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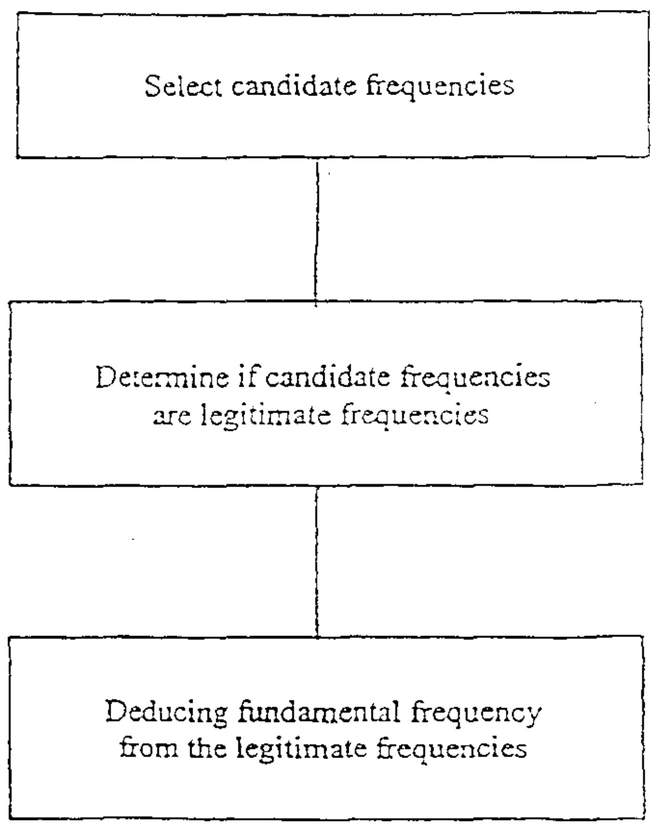
(54) Title: FAST FIND FUNDAMENTAL METHOD

(57) Abstract

The present invention contains three methods for quickly deducing the fundamental frequency of a complex wave form or signal. One method uses the relationships between and among the frequencies of higher harmonics including ratios of frequencies, differences between frequencies, ratios of frequency differences, and relationships stemming from the fact that harmonic frequencies are modeled by functions of an integer variable whose values represent harmonic ranking numbers. Another method depicts the predicted/modeled relationships of the harmonics of selected frequency registers on logarithmic scales, records the frequencies of detected partials on like scales, and moves the scales with respect to each other searching for a match of three harmonics. When such a match is found, possible harmonic ranking numbers and the implied fundamental frequency can be extracted directly. When the detected partials match more that one set of predicted/modeled harmonic relationships, algorithms of the first method are used to select the deduced fundamental. By still another method, harmonic frequencies for a plurality of fundamentals are amassed and organized so that partials linked to an unknown fundamental can be compared with them and the unknown fundamental deduced.



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FAST FIND FUNDAMENTAL METHOD

CROSS-REFERENCE

This application is related to and claims the benefit of Provisional Patent Application Serial No. 60/106,150 filed October 29, 1998 which is incorporated herein by reference.

BACKGROUND AND SUMMARY OF THE INVENTION

This invention relates to electronic music production and reproduction and to methods for modifying electronic analogs of sound during the process of amplifying and enhancing the signals generated by a note, and in general to systems having the objective of quickly determining the fundamental frequency of a compound wave which is the sum of multiple frequencies.

There is an irreducible minimum limit to the length of time required to measure the frequency of a sine wave signal to a specified pitch accuracy (e.g., to ¼ of a semitone). That minimum time is inversely proportional to the frequency of the signal being processed. Keeping pitch accuracy constant, the minimum amount of time required to measure the frequency of a pure sine wave of 82.4 Hz would be eight times longer than the minimum time required to measure the frequency of a pure sine wave of 659.2 Hz. Accordingly, the lag time for measuring and reproducing the fundamental frequencies of low bass notes which are produced by instruments not incorporating keyboards (or other means of revealing the fundamental frequency as a note is sounded) is problematic. For example, when the signals from low bass notes are processed by synthesizers before they are amplified and reproduced, an annoying lag time commonly results.

Throughout this patent, a partial or partial frequency is defined as a definitive energetic frequency band, and harmonics or harmonic frequencies are defined as partials which are generated in accordance with a phenomenon based on an integer relationship such as the division of a mechanical object, e.g., a string, or of an air column, by an integral number of nodes. The relationships between and among the harmonic frequencies generated by many classes of oscillating/vibrating devices, including musical instruments, can be modeled by a function G(n) such that

$$f_n = f_1 \times G(n)$$

where f_n is the frequency of the n^{th} harmonic, f_1 is the fundamental frequency, known as the 1st harmonic, and n is a positive integer which represents the harmonic ranking number. Known examples of such functions are:

$$f_n = f_1 \times n; \text{ and,}$$

$$f_n = f_1 \times n \times [1 + (n^2 - 1)\ \beta]^{½}.$$

Where β is a constant, typically .004.

A body of knowledge and theory exists regarding the nature and harmonic content of complex wave forms and the relationships between and among the harmonic partials produced both by vibrating objects and by electrical/electronic analogs of such objects. Examples of texts which contribute to this body of knowledge are 1) The Physics of Musical Instruments by Fletcher and Rossing, 2) Tuning, Timbre, Spectrum, Scale by Sethares, and 3) Digital Processing of Speech

Signals by Rabiner and Schafer. Also included are knowledge and theory concerning various ways to measure/determine frequency, such as fixed and variable band-pass and band-stop filters, oscillators, resonators, fast Fourier transforms, etc. An overview of this body of knowledge is contained in the Encyclopedia Britannica.

Examples of recent patents which specifically address ways to measure a fundamental frequency are:

U.S. Patent 5,780,759 to Szalay describes a pitch recognition method that uses the interval between zero crossings of a signal as a measure of the period length of the signal. The magnitude of the gradient at the zero crossings is used to select the zero crossings to be evaluated.

U.S. Patent 5,774,836 to Bartkowiak et al. shows an improved vocoder system for estimating pitch in a speech wave form. The method first performs a correlation calculation, then generates an estimate of the fundamental frequency. It then performs error checking to disregard "erroneous" pitch estimates. In the process, it searches for higher harmonics of the estimated fundamental frequency.

U.S. Patent 4,429,609 to Warrander shows a device and method which performs an A to D conversion, removes frequency bands outside the area of interest, and performs analysis using zero crossing time data to determine the fundamental. It delays a reference signal by successive amounts corresponding to intervals between zero crossings, and correlates the delayed signal with the reference signal to determine the fundamental.

The present invention is a method to quickly deduce the fundamental frequency of a complex wave form or signal by using the relationships between and among the frequencies of higher harmonics.

The method includes selecting at least two candidate frequencies in the signal. Next, it is determined if the candidate frequencies are a group of legitimate harmonic frequencies having a harmonic relationship. Finally, the fundamental frequency is deduced from the legitimate frequencies.

In one method, relationships between and among detected partial frequencies are compared to comparable relationships that would prevail if all members were legitimate harmonic frequencies. The relationships compared include frequency ratios, differences in frequencies, ratios of those differences, and unique relationships which result from the fact that harmonic frequencies are modeled by a function of a variable which assumes only positive integer values. That integer value is known as the harmonic ranking number. Preferably, the function of an integer variable is $f_n = f_1 \times n \times (S)^{\log_2 n}$ where S is a constant and typically, $1 \le S \le 1.003$ and n is the harmonic ranking number. The value of S, hereafter called the sharping constant, determines the degree to which harmonics become progressively sharper as the value of n increases.

Other relationships which must hold if the candidate partial frequencies are legitimate harmonics stem from the physical characteristics of the vibrating/oscillating object or instrument that is the source of the signal, i.e., the highest and lowest fundamental frequencies it can produce and the highest harmonic frequency it can produce.

Another method for determining legitimate harmonic frequencies and deducing a fundamental frequency includes comparing the group of candidate frequencies to a fundamental frequency and its harmonics to find an acceptable match. One method creates a harmonic multiplier scale on which the values of G(n) are recorded. Those values are the fundamental frequency multipliers for each value of n, i.e., for each harmonic ranking number. Next a like scale is created where the values of candidate partial frequencies can be recorded. After a group of candidate partial frequencies have been detected and recorded on the candidate scale, the two scales are compared, i.e., they are moved with respect to each other to locate acceptable matches of groups of candidate frequencies with groups of harmonic multipliers. Preferably the scales are logarithmic. When a good match is found, then a possible set of ranking numbers for the group of candidate frequencies is determined (or can be read off directly) from the harmonic ranking number scale. Likewise the implied fundamental frequency associated with the group of legitimate partial candidate frequencies can be read off directly. It is the frequency in the candidate frequency scale which corresponds to (lines up with) the "1" on the harmonic multiplier scale.

If the function G(n) is different for different frequency registers so that the harmonics in one frequency register are related in ways that are different from the ways they are related in other frequency registers, then different harmonic multiplier scales are generated, one for each of the different frequency registers. Partial frequencies are recorded on the scale appropriate for the frequency register in which they fall and are compared with the harmonic multiplier scale which corresponds to that frequency register.

In another matching method, the candidate frequencies are compared to a plurality of detected measured harmonic frequencies stemming from a plurality of fundamental frequencies. The detected and measured harmonic frequencies are preferably organized into an array where the columns are the harmonic ranking numbers and the rows are the harmonic frequencies organized in fundamental frequency order. When three or more detected partials align sufficiently close to three measured harmonic frequencies in a row of the array, the harmonic ranking numbers and the fundamental are known.

Since the frequencies of the higher harmonics normally can be determined more quickly than the fundamental frequency, and since the calculations to deduce the fundamental frequency can be performed in a very short time, the fundamental frequencies of low bass notes can be deduced well before they can be measured.

Other advantages and novel features of the present invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram of a method of deducing the fundamental frequency according to the present invention.

Figure 2 is a block diagram of a specific implementation of the method of Figure 1.

Figure 3 illustrates a logarithmic scale whereon harmonic multipliers are displayed for Harmonics 1 through 17 and a corresponding logarithmic scale whereon the frequencies of four detected partials are displayed.

Figure 4 is an enlargement of a selected portion of the Figure 3 scales after those scales are moved relative to each other to find a good match of three candidate frequencies with harmonic multipliers.

Figure 5 is an enlargement of a narrow frequency band of Figure 4 showing how matching bits can be used as a measure of degree of match.

Figure 6 is a block diagram of a system implementing the method of Figures 1-4.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In order to deduce the fundamental frequency, f_1, from higher harmonics, anomalous frequencies must be screened out and the harmonic ranking numbers of at least one legitimate harmonic group must be determined. Alternatively, the number of unoccupied harmonic positions (missing harmonics) bracketed by two legitimate harmonics must be determined. The general method, illustrated in Figure 1, selects candidate frequencies. Next, it determines if the candidate frequencies are legitimate harmonic frequencies having the same underlying fundamental frequency. Finally, the fundamental frequency is deduced from the legitimate frequencies.

Definitions and Notation

The following definitions and notation will be used throughout this patent:

f_H, f_M, f_L: The candidate frequencies of a trio of partials, organized in descending frequency order.

R_H, R_M, R_L: The ranking numbers associated with f_H, f_M, f_L.

F_L: The lowest fundamental frequency, f_1, which can be produced by the source of the signal.

F_H: The highest fundamental frequency, f_1, which can be produced by the source of the signal.

F_{MAX}: Highest harmonic frequency which can be produced by the source of the signal.

Relationships and Limiting Conditions

The method uses relationships between and among higher harmonics, the conditions which limit choices, the relationships the higher harmonics have with the fundamental, and the range of possible fundamental frequencies. Examples are:

If $f_{R_Z} = f_1 \times G(R_Z)$ models the frequency of the R_Z th harmonic, and

If f_H, f_M and f_L are legitimate harmonic frequencies, and

If R_H, R_M and R_L are the ranking numbers associated with f_H, f_M f_L, then the following ratio relationships must hold:

a) Ratios of detected candidate frequencies must be approximately equal to ratios obtained by substituting their ranking numbers in the model of harmonics, i.e.,

$$f_H \div f_M \approx f_{R_H} \div f_{R_M}$$

$$f_M \div f_L \approx f_{R_M} \div f_{R_L}$$

b) The ratios of differences between detected candidate frequencies must be consistent with ratios of differences of modeled frequencies, i.e.,

$$(f_H - f_M) \div (f_M - f_L) \approx (f_{R_H} - f_{R_M}) \div (f_{R_M} - f_{R_L})$$

c) The candidate frequency partials f_H, f_M, f_L, which are candidate harmonics, must be in the range of frequencies which can be produced by the source or the instrument.

d) The harmonic ranking numbers R_H, R_M, R_L must not imply a fundamental frequency which is below F_L or above F_H, the range of fundamental frequencies which can be produced by the source or instrument.

e) When matching integer variable ratios to obtain possible trios of ranking numbers, the integer R_M in the integer ratio R_H / R_M must be the same as the integer R_M in the integer ratio R_M / R_L, for example. This relationship is used to join Ranking Number pairs $\{R_H, R_M\}$ and $\{R_M, R_L\}$ into possible trios $\{R_H, R_M, R_L\}$.

Summary of Methods

The methods analyze a group of partials or candidate frequencies and ascertain whether or not they include anomalous frequencies. Preferably each group analyzed will contain three partials. If the presence of one or more anomalous frequencies is not determined, the group is considered to be a group of legitimate harmonic frequencies. The ranking number of each harmonic frequency is determined, and the fundamental frequency is deduced. When the presence of one or more anomalous frequencies is determined, a new partial or candidate frequency is detected, measured and selected and anomalous frequencies are isolated and screened out. This process continues until a group of legitimate harmonics frequencies remain. In the process, the ranking numbers of legitimate harmonic frequencies are determined and verified. The fundamental frequency is then computed by a variety of methods. Adjustments are made considering the degree to which harmonics vary from $f_n = f_1 \times n$.

