

Oct. 25, 1960

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2,957,948

FREQUENCY BAND COMPRESSION

Filed July 20, 1956

2 Sheets-Sheet 1

FIG. 1

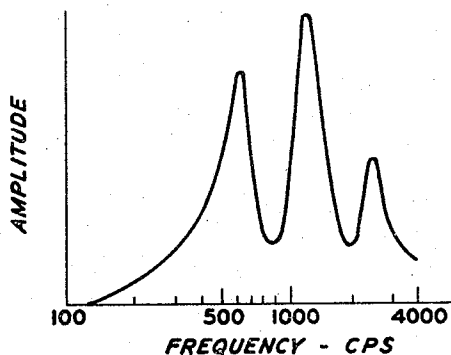
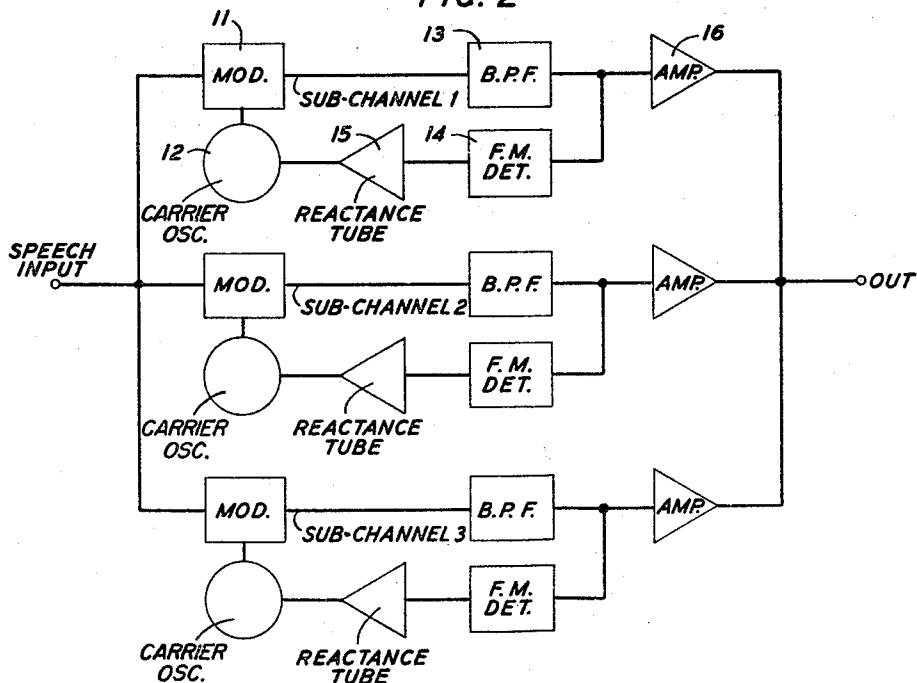


