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(12) (19) (CA) **Brevet-Patent**

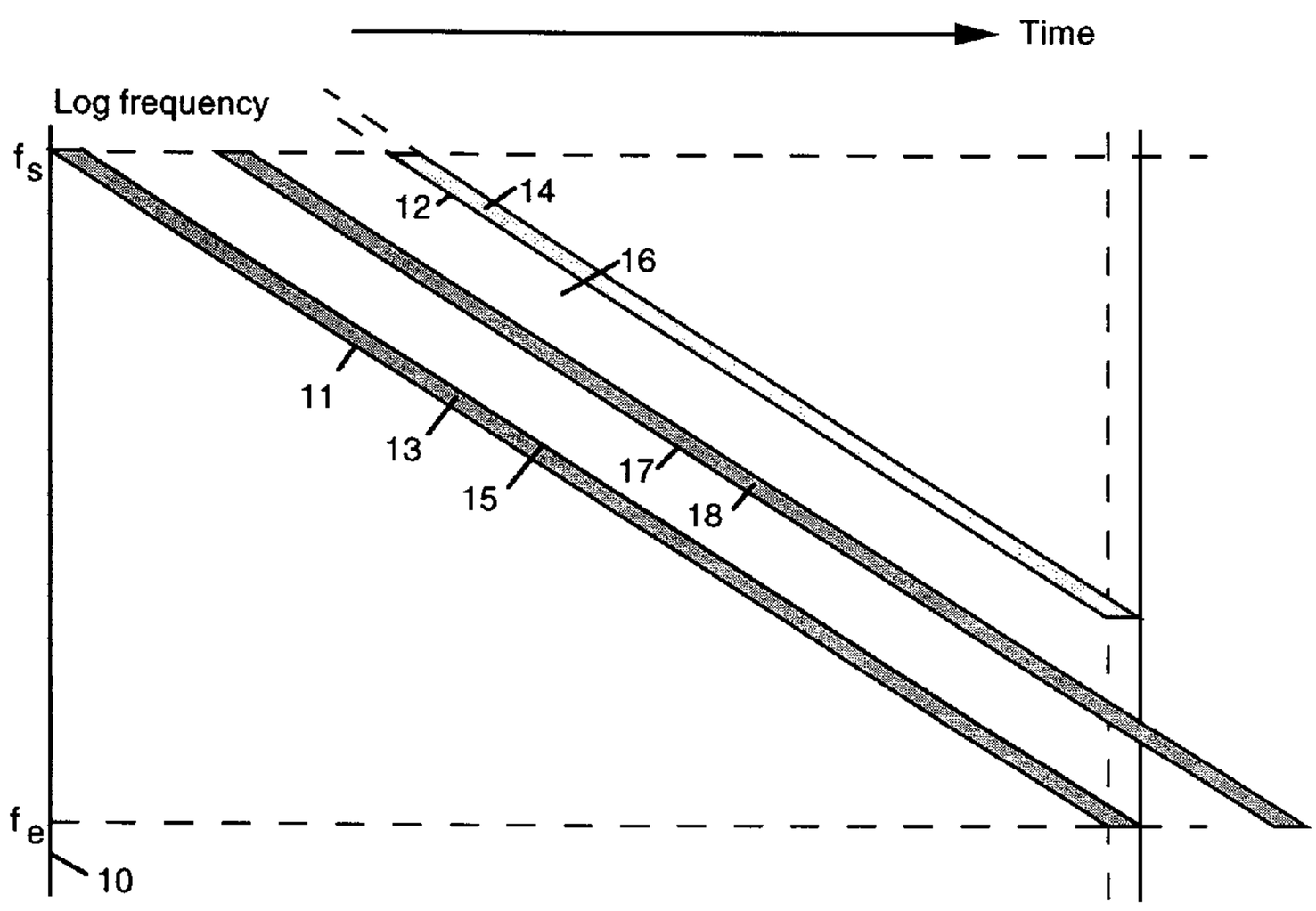
(11) (21) (C) **2,185,751**
(22) 1996/09/17
(43) 1998/02/21
(45) 2000/11/14

(72) Anstey, Nigel A., GB
(73) Anstey, Nigel A., GB

(51) Int.Cl.[6] G01V 1/00, G01V 1/02
(30) 1996/08/20 (9617445.3) GB

(54) **METHODE DE LEVE SISMIQUE EN 3-D UTILISANT PLUSIEURS SOURCES SIMULTANEMENT**

(54) **3-D SEISMIC SURVEY USING MULTIPLE SOURCES SIMULTANEOUSLY**



(57) Dans les relevés sismiques tridimensionnels utilisant le système Vibroseis, on peut réaliser des économies en se servant simultanément de sources multiples dans le même ensemble géophonique. Chaque source émet un signal précis, permettant de distinguer leur réflexion respective. Ces signaux devraient avoir peu ou pas de corrélation entre eux, et chacun devrait être sensiblement protégé contre la distorsion harmonique d'un autre signal. La présente invention se sert de signaux à balayage de fréquence longs mais identiques, pour lesquels le temps de balayage d'un octave dépasse doublement le temps maximal de parcours de l'onde

(57) In three-dimensional seismic surveys using the Vibroseis system, cost savings can be made if multiple sources are used simultaneously, into the same set of geophones. Each source radiates a distinctive source signal, so that reflections generated by each one may be separated from those generated by the others. These signals should have little or no correlation with each other, and each should be substantially immune from harmonic distortion present in any of the others. The invention employs long but identical swept-frequency signals, for which the time to sweep through one octave exceeds twice the maximum seismic travel time of

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séismique en question. Pour un signal à balayage de fréquence, un espace de temps de fréquence est défini entre le signal lui-même et une harmonique désignée (par exemple, la seconde), et les autres signaux à balayage de fréquence sont reçus dans des subdivisions de l'espace de temps de fréquence. Cette invention convient particulièrement aux vibrateurs peu coûteux de balancement de masses.

interest. For one swept-frequency signal a frequency-time space is defined between the signal itself and a nominated harmonic (for example, the second), and the other swept-frequency signals are accommodated within partitions of this frequency-time space. The invention is particularly appropriate to inexpensive swinging-weight vibrators.

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3-D SEISMIC SURVEY USING MULTIPLE SOURCES SIMULTANEOUSLY

ABSTRACT

In three-dimensional seismic surveys using the Vibroseis system, cost savings can be made if multiple sources are used simultaneously, into the same set of geophones. Each source radiates a distinctive source signal, so that reflections generated by each one may be separated from those generated by the others. These signals should have little or no correlation with each other, and each should be substantially immune from harmonic distortion present in any of the others. The invention employs long but identical swept-frequency signals, for which the time to sweep through one octave exceeds twice the maximum seismic travel time of interest. For one swept-frequency signal a frequency-time space is defined between the signal itself and a nominated harmonic (for example, the second), and the other swept-frequency signals are accommodated within partitions of this frequency-time space. The invention is particularly appropriate to inexpensive swinging-weight vibrators.

(Figure 4)

3-D SEISMIC SURVEY USING MULTIPLE SOURCES SIMULTANEOUSLY

CROSS REFERENCES TO RELATED APPLICATIONS

This patent application is based on British patent application 9617445.3, of the same title. Applicant filed this British application on August 20, 1996, and herewith claims the priority date of this application. A previous British application 9520942.5, of the same title, was filed October 12, 1995; this application has been withdrawn. One seismic vibrator that may be used with this invention is described in US Patent 4,749,057, entitled "Seismic exploration with a swinging-weight vibrator," to the present inventor. Other vibrators that may be used with the invention are described in Serial no. 2,187,843, entitled "Swinging-weight vibrator for seismic exploration," corresponding to British application 9524689.8, filed December 2, 1995.

TECHNICAL FIELD

This invention is concerned with the selection and control of vibratory signals used in the Vibroseis system of seismic exploration for oil and gas, particularly in three-dimensional (3-D) seismic surveys using multiple vibratory sources simultaneously.