Method I

The following is an example of a method implementing the compact flow chart of the method of Figure 1 to deduce the fundamental frequency and is illustrated in Figure 2. The method tests a trio of detected candidate partial frequencies to determine whether its members consist only of legitimate harmonic frequencies of the same fundamental frequency. When that is not true, additional candidate frequencies are inducted and substituted for ones in the trio at hand until a trio of legitimate harmonics has been found. When such a trio is found, the ranking numbers associated with each member are determined and the fundamental frequency is deduced.

The method as described herein illustrates the kinds of logical operations that will be accomplished either directly or indirectly. The actual implementation will incorporate shortcuts, eliminate redundancies, etc., and may differ in other ways from the implementation described below.

The method is presented as a set of steps described in general terms and in parallel a numerical example illustrates the required calculations for various steps.

Definitions of Instrument Constants

K_1 is the highest harmonic ranking number which will be assigned/considered. The value of K_1 is set by comparing the expected % error in the measurement of the frequency of the K_1^{th} harmonic with the value of the quotient of the integer ratio

$$[(K_1 + 1) \div K_1] \div [K_1 \div (K_1 - 1)]$$

A default value for K_1 will be set equal to 17 and will be revised to conform to knowledge of the instrument at hand and the expected error in frequency measurements.

K_2 is the maximum expected number of missing harmonics between two adjacent detected harmonic frequencies. The default value of K_2 is set equal to 8.

K_3 is equal to the expected maximum sum of the missing harmonics between two harmonics containing one intervening or intermediate harmonic, plus 1. The default value for K_3 is set equal to 12.

Step 1. Set constants/parameters for the instrument or signal source.

Example: F_H = 300 Hz, F_L = 30 Hz, F_{MAX} = 2,100 Hz; K_1 = 17, K_2 = 8, K_3 = 12

For simplicity and brevity, the function describing the relationship between and among harmonic frequencies G(n) is assumed to be $f_1 \times n$.

Step 2. Detect, measure and select the frequencies of three partials, for example. The frequencies are detected and measured in the order in which they occur. Three frequencies or partials, having an energy level significantly above the ambient noise level for example, are selected as candidates of possible legitimate harmonics. Higher frequencies, and consequently higher order harmonic frequencies, naturally are detected and measured first. The following example assumes an exception where a lower harmonic is detected before a higher one, and illustrates how that exception would be processed.

Example: 1st frequency measured = 722 Hz,
2nd frequency measured = 849 Hz,
3rd frequency measured = 650 Hz.

Step 3. The three candidate frequencies are arranged in order of frequency and labeled f_H, f_M, f_L.

Example: f_H = 849 Hz, f_M = 722 Hz, f_L = 650 Hz.

Step 4. Possible trios of ranking numbers are determined for the candidate frequencies f_H, f_M, f_L. The quotients of the ratios f_H/f_M and f_M/f_L are compared to the quotients of integer ratios I_a/I_b, where I_a and I_b are both $\leq K_1$, a given threshold. Here K_1 is set equal to 17 for illustrative purposes. When the quotient of a frequency ratio is sufficiently close to the quotient of an integer ratio, that integer ratio is retained as one representing a pair of possible ranking numbers for the frequency ratio it matches. The ratios may also be f_H/f_L and f_M/f_L or f_H/f_M and f_H/f_L or any of the inverses.

Example: For $f_H/f_M = 1.176$, the closest integer ratio quotients are 1.1818 = 13/11 and 1.1667 = 7/6 or 14/12. Note that 26/22 is not considered because 26 > 17. For $f_M/f_L = 1.111$, the closest integer ratio quotients are 1.111 = 10/9 and 1.10 = 11/10.

When the common frequency of the two ratios are equal, then a possible trio of ranking numbers $\{R_H, R_M, R_L\}$ is formed. In this example, it is when the denominator of the integer fraction f_H/f_M is equal to the numerator of the integer fraction f_M/f_L.

Example: Since only $f_H/f_M = 13/11$ and $f_M/f_L = 11/10$ lead to the same ranking number for f_M, the only possible trio in this example is $\{R_H, R_M, R_L\} = \{13, 11, 10\}$.

Step 5. All possible trios of ranking numbers are eliminated which imply a fundamental frequency f_1 outside the range defined by F_L and F_H.

Example: The fundamental f_1 is the candidate frequency divided by its ranking number. The only possible trio, {13, 11, 10}, is not screened out because $f_H/13 = 65.308$, $f_M/11 = 65.636$, and $f_L/10 = 65.00$ are all within the range defined by $F_L = 30$ and $F_H = 300$.

Step 6. The differences $D_{H,M} = f_H - f_M$ and $D_{M,L} = f_H - f_L$ are calculated and the ratio $D_{H,M}/D_{M,L}$ is computed.

Other difference ratios which could have been similarly used are $D_{H,L}/D_{M,L}$ or $D_{H,L}/D_{H,M}$.

Example: $D_{H,M}$ = 849-722=127, $D_{M,L}$ = 722-650 = 72, and $D_{H,M}/D_{M,L}$ = 127 / 72 = 1.764.

Step 7. The quotient of the difference ratio $D_{H,M}$ / $D_{M,L}$ is compared to the quotients of small integer ratios I_c/I_d where $I_c < K_2$, and $I_c + I_d < K_3$. Note: Throughout the example, the value of K_2 = 8 and K_3 = 12. K_2 = 8 corresponds to the assumption that f_H and f_M differ by no more than 7 times the fundamental frequency, or the harmonic ranking numbers R_H and R_M differ by no more than 7. Likewise, K_3 = 12 assumes that f_H and f_L will differ by no more than 11 times the fundamental frequency and the ranking numbers R_H and R_L differ by no more than 11. A cursory review of field data confirms these assumptions. If the other difference ratios are used, the values of K_2 and K_3 are appropriately set using the same analysis.

Example: $D_{H,M}$/ $D_{H,L}$ = 1.764 ≈ 1.75 = 7/4. This ratio at first qualifies for consideration because 7 < 8 and 7 + 4 < 12.

Step 8. Any difference ratio which implies a fundamental frequency $f_1 < F_L$ is disqualified.

Example: Here the difference ratio 7/4 implies that the difference between the highest frequency f_H = 849 Hz and the lowest frequency f_L = 650 Hz which equals 198 Hz, should be approximately equal to (7+4) or 11 times the fundamental frequency. Thus, the implication is that f_1 = 199/11 = 18.1, which is less than F_L = 30.

The same is true for $D_{H,M}/I_c$ and $D_{M,L}/I_d$. This alone implies that one or more anomalous frequencies exist. Step 9 will show that still another comparison implies anomalous frequencies are in this trio of candidate frequencies.

Step 9. Any trio of ranking numbers R_H, R_M, R_L is disqualified if the integer ratio I_c/I_d which matches the frequency difference ratio is inconsistent with the corresponding ranking number ratios $(R_H-R_M) \div (R_M-R_L)$.

Example: The only possible ranking number trio was {13, 11, 10 }. It is screened out because $7/4 \neq (13 - 11) \div (11 - 10) = 2$.

Step 10. a) If there are unresolvable inconsistencies, go to Step 11.

Example: The first time through, before a new frequency is selected and anomalous frequencies are eliminated, there were unresolvable inconsistencies. All possible ranking number trios were screened out, and the difference ratio led to an inconsistency.

b) If there are no unresolvable inconsistencies, and a consistent trio has therefore been found to be legitimate, go to Step 17 to deduce the fundamental frequency.

Example: In this case, after a new frequency has been inducted and the 2^{nd} frequency in the original trio has been replaced, no unresolvable inconsistencies are found as shown below.

Step 11. Have all the frequencies that have been measured and detected been selected? If no, go to Step 12, if yes, go to Step 16.

Steps 12-14. To find a trio of candidate frequencies, the original three candidate frequencies are used with one or more additional candidate frequencies to determine a legitimate trio. If it is the first time through the process for a trio, proceed to Step 13 to select a fourth candidate frequency and on to Step 14 to replace one of the frequencies in the trio. The determination of a legitimate trio consisting of the fourth candidate frequency and two of the original trio of candidate frequencies is conducted beginning at Step 3.

If the first substitution of the fourth candidate frequency does not produce a legitimate trio, Step 12 proceeds directly to Step 14. A second original candidate frequency is replaced by the fourth candidate to form a new trio. If this does not produce a legitimate trio, the fourth candidate will be substituted for a third original candidate frequency.

If no legitimate or consistent trio has been found after substituting the fourth candidate frequency for each of the frequencies in the original trio, which is determined as the third pass through by Step 12, go to Step 15.

Example: Since there are unresolvable inconsistencies in the original trio {849, 722, 650}, a new frequency is selected. The new frequency is 602 Hz.

The value 849 is replaced by 602 to form the trio {722, 650, 602}which is designated as new candidate trio $\{f_H, f_M, f_L\}$.

For $f_{H'}/f_{M'}$ = 1.111, the closest integer ratios are 10/9, 11/10, and 9/8.

For f_M/f_L = 1.0797, the closest integer ratios are 14/13, 13/12, and 15/14. There are no matching ranking numbers.

Again, no consistent trio is found.

A different frequency in the original trio is replaced, i.e., 722 is replaced by 602 and the original frequency 849 reinserted to form the trio {849, 650, 602}which is designated as new candidate trio $\{f_H, f_M, f_L\}$.

For f_H/f_M = 1.306, the closest integer ratios are 13/10, 17/13, and 14/11.

For f_M/f_L = 1.0797, the closest integer ratios are 14/13, 13/12, and 15/14.

f_H/f_M = 17/13 and f_M/f_L = 13/12 form a possible ranking number trio which is $\{R_H, R_M, R_L\}=\{17, 13, 12\}$.

$(f_H - f_M) \div (f_M - f_L) = 199/48 = 4.146 \approx 4$.

$(R_H - R_M) \div (R_M - R_L) = 4/1 = 4$, which is consistent with the frequency difference ratio.

Also $f_H \div R_H = 49.94, f_M \div R_M = 50, f_L \div R_L = 50.17$. All are greater than F_L = 30.

All conditions are met and therefore R_H, R_M, and R_L are assumed to be 17, 13 and 12 respectively and the candidate frequencies 849, 650, 602 are considered a legitimate trio. The fundamental frequency is now determined at Step 17.

Step 15. A fifth and sixth candidate frequencies are selected. The fourth frequency is combined with the fifth and sixth candidate frequencies to form a new beginning trio and the method will be executed starting with Step 3. Step 12 will be reset to zero pass throughs.

Step 16: If after all frequencies detected and measured have been selected and determined by Step 11 and no consistent or legitimate trio has been found at Steps 7-10, the lowest of all the frequencies selected will be considered the fundamental.

Step 17. Deduce the fundamental frequency by any one of the following methods for example wherein $G(n) = n$, $f_H = 849$ Hz, $f_M = 650$ Hz, $f_L = 602$ Hz, $\{R_H, R_M, R_L\}=\{17, 13, 12\}$:

a) $f_1 = f_H/R_H$

b) $f_1 = f_M/R_M$

c) $f_1 = f_L/R_L$

d) $f_1 = (f_H - f_M) \div (R_H - R_M)$

e) $f_1 = (f_M - f_L) \div (R_M - R_L)$

f) $f_1 = (f_H - f_L) \div (R_H - R_L)$

Example: After a consistent legitimate trio of frequencies with associate ranking numbers is found to be {849, 650, 602} and {17, 13, 12}:

a) $f_1 = 849/17 = 49.94$ Hz

b) $f_1 = 650/13 = 50.00$ Hz

c) $f_1 = 602/12 = 50.17$ Hz

d) $f_1 = (849 - 650) \div (17 - 13) = 49.75$ Hz

e) $f_1 = (650 - 602) \div (13 - 12) = 48.00$ Hz

f) $f_1 = (849 - 602) \div (17 - 12) = 49.4$ Hz

The deduced fundamental could be set equal to any of a variety of weighted averages of the six computed values. For example:

The average value of f_1, using the ratio method of computation, e.g., a) through c) above, = 50.04 Hz.

The value of f_1, considering that frequency difference method which spans the largest number of harmonics, as given by f) above, = 49.4.

Averaging the values of f_1 computed by the ratio methods and the difference method which spans the greatest number of harmonics gives $(50.04+49.4)\div 2=49.58$.

These three averaging methods should produce reasonable values for the deduced fundamental frequency. The last is preferred unless/until field data indicate a better averaging method.

b) If the harmonics of the instrument at hand had been modeled by the function $f_n = f_1 \times n \times (S)^{\log_2 n}$, where S>1, a more precise method of deducing the fundamental would be as follows:

a) $f_1 = (f_H \div S^{\log_2 R_H}) \div R_H$

b) $f_1 = (f_M \div S^{\log_2 R_M}) \div R_M$

c) $f_1 = (f_L \div S^{\log_2 R_L}) \div R_L$

d) $f_1 = [(f_H \div S^{\log_2 R_H}) - (f_M \div S^{\log_2 R_M})] \div (R_H - R_M)$

e) $f_1 = [(f_M \div S^{\log_2 R_M}) - (f_L \div S^{\log_2 R_L})] \div (R_M - R_L)$

f) $f_1 = [(f_H \div S^{\log_2 R_H}) - (f_L \div S^{\log_2 R_L})] \div (R_H - R_L)$

If the sharping constant S had been set equal to 1.002, the deduced values of the fundamental would have been as follows:

a) $f_1 = 49.535$ Hz.

b) $f_1 = 49.63$ Hz.

c) $f_1 = 49.81$ Hz.

d) $f_1 = 49.22$ Hz.

e) $f_1 = 47.51$ Hz.

f) $f_1 = 48.88$ Hz.

The average value of f_1, using the ratio method of computation, e.g., a) through c) above, equals 49.66 Hz.

The value of f_1, considering that frequency difference method which spans the largest number of harmonics as given by f) above, equals 48.88 Hz.