FIG. 2



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FIG. 4

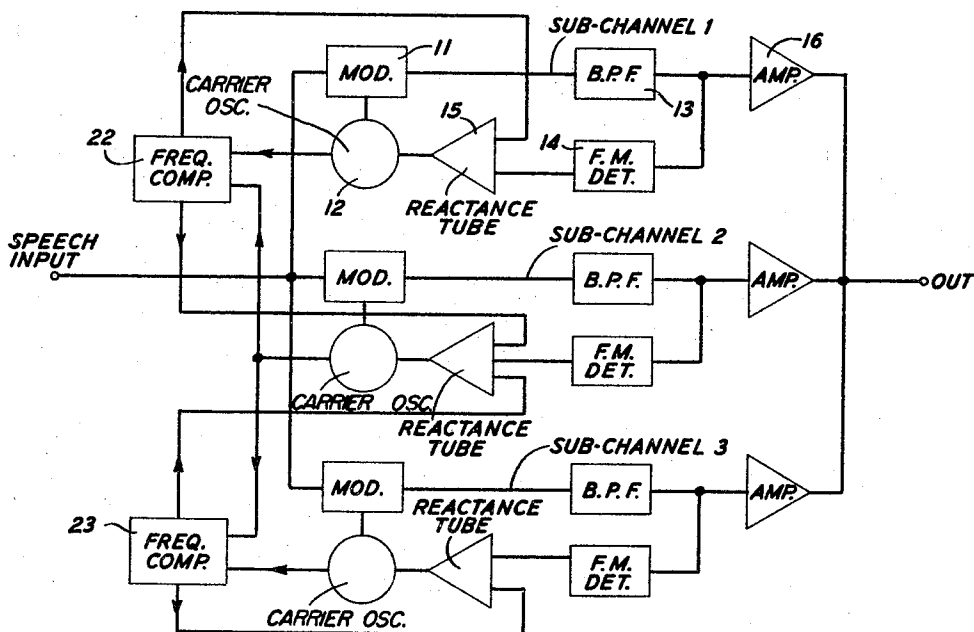
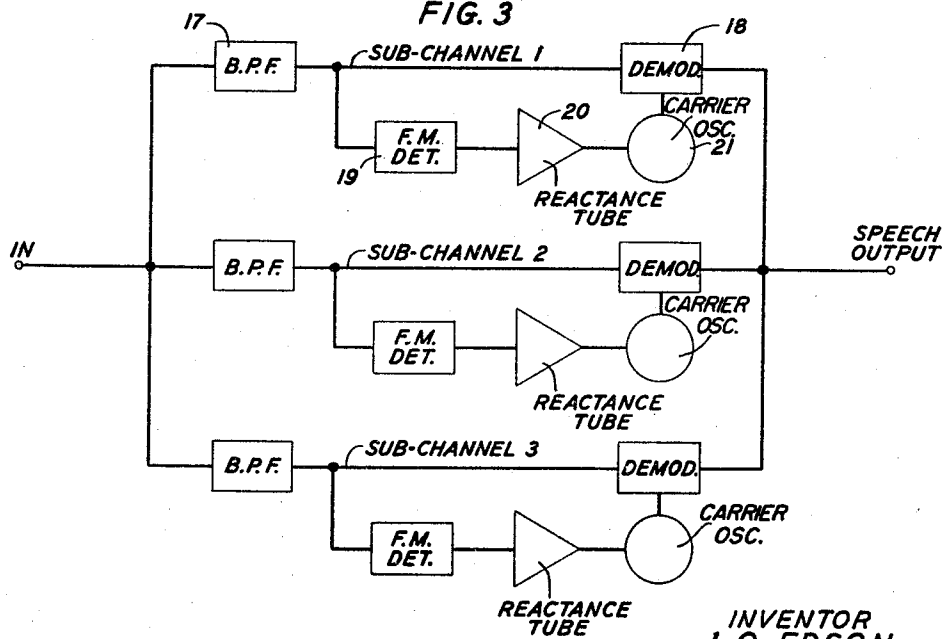


FIG. 3



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FREQUENCY BAND COMPRESSION

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10 Claims. (Cl. 179—15.55)

This invention relates generally to arrangements for reducing the frequency band needed for the transmission of intelligence in electrical form and more particularly, although in its broader aspects not exclusively, to arrangements for reducing the frequency band required for the transmission of speech signals.

One important object of the invention is to simplify the circuitry required for the compression of the bandwidth of speech signals.

Another important object is to increase the flexibility, and hence the range of application, of arrangements for reducing the bandwidth required for the transmission of speech signals.

It has been known for quite some time that the nature of the frequency spectrum of most human speech is such as to permit major reductions in the bandwidth required for the transmission of speech signals in electrical form with little important loss in intelligibility. While the energy distribution over the voice-frequency spectrum is fairly uniform in the case of unvoiced or consonant sounds, it nearly always contains three distinct resonance peaks in the case of voiced or vowel sounds. These three resonance peaks represent the three principal formants of the human voice and tend to move up and down the frequency scale within their respective ranges substantially independently of one another in the course of normal speech. It has been determined experimentally that a major portion of the information contained in a speech signal is included in these formants. Although there is an inevitable reduction in quality with respect to the unvoiced sounds, it is therefore possible to reduce the frequency band needed for the transmission of speech signals by transmitting only those frequency bands which contain the formants themselves. The percentage of band reduction may be of the order of fifty percent or more without significant loss of transmitted information.

In the past, the circuitry required for frequency band reduction by way of the exclusion of those portions of the voice-frequency band not including the formants has tended either to be rather complex or to be somewhat lacking in flexibility, particularly with regard to the degree of frequency band compression. Many of the simpler arrangements, for example, have required the degree of compression to be an integral multiple. The present invention helps overcome these disadvantages of the prior art and not only simplifies the circuitry of frequency band compression systems but also permits the amount of compression to be any number at will. In addition, the invention even permits different compression ranges to be used within a single speech signal transmission channel.