BACKGROUND ART

The dominant technique for seismic exploration on land (the Vibroseis system) involves the transmission into the earth of a long vibratory signal, the reflection of this signal from deep rock layers, the subsequent reception of the reflected signal by geophones disposed at the surface, and the cross-correlation of the received signal against the transmitted signal. The transmitted signal must be unique, of a defined frequency range, and nonrepetitive within the maximum reflection time of interest; the signal employed is usually of swept-frequency form. Both upsweeps and downsweeps are used.

Standard practice involves a group of several large truck-mounted vibrators for transmission of the swept-frequency signal into the earth. The vibrators are driven in synchronism, to follow a prescribed swept-frequency signal. At each test location, the group of vibrators might emit eight sweeps, each of perhaps 26 s duration and with a 6-s gap between sweeps.

Traditionally, seismic work is done along lines (2-D), with a single group of vibrators and many geophones progressively traversing each line of a wide grid of lines, in turn. In recent years the emphasis has moved to 3-D surveys, in which (typically) a plurality of parallel source lines is laid out at right angles or parallel to a plurality of parallel geophone lines, and in which a single group of vibrators traverses each source line in turn, recording into the geophones on all geophone lines.

This technique is very satisfactory, but slow and expensive.

The time and cost of a 3-D survey can be reduced by simultaneous use of a plurality of groups of vibrators, generally with one group traversing each source line. This technique is sometimes called "simultaneous recording;" here, more descriptively, it is called "multiple-source recording" or simply "multisource." The multisource technique increases the capital cost (in that it requires more vibrators) but decreases the operational cost (in that it is faster).

In the aforesaid US Patent 4, 749,057 and the aforesaid copending Applications, vibrator cost is tackled by replacing the usual expensive hydraulic vibrators with simpler swinging-weight vibrators.

A critical matter in the multisource technique is the choice of signal to be radiated by each group of vibrators. Clearly it is essential that the signal radiated from each group, operating on its own source line, should be highly distinctive; only thus can the superposed geophone output be separated into the components derived from each source line. Yet the signal bandwidth, signal spectrum and total energy radiated should be substantially the same.

Several methods have been proposed for developing such highly distinctive signals. One method uses a coded sequence of sweeps (each over the full bandwidth), with the code expressed as binary switching of the polarity of the sweeps; a variation on this uses wider phase variations, in conjunction with higher-order codes. Another method codes the direction of the sweeps (upsweeps and downsweeps), both of the full bandwidth; a variation uses both this and the polarity, in quaternary code. Another uses random or pseudorandom signals constrained to the full desired bandwidth. And the original multisource method (US patent 3,885,225, to Anstey and Taner) divided the bandwidth into subsweeps, with the vibrator group on one line (at any

one time) radiating a part of the bandwidth different from that being radiated from each of the other groups.

Some of the factors affecting the choice between these methods are concerned with practical aspects in the field. Others, however, are concerned with the degree of signal distinction afforded by the different methods.

One measurement of the degree of distinction is that of "correlation noise:" the cross-correlation function of one distinct signal with another should be very small, lest the correlation noise from a strong false correlation should swamp a weak true correlation.

Another measurement concerns the susceptibility of one signal to harmonic distortion in another. This is a variation on the well-known susceptibility of a swept-frequency signal to "harmonic ghosts," generated when harmonics introduced by the vibrator and the vibrator/ground coupling yield false (harmonic) correlations at times spaced apart from the true (fundamental) correlation. The problem is compounded in multisource practice using a distinction of frequency: a vibrator nominally emitting a frequency of 15 Hz (for example) is distinct and separable from one emitting 30 Hz .... except to the degree that the first vibrator generates a second harmonic.

OBJECTS OF THE INVENTION

Accordingly it is an object of the present invention to provide distinctive signals for use in 3-D seismic surveys employing multiple sources simultaneously.

It is a further object to provide signals that have reduced susceptibility to false correlations between them.

It is a further object to provide signals for use with inexpensive swinging-weight vibrators.

DISCLOSURE OF THE INVENTION

These objects are achieved, in a system of seismic exploration characterized by simultaneous radiation of swept-frequency signals from a plural number N of

vibrators or groups of vibrators, by a method that comprises the following steps in combination:

a) choosing the desired start frequency and end frequency of the said swept-frequency signals;

b) choosing the maximum travel time of interest;

c) choosing or observing, for a representative vibrator or group of vibrators, the relation between fundamental sweep frequency and sweep time;

d) deducing, for said relation, a frequency-time space between said relation and a nominated harmonic of such relation;

e) dividing said frequency-time space into N partitions, each having a frequency extent from the said start frequency to the said end frequency, and each having a time extent, at each frequency, not less than the said maximum travel time of interest;

f) allocating each of the N vibrators or groups of vibrators to one of the said N partitions; and

g) controlling the frequency-time relation of each vibrator or group of vibrators so that all seismic signals derived from it, up to the said maximum travel time of interest, fall within its said partition.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described with reference to the drawings, in which:

Figure 1 illustrates a sweeping arrangement common in the prior art, radiating a plurality of identical sweeps at each vibration point;

Figure 2 illustrates a single long sweep having the same bandwidth and energy;

Figure 3 depicts, for a frequency axis scaled logarithmically, the frequency-time space between a fundamental sweep and its second harmonic;

Figure 4 illustrates the insertion of a second sweep into the frequency-time space of Figure 3;

Figure 5 illustrates the insertion of four sweeps into the frequency-time space of Figure 3;

Figure 6 shows one method of realizing a correction break, by which one sweep signal may be maintained in a spaced-apart relation to another;

Figure 7 is the counterpart of Figure 5 for a frequency axis scaled linearly;

Figure 8 is a counterpart of Figure 4, showing how the two sweeps may be divided into segments separated by the maximum travel time of interest; and

Figure 9 is a counterpart of Figures 4 and 8, but combining the option of a higher sweep rate and double sweeping.

BEST MODE FOR CARRYING OUT THE INVENTION

Figure 1 illustrates at 1 a typical signal radiated in conventional 2-D seismic work. The signal may be radiated by perhaps four or five hydraulic vibrators, each slaved to the same signal. As an example, the frequency may sweep down from frequency f_s to frequency f_e (typically 3.5 octaves, from 113 to 10 Hz) in 26 s. There is then a 6-s gap, during which the vibrators may move a small distance, before the cycle repeats. The move time 2 is often chosen to coincide with the maximum travel time of interest, which is typically 6s. As an example, eight such sweeps may be radiated, and their corresponding geophone outputs summed, for each vibration point. Then, since one cycle occupies 32 s, the total time spent at each vibration point is 256 s, of which 208 s is vibrating time.

The graphs of Figure 1 define a frequency-time space occupied by each sweep. Thus the sweep 1a and the time of interest 2a define a parallelogram 3; at any time 4 the range of frequencies being received is shown by the bar 5, while any frequency 6 is received over the time range 7.

The practice of recording several or many sweeps at each vibration point is derived in part from the limited storage of early correlators and in part from sampling concerns in early array theory. Today, storage limitations are removed, while geophone spacing and spread geometry (coupled with the surface-compensation feature of the swinging-weight vibrator) remove the need for the vibrators to move within the source array. Consequently the eight sweeps of Figure 1 may be replaced today by the one sweep 8 of Figure 2; this has the same start and end frequencies, the same total vibrating time (208 s) and, in the illustration, the same maximum travel time of 6 s. The energy radiated per vibration point is the same. The sweep rate, of course, is much less.

The sweeps of Figure 1 and Figure 2 are shown as straight lines. If the frequency axis 9 of the graphs is linear, this implies the traditional linear sweep of constant sweep rate, much used with hydraulic vibrators. However, the swinging-weight vibrators of the aforesaid copending Applications offer various combinations of force-frequency and frequency-time relations (all of which may be modified, if desired, by the swinging-weight vibrator's automatic compensation for varying surface conditions). Of these combinations, two in particular may be used as

examples: the constant-eccentricity configuration, in which the sweep rate is large at high frequency and small at low frequency, and the specific variable-eccentricity configuration that keeps the sweep rate approximately constant. The second of these, then, corresponds approximately to the graphs of Figures 1 and 2 when the frequency axis 9 is linear. The first corresponds approximately to the same graphs when the frequency axis is logarithmic.