Averaging the values of f_1 computed by the ratio method and the difference method which spans the greatest number of harmonics gives

$(49.66 + 48.88) \div 2 = 49.27$.

Any of these three averaging methods may be used to deduce the fundamental. The last is preferred.

If after Step 9 is completed, two or more consistent sets of ranking numbers remain, the fundamental f_1 should be recalculated with each set of ranking numbers and the lowest frequency obtained which is consistent with conditions described in Steps 3 through 9 is selected as the deduced fundamental frequency f_1.

The description and examples given previously assume harmonic frequencies are modeled by

$f_n = f_1 \times G(n) = f_1 \times n \times (S)^{\log_2 n}$ where $1 \le S \le 1.003$. The latter function, with S being this close to 1, implies that f_n / f_m will be approximately equal to the integer ratio n/m, that the ratio of the frequency differences $(f_H - f_M) \div (f_M - f_L)$ will be approximately equal to a small integer ratio and that $f_X - f_Y \approx (X - Y) \times f_1$.

In the general case, trios of legitimate harmonic partials are isolated and their corresponding ranking numbers are determined by

a) Comparing the quotients of $f_H \div f_M$ and $f_M \div f_L$ to the quotients of ratios $G(R_H) \div G(R_M)$ and $G(R_M) \div G(R_L)$ respectively.

b) Comparing the frequency difference ratios $(f_H - f_M) \div (f_M - f_L)$ with function difference ratios $[G(R_H) - G(R_M)] \div [G(R_M) - G(R_L)]$.

c) Comparing fundamental frequencies that are implied by possible combinations of ranking numbers to both the lowest fundamental frequency and the highest harmonic frequency that can be produced by the instrument at hand.

Method II

An alternative method for isolating trios of detected partials which consist only of legitimate harmonic frequencies having the same underlying fundamental frequencies, for finding their associated ranking numbers, and for determining the fundamental frequency implied by each such trio is illustrated in Figures 3, 4 and 5. The method marks and tags detected partial frequencies on a logarithmic scale and matches the relationships between and among those partials to a like logarithmic scale which displays the relationships between and among predicted/modeled harmonic frequencies.

Hereafter an example is used to clarify the general concepts. It illustrates a method that could be used to match or find a best fit of received signals to the signatures or patterns of harmonic frequencies and only illustrates the kinds of logical operations that would be used. The example should be considered as one possible incarnation and not considered as a limitation of the present invention.

For purposes of this example it is assumed that the harmonics produced by the instrument at hand are modeled by the function $f_n = f_1 \times n \times (S)^{\log_2 n}$, where n is a positive integer 1, 2,…, 17, and S is a constant equal to 1.002. Based on that function, a Harmonic Multiplier Scale, hereafter called the HM Scale, is established where each gradient marker represents a cent which is 1/100 of a semitone or 1/1200 of an octave. The first mark on the scale represents the harmonic multiplier 1, i.e., the number which when multiplied by f_1 gives f_1. Each successive mark on the scale represents the previous multiplier number itself multiplied by $[2 \times S]^{1/1200}$ Assume that a string of bits is used each representing one cent. The n^{th} bit will represent the multiplier $[(2 \times S)^{1/1200}]^{(n-1)}$. Selected bits along the HM Scale will represent harmonic multipliers and will be tagged with the appropriate harmonic number: f_1 will be represented by bit 1, f_2

by bit 1200, f_3 by bit 1902, f_4 by bit 2400,..., f_{17} by bit 4905. This scale is depicted in Figure 3.

Another scale is established for marking and tagging candidate partial frequencies as they are detected. The starting gradient marker, represented by bit 1, will represent the frequency F_L; the next by $F_L \times [(2 \times S)^{1/1200}]^1$, the next by $F_L \times [(2 \times S)^{1/1200}]^2$. The n^{th} bit will represent $F_L \times [(2 \times S)^{1/1200}]^{n-1}$. This scale is known as the Candidate Partial Frequency Scale and is hereafter called the CPF Scale. It is depicted along with the HM Scale in Figure 3.

As partials are detected their frequencies are marked and tagged on the CPF Scale. When three have been so detected, marked and tagged, the CPF Scale is moved with respect to the HM Scale, searching for matches. If a match of the three candidate frequencies is not found anywhere along the scales, another partial frequency is detected, marked and tagged and the search for three that match continues. When members of a trio of candidate partials match a set of multipliers on the CPF Scale to within a specified limit, then the candidate frequencies are assumed to be legitimate harmonic frequencies, their ranking numbers matching the ranking numbers of their counterparts on the CPF Scale. Likewise, the implied fundamental can be deduced directly. It is the frequency position on the CPF matching the "1" on the HM Scale.

Figure 4 shows the portion of the scales in which the detected candidate frequencies lie after the scales have been shifted to reveal a good alignment of three frequencies, i.e., the 4^{th}

frequency detected, 421 Hz, combined with the 1st and 3[rd] frequencies detected, 624 Hz and 467 Hz.

One method for measuring the degree of alignment between a candidate partial and a harmonic multiplier is to expand the bits that mark candidate partial frequencies and harmonic multipliers into sets of multiple adjacent bits. In this example, on the HM Scale, 7 bits are turned on either side of each bit which marks a harmonic multiplier. Likewise, on the CPF Scale, 7 bits are turned on either side of each bit marking a candidate partial frequency. As the scales are moved with respect to each other, the number of matching bits provides a measure of the degree of alignment. When the number of matching bits in a trio of candidate frequencies exceed a threshold, e.g., 37 out of 45 bits, then the alignment of candidate partials is considered to be acceptable and the candidate frequencies are designated as a trio of legitimate harmonic frequencies. Figure 5 illustrates the degree of match, e.g., 12 out of a possible 15, between one candidate partial frequency, i.e., 624 Hz, and the multiplier for the 12[th] harmonic.

When an acceptable alignment or match is found, the implied ranking numbers are used to test for unresolvable inconsistencies using the logical Steps 6 through 9 of Method 1. If no unresolvable inconsistencies are found and the implied fundamental is lower then F_L or higher than F_H, then the scales are moved in search of alignments implying a higher fundamental or a lower fundamental respectively. When no unresolvable inconsistencies are found and the implied fundamental lies between F_L

and F_H, then the implied fundamental f_1 becomes the deduced fundamental.

Some classes of instruments/devices have resonance bands and/or registers which produce harmonics which are systematically sharper than those in other resonance bands and/or registers. Likewise, the harmonics of some instruments may be systematic and predictable in some frequency bands and not in others. In these cases, Method II can be used as follows:

1. Isolate the frequency bands where S is consistent throughout the band.
2. Build an HM Scale to be used only for the frequencies in that frequency band based on the S for that band.
3. Build other HM Scales for other frequency bands where different values of S apply.
4. When frequencies are detected, locate them in the CPF Scale which is constructed with the value of S appropriate for the band that contains that frequency.
5. Ignore detected frequencies which lie in frequency bands where the harmonics are not predictable.
6. Search for matches between harmonic multiplier patterns and detected candidate frequency patterns using like scales (same S value).

<u>Method III</u>

Another method of deducing the fundamental frequency entails the detection and measurement or calculation of harmonic frequencies for a plurality of fundamental frequencies. The frequencies are organized in an array with fundamental frequencies being the rows and harmonic ranking numbers being the columns. When a note with unknown fundamental frequency is played, the frequencies of the higher harmonics, as they are detected, are compared row by row to the harmonic frequencies displayed in the array. A good match with three or more frequencies in the array or with frequencies interpolated from members of the array indicate a possible set of ranking numbers and a possible deduced fundamental frequency. When a trio of detected frequencies matches two or more trios of frequencies in the array, and thus two or more fundamental frequencies are implied, the deduced fundamental frequency is set equal to the lowest of the implied fundamental frequencies that is consistent with the notes that can be produced by the instrument at hand. The array is an example of only one method of organizing the frequencies for quick access and other methods may be used.

Methods I, II and III above can be used to isolate and edit anomalous partials. For example, given a monophonic track of music, after all partials have been detected during a period of time when the deduced fundamental remains constant, these methods could be used to identify all partials which are not legitimate members of the set of harmonics generated by the given fundamental. That information could be used, for example, for a) editing extraneous sounds from the track of music; or b) for analyzing the anomalies to determine their source.

Normally three or more legitimate harmonic frequencies will be required by either Method I, II, or III although in some special cases only two will suffice. In order to deduce the fundamental frequency from two high-order harmonics, the following conditions must prevail: a) It must be known that anomalous partial frequencies which do not represent legitimate harmonics are so rare that the possibility can be ignored; and b) The ratio of the two frequencies must be such that the ranking numbers of the two frequencies are uniquely established. For example, suppose the two frequencies are 434 Hz and 404 Hz. The quotient of the ratio of these frequencies lies between 14/13 and 15/14. If $F_L = 30$ Hz, then the ranking numbers are uniquely established as 14 and 13, since brake $434 \div 15 = 28.9$ which is less than 30 and thus disqualified. The difference of the two candidate frequencies is 30, which is acceptable since it is not less than F_L. Also, the ratio $(F_H - F_L) \div (R_H - R_L) = 30$ which again is not less than F_L.

The function $f_n = f_1 \times n \times (S)^{\log_2 n}$ is used to model harmonics which are progressively sharper as n increases. S is a sharping constant, typically set between 1 and 1.003 and n is a positive integer 1, 2, 3,..., T, where T is typically equal to 17. With this function, the value of S determines the extent of that sharping. The harmonics it models are consonant in the same way harmonics are consonant when $f_n = n \times f_1$. I.e., if f_n and f_m are the n^{th} and m^{th} harmonics of a note, then

$$f_n/f_m = f_{2n}/f_{2m} = f_{3n}/f_{3m} = \ldots = f_{kn}/f_{km}$$

where k is a positive integer.

A system which implements the method is shown in Figure 6. A preprocessing stage receives or picks up the signal from the source. It may include a pickup for a string on a musical instrument. The preprocessing also conditions the signal. This may include normalizing the amplitude of the input signal, and frequency and/or frequency band limiting. Next a frequency detection stage isolates frequency bands with enough energy to be significantly above ambient noise and of appropriate definition.

The fast find fundamental stage performs the analysis of the candidate frequencies and deduces the fundamental. The post processing stage uses information generated by the fast find fundamental stage to process the input signal. This could include amplification, modification and other signal manipulation processing.

The present method has described using the relationship between harmonic frequencies to deduce the fundamental. The determination of harmonic relationship and their rank alone without deducing the fundamental also is of value. The fundamental frequency may not be present in the waveform. The higher harmonics may be used to find other harmonics without deducing the fundamental. Thus, post processing will use the identified harmonics present.

Although the present invention has been described with respect to notes produced by singing voices or musical instruments, it may include other sources of a complex wave which has a fundamental frequency and higher harmonics. These could include a speaking voice, complex machinery or other mechanically vibrating elements, for example.

Although the present invention has been described and illustrated in detail, it is to be clearly understood that the same is by way of illustration and example only, and is not to be taken by way of limitation. The spirit and scope of the present invention are to be limited only by the terms of the appended claims.

What is claimed:

1. A method of deducing a fundamental frequency from harmonics present in a signal, the method comprising:

selecting at least two candidate frequencies in the signal;

determining if the candidate frequencies are a group of legitimate harmonics frequencies having a harmonic relationship; and

deducing the fundamental frequency from the legitimate frequencies.

2. A method according to Claim 1, wherein determining legitimate frequencies includes using one or more of ratio of the candidate frequencies, difference of the candidate frequencies and ratio of the candidate frequency with the difference.

3. A method according to Claim 2, including determining if the ratios are equal to a ratio of harmonic model $f_n = f_1 \times G(n)$ where f_1 is a fundamental frequency and n is a ranking number of the candidate frequency.

4. A method according to Claim 3, wherein $G(n) = n \times (S)^{\log_2 n}$, where S is a constant.

5. A method according to Claim 3, wherein $G(n) = n$.

6. A method according to Claim 1, wherein determining legitimate frequencies includes determining if a ratio of the candidate frequencies is substantially equal to a ratio of acceptable harmonic ranking numbers.

7. A method according to Claim 1, wherein determining legitimate frequencies includes determining acceptable harmonic ranking numbers for the candidate frequencies.

8. A method according to Claim 7, wherein acceptable harmonic ranking numbers are determined as a function of the source of the signal.

9. A method according to Claim 1, including selecting three candidate frequencies in the signal and determining legitimate harmonic frequencies includes using one or more of ratios of the candidate frequencies, differences of the candidate frequencies, and ratio of differences of the candidate frequencies.

10. A method according to Claim 9, including determining three acceptable harmonic ranking numbers for the candidate frequencies from the ratios of the three candidate frequencies.

11. A method according to Claim 9, including determining ratios of integers which are substantially equal to the ratios of the candidate frequencies and determining harmonic ranking numbers for each candidate frequency from a match of a

number from the integer ratios of one of the candidate frequency with the other two candidate frequencies.

12. The method according to Claim 9, including determining harmonic ranking numbers for the candidate frequencies; and determining if the difference ratio is equal to the ratio of the difference of the ranking numbers.

13. The method according to Claim 9, including determining a ratio of integers which are substantially equal to the difference ratio; and determining if the integers of the ratio are in a predetermined range.

14. A method according to Claim 13, including determining if the integers of the ratio are each below a first value and the sum of the integers is below a second value.

15. A method according to Claim 9 including selecting a fourth candidate frequency in the signal if the first three candidate signal are not determined to be group of legitimate frequencies and determining if the fourth candidate frequency and two of the first three candidate frequencies are a group of legitimate frequencies having a harmonic relationship.

16. A method according to Claim 1 wherein determining legitimate frequencies includes comparing the candidate frequencies to a fundamental

frequency and its higher harmonics to find at least one acceptable match.

17. A method according to Claim 16, wherein a harmonic scale is created for the harmonics, a candidate scale is created for the candidate frequencies, and the candidate scale and the harmonic scale are moved relative to each other to find at least one acceptable match.