In accordance with a principal feature of the invention, the frequency band occupied by a speech signal is compressed by transmitting each of the principal formants of the signal through a separate sub-channel, each of which includes a carrier oscillator, a modulator, and means to restrict the frequency excursions of the carrier

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sideband amplitude peak corresponding to the formant by varying the operating frequency of the carrier oscillator. In each sub-channel, the output of the carrier oscillator is modulated by the speech to produce a sideband having amplitude peaks corresponding to the respective formants in its amplitude-frequency characteristic and the portion of the band containing the pertinent one of the peaks is selected by filtering. Frequency-sensitive means is provided in each sub-channel to detect any departure of the selected sideband amplitude peak from a predetermined central frequency, and the operating frequency of the carrier oscillator is varied under the control of the detected departures. In accordance with another important feature of the invention, filters having fixed pass bands are used, as mentioned above, to pass those portions of the carrier frequency band which include the amplitude peaks corresponding to the formants, and the remaining frequencies are discarded. Since the frequency excursions of the respective sideband amplitude peaks are considerably more restricted than those of the formants themselves, a considerable saving in frequency space can be effected with a relatively small loss in the amount of information transmitted. As pointed out above, the range of compression made possible by the invention need not be only an integral multiple but may be any number at will.

While the excursions of the three principal formants of a speech signal are usually confined to separate portions of the voice-frequency spectrum, each does, for some sounds, occasionally extend beyond its normal range into portions of the spectrum normally occupied by the next adjacent formants. There is, therefore, a possibility that two formants will sometimes fall into the same sub-channel, causing a marked increase in distortion for some voices and for some vowel sounds. In accordance with another important feature of the invention, the possibility of such distortion is eliminated by providing interlock means for preventing two adjacent sub-channels from locking onto the same speech signal formant simultaneously. In one form, the interlock means includes frequency-sensitive means to detect the magnitude and the direction of any departure of the carrier oscillator in each one of a pair of adjacent sub-channels from a predetermined central frequency and means to shift the operating frequency of both carrier oscillators in the direction toward their own center values when the detected departures are opposite to one another in sign and exceed a predetermined limit in magnitude.

Other objects and features of the invention will become apparent upon study of the following detailed description of several specific embodiments.

In the drawings:

Fig. 1 illustrates the amplitude-frequency characteristic of a typical voiced or vowel sound;

Fig. 2 illustrates a speech signal frequency compressor embodying several important features of the invention;

Fig. 3 illustrates an arrangement embodying features of the invention for restoring frequency-compressed speech signals approximately to their original form; and

Fig. 4 shows an alternative to the embodiment of the invention illustrated in Fig. 2 which includes means to prevent the carrier oscillators of two adjacent sub-channels from locking onto the same speech formant simultaneously.

Fig. 1 shows the amplitude-frequency characteristic of a typical voiced or vowel sound with formants at approximately 600, 1200, and 2500 cycles. For normal speech, these formants move up and down the frequency scale within their respective ranges substantially independently of one another. To a first approximation, the first formant confines itself to the range from 200 to 1000 cycles, the second confines itself to the range from 1000 to 2000

cycles, and the third confines itself to the range from 2000 to 3500 cycles. There are a few important exceptions to this generalization, but they will be dealt with in detail later.

As can be seen from the energy distribution curve illustrated in Fig. 1, the frequency band required for the transmission of speech signals can be cut by a factor of as much as two without important loss of information if the frequencies transmitted are those containing the speech formants. For the speech sound having the illustrated characteristic, for example, transmission of only those frequencies in the band from 400 to 800 cycles, from 950 to 1450 cycles, and from 2125 to 2875 cycles would lose little of the information contained in the signal. There would be some decrease in the naturalness of the received signal, but that would be relatively unimportant when considered in relation to the two to one saving in bandwidth.

Since in actual speech the respective formants do not remain in fixed frequency positions but, rather, move up and down the frequency scale within their respective ranges substantially independently of one another, a band saving of this magnitude could not be accomplished by filtering alone without serious loss of frequencies within the formants themselves and, hence, without serious loss of the information content of the transmitted speech signals. The present invention accomplishes this reduction in bandwidth with no important loss of the transmitted intelligence in a manner that is not only simpler but is also more flexible than any which has been known in the past.