Figure 3 repeats Figure 2 with the frequency axis 10 explicitly logarithmic, and adds the second harmonic 12; on a logarithmic scale, of course, the second harmonic 12 is parallel to the fundamental 11. The fundamental 11 and the harmonic 12 are associated with parallelograms 13 and 14; these define, as before, the frequencies actually in use at any time, and the time range in use at any frequency. Although shown (in dashed form), the harmonic above the highest frequency f_S of the fundamental sweep is irrelevant.

Between the upper limit 15 of the fundamental parallelogram and the lower limit 12 of the harmonic parellelogram is the frequency-time space 16. An essential feature of the present invention is that, while one vibrator or group of synchronized vibrators is assigned the fundamental parallelogram 13, one or more vibrators or groups of synchronized vibrators are assigned fundamental parallelograms within the frequency-time space 16. (In the following material the phrase "vibrator or group of synchronized vibrators" will be abbreviated to "vibrator" without loss of generality.)

Figure 4 gives an illustration. Two vibrators are shown; one occupies the fundamental parallelogram 13, and one a fundamental parallelogram 18 in the middle of the frequency-time space 16.

The merits of the present invention may be seen clearly in this simple illustration.

First, since the desired seismic signal from fundamental sweep 11 radiated by the first vibrator is entirely contained within parallelogram 13, and that from fundamental sweep 17 radiated by the second vibrator is within parallelogram 18, the two signals are totally separable, in principle, provided that the parallelograms never touch.

Second, the criterion that the parallelograms should not touch is easily understood,

easily monitored, and easily implemented by the control system (such as that described in the aforesaid copending application Serial no. 2,187,843).

Third, the technique provides total immunity from false correlations associated with classical harmonic distortion.

Fourth, this immunity may be extended to the third harmonic of the subharmonic (having a frequency 1.5 times the fundamental) by correspondingly restricting the frequency-time space 16; recent research suggests that the period-doubling phenomenon known from chaos theory may cause this harmonic to become significant when the vibrator is driven very hard.

Fifth, the technique lends itself to long sweeps, which may be manipulated to yield low correlation noise.

The matter of sweep length and correlation noise needs further discussion. In the example of Figure 4, the criterion that the parallelograms 13, 18 and 14 should not touch may be restated to say that the time to sweep through one octave must be greater than twice the maximum travel time of interest. Thus for a maximum travel time of 6 s, a bandwidth of 3 octaves imposes a minimum sweep length of 36 s, and a bandwidth of 3.5 octaves a minimum sweep length of 42 s.

In practice a safety corridor between the parallelograms is desirable. In the illustration this corridor is about 24 s wide in the time direction and 0.4 octave wide in the frequency direction. Thus a separation of 80 dB between a late weak arrival from the first vibrator and a strong early arrival from the second requires a frequency discrimination of 200 dB/octave between the sweeps; this is readily provided, over most of their extent, by sweeps of the length depicted. The exception occurs at the ends of the sweeps; as is well known in the art, this problem can be solved by appropriate tapering of the ends of the sweep (which may occur in the earth, or be applied in the correlation or later processing).

Figure 5 is the counterpart of Figure 4 for four vibrators, represented by the four spaced parallelograms 13, 21, 18 and 22. The safety corridors are now reduced to about 9 s in time, or about one-seventh of an octave in frequency. Whether or not this is sufficient depends on the local character of the earth. In many situations, and with suitable spread geometry, four or even more parallelograms (meaning four or

more source lines) can be recorded simultaneously, thus yielding major reductions in the cost of 3-D surveys.

The above discussion assumes that each of the several vibrators follows its planned sweep exactly. With hydraulic vibrators, of course, this can be guaranteed. Swinging-weight vibrators may also be slaved, using the techniques of copending application Serial no. 2,187,843. But it is one of the advantages of swinging-weight vibrators that they provide a measure of automatic compensation of variations in the vibrator/ground coupling, which they do by natural variations in the sweep rate. Therefore some meandering of the parallelograms can be advantageous, and the problem arises as to the balance to be drawn between the merit of strict control (preserving a prescribed safety corridor) and that of loose control (allowing some meander, and so some compensation of surface conditions).

In the situation where the several vibrators are within one group, and therefore likely to be operating on similar surface material, very loose control is allowable; the frequency-time relations of all vibrators, while showing significant variation of sweep rate, remain quasi-parallel.

Where the vibrators are on different source lines, and therefore widely spaced from each other, the surface material on which they are operating may be markedly different. Their quasi-parallelograms are therefore more at risk of touching, and so greater control must be applied to prevent this. In general, the object is to allow as much meander, and therefore as much compensation of surface conditions, as is allowed by the stipulation that the quasi-parallelograms do not come within a defined safety corridor of each other.

If, in a particularly important situation, this approach does not yield as much compensation of surface conditions as would be desirable, it is possible to introduce "correction breaks." One example is illustrated in Figure 6.

In the figure, parallelogram 24 is in danger of touching parallelogram 23. As this situation is sensed, the vibration of the vibrators is temporarily annulled at 25 and 26, for a period at least equal to the maximum travel time of interest; during the break in emission all vibrators are brought up to the frequency at which the break started, and after the break all vibrators are triggered at times 27, 28 that restore

safe separation of the parallelograms 29, 30. This arrangement is readily accommodated in the processing.

Figures 3-5 have illustrated the case of swinging-weight vibrators having a constant decrement. Such vibrators are likely to be applying much more force to the earth at high frequencies than at low frequencies. If this is judged undesirable, in a particular situation, the vibrator eccentricity may be programmed to yield less variation of force with frequency, and a frequency-time relation that is more nearly linear.

Figure 7 shows a counterpart of Figure 5 in such a situation. With linear scaling of the frequency axis, the fundamental frequency-time relation is now a straight line. The frequency-time space between the fundamental and the second harmonic appears more generous at early times and high frequencies, but distinctly less generous at late times and low frequencies.

The appearance is therefore that more vibrators could be accommodated safely at the high frequencies, but that at low frequencies there is a problem to "steer" additional vibrators through the diminishing space.

In this situation the first matter of importance is to maintain the slow sweep rates of the former examples. In the case of swinging-weight vibrators, this ordinarily requires a significant increase in the moment of inertia of the flywheel(s), and a corresponding increase in motor power. With a slow sweep rate restored, the vibrators can be steered through the available frequency-time space using a combination of motor control and correction breaks as above.

Figure 8 shows how the two-vibrator scheme of Figure 4 may be combined with an adaptation of Figure 6 to divide each sweep 31, 32 into segments 33, 34 separated by (at least) the maximum travel time of interest. In effect, this arrangement incorporates correction breaks as standard practice, for a small sacrifice of overall recording time.

Figure 9 illustrates a variation for the situation where the natural sweep rate is higher than desired, but where it is inconvenient to tackle the problem with larger flywheels. In this situation each part of each frequency segment 35 may be swept

twice (as at 36), with a flywheel-acceleration period (typically, not less than the maximum travel time) between segments. The frequency-time space between the fundamental sweep and its harmonic is reduced in width, but is still sufficient to allow one or more additional vibrators to operate within it.