18. A method according to Claim 17, wherein the candidate scale and the harmonic scale are logarithmic scales of the same base.

19. A method according to Claim 17 including creating a plurality of harmonic scales and corresponding candidate scale of different harmonic relationships.

20. A method according to Claim 16 including storing a plurality of groups of harmonic frequencies with their ranking numbers and comparing the candidate frequencies to the group of harmonic frequencies to determine at least one acceptable match.

21. A method according to Claim 1 wherein determining legitimate frequencies includes: creating a logarithmic harmonic scale for a group of harmonics; creating a logarithmic candidate scale, for the candidate frequencies of the same base at the harmonic scale; and moving the

candidate scale and the harmonic scale relative to each other to find at least one acceptable match.

22. A method according to Claim 21, including determining the ranking number of the candidate frequencies from the match of the candidate scale to the harmonic scale, and using the ranking numbers to determine a group of legitimate frequencies.

23. A method according to Claim 1, including determining the ranking number of the legitimate frequencies; and wherein the fundamental frequency is deduced using one or more of the legitimate frequency being divided by its ranking number and differences of the legitimate frequencies being divided by differences of their ranking numbers.

24. A method according to Claim 23, wherein the fundamental frequency is deduced using a weighted average of the quotients.

25. A method according to Claim 23, wherein the fundamental frequency is deduced by dividing the legitimate frequencies by $(S)^{\log_2 n}$, where n is the ranking number and S is a constant.

26. A method of determining a fundamental frequency from harmonics present in a signal, the method comprising:

selecting at least two candidate frequencies in the signal; and

deducing the fundamental frequency from ratio, difference and harmonic ranking number of the candidate frequencies.

27. A method of determining a set of partial frequencies in a signal which are legitimate harmonic frequencies of a common fundamental frequency, the method comprising:

selecting at least two candidate frequencies in the signal;

comparing relationships of the candidate frequencies with corresponding modeled relationships of harmonic frequencies;

determining a harmonic ranking number for each candidate frequency; and

deducing the common fundamental frequency from the candidate frequencies and the ranking numbers.

28. A method according to Claim 27, wherein the modeled relationship is $f_n = f_1 \times n \times (S)^{\log_2 n}$, where n is the ranking number, f_1 is a fundamental frequency and S is a constant.

29. A method of determining a set of partial frequencies in a signal which are legitimate harmonic frequencies of a common fundamental frequency, the method comprising:

selecting at least two candidate frequencies in the signal;

marking the candidate frequencies on a logarithmic candidate scale; and

comparing the candidate frequencies on the logarithmic candidate scale to a logarithmic harmonic scale which includes a modeled harmonic relationship of harmonic frequencies to determine if the candidate frequencies are legitimate harmonic frequencies of a common fundamental frequency.

30. A method according to Claim 29, including determining harmonic ranking numbers for the candidate frequencies and the common fundamental frequency of the candidate frequencies from the comparison.

31. A method according to Claim 29, wherein the modeled relationship is
$f_n = f_1 \times n \times (S)^{\log_2 n}$, where n is the ranking number, f_1 is a fundamental frequency and S is a constant.

32. A method of determining a set of partial frequencies in a signal which are legitimate harmonic frequencies of a common fundamental frequency, the method comprising:

selecting at least two candidate frequencies in the signal;

comparing the candidate frequencies to a plurality of groups of harmonic frequencies to find acceptable matches; and

selecting the lowest deduced fundamental frequency from the acceptable scale matches as the legitimate harmonic frequencies of a common fundamental frequency.

33. A method according to Claim 1, including storing the method as instructions in a digital signal processor.

Figure 1

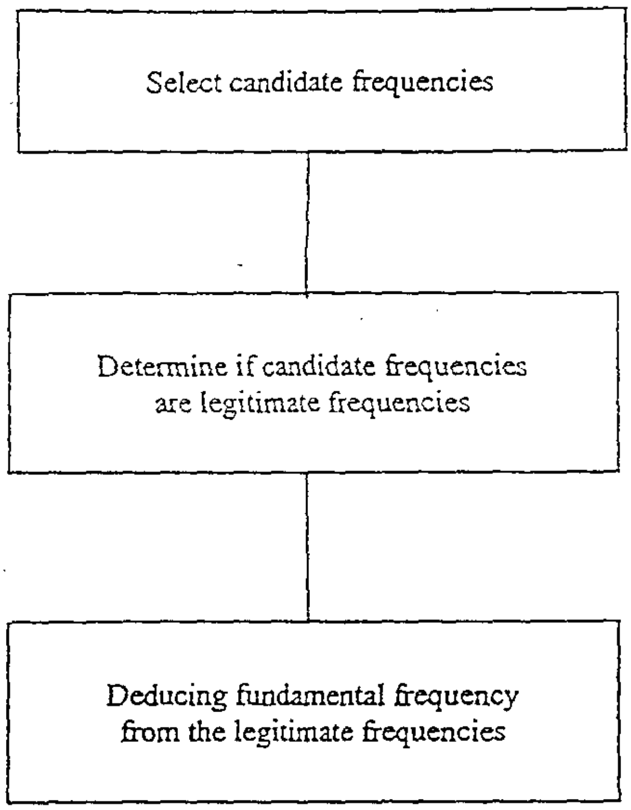
Select candidate frequencies
Determine if candidate frequencies are legitimate frequencies
Deducing fundamental frequency from the legitimate frequencies

Figure 2

Step 1.	Set constants for Instrument or source (F_H, F_L, F_{MAX}, G(n), K_1, K_2, K_3)
Step 2.	Select three candidate frequencies.
Step 3.	Designate candidate frequencies f_H, f_M, f_L.
Step 4.	Determine possible trios R_H, R_M, R_L for f_H, f_M, f_L.
Steps 5.	Disqualify trios which imply $f_1 < F_L$ or $f_1 > F_H$.
Steps 6.	Form frequency difference ratios.
Step 7.	Initially qualify.
Step 8.	Disqualify difference ratio which implies $f_1 < F_L$.
Step 9.	Disqualify ranking number trios which are inconsistent with difference ratios.
Step 10.	Does one or more consistent trios of Ranking numbers remain? Yes – 17 No ↓
Step 11.	All frequency selected? Yes – 16 No ↓
Step 12.	1st? No – ; Yes ↓ — 3rd? No – 14; Yes – 15
Step 13.	Select new frequency. Yes ↓
Step 14.	Replace one of the frequencies in the trio f_H, f_M, f_L with the new candidate. – 3
Step 15.	Select 2 new frequencies. – 3
Step 16.	Set the f_1 equal to the lowest candidate frequency.
Step 17.	Deduce f_1.

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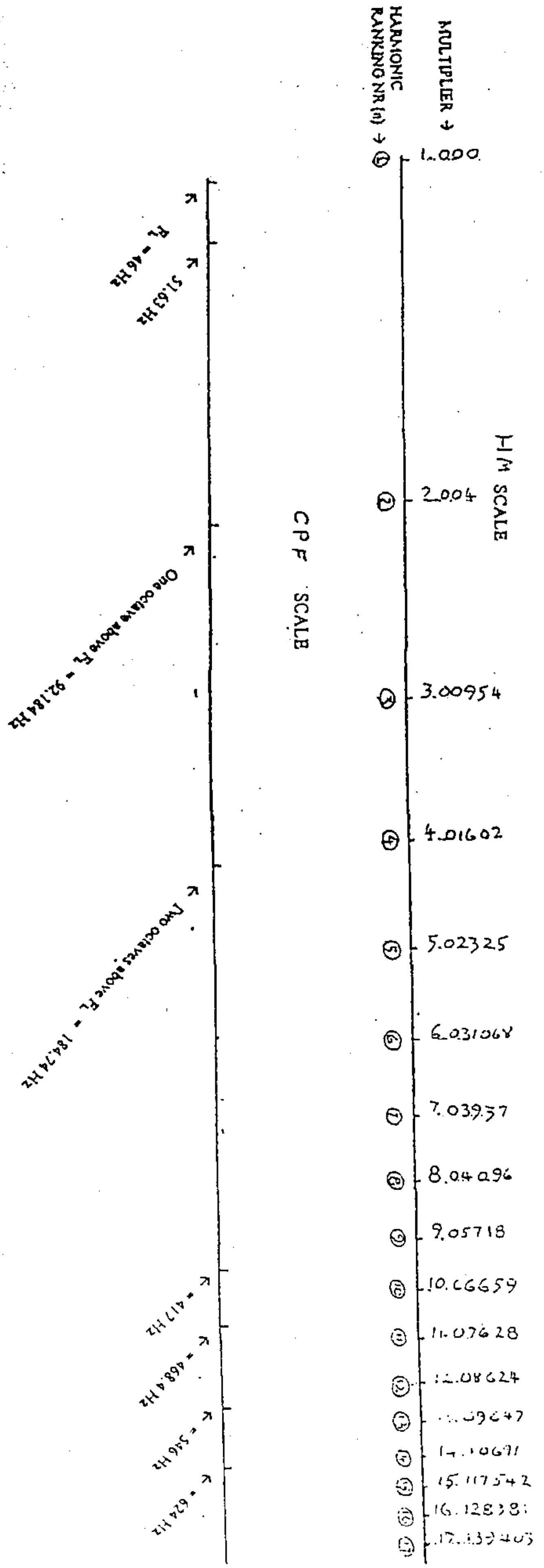
MULTIPLIER →
HARMONIC RANKING NR (n) →
1.000
2.004
3.00954
4.01602
5.02325
6.031068
8.04096
9.05718
11.07628
12.08624
15.117542
16.128381
H/M SCALE
CPF SCALE
FL = 46 Hz
51.63 Hz
One octave above FL = 92.184 Hz
Two octaves above FL = 184.74 Hz
= 417 Hz
= 468.4 Hz
= 526 Hz
= 624 Hz

FIG.3

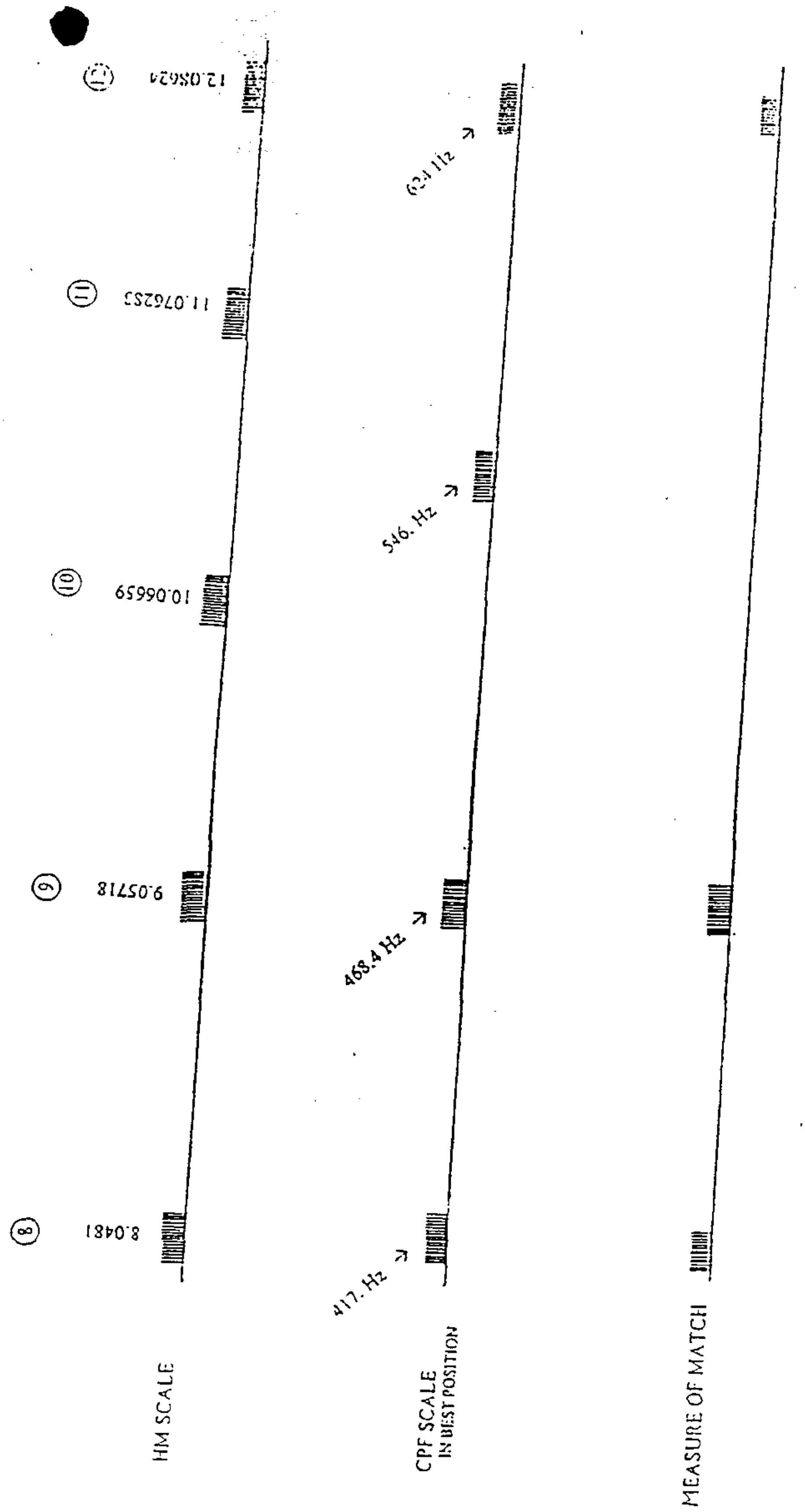
12.08624
(12)
11.07625
(11)
10.06659
(10)
9.05718
(9)
8.0481
(8)
HM SCALE
624 Hz
546. Hz
468.4 Hz
417. Hz
CPF SCALE
IN BEST POSITION
MEASURE OF MATCH

