836

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01R19/25

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01R G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 260 647 A (SWERLEIN RONALD L) 9 November 1993 (1993-11-09) abstract; figure 1 column 1, line 28 - column 2, line 58 ---	1,5,9
A	US 5 274 569 A (PRASAD MOHIT K) 28 December 1993 (1993-12-28) abstract; figures 1A,B ---	1,5,9
A	US 5 610 827 A (REILLY ROBERT J) 11 March 1997 (1997-03-11) abstract; figures 1-3 ---	1,5,9
A,P	US 5 818 585 A (BELLEMORE DAVID G ET AL) 6 October 1998 (1998-10-06) abstract; figure 3 --- -/--	1,5,9

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
9 September 1999	16/09/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Fritz, S

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International Application No
PCT/US 99/11836

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 463 600 A (MATSUSHITA ELECTRIC IND CO LTD) 2 January 1992 (1992-01-02) abstract; claims; figures	1,5,9

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 99/11836

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5260647 A	09-11-1993	NONE	
US 5274569 A	28-12-1993	JP 5198098 A	06-08-1993
US 5610827 A	11-03-1997	NONE	
US 5818585 A	06-10-1998	NONE	
EP 0463600 A	02-01-1992	JP 2689707 B	10-12-1997
		JP 4106430 A	08-04-1992
		DE 69115575 D	01-02-1996
		DE 69115575 T	24-10-1996
		JP 2762775 B	04-06-1998
		JP 4252924 A	08-09-1992