I claim:

1. In a system of seismic exploration characterized by simultaneous radiation of swept-frequency signals from a plural number N of vibrators or groups of vibrators, the method that comprises the following steps in combination:
a) choosing the desired start frequency and end frequency of the said swept-frequency signals;
b) choosing the maximum travel time of interest;
c) choosing or observing, for a representative vibrator or group of vibrators, the relation between fundamental sweep frequency and sweep time;
d) deducing, for said relation, a frequency-time space between said relation and a nominated harmonic of such relation;
e) dividing said frequency-time space into N partitions, each having a frequency extent from the said start frequency to the said end frequency, and each having a time extent, at each frequency, not less than the said maximum travel time of interest;
f) allocating each of the N vibrators or groups of vibrators to one of the said N partitions; and
g) controlling the frequency-time relation of each vibrator or group of vibrators so that all seismic signals derived from it, up to the said maximum travel time of interest, fall within its said partition.

2. A method according to claim 1, in which the said nominated harmonic is the second harmonic, having a frequency twice that of the fundamental.

3. A method according to claim 1, in which the said nominated harmonic is a harmonic of a subharmonic, having a frequency one and one-half times that of the fundamental.

4. A method according to claim 1, in which the said vibrators are of swinging-weight type.

5. A method according to claim 4, further providing correction breaks in which the following steps are implemented:
a) sensing the approach of the frequency-time relation of any vibrator to the limit of its allocated partition;

b) annulling the vibration of one or more vibrators for a period at least equal to the maximum travel time of interest;

c) during this period, maintaining the frequency substantially constant;

d) restoring the vibration of one or more vibrators at times that place their frequency-time relations acceptably within their allocated partitions.

6. A method according to claim 1, in which the overall frequency range of the said swept-frequency signals is divided into a number of segments each with its defined frequency-time space and its N partitions.

FIG 1

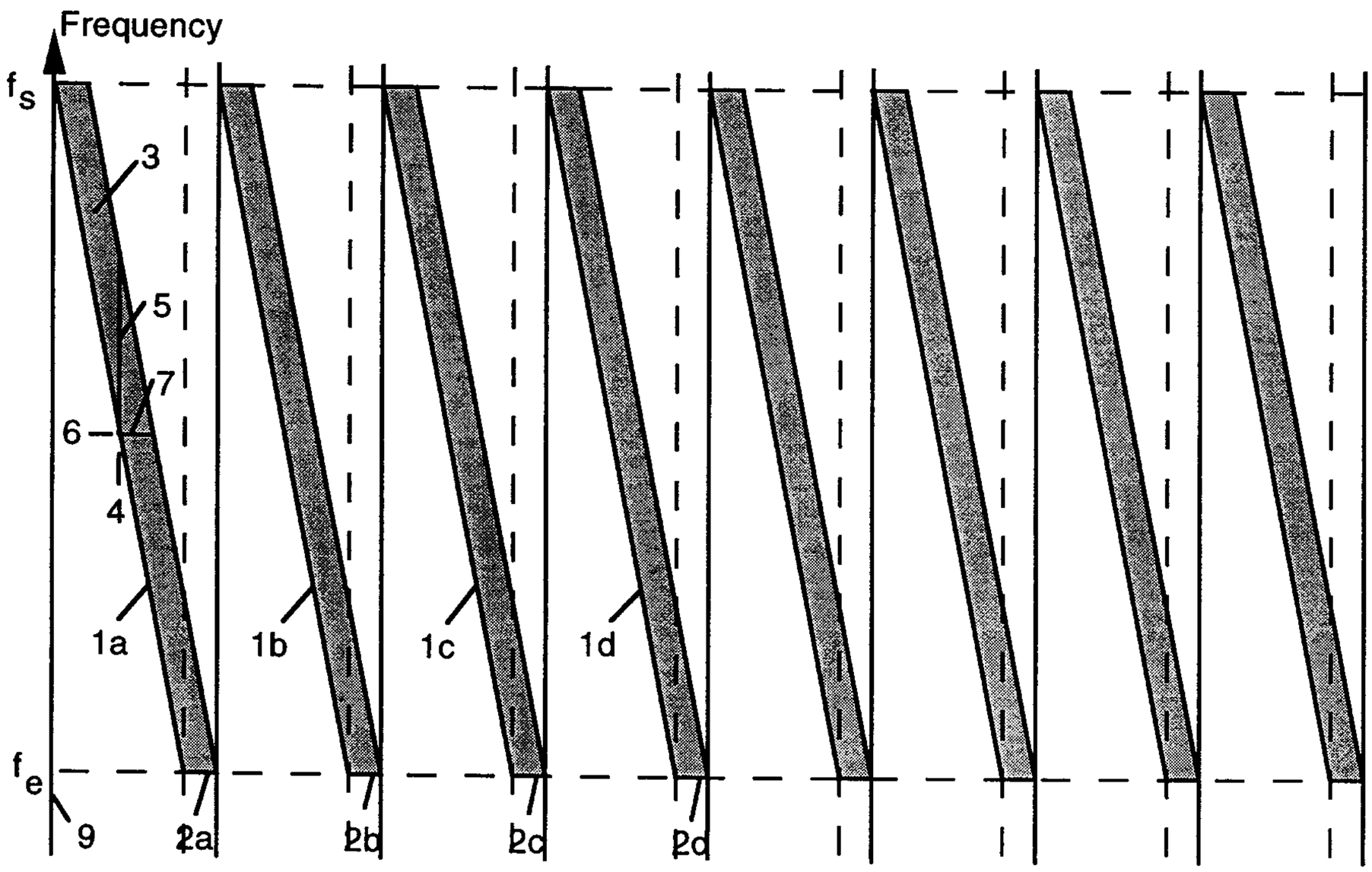
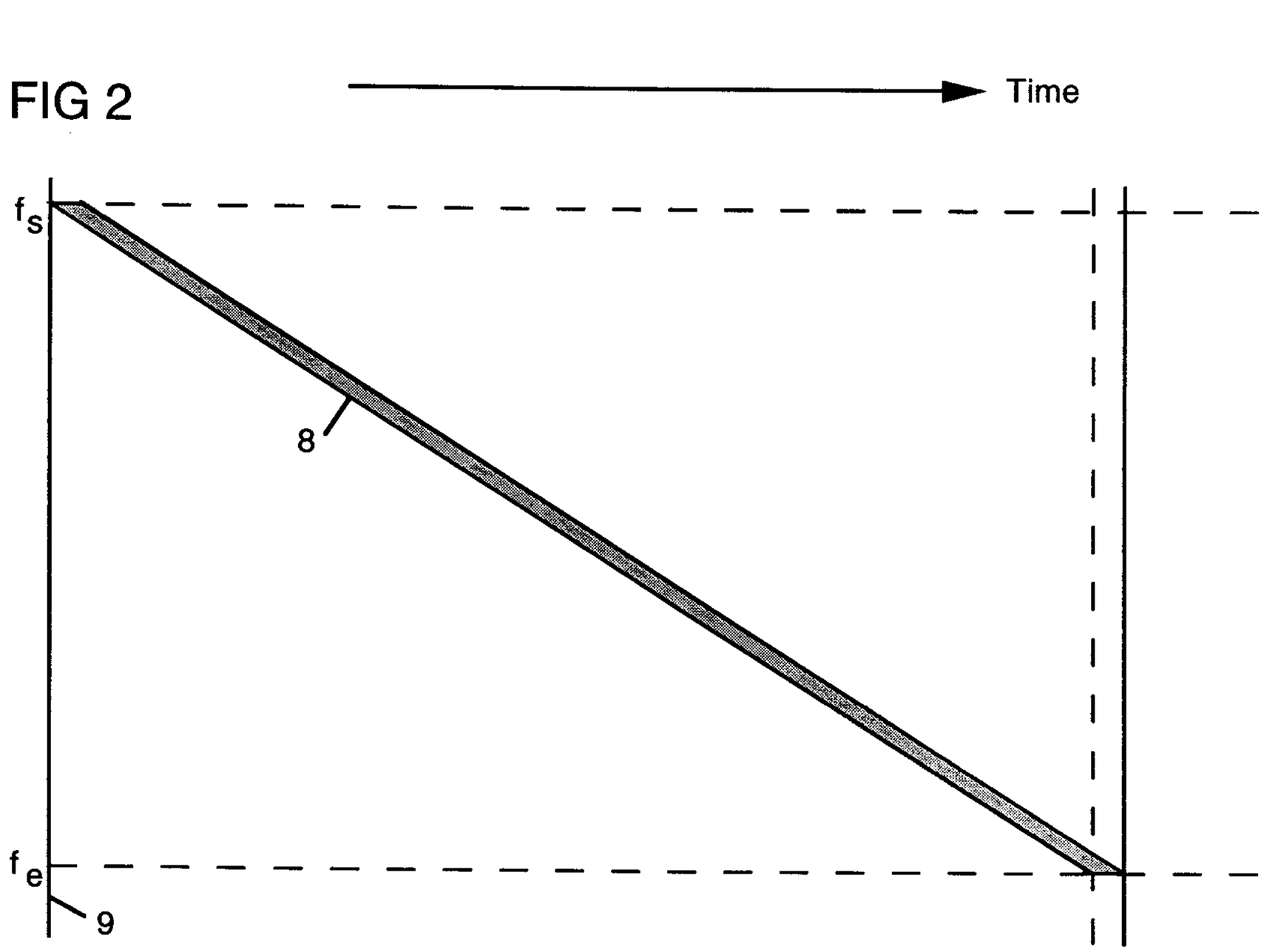