Figure 4


12th harmonic multiplier
HM Scale
b b b b b b b b b b b b b b b
624 Hz.
CPF Scale
b b b b b b b b b b b b b b b
Overlap
b b b b b b b b b b b b

FIGURE 5

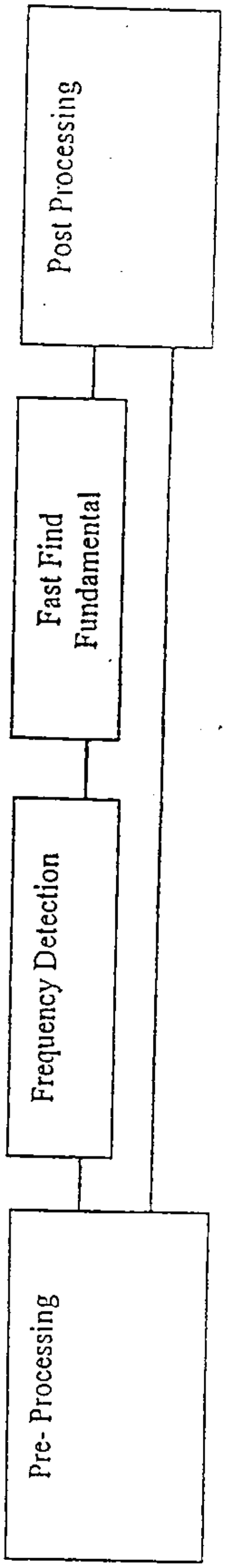
Pre- Processing
Frequency Detection
Fast Find
Fundamental
Post Processing

FIG. 6

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G10H 3/18

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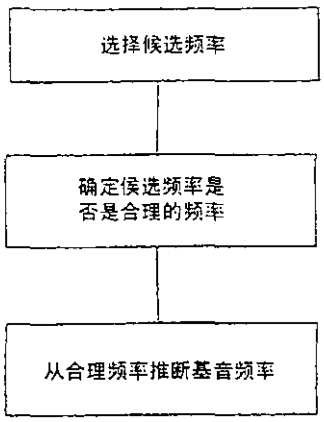
权利要求书4页 说明书20页 附图页数6页

[54]发明名称 快速找到基音的方法

[57]摘要

本发明包含三种快速推断复杂波形或者信号的基音频率的方法。一种方法是利用较高泛音的频率之间的关系，包括：频率比，频率之间的差，频率差比，和来自这种事实的关系，泛音频率由一个整数变量的函数来模型化，该整数的值代表泛音阶数。另一种方法是：所选频率的泛音的预计的/模型化的关系处在对数音阶上，在一个类似的音阶上记录所检测的分音频率，以及相互相对地移动音阶，以寻找三个泛音的匹配。当这样一个匹配找到时，可能的泛音阶数和隐含的基音频率能被直接推断出来。当检测分音还匹配一个预计的/模型化泛音关系的集时，第一种方法的对数被用来选择推断的基音。还有一种方法是：数个基音的泛音频率被收集和编排，这样，与一个未知基音联结的分音能与它们比较，并且未知的基音被推断。



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权 利 要 求 书

1．一种从在一个信号中存在的泛音推断一个基音频率的方法，该方法包括：

选择至少两个在该信号中的候选频率；

确定该候选频率是否是一组具有泛音关系的合理的泛音频率；和

从合理的频率推断所述的基音频率。

2．根据权利要求 1 所述的方法，其中，确定合理的频率包括采用一个或者一个以上候选频率的比，候选频率的差，和候选频率的差之比。

3．根据权利要求 2 所述的方法，包括确定这些比是否是等于泛音模型 $f_n=f_1\times G(n)$的比，其中，f_1 是基音频率，和 n 是所述候选频率的阶数。

4．根据权利要求 3 所述的方法，其中，$G(n)=n\times(S)^{\log_2 n}$，这里，S 是一个常数。

5．根据权利要求 3 所述的方法，其中，G(n)= n 。

6．根据权利要求 1 所述的方法，其中，确定合理的频率包括：确定一个候选频率比是否实质上等于一个可接受的泛音阶数比。

7．根据权利要求 1 所述的方法，其中，确定合理的频率包括：确定该候选频率的可接受的泛音阶数。

8．根据权利要求 7 所述的方法，其中，可接受的泛音阶数作为一个信号源的函数被确定。

9．根据权利要求 1 所述的方法，包括选择三个在信号中的候选频率和确定合理的泛音频率，包括采用一个或者一个以上的候选频率的比、候选频率的差、和候选频率差的比。

10．　根据权利要求 9 所述的方法，包括从三个候选频率的比确

定三个候选频率的可接受的泛音阶数。

11. 根据权利要求9所述的方法，包括确定实质上等于候选频率之比的整数比，以及从一个候选频率与其它两个候选频率的整数比的一个阶匹配确定每一个候选频率的泛音阶数。

12. 根据权利要求9所述的方法，包括确定候选频率的泛音阶数；以及确定差比是否等于阶数的差比。

13. 根据权利要求9所述的方法，包括确定一个实质上等于差比的整数比；以及确定比的整数是否在一个预定的范围内。

14. 根据权利要求13所述的方法，包括确定比的整数是否每个在一个第一值之下和整数的和是否在一个第二值之下。

15. 根据权利要求9所述的方法，包括假如头三个候选信号被确定不是合理的频率组，则在信号中选择第四候选频率，并确定第四候选频率和头三个候选频率中的两个是否是一组具有一种泛音关系的合理的频率。

16. 根据权利要求1所述的方法，其中，确定合理的频率包括将候选频率与一个基音频率和它的较高的泛音比较，以找到至少一个可接受的匹配。

17. 根据权利要求16所述的方法，其中，为泛音而产生一个泛音音阶，为候选频率而产生一个候选音阶，以及候选音阶和泛音音阶相互相对移动，以找到至少一个可接受的匹配。

18. 根据权利要求17所述的方法，其中，候选音阶和泛音音阶是同底的对数音阶。

19. 根据权利要求17所述的方法，包括产生数个泛音音阶及对应的不同泛音关系的候选音阶。

20. 根据权利要求16所述的方法，包括存储带它们的阶数的数个泛音频率组，将候选频率与泛音频率组比较，以确定至少一个可接受的匹配。

21．根据权利要求 1 所述的方法，其中，确定合理的频率包括：为一组泛音产生一个对数泛音音阶；为候选频率产生一个与泛音音阶的同底的对数候选音阶；以及相互相对地移动候选音阶和泛音音阶，以找到至少一个可接受的匹配。

22．根据权利要求 21 所述的方法，包括根据候选音阶与泛音音阶的匹配来确定候选频率的阶数，以及利用阶数来确定一组合理的频率。

23．根据权利要求 1 所述的方法，包括确定合理频率的阶数；并且其中，基音频率采用一个或者一个以上合理的频率和合理频率的差来推断，所述的合理频率用其阶数相除，所述的合理频率的差用其阶数的差相除。

24．根据权利要求 23 所述的方法，其中，基音频率采用一个商的加权平均来推断。

25．根据权利要求 23 所述的方法，其中，基音频率用 $(S)^{\log_2 n}$ 除以合理的频率来推断，这里，n 是阶数，S 是一个常数。

26．一种从存在于一个信号中的泛音确定一个基音频率的方法，该方法包括：

在该信号中选择至少两个候选频率；和

从候选频率的比、差、以及泛音阶数，推断出基音频率。

27．一种确定在一个信号中的一组分音频率的方法，该频率是一个共同基音频率的合理泛音频率，该方法包括：

选择至少两个在信号中的候选频率；

将候选频率的关系与对应泛音频率的模型化关系比较；

为每一个候选频率确定一个泛音阶数；以及

根据候选频率和阶数推断共同的基音频率。

28．根据权利要求 27 所述的方法，其中，该模型化关系是 $f_n = f_1 \times n \times (S)^{\log_2 n}$，这里，n 是阶数，$f_1$ 是一个基音频率，S 是

一个常数。

29．一种确定在一个信号中的一组分音频率的方法，该频率是一个共同基音频率的合理泛音频率，该方法包括：

选择至少两个在该信号中的候选频率；

在一个对数候选音阶上标注候选频率；和

将在对数候选音阶上的候选频率与一个对数泛音音阶进行比较，以确定候选频率是否是一个共有基音频率的合理泛音频率，所述的泛音音阶包括一个模型化泛音频率的泛音关系。

30．根据权利要求29所述的方法，包括根据比较的结果来确定候选频率的泛音阶数和候选频率的共有基音频率。

31．根据权利要求30所述的方法，其中，模型化关系是：$f_n=f_1\times n\times(S)^{\log_2 n}$，这里，n是阶数，$f_1$是一个基音频率，S是一个常数。

32．一种确定在一个信号中的一组分音频率的方法，该频率是一个共有基音频率的合理泛音频率，该方法包括：

选择至少两个在该信号中的候选频率；

将该候选频率与数个泛音频率组比较，以找到可接受的匹配；和

根据可接受的音阶匹配选择最低的推断基音频率作为一个共有基音频率的合理泛音频率。

33．根据权利要求1所述的方法，包括存贮该方法作为在一个数字信号处理器中的指令。

说　明　书

快速找到基音的方法

交叉参考

本申请涉及 1998 年 10 月 29 日申请的流水号为 60/106,150 的临时专利申请，并要求该申请的权益，该申请在此可结合起来作为参考。

发明的背景和概述

本发明涉及电子音乐的产生和再现，还涉及在放大和增强由音符产生的信号过程中改善声音的电子模拟的方法，并且一般地涉及具有快速确定复合波的基音频率的目的的系统，该复合波是多个频率的总和。

测量一个正弦波信号的频率达到一个特定的音高精度（例如，半音的 1/4）所要求的时间长度具有一个最小值的限制。该最小时间与待处理信号的频率成反比。保持音高精度为常数，要求测量一个 82.4 赫兹的纯正弦波的频率的时间最小量将是要求测量一个 659.4 赫兹的纯正弦波的频率的最小时间的 8 倍还长。因此，存在这样的问题，即，对于不用键盘（或者当发一个音符的音时，表示基音频率的其它装置）的乐器产生的低音音符的基音频率来说，其测量和再现需要很长时间。例如，当来自低音音符的信号在它们被放大和再现之前由合成器处理时，通常，导致一个令人烦恼的延迟时间。

在整个专利中，一个分音(partial)或者分音频率定义为一个确定的能量频带，而泛音(harmonics)或者泛音频率被定义为：根据一种整数关系，比如，一个机械物体，例如，一条弦，或者一个气柱用结点的整数来分割这种现象所产生的分音。由多级振荡/振动装置产

生的泛音频率之间的关系，包括乐器，可以用一个函数 G（n）来建立模型：

$f_n=f_1 \times G(n)$

这里，f_n 是第 n 个泛音的频率，f_1 是基音频率，也就是所谓的第 1 个泛音，n 是一个正整数，它代表泛音阶数(harmonic ranking number)。这类函数的已知例子是：

$f_n=f_1\times n$ ；以及，

$f_n=f_1 \times n \times[1+(n^2-1)\beta]^{1/2}$ 。

这里，β 是一个常数，通常是 0.004。

关于复杂波形的特性和泛音含量以及靠振动物体和这类物体的电气/电子模拟量产生的泛音分音之间的关系，知识和理论本身是存在的。有助于知识本身的理解的教科书例子是：1）Fletcher 和 Rossing 的《乐器物理》，2）Sethares 的《调音、音色、频谱、音阶》，以及 3）Rabiner 和 Schafer 的《语音信号的数字处理》。还包括与测量/确定频率的方法有关的知识和理论，例如，固定的和可变的带通和带阻滤波器，振荡器，谐振器，快速傅立叶变换等。知识本身的总述包含在大不列颠百科全书中。

最近特别谈到测量基音频率的方法的专利例如有：

授予 Szalay 的美国专利 5,780,759 描述了一种音高识别方法，该方法采用一个信号的零交点之间的间隔作为该信号的周期长度的一个计量单位。零交点的梯度大小被用来选择零交点，以便评估。

授予 Bartkowiak 等人的美国专利 5,774,836 显示了一种改进的声码器系统，该系统用来估计在一个语音波形中的音高。该方法首先进行一个相关的计算，然后，产生一个基音频率的估计。它再进行错误校验，以去除“错误的”音高估计。在这个过程中，该方法寻找该估计的基音频率的较高的泛音。

授予 Warrander 的美国专利 4,429,609 显示了一种装置和方法，

该装置和方法进行 A/D 转换，去除在有影响的区域之外的频带，并采用零交点时间数据来完成分析，以确定基音。它靠对应于零交点之间的间隔的逐次量来延迟一个参考信号，并把参考信号与延迟信号结合起来，以确定该基音。

本发明是一种采用较高的泛音频率之间的关系，快速推断一个复杂波形或者信号的基音频率的方法。

该方法包括选择至少两个在信号中的候选频率。接着，它要确定该候选频率是否是一组合理的(legitimate)、具有泛音关系的泛音频率。最后，基音频率从合理的频率中被推断出来。

在一种方法中，被检测的分音频率之间的关系与可比关系进行比较，可比关系取决于所有的组成是否是合理的泛音频率。被比较的关系包括频率比，频率差，这些频率差的比，以及由泛音频率靠一个假定只是正整数值的变量函数来模型化的事实引出的特有关系。这个整数值叫做泛音阶数。最好是，整数变量的函数是 $f_n=f_1\times n\times (S)^{\log_2 n}$，其中，S 是一个常数，通常，$1\leqslant S\leqslant 1.003$，n 是泛音阶数。S 的值，以下称为升音常数，确定泛音随 n 的值增加而逐步升高的程度。

其它的关系必须保持候选分音频率是否是根据作为信号源的振动/振荡物体或者仪器的物理特征的合理的泛音主干(stem)，即，它能产生的最高和最低基音频率以及它能产生的最高泛音频率。