Several important features of the invention are embodied in the frequency-band compressor illustrated in block diagram form in Fig. 2. There, the speech signal channel is split into three separate sub-channels, one corresponding to each of the principal formants. Sub-channel 1 corresponds to the first formant, sub-channel 2 corresponds to the second, and sub-channel 3 corresponds to the third. Each sub-channel includes a modulator 11, a variable frequency carrier oscillator 12, a band-pass filter 13, an FM detector 14, a reactance tube circuit 15, and an output power amplifier 16. In each sub-channel, the modulator 11 has its signal input circuit connected to receive the incoming speech signal which is to be compressed in frequency, its carrier input circuit connected to carrier oscillator 12, and its output circuit connected to the input side of filter 13. The output side of filter 13 is connected to the input side of amplifier 16, while the output side of amplifier 16 is connected to a common transmission circuit for all three sub-channels. Between filter 13 and amplifier 16, a portion of the carrier frequency signal energy is taken off and applied to the input side of FM detector 14, the output side of which is connected through reactance tube circuit 15 to control the frequency of carrier oscillator 12.

In sub-channel 1 of the embodiment of the invention illustrated in Fig. 2, the speech signal enters modulator 11 and is converted to carrier. The output of modulator 11 includes both upper and lower sidebands, each of which have an amplitude-frequency characteristic like that of the speech signal. Filter 13 is provided with a pass band which encompasses the amplitude peak of one of the sidebands (e.g., the lower) corresponding to the first speech formant when the formant occupies a predetermined central frequency (e.g., 600 cycles) but is narrower than the frequency band through which the formant normally ranges. A portion of the output of band-pass filter 13 is transmitted to the line through amplifier 16 and a portion enters FM detector 14. Detector 14, which includes at least one limiter followed by either a frequency discriminator or a ratio detector, has a voltage-frequency characteristic of the usual kind providing negative output voltages in response to frequencies above the center frequency and positive voltages for frequencies below the center frequency. The center frequency of the detector

is made equal to the carrier frequency occupied by the sideband amplitude peak when the speech formant corresponding thereto occupies its center frequency (i.e., when the formant is at 600 cycles). FM detector 14 is thus arranged to give zero voltage output if the input signal is absent or if it has a resonance peak at the center frequency of the first formant range.

The range of the first formant is substantially from 200 to 1000 cycles. FM detector 14 is arranged, therefore, so that an input signal having a resonance peak at 600 cycles produces no output from the detector. Input signals having peaks below 600 cycles produce negative output voltages from detector 14 and input signals having peaks above 600 cycles produce positive output voltages. The output from FM detector 14 is applied to reactance tube 15 in order to control the frequency of carrier oscillator 12. Carrier oscillator 12 is thus frequency modulated under the control of the output from band-pass filter 13. The center frequency of oscillator 12, which is the frequency produced at the input side of filter 13 with zero input to the reactance tube 15, is chosen so that an input signal having a peak at 600 cycles is modulated to fall just in the middle of the pass band of filter 13. The polarity of the control circuit is arranged so that lowering the frequency of the input signal peak below the center value of 600 cycles has the effect of raising the frequency of oscillator 12 and raising the frequency of the peak above 600 cycles has the effect of lowering the oscillator frequency.

Under the above described conditions, the frequency of the amplitude peak of sideband output of modulator 11 does not vary as much as does the frequency of the amplitude peak of the input signal which produces it. If, for example, variable frequency carrier oscillator 12 is fixed to vary one cycle for each cycle of variation at the output of band-pass filter 13, the output of modulator 11 varies one cycle for each two cycles of variation at the input to modulator 11. Such an adjustment gives a frequency compression of two to one. Increasing the sensitivity of either FM detector 14 or reactance tube 15 permits further increases in the amount of compression and further reduction in the bandwidth of band-pass filter 13.

The other two speech formants are treated in substantially the same manner by sub-channels 2 and 3. The amount of compression used in the three sub-channels may be the same but it is not at all necessary that it be. If there is, for example, a maximum permissible amount of compression which is different for each of the three formants, the amounts of compression provided by the respective sub-channels may be fixed to coincide with such maximum values. Furthermore, the three frequency bands passed by the bandpass filter 13 in the respective sub-channels may be adjacent in the frequency spectrum or may, alternatively, be placed at any three desirable spots by suitable choice of the FM detectors 14 and the center frequencies of the carrier oscillators 12. The three sub-channel outputs may be transmitted by any of the well known methods of carrier transmission.