FIG 2



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FIG 3

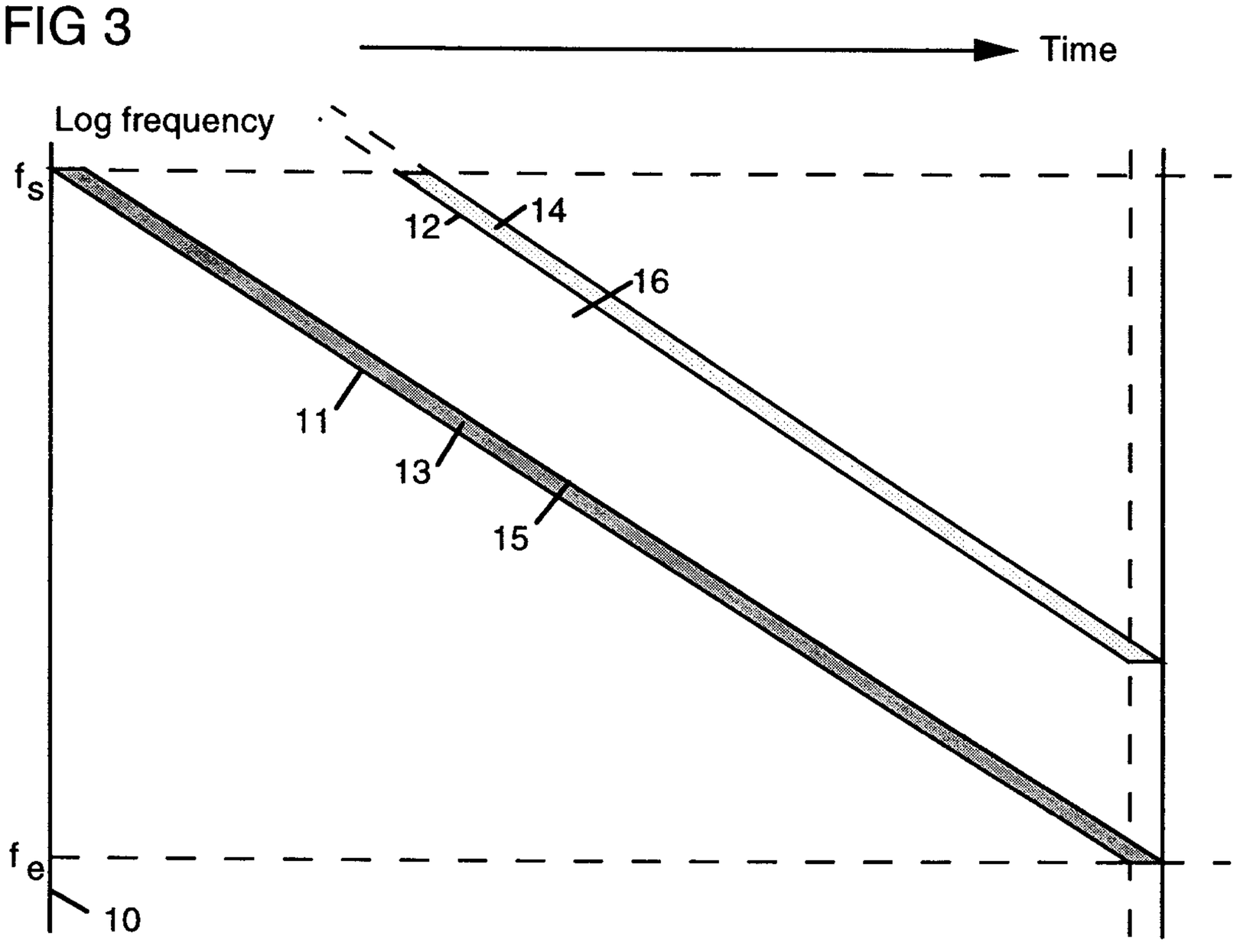
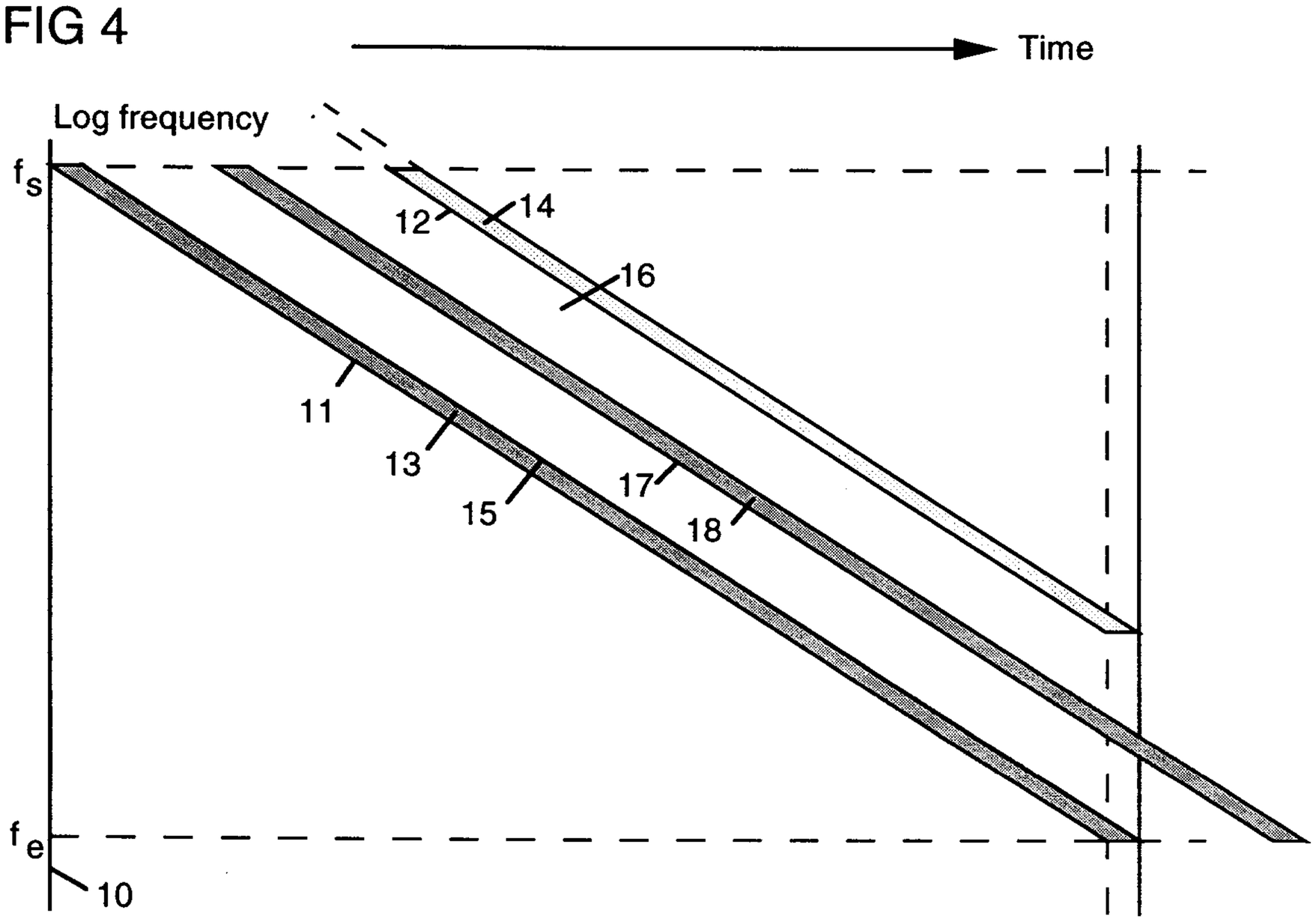