确定合理的泛音频率和推断一个基音频率的另一种方法包括：将候选频率组与一个基音频率及其泛音比较，以找出一个可接受的匹配。一种方法是产生一个泛音倍数音阶(harmonic multiplier scale)，在该音阶(scale)上，G（n）的值被记录。这些数值对于 n 的每一个值，即，对于每一个泛音阶数，都是基音频率的倍数。接着，一个类似的音阶被产生，在那里，候选分音频率的数值能被记录。在一组候选分音频率已经被检测和记录之后，两个音阶被比较，即，它

们相互相对被移动，以定位候选频率组与泛音倍数组的可接受的匹配。最好是，该音阶是对数的。当一个好的匹配找到时，候选频率组的一个可能的阶数集就由泛音阶数音阶来确定（或者能被直接读出）。同样地，与合理的分音候选频率组相关的隐含基音频率能被直接地读出。这是在候选频率音阶中的频率，它对应（相应于）泛音倍数音阶上的“1”。

假如函数 G（n）对于不同的频率寄存器是不同的，以致于在一个频率寄存器中的泛音方式是相关的，这些方式不同于其它频率寄存器中相关的方式，然后，不同的泛音倍数音阶被产生，对于不同的频率寄存器中的每一个，都有一个对应的音阶。分音频率被记录在频率寄存器的合适音阶上，在频率寄存器中，它们终止，并与对应于频率寄存器的泛音倍数音阶比较。

在另一种匹配方法中，候选频率与被检测、测量的来自数个基音频率的多个泛音频率比较。被检测和测量的泛音频率最好组成一个阵列，按基音频率次序组成，列是泛音阶数，行是泛音频率。当三个或者三个以上被检测的分音阵列充分地接近在该阵列的一行中的三个测量到的泛音频率时，泛音阶数和基音就已知了。

因为更高的泛音频率通常能比基音频率更快地被确定，推断基音频率的计算能在一个很短的时间内完成，因此，低音音符的基音频率能在它们被测量到之前被很好地推断。

从下面结合附图对发明的详细描述中，可以更加清楚地了解本发明的其它优点和新颖的特征。

附图的简单说明

图 1 是根据本发明推断基音频率的一种方法的方框图。

图 2 是具体实现图 1 的方法的方框图。

图 3 表示一个对数音阶及一个相应的对数音阶，其中，在对数

音阶上，示出了泛音 1—17 的倍数，在相应的对数音阶上，示出了四个被检测的分音。

图 4 是放大图，表示图 3 中音阶所选择的部分在这些音阶相互相对移动之后，找出三个候选频率与泛音倍数的一个好匹配。

图 5 是图 4 的一个窄频带的放大图，表示匹配位怎样能用作一个匹配程度的计量单位。

图 6 是一个实现图 1—4 的方法的一个系统的方框图。

优选实施例的详细描述

为了从较高的泛音推断基音频率 f_1，异常的频率必须被筛选出来，并且至少一个合理泛音组的泛音阶数必须被确定。或者，由两个合理的泛音包括的未占据泛音位置（失去的泛音）的数目必须被确定。一般的方法，如在图 1 所示，选择候选频率。接着，它确定候选频率是否是合理的泛音频率，该频率具有相同基础的基音频率。最后，基音频率从合理的频率来推断。

定义和符号

下面的定义和符号将用于整个专利中：

f_H，f_M，f_L：　分音三音组的候选频率，以下降的频率次序排列。

R_H，R_M，R_L：与 f_H，f_M，f_L 相关的阶数。

F_L：　最低的基音频率，f_1，能由信息源产生。

F_H：　最高的基音频率，f_1，能由信息源产生。

F_{MAX}：　最高的泛音频率，能由信息源产生。

关系和限制条件

本方法利用：较高泛音之间的关系、限制选择的条件、较高泛音与基音具有的关系、以及可能的基音频率的范围。例子是：

假如 $f_{RZ}=f_1\times G(R_Z)$ 使第 R_Z 个泛音的频率模型化，并且

假如 f_H，f_M 和 f_L 是合理的泛音频率，以及

假如 R_H，R_M 和 R_L 是与 f_H，f_M，f_L 相关的阶数，那末，

下面的比关系必须保持：

a）被检测的候选频率的比必须大约等于通过在泛音模型中取代它们的阶数所获得的比，即，

$f_H \div f_M \approx f_{RH} \div f_{RM}$

$f_M \div f_L \approx f_{RM} \div f_{RL}$

b）被检测的候选频率之间的差之比必须是与模型化的频率的差之比相一致，即，

$$(f_H - f_M)\div(f_M - f_L)\approx(f_{RH} - f_{RM})\div(f_{RM} - f_{RL})$$

c）候选频率分音 f_H，f_M，f_L，它们是候选泛音，必须是在可以由源或者乐器产生的频率的范围内。

d）泛音阶数 R_H，R_M，R_L 不必隐含一个低于 F_L 或高于 F_H 基音频率，基音频率的范围可以由源或者乐器产生。

e）当匹配整数变量比，以获得阶数的可能三音组时，在整数比 R_H/R_M 中的整数 R_M 必须与在整数比 R_M/R_L 中的整数 R_M 相同，例如，这种关系用来将阶数对 $\{R_H, R_M\}$ 和 $\{R_M, R_L\}$ 加入可能的三音组 $\{R_H, R_M, R_L\}$。

方法的概述

本方法分析一组分音或者候选频率，并确定它们是否包括异常的频率。最好是，被分析的每一组将包含三个分音。假如确定不存在一个或者一个以上的异常频率，则认为该组是一组合理的泛音频率。每一泛音频率的阶数被确定，基音频率被推断。当确定存在一个或者一个以上的异常频率时，一个新的分音或者候选频率被检测、测量和选择，异常的频率被分隔和筛选出来。这一过程持续到一组合理泛音频率保留为止。在这一过程中，合理的泛音频率的阶数被

确定和确认。然后，基音频率用多种方法计算。考虑泛音不同于 $f_n = f_1 \times n$ 的程度，而进行调整。

方法 I

下面是实现图 1 的方法的简要流程图以推断基音频率的一种方法的例子，并表示在图 2 中。该方法测试被检测的候选分音频率的三音组，以确定其成分是否只是相同的基音频率的合理泛音频率。当不是这样时，附加的候选频率就被引入，并用来代替现有的三音组中的频率，直到一个合理泛音的三音组已经被找到为止。当这样的一个三音组被找到时，与每一个成分相关的阶数就被确定，基音频率被推断。

在此描述的这种方法表明了逻辑运算的种类，该运算将直接或者间接地被完成。实际执行将通过捷径，消除冗余信息等，并可以以其它的方式区别于下面所描述的执行。

该方法用一般术语描述的一系列步骤被呈现出来，同时一个数字表示的例子表明了对不同步骤所要求的计算。

乐器常数的定义

K_1 是最高的泛音阶数，该数将被赋值/估量。将在测量第 K_1 个泛音的频率过程中的预计的%误差与整数比的商值进行比较，由此来设定 K_1 的值

$$[(K_1+1) \div K_1] \div [K_1 \div (K_1-1)]$$

K_1 的一个默认值将被设定等于 17，并将修改以符合在手边的乐器的知识和在频率测量中预计的误差。

K_2 是两个邻近被检测的泛音频率之间漏掉的泛音的最大预计数。K_2 的默认值被设定等于 8。

K_3 等于两个泛音之间漏掉的泛音的预计最大值之和，加 1，所

述的泛音包含一个插入的或中间的泛音。K_3 的默认值被设定等于12。

步骤 1. 为乐器或者信号源设定常数/参数。

例如：F_H =300 H_Z，F_L =30 H_Z ，F_{max} =2,100 H_Z；K_1 =17，K_2=8，K_3=12

为了简化和简洁，描述泛音频率 G（n）之间的关系的函数被假定为 $f_1 \times n$ 。

步骤 2. 检测、测量和选择，例如，三个分音的频率。这些频率按它们产生的阶被检测和测量。三种频率或者分音，具有一个明显超过，例如，环境噪音级的能级，被选择作为可能的合理泛音的候选者。较高的频率，和次高的泛音频率，自然地被首先检测和测量。下面的例子假定一种例外，并表明怎样处理这种例外情况，在这种例外情况下，较低的泛音在一个较高的泛音之前被检测。

例如：测得第 1 频率= 722 H_Z ，

测得第 2 频率= 849 H_Z ，

测得第 3 频率= 650 H_Z 。

步骤 3. 这三个候选频率以频率的大小阶排列，标记为 f_H，f_M, f_L 。

例如：f_H =849 H_Z，f_m =722 H_Z，f_L =650 H_Z 。

步骤 4. 对于候选频率 f_H，f_M，f_L，可能的阶数的三音组被确定 。f_H/f_M 和 f_M/f_L 比值的商与整数比 I_a/I_b 的商进行比较，这里，I_a 和 I_b 都≤K_1，一个给定的阈值。在此，为说明的目的，K_1 被设定等于 17。当一个频率比的商充分地接近一个整数比的商时，该整数比被保留作为代表一对频率比的可能的阶数和与它匹配的数。比值还可以是 f_H

$/ f_L$ 和 f_M / f_L 或者 f_H/f_M 和 f_H / f_L 或者任何的倒数。

例如：当 f_H/f_M =1.176 时，最接近的整数比的商是 1.1818=13/11 和 1.1667=7/6 或者 14/12。注意 26/22 不会被考虑，因为 26＞17。当 f_M / f_L=1.111 时，最接近的整数比的商是 1.111=10/9 和 1.10=11/10。

当两个比的共有频率相等时，则形成一个可能的阶数三音组 {R_H，R_M，R_L}。在这个例子中，它是当整数分数 f_H/ f_M 的分母与整数分数 f_M / f_L 的分子相等时的情形。

例如：因为只有 f_H/ f_M =13/11 和 f_M / f_L=11/10 导致 f_M 的相同的阶数，所以，在这个例子中仅有可能的三音组是{R_H，R_M，R_L}={13，11，10}。

步骤 5. 所有阶数的可能三音组被排除，这隐含着一个由 F_L 和 F_H 确定的在该范围外的基音频率 f_1 。

例如：基音 f_1 是由它的阶数相除的候选频率。仅有的可能三音组{13，11，10}，不会被筛选掉，因为 f_H/13=65.308，f_M /11=65.636，以及 F_L/10=65.00 都是在 F_L=30 和 F_H=300 确定的范围内。

步骤 6. 差值 $D_{H,M}= f_H- f_M$ 和 $D_{M,L}= f_H- f_L$ 被计算，$D_{H,M}/D_{M,L}$ 的比值被算出。其它的能被相似使用的差比是 $D_{H,L}/D_{M,L}$ 或者 $D_{H,L}/D_{H,M}$ 。

例如：$D_{H,M}$=849-722=127，$D_{M,L}$=722-650=72，并且

$D_{H,M}/D_{M,L}$=127/72=1.764。

步骤 7. 差比的商 $D_{H,M}/D_{M,L}$ 与小整数比 I_c/I_d 的商相比较，这里，$I_c < K_2$，和 $I_c+ I_d< K_3$。注意：整个例子中，数值 K_2=8 和 K_3=12。K_2=8 对应一个假定：f_H 和 f_M 相差不大于 7 倍的基音频率，或者泛音阶数 R_H 和 R_M 相差不大于 7。同样地，K_3=12 是假定：f_H 和 f_L 将相差不大于 11 倍基音频率，并且阶数 R_H 和 R_L 相差不大于 11。域数据的

粗略检查确定了这些假定。假如其它的差比被使用，则 K_2 和 K_3 的值采用相同的分析而被大约地设定。

例如：$D_{H,M}/D_{H,L}=1.764\approx1.75=7/4$。这个比适合首先考虑，因为 7<8 并且 7+4<12。

步骤 8. 任何隐含着基音频率 $f_1<F_L$ 的差比是不合格的。

例如：在此，差比 7/4 隐含着最高频率 f_H=849H_Z 和最低频率 f_L=650H_Z 之间的差等于 198 H_Z，应该是大约等于 7+4 或者 11 倍基音频率。这样，隐含着 f_1=199/11=18.1，小于 F_L=30。对于 $D_{H,M}/I_c$ 和 $D_{M,L}/I_d$ ，同样是正确的。这只是隐含着一个或者一个以上异常频率的存在。步骤 9 将表示：另一种比较仍然隐含着异常频率是在三音组的候选频率中。

步骤 9. 假如与频率差比匹配的整数比 I_c/I_d 同对应的阶数比（R_H-R_M）÷（R_M-R_L）不一致，则任何阶数 R_H，R_M，R_L 的三音组都是不合格的。

例如：只有可能的阶数三音组是{13，11，10}。它被筛选掉，因为 7/4≠（13-11）÷（11-10）=2。

步骤 10. a）假如存在不协和的不一致(unresolvable inconsistenies)，则进入步骤 11。

例如：第一次通过，一个新的频率被选择并且异常频率被消除之前，存在不协和的不一致。所有可能的阶数三音组被筛选掉，差比导致不一致。

b）假如没有不协和的不一致，那么，一致的三音组已经被发现是合理的，则进入步骤 17，以推断基音频率。

例如：在这种情况下，一个新的频率已经被引入和在原始的三

音组中的第二频率已经被取代之后，没有发现不协和的不一致，如下面所示。

步骤 11. 所有已经被测量和检测的频率已经被选择了吗？假如不是，进入步骤 12，假如是，进入步骤 16。

步骤 12-14. 为了找到一个候选频率的三音组，原始的三个候选频率与一个或者一个以上的附加候选频率被使用，以确定一个合理的三音组。对一个三音组，假如它是第一次经过这一过程，则进入步骤 13，以选择一个第 4 候选频率，进入步骤 14，以取代三音组中的一个频率。确定一个由第四候选频率和原始候选频率三音组中的两个候选频率所组成的合理三音组从步骤 3 开始进行。