The operation of the embodiment of the invention illustrated in Fig. 2 may perhaps be better understood if the frequency values associated with a specific example are considered. As has already been pointed out, the general range for the first speech formant is from 200 to 1000 cycles, the general range for the second is from 1000 to 2000 cycles, and the general range for the third is from 2000 to 3500 cycles. The total bandwidth required for transmission of all of the information that either is or can be contained in these bands is thus 3300 cycles. If a two to one band reduction is chosen, the embodiment of the invention illustrated in Fig. 2 permits a speech signal of this type to be compressed to approximately 1650 cycles with no important loss of information. The two to one reduction ratio is chosen, however, only for simplicity in the computations. Any other ratio such

as, for example, one and three-quarters or one and seven-eighths to one could have been selected instead.

Assume, for the sake of example, that transmission is desired at carrier frequencies of the order of 50 kilocycles and that the bands passed by the respective filters 13 are to be adjacent to one another in the frequency spectrum. The desired results may be obtained by providing the carrier oscillators 12 in the first, second and third sub-channels with center frequencies of 52,050 cycles, 52,500 cycles, and 53,125 cycles, respectively. With lower sideband transmission, the band-pass filters in the first, second, and third sub-channels would have pass bands of from 51,250 to 51,650 cycles, from 50,750 to 51,250 cycles, and from 50,000 to 50,750 cycles, respectively. For formant center frequencies of 600, 1500, and 2750 cycles, the corresponding center frequencies in the lower sidebands produced by the modulators 11 are 51,450, 51,000, and 50,375 cycles, respectively. When the speech formants and the corresponding amplitude peaks in the amplitude-frequency characteristics of the carrier sidebands occupy these center frequencies, the positive and negative outputs of each FM detector balance each other and no resultant voltages are passed along to reactance tube 15.

When any formant goes above its respective center frequency, and the corresponding sideband amplitude peak goes down in frequency, the net positive signal at the reactance tube input raises the carrier frequency. Raising the carrier frequency has the effect of raising the lower sideband and, since the amplitude peak in the lower sideband decreases in frequency whenever the formant increases in frequency, the effect is to shift the amplitude peak in the sideband back toward the center frequency of the corresponding band-pass filter 13. The sideband amplitude peak thus tends to have its frequency excursions reduced in magnitude and is kept within the bounds established by the band-pass filter 13.

The carrier oscillators 12 in all three sub-channels in the embodiment of the invention illustrated in Fig. 2 follow shifts in the frequencies of their respective formants in the manner described, keeping the carrier sideband amplitude peaks within the ranges established by the band-pass filters 13. In the example given, the frequency bands passed by the three filters are adjacent to one another in the spectrum. These frequency bands are combined at the output sides of the amplifiers 16 for transmission to the receiving end of the system.

Fig. 3 shows, in block schematic form, an arrangement embodying additional features of the invention which serves to receive the signals transmitted by the frequency-band reducer of Fig. 2 and reverse the process to restore the speech signal to substantially its original bandwidth. Like the band reducer shown in Fig. 2, the frequency-band expander illustrated in Fig. 3 includes three separate sub-channels, one corresponding to each of the three principal speech formants. As in Fig. 2, these sub-channels are substantially identical to one another from a functional standpoint, differing principally with respect to operating frequencies. Each sub-channel in Fig. 3 includes a band-pass filter 17, a demodulator 18, an FM detector 19, a reactance tube circuit 20, and a variable-frequency carrier oscillator 21. In each sub-channel, band-pass filter 17 has substantially the same pass band as the corresponding filter 13 in Fig. 2 and FM detector 19, reactance tube 20, and carrier oscillator 21 are substantially identical to detector 14, reactance tube 15, and carrier oscillator 12 in the corresponding sub-channel in Fig. 2.

In each sub-channel in the embodiment of the invention illustrated in Fig. 3, the entire band-reduced speech signal transmitted from the compressor illustrated in Fig. 2 is applied to the band-pass filter 17, which selects the portion containing the sideband amplitude peak corresponding to its respective assigned speech formant. The major portion of the output of filter 17 is applied to the

sideband input circuit of demodulator 18. The output circuit of demodulator 18 is connected in common with the output circuits of demodulators 18 in the other sub-channels to a combined speech output circuit. The remainder of the output of band-pass filter 17 is connected through FM detector 19 and reactance tube 20 to the carrier oscillator 21. The output of oscillator 21 is applied to the carrier input circuit of demodulator 18.