FIG 4



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FIG 5

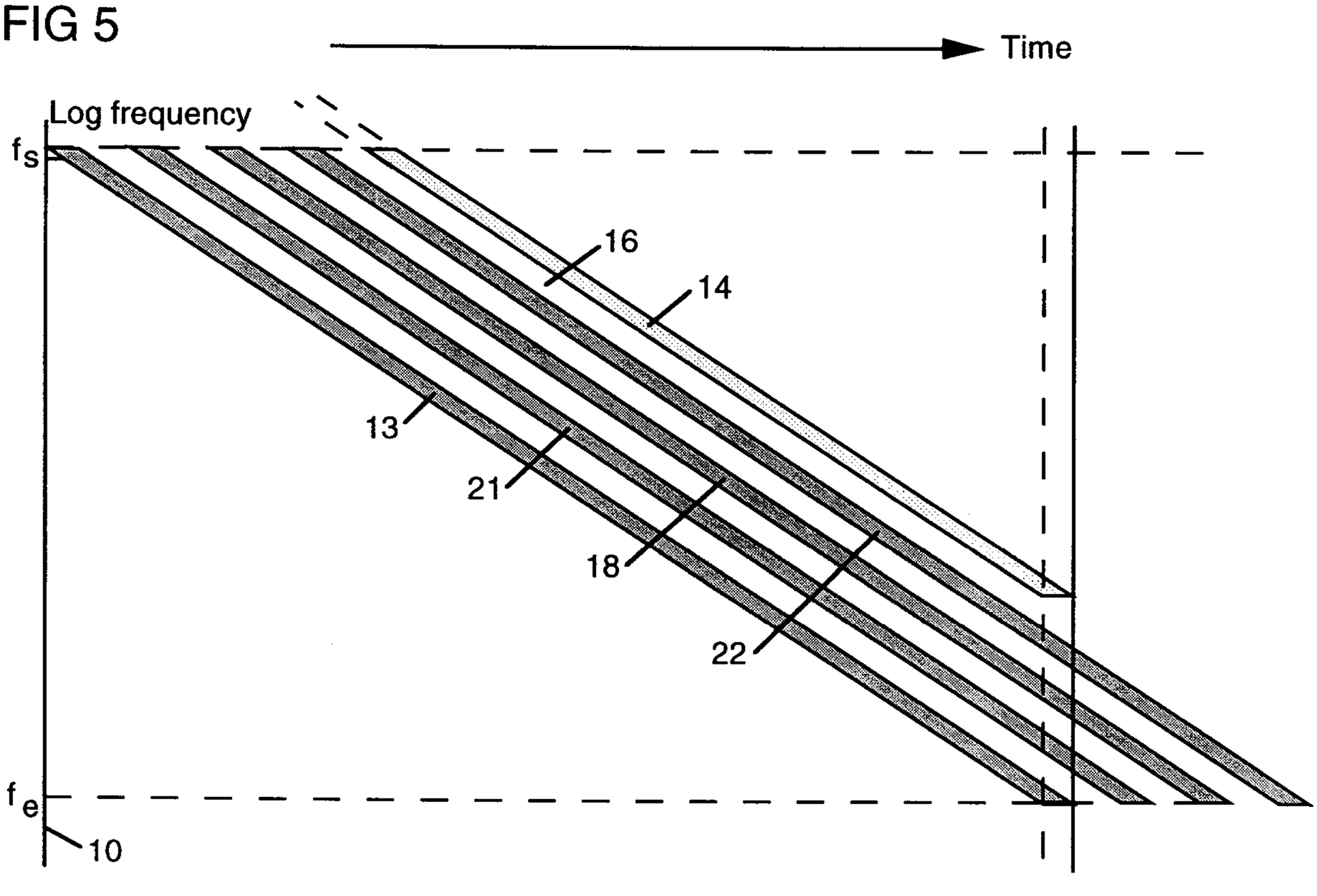
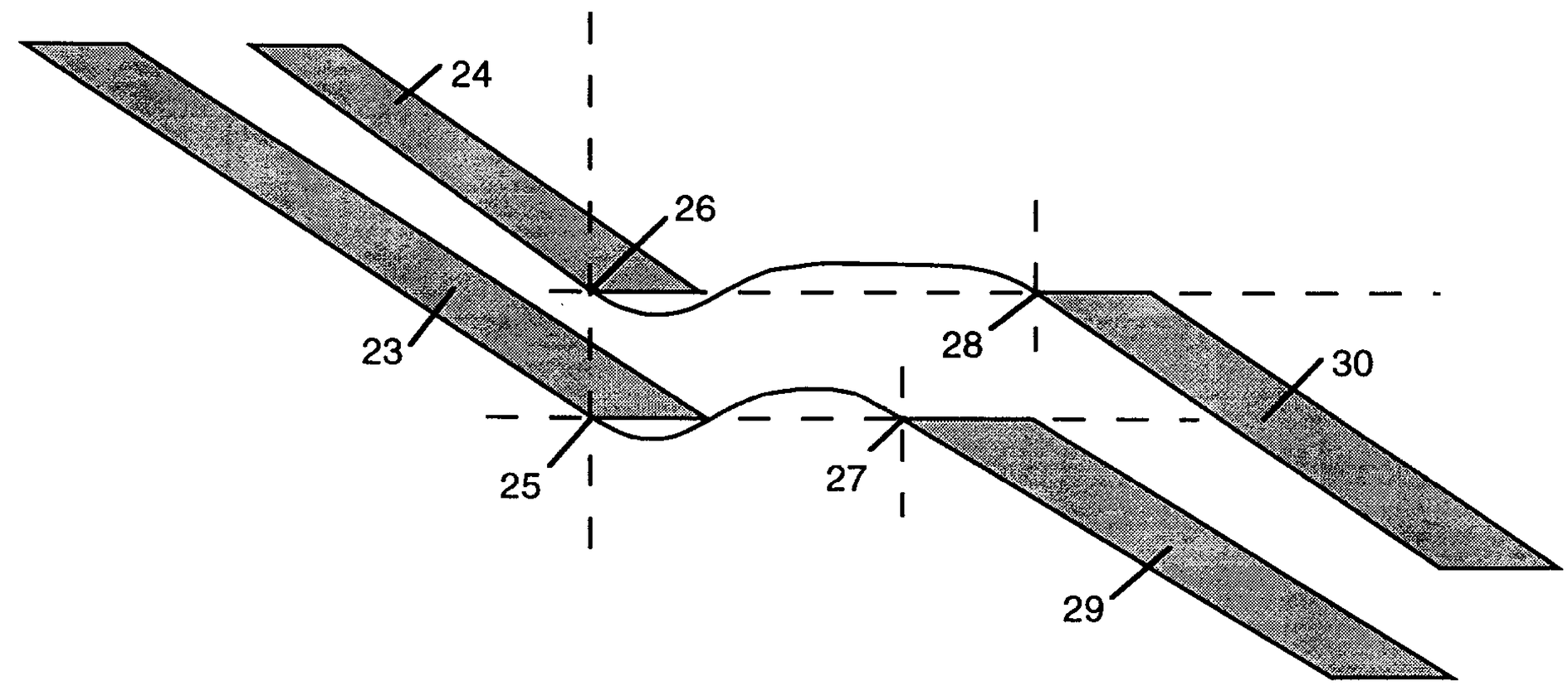