假如第四候选频率的第 1 次取代没有产生一个合理的三音组，则从步骤 12 直接进入步骤 14。一个第二原始候选频率由第四候选频率取代，以形成一个新的三音组。假如这没有产生一个合理的三音组，则第四候选将取代第三原始候选频率。

假如，第三次通过步骤 12 时确定：第四候选频率取代了原始三音组中的每一个频率之后，没有发现合理的或者一致的三音组，则进入步骤 15。

例如：因为在原始的三音组{849，722，650}中存在不协和的不一致，则选择一个新的频率。该新的频率是 602 H_Z 。

数值 849 由 602 所取代，以形成三音组{722，650，602}，该组被指定作为新的候选三音组{f_H，f_M，f_L}。

因 f_H / f_M=1.111，故最接近的整数比是 10/9，11/10，和 9/8。

因 f_M / f_L=1.0797，故最接近的整数比是 14/13，13/12，和 15/14。不存在匹配的阶数。

而且，没有一致的三音组被找到。

在原始的三音组中的一个不同频率被取代，即，722 由 602 所取代，再插入原始的频率 849，以形成三音组{849，650，602}，该组被指定作为新的候选三音组{f_H， f_M，f_L}。

因 $f_H/f_M=1.306$，故最接近的整数比是 13/10，17/13，和 14/11。

因 $f_M/f_L=1.0797$，故最接近的整数比是 14/13，13/12，和 15/14。

$f_H/f_M=17/13$，而 $f_M/f_L=13/12$，形成一个可能的阶数三音组，它就是： {R_H，R_M，R_L}={17，13，12}。

$(f_H-f_M)\div(f_M-f_L)=199/48=4.146\approx4$。

$(R_H-R_M)\div(R_M-R_L)=4/1=4$，它与频率差比相一致。

而且，$f_H\div R_H=49.94$，$f_M\div R_M=50$，$f_L\div R_L=50.17$。所有的都是大于 $F_L=30$。

所有的条件都满足，因此，R_H，R_M，和 R_L 被假定为：分别是 17，13 和 12，候选频率 849，650，602 被认为是一个合理的三音组。现在在步骤 17 中确定基音频率。

步骤 15.一个第五和第六候选频率被选择。第四频率与第五和第六候选频率组合，以形成一个新开始的三音组，该方法将从步骤 3 开始被执行。步骤 12 将被复位到 0 通过。

步骤 16. 假如所有检测和测量到的频率通过步骤 11 已经被选择和确定之后，没有一致或者合理的三音组在步骤 7-10 已经被找到，所有被选择的频率中的最低的将被认为是基音。

步骤 17. 通过下面的任何一种方法来推断基音频率，例如，其中，$G(n)=n$，$f_H=849\ H_Z$，$f_M=650\ H_Z$，$f_L=602\ H_Z$，{R_H，R_M，R_L}={17，13，12}：

a) $f_1=f_H/R_H$

b） $f_1 = f_M / R_M$

c） $f_1 = f_L / R_L$

d） $f_1 = (f_H - f_M) \div (R_H - R_M)$

e） $f_1 = (f_M - f_L) \div (R_M - R_L)$

f) $f_1 = (f_H - f_L) \div (R_H - R_L)$

例如：找到一个带相应的阶数的一致的合理频率三音组是{849，650，602}和{17，13，12}之后：

a） $f_1=849/17=49.94\ H_Z$

b） $f_1=650/13=50.00\ H_Z$

c） $f_1=602/12=50.17\ H_Z$

d） $f_1=(849-650) \div (17-13) =49.75\ H_Z$

e） $f_1=(650-602) \div (13-12) =48.00\ H_Z$

f） $f_1=(849-602) \div (17-12) =49.4\ H_Z$

该推断的基音能被设定等于 6 个计算值的各种加权平均数的任何值。例如：

采用比的计算的方法，例如，从 a）到 c)，计算得出 f_1 的平均值 $=50.04\ H_Z$。

考虑到频率差方法，跨过泛音的最大数，根据 f）以上所给定的数值，计算得出 f_1 的值 $=49.4\ H_Z$。

通过比方法和跨过泛音的最大数的差方法计算，得到平均 f_1 的值为：

$(50.04+49.4) \div 2=49.58$。

这三种平均方法应该为推断基音频率产生合理值。最后的是优选的，除非/直到域数据引入一个更好的平均方法。

b)假如在手边的乐器的泛音已经按照函数 $f_n=f_1 \times n \times (S)^{\log_2 n}$ 模型化，这里，S>1，一种更精确的推断基音的方法将如下面所述：

a） $f_1=(f_H \div S^{\log_2 R_H}) \div R_H$

b） $f_1=（f_M \div S^{\log_2 R_M}）\div R_M$

c） $f_1=（f_L \div S^{\log_2 R_L}）\div R_L$

d） $f_1=[（f_H \div S^{\log_2 R_H}）-（f_M \div S^{\log_2 R_M}）]\div（R_H - R_M）$

e） $f_1=[（f_M \div S^{\log_2 R_M}）-（f_L \div S^{\log_2 R_L}）]\div（R_M - R_L）$

f） $f_1=[（f_H \div S^{\log_2 R_H}）-（f_L \div S^{\log_2 R_L}）]\div（R_H - R_L）$

假如高音调的常数 S 已经被设定等于 1.002，则基音的推断值将如下面所述：

a） f_1=49.535 H_Z。

b） f_1=49.63 H_Z。

c） f_1=49.81 H_Z。

d） f_1=49.22 H_Z。

e） f_1=47.51 H_Z。

f） f_1=48.88 H_Z。

采用比的计算方法，例如，从 a）到 c)，计算得出 f_1 的平均值等于 49.66 H_Z。

考虑到频率差方法，跨过泛音的最大数，根据 f）以上所给定的数值，计算得出 f_1 的值等于 48.88 H_Z。

通过比方法和跨过泛音的最大数的差方法计算，得到平均 f_1 的值为：

（49.66+48.88）÷2=49.27 。

这三种平均方法中的任何一种都可以用于推断基音。最后的是优选的。

假如在步骤 9 完成之后，两个或者两个以上一致的阶数组保留，则基音 f_1 应该与阶数组的每一个重新计算，获得的最低频率，它与在步骤 3 到 9 中描述的条件一致，被选择作为推断的基音频率 f_1。

前面的描述和给定的例子都假定泛音频率以

$f_n= f_1 \times G（n）= f_1 \times n \times（S）^{\log_2 n}$ 为模型，这里，$1 \leqslant S \leqslant 1.003$。

后面的函数中，S 是这样的接近 1，隐含着 f_n/f_m 将大约等于整数比 n/m，频率差的比（f_H - f_M）÷（f_M - f_L）将大约等于一个小的整数比和，以及 $f_x-f_y\approx(X-Y)\times f_1$。

在一般的情况下，合理的泛音分音的三音组被分离，它们对应的阶数按下述方法确定：

a）将 $f_H\div f_M$ 和 $f_M\div f_L$ 的商与比值 G（R_H）÷G（R_M）以及比值（R_M）÷G（R_L）的商分别进行比较。

b）将频率差比（f_H - f_M）÷（f_M - f_L）与函数差比 [G（R_H - G（R_M）]÷[（R_M）- G（R_L）]进行比较。

c）将阶数的可能组合所隐含的基音频率与在手边的乐器能产生的最低的基音频率和最高的泛音频率进行比较。

方法 II

另一种分离检测到的分音的三音组的方法如图 3，4 和 5 所示，该分音只是由具有同样基础的基音频率的合理泛音频率组成，以便找到它们的相关阶数，并确定由每一个这样的三音组所隐含的基音频率。该方法标记和记录被检测的分音频率在一个对数音阶上，并将这些分音之间的关系与一个类似的表示预计的/模型化的泛音频率之间的关系的音阶进行匹配。

用下面的一个例子来说明一般的概念。它表明一种能用来匹配或者找到对泛音频率的调号或者图谱的最合适接收信号的方法，并且仅表明将采用的逻辑运算的种类。该例子应该被认为是本发明的一种可能的体现，而不应认为是一种限制。

为了说明这一例子，假定：在手边的乐器产生的泛音按照函数 $f_n=f_1\times n\times(S)^{\log_2 n}$ 模型化，这里，n 是一个正整数 1，2，…，17，而 S 是一个等于 1.002 的常数。根据该函数，一个泛音倍数音阶（以下称之为 HM 音阶）被建立，其中，每一个梯度标号代表百

分之一，它是半音的 1/100 或者八音度的 1/1200。在音阶上的第一标记代表泛音倍数 1，即，当用 f_1 乘以该数字时，得到 f_1。在音阶上的每一个相继的标记代表前一个倍数数字本身用$[2\times S]^{1/1200}$相乘。假定采用一串位（bits），每一位代表百分之一。第 n 位将代表倍数$[(2\times S)^{1/1200}]^{(n-1)}$。沿 HM 音阶所选择的位将代表泛音倍数，并将用适当的泛音数标记：f_1 将由位 1，f_2 由位 1200，f_3 由位 1902，f_4 由位 2400，…，f_{17} 由位 4905 代表。该音阶如图 3 所示。

另一种音阶被建立，以便标记和记录被检测到的候选分音频率。开始的梯度标号，由位 1 代表，将代表频率 F_L；下一个，用 $F_L\times[(2\times S)^{1/1200}]^1$，再下一个，用 $F_L\times[(2\times S)^{1/1200}]^2$ 代表。第 n 位将代表 $F_L\times[(2\times S)^{1/1200}]^{n-1}$。该音阶通常称为候选分音频率音阶，以下称 CPF 音阶。它与 HM 音阶一起在图 3 中示出。

当分音被检测时，它们的频率被标记和记录在 CPF 音阶上。当三个已经这样被检测、标记和记录时，CPF 音阶相对于 HM 音阶移动，寻找匹配。假如在音阶的任何地方都没有找到三个候选频率的一个匹配，则另一个分音频率被检测、标记和记录，寻找匹配的三个将继续。当候选分音的一个三音组的成分在一个特定的限度内匹配 CPF 音阶上的一组倍数时，则候选频率被假定是合理的泛音频率，它们的阶数与在 CPF 音阶上其对应部(counterparts)的阶数匹配。同样地，所隐含的基音能被直接推断。它是在 CPF 上的频率位置与在 HM 音阶上的“1”匹配。

图 4 表示音阶的部分，在该部分，音阶被移动到揭示三个频率的一个好的调准之后，被检测的候选频率就出来了，即，第 4 频率被检测到了，421 H_Z，与被检测的第 1 和第 3 频率，624H_Z 和 467H_Z 组合。

一种测量一个候选分音和一个泛音倍数之间的调准(alignment)程度的方法是扩大位，该位标记候选分音频率及泛音倍数，使它们

成为多个邻近位的集。在这个例子中，在 HM 音阶上，7 个位在每个标记泛音倍数的位的两边转动(turned)。同样地，在 CPF 音阶上，7 个位在每个标记候选分音频率的位的两边转动。当音阶相互相对移动时，匹配位的数字提供一个调准程度的大小。当在一个候选频率的三音组中匹配位的数字超过一个阈值时，例如，45 个位中的 37 个位，则候选分音的调准被认为是可接受的，候选频率被指定作为一个合理泛音频率的三音组。图 5 表示匹配的程度，例如，在一个候选分音频率，即，624H_Z，与第 12 泛音的倍数之间一个可能的 15 中的 12。

当一个可接受的调准或者匹配被找到时，采用方法 I 的步骤 6-9，所隐含的阶数被用来测试不协和的不一致 。假如没有不协和的不一致被找到，所隐含的基音是比 f_L 更低或者比 f_H 更高，则音阶分别被移动，寻找分别隐含一个更高的基音或者一个更低的基音的调准。当没有不协和的不一致被找到时，所隐含的基音就存在在 f_L 和 f_H 之间，然后，所隐含的基音 f_I 变成推断的基音。

某些等级的乐器/装置具有共鸣带和/或音区，它们产生的泛音从系统上比在其它共鸣带和/或音区的泛音更高。同样地，一些乐器的泛音在一些频带可以是系统的和可预测的，而在其它频带正相反。在这些情况下，方法 II 能按下面的步骤使用：

1. 分隔 S 在整个频带一致的频带。

2. 建立一个 HM 音阶，只用于基于 S 所属频带的该频带的频率。

3. 建立另一个 HM 音阶，用于其它的 S 不同值应用的频带。

4. 当频率被检测时，将它们定位在 CPF 音阶中，该音阶用 S 的数值构成，S 的数值适用于包含该频率的频带。

5. 忽略检测的频率，这些检测的频率位于泛音不可预测的频带内。

6. 采用类似音阶（相同的 S 值），寻找泛音倍数模式和被检测

的候选频率模式之间的匹配。

方法 III

另一种推断基音频率的方法需要检测和测量或者计算数个基音频率的泛音频率。这些频率被编在一个行是基音频率，列是泛音阶数的阵列中。当一个具有未知基音频率的音符被演奏时，较高的泛音的频率在它们被检测到时逐行地与表示在该阵列中的泛音频率比较。与该阵列中三个或者三个以上频率的良好匹配(good match)或者与从该阵列成分插入的频率的良好匹配表示一个可能的阶数组和一个可能的推断基音频率。当一个被检测的频率三音组与在该阵列中的两个或者两个以上基音频率匹配，并因此包含两个或者两个以上基音频率时，推断的基音频率被设定等于包含的基音频率的最低值，它与在手边的乐器能产生的音符一致。该阵列只是一个为快速取得而编排频率的一种方法的例子，其它的方法也可以被使用。

上面的方法 I，II 和 III 能用于分隔和编辑异常分音。例如，给定一个单声道音乐，在一个时间过程中所有的分音被检测之后，当推断的基音保持一定时，这些方法能用来识别所有的不是给定基音产生的泛音集的合理成分的分音。该信息能被使用，例如，用于：a）编辑来自音乐声道的外来的声音；或者 b）分析异常的东西，以确定它们的源。