In the operation of the speech band expander shown in Fig. 3, if the FM detector 19, reactance tube 20, and carrier oscillator 21 in each sub-channel match corresponding components of the band reducing transmitter, the carrier supplied to each demodulator 18 is identical at every instant, except for transmission delay, to the carrier supplied to the corresponding modulator 11 in Fig. 2. The detailed operation of the embodiment of the invention illustrated in Fig. 3 may best be explained by dealing with the action of a corresponding sub-channel (e.g., sub-channel 1) in both Fig. 2 and Fig. 3. Application of a speech signal having a formant at 600 cycles to the inputs of the modulators 11 in Fig. 2 produces a sideband out of the modulator 11 in sub-channel 1 having a corresponding amplitude peak at the center frequency of band-pass filter 13. This results in zero output from the FM detector 14, and carrier oscillator 12 rests at its center frequency. The sideband is transmitted to the receiver illustrated in Fig. 3 and is selected by the band-pass filter 17 in sub-channel 1, resulting in the application of the center frequency of carrier oscillator 21 to the carrier input circuit of demodulator 18. Demodulator 18 thus returns the signal to 600 cycles at the speech output circuit.

If the frequency of the relevant formant of the input speech signal is changed, the oscillator 12 at the transmitting end of the system follows the signal partially and thus reduces the variation in the frequency of the amplitude peak of the sideband. The sideband amplitude peak is still passed by the band-pass filter 13 and the receiver carrier oscillator 21 varies in frequency in a similar manner. The frequency variation of the receiver carrier oscillator 21 is opposite to that of the sideband amplitude peak, so that the output again is restored to the original frequency range of variation and the output signal is identical with the input speech signal if the two carrier oscillators track one another accurately. The system still follows the signal and reproduces the output faithfully if the frequency of the signal amplitude peak is changed rapidly, provided that the rate of varying the amplitude peak of the signal is not greater than one-half the bandwidth of the corresponding sub-channel band-pass filter.

As has already been pointed out, the three principal speech formants are usually restricted to the respective ranges from 200 to 1000 cycles, from 1000 to 2000 cycles, and from 2000 to 3500 cycles. This is, however, not always true. For some voices and for some speech sounds, any of the formants may occasionally go as much as 200 cycles above or below its normal range. Past systems have tended to divide the spectrum rigidly into sub-channels. In such arrangements, there is always a possibility of two formants falling into the same sub-channel, resulting in distortion in the final output signal.

The embodiment of the invention illustrated in Fig. 4 is an alternative to the speech band reducer illustrated in Fig. 2 which eliminates this type of difficulty by increasing the permissible formant range. The same bandpass filters 11 that are used in Fig. 2 are used in Fig. 4, but an increase in the sensitivity of either FM detector 14 or reactance tube 15 in each sub-channel permits the carrier oscillators 12 to follow frequencies outside of their normal ranges. If such adjustments were carried out without further modification of the equipment, there would be some danger of a single formant in the vicinity of 1000 cycles, for example, causing both sub-channels 1 and 2 to seize the frequency and deliver output from both of their

respective band-pass filters 13. The two signals would go to the receiver, be selected by the corresponding band-pass filters 17 at the receiver, and be demodulated to frequencies substantially equal to one kilocycle at the output of the demodulators 18. Imperfection in oscillator tracking could result in these frequencies being not quite identical. Since their amplitudes would be substantially the same, very objectionable beats could result. The embodiment of the invention illustrated in Fig. 4 is a frequency-band reducer like that of Fig. 2 modified to prevent such an occurrence.

In accordance with a feature of the invention, a frequency comparator 22 is connected between sub-channels 1 and 2 in Fig. 4 to check the frequencies of the two carrier oscillators 12. If comparator 22 finds the oscillator of sub-channel 2 working near the one kilocycle boundary but slightly above it, it introduces an inhibiting voltage in the sub-channel 1 reactance tube circuit to prevent the oscillator of sub-channel 1 from invading the territory primarily assigned to the oscillator of sub-channel 2 (i.e., the range from 1000 to 2000 cycles). Similarly, if it finds the oscillator of sub-channel 1 working near the top of but within its primary range, it injects the voltage into the reactance tube circuit of sub-channel 2 to prevent the oscillator of sub-channel 2 from invading the primary range of sub-channel 1 (i.e., the range from 200 to 1000 cycles). Thus, if sub-channel 1 is locked onto a frequency below the middle part of its range, the oscillator of sub-channel 2 is permitted to invade the upper part of the range primarily assigned to sub-channel 1. If, however, sub-channel 1 follows its dominant frequency up into the upper range of its primary assigned band, subchannel 2 is prevented from seizing this same frequency.