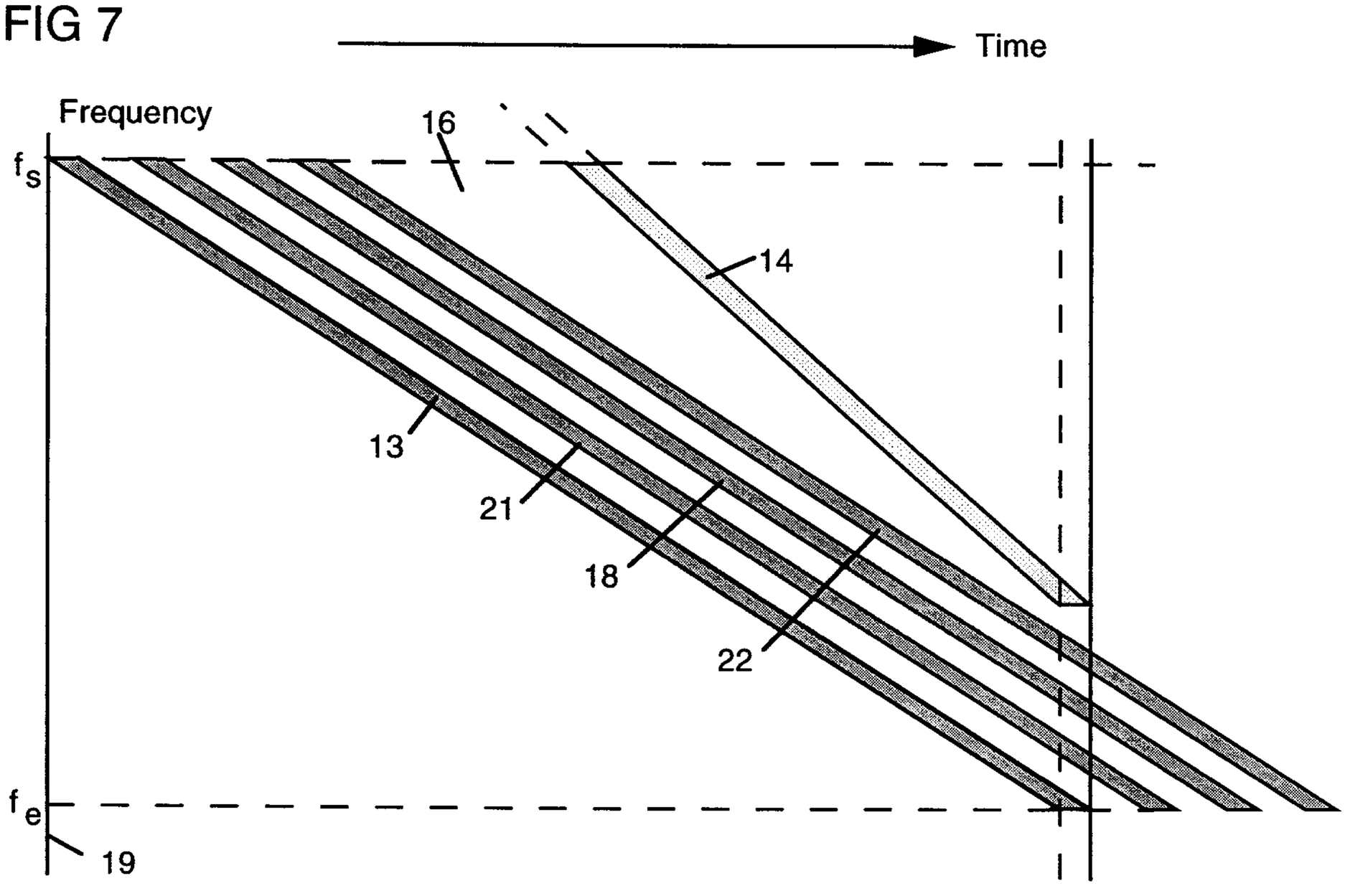
FIG 6



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FIG 7



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FIG 8

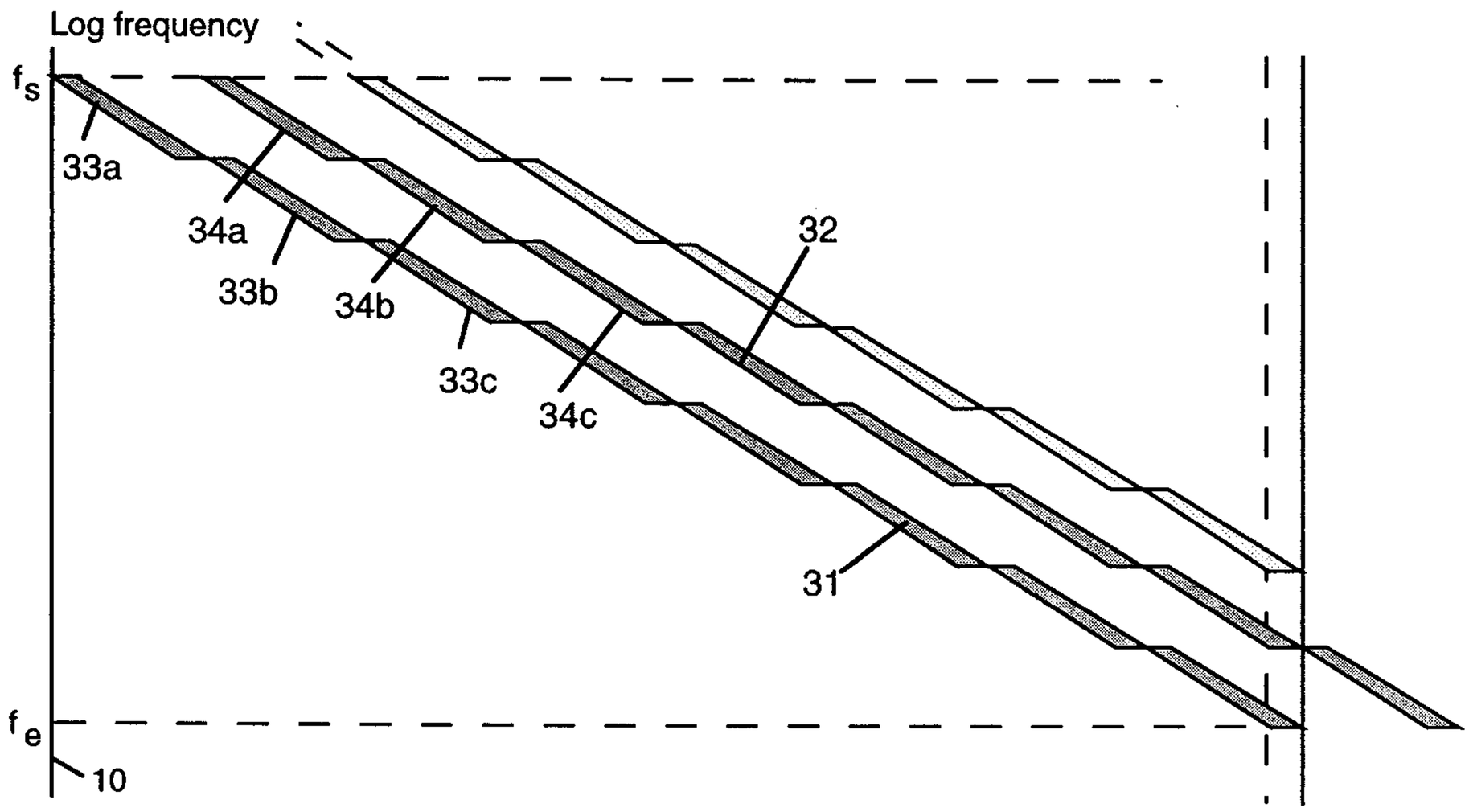