尽管在一些特殊的情况下，只要两个合理的泛音就充足了，但通常，方法 I、II 或者 III 将要求三个或者三个以上合理的泛音频率。为了从两个高次泛音推断出基音频率，下面的条件必须优先：a）必须知道不代表合理泛音的异常分音频率是极少的，以致该可能性能被忽略；和 b）两个频率的比必须是这样：两个频率的阶数被唯一地建立。例如，假设两个频率是 434H_Z 和 404H_z，该频率比的商就处在 14/13 和 15/14 之间。假如 f_L=30H_Z ，那末，阶数被唯一地建

立为 14 和 13，因为阻碍条件(brake) $434\div15=28.9$ ，小于 30 ，这样，不符合要求。两个候选频率的差是 30，是可接受的，因为它不小于 F_L 。还有，比值：$(F_H-F_L)(R_H-R_L)=30$ ，仍不小于 F_L 。

函数 $f_n=f_1\times n\times(S)^{\log_2 n}$ 用于使泛音模型化，这些泛音随 n 增加而逐级变高。S 是变高的常数，通常设定在 1—1.003 之间，n 是一个正整数 1，2，3，---，T，这里，T 通常等于 17。根据该函数，由 S 的值来确定变高的范围。当 $f_n=n\times f_1$ 时，与泛音是谐和的方式一样，模型化的泛音也是谐和的。即，假如 f_n 和 f_m 是一个音符的 n 次和 m 次泛音，那末，$f_n/f_m=f_{2n}/f_{2m}=f_{3n}/f_{3m}=\cdots=f_{kn}/f_{km}$ ，其中，k 是一个正整数。

实现该方法的系统被表示在图 6 中。预处理级接收或者拾起来自源的信号。它可以包括一个在乐器上弦的拾音器。预处理还调节(conditions)信号。这可以包括使输入信号的幅度、及频率和/或频带的限制标准化。接着，用一个频率检测级分隔具有足够能量的频带，该频带明显是环境噪音并有适当的界定。

快速找到基音级完成候选频率的分析和推断该基音。后处理级采用由快速找到基音级产生的信息，以处理该输入信号。这可以包括放大、调制和其它的信号操作处理。

本方法已经描述了利用泛音频率之间的关系来推断基音。只确定泛音关系和它们的阶，而不推断基音，这也是有价值的。基音频率可以不存在于波形中。较高的泛音可以用于找到其它的泛音，而不推断基音。这样，后处理将采用现有识别的泛音。

尽管本发明已经针对歌唱或者乐器产生的声音进行了描述，但它可以包括其它的复杂波的源，该波具有一个基音频率和较高的泛音。这些能包括：例如，一个说话的声音，复杂机械或者其它机械振动单元的声音。

尽管本发明已经被详细地描述和展示，但是，很显然，这仅仅是

展示和举例的目的，而不是限制性的。本发明的精神和范围只能由附属的权利要求来限定。

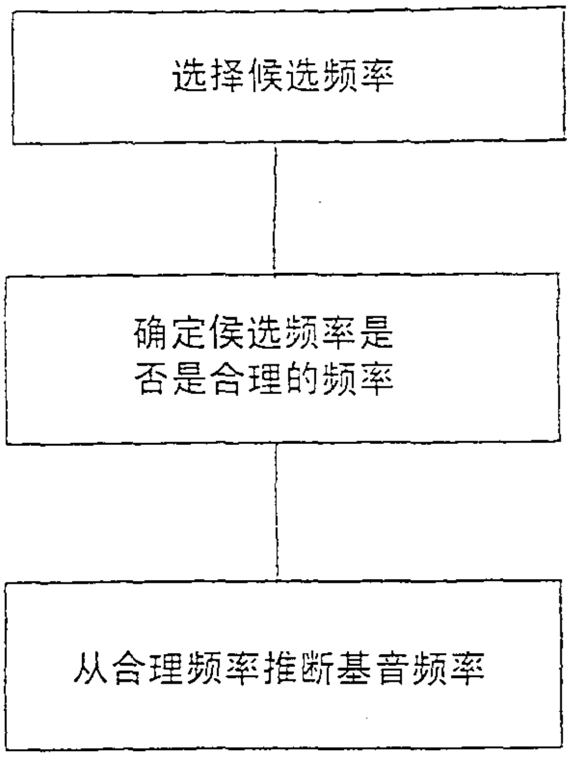


图1

图 2

步骤 1. 为乐器或者源设定常数（F_H, F_L, F_{MAX}, G(n), K_1, K_2, K_3）

步骤 2. 选择三个候选频率。

步骤 3. 指定候选频率 f_H, f_M, f_L .

步骤 4. 确定 f_H, f_M, f_L 的可能的三音组（R_H，R_M，R_L）。

步骤 5. 排除隐含 $f_1<f_L$ 或者 $f_1>F_H$ 的三音组。

步骤 6. 形成频率差比。

步骤 7. 初步限定。

步骤 8. 排除隐含的 $f_1<F_L$ 的差比。

步骤 9. 排除与差比不一致的阶数的三音组。

步骤 10. 一个或者一个以上一致阶数的三音组保留吗？是→17

否↓

步骤 11. 所有的频率选择吗？是→16

否↓

步骤 12. 第 1 次？否→ 第 3 次？否→14

是↓ 是→15

步骤 13. 选择新频率。

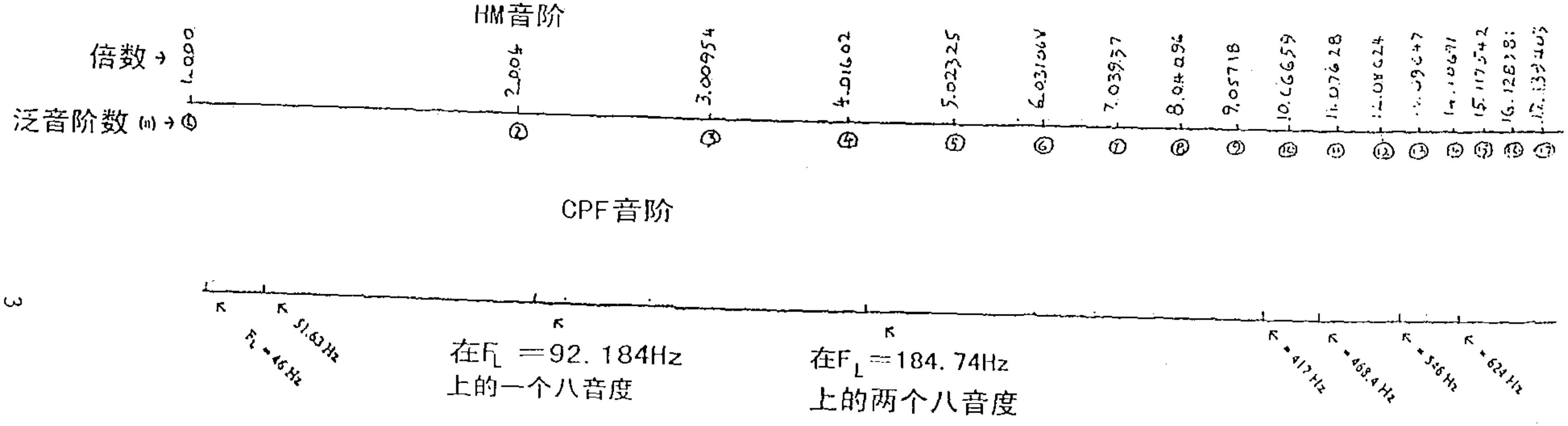
是↓

步骤 14. 用新频率取代三音组 f_H, f_M, f_L 中的一个频率 。→3

步骤 15. 选择 2 个新频率。→3

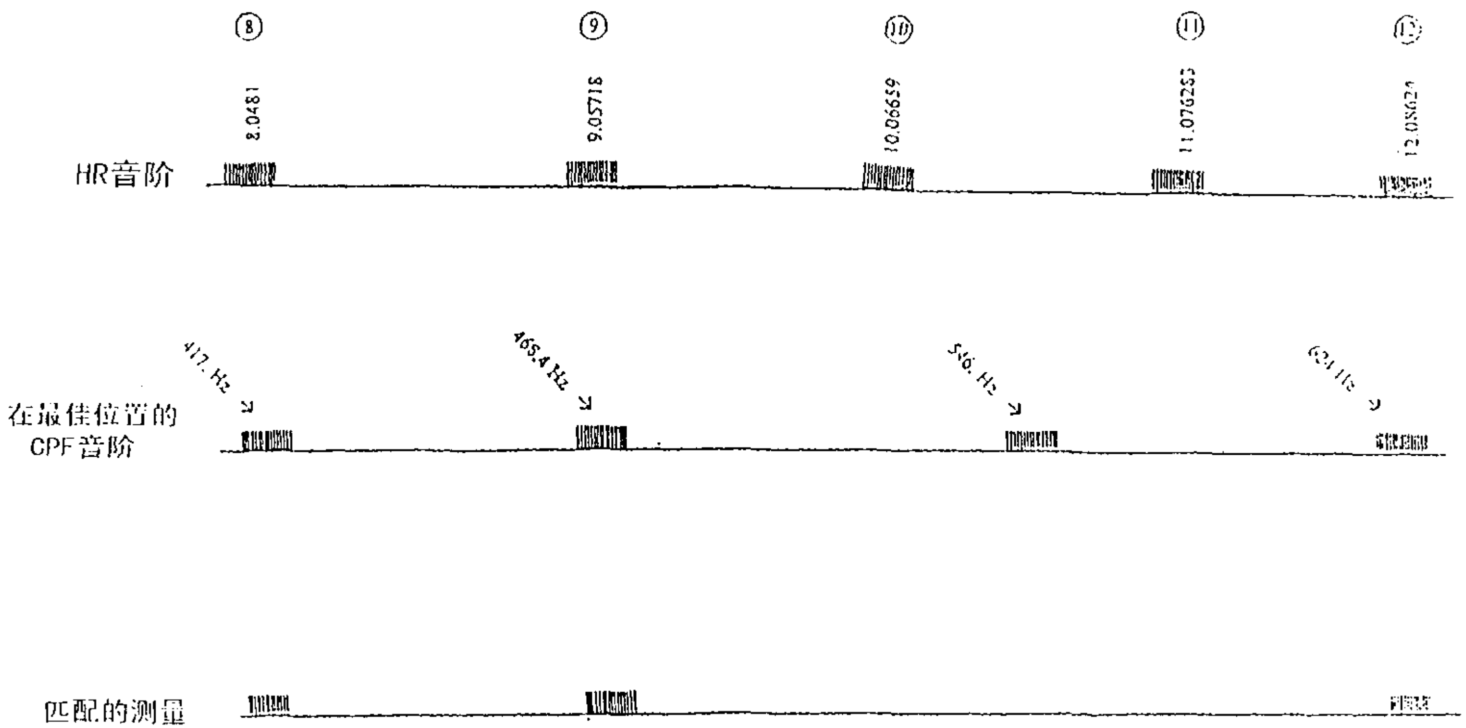
步骤 16. 设定 f_1 等于最低候选频率。

步骤 17. 推断 f_1 。



HM音阶
倍数
泛音阶数 (n)
1.000
2.004
3.00954
4.01602
5.02325
7.03937
9.05718
10.06659
CPF音阶
F_L = 46 Hz
51.63 Hz
在F_L ＝92.184Hz
上的一个八音度
在F_L ＝184.74Hz
上的两个八音度
= 417 Hz
= 468.4 Hz
= 526 Hz
= 624 Hz

图3



HR音阶
在最佳位置的
CPF音阶
匹配的测量
8
9
10
11
8.0481
9.05718
10.06659
11.076253
417. Hz
465.4 Hz
546. Hz

图4

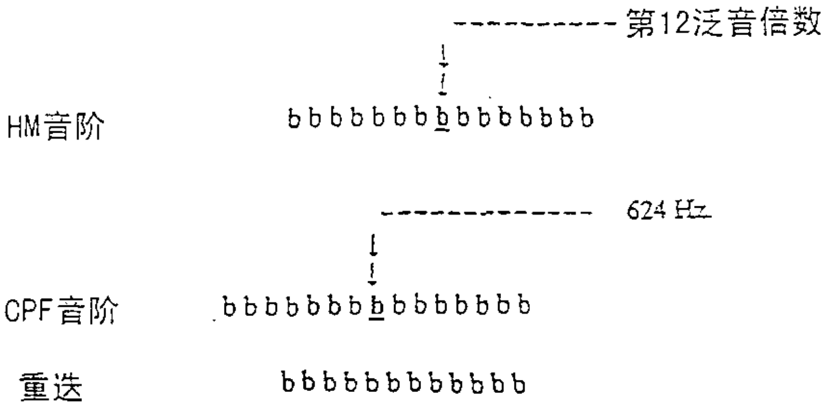


图5

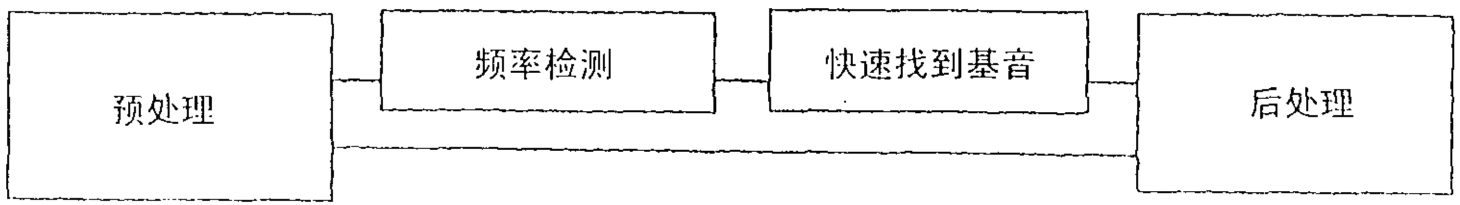


图6