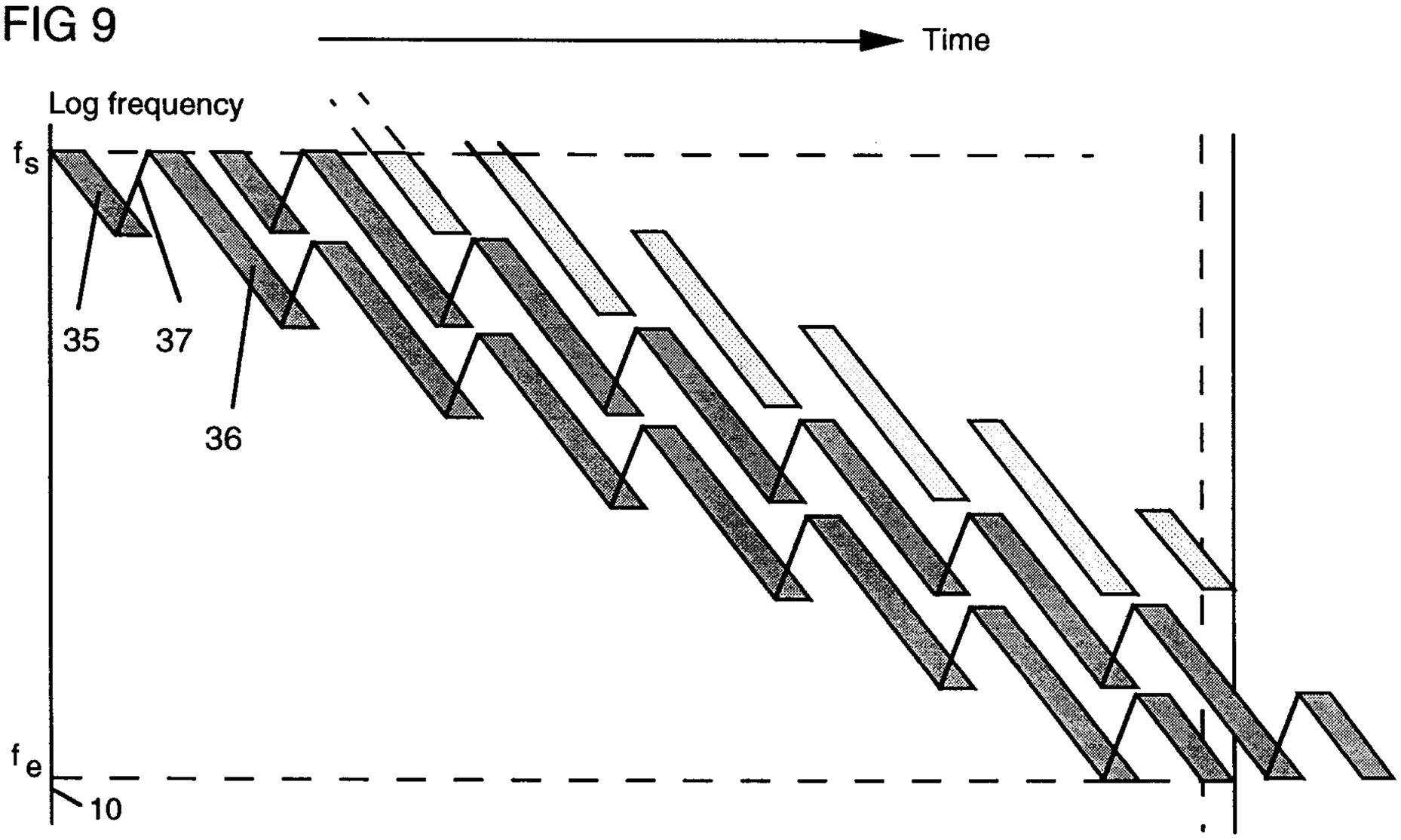
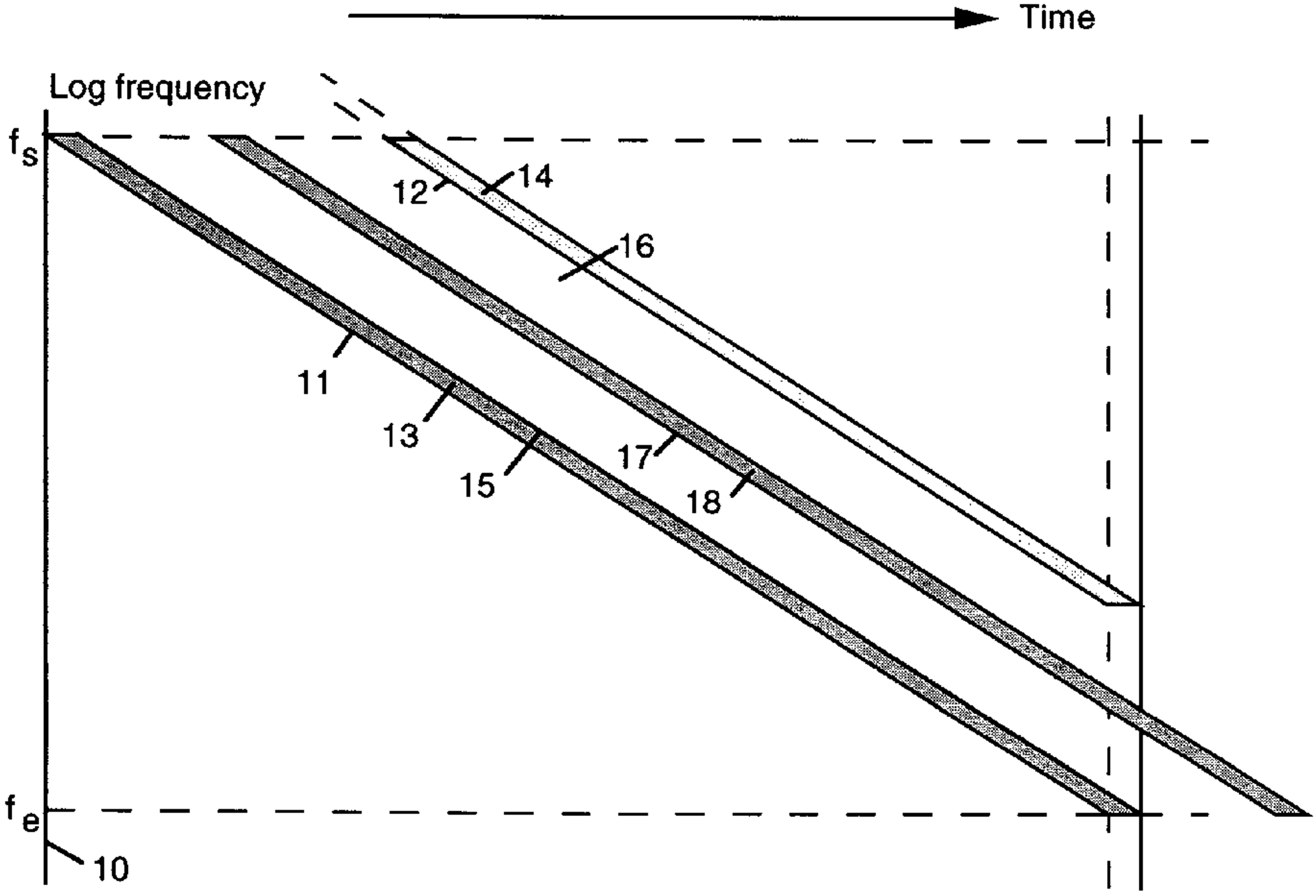


FIG 9



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Time
Log frequency
f_s
12
14
16
11
13
15
17
18
f_e
10