In a similar manner, another frequency comparator 23 is connected between sub-channels 2 and 3. The carrier oscillators of sub-channels 2 and 3 are compared in frequency and signals are impressed on the reactance tube circuits of sub-channels 2 and 3 to prevent simultaneous operation of the two sub-channels on a single frequency, while permitting either one to operate by itself in the intermediate zone.

In accordance with the present invention, each frequency comparator in Fig. 4 includes a pair of frequency discriminators connected to respective carrier oscillators 12. These discriminators are each adjusted to yield a positive output voltage if the associated oscillator 12 operates above its center frequency and a negative output voltage if the frequency is low. The sensitivities are fixed so that the output voltages are equal as each carrier oscillator 12 reaches the edge of its primary operating range.

In each frequency comparator, the discriminator output voltages are combined so that the output from the higher sub-channel subtracts from that of the lower sub-channel. If both oscillators are operating simultaneously at a frequency at the junction of their normal ranges, the output is positive and twice the reference value produced by either alone. In accordance with a feature of the invention, this signal is applied to a device (sometimes called a slicer or threshold device) which is operated whenever the input voltage exceeds a certain value. The threshold level is, by way of example, set at about fifteen times the reference voltage produced when one carrier oscillator 12 reaches the edge of its range.

Operation of the slicer in one of the frequency comparators in Fig. 4 closes electronic switches which, in turn, connect diode limiters to the input of both reactance tubes 15. The bias batteries to which the electronic switches connect the diode limiters are fixed in magnitude so that the respective carrier oscillators 12 are confined to their primary frequency ranges whenever the electronic switches are operated. In this manner, they are prevented from tracking simultaneously a single frequency near the edge between their respective ranges.

It is to be understood that the above-described arrange-

ments are illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. An arrangement for compressing the bandwidth required for the transmission of a signal having at least one amplitude peak in its amplitude-frequency characteristic which varies in frequency with time and contains a major portion of the intelligence making up said signal which comprises a carrier oscillator, means to amplitude modulate the output of said carrier oscillator with said signal and produce a sideband having an amplitude-frequency characteristic like that of said signal, and means to restrict the frequency excursions of the amplitude peak of said sideband by varying the frequency of said carrier oscillator.

2. An arrangement for compressing the bandwidth required for the transmission of a signal having at least one amplitude peak in its amplitude-frequency characteristic which varies in frequency with time and contains a major portion of the intelligence making up said signal which comprises a carrier oscillator, means to amplitude modulate the output of said carrier oscillator with said signal and produce a sideband having an amplitude-frequency characteristic like that of said signal, a band-pass filter having a pass band narrower than the bandwidth of said signal but encompassing the amplitude peak of said sideband when said sideband amplitude peak occupies a predetermined central frequency, frequency-sensitive means to detect any departure of said sideband amplitude peak from said predetermined central frequency, and means responsive to said frequency-sensitive detection means to shift the frequency of said carrier oscillator in the direction required to restore said sideband amplitude peak to said predetermined central frequency.

3. An arrangement for transmitting a signal having at least one amplitude peak in its amplitude-frequency characteristic which varies in frequency with time and contains a major portion of the intelligence making up said signal between two stations with reduced bandwidth, said arrangement comprising a frequency compressor at one of said stations which includes a first carrier oscillator, means to amplitude modulate the output of said first carrier oscillator with said signal and produce a sideband having an amplitude-frequency characteristic like that of said signal, and means to restrict the frequency excursions of the amplitude peak of said sideband by varying the frequency of said first carrier oscillator, and a frequency expander at the other of said stations which includes a second carrier oscillator, means to demodulate said sideband with the output of said second carrier oscillator and reproduce said signal, and means to vary the frequency of said second carrier oscillator in synchronism with the frequency of said first carrier oscillator.

4. An arrangement for transmitting a signal having at least one amplitude peak in its amplitude-frequency characteristic which varies in frequency with time and contains a major portion of the intelligence making up said signal between two stations with reduced bandwidth, said arrangement comprising a frequency compressor at one of said stations which includes a first carrier oscillator, means to amplitude modulate the output of said first carrier oscillator with said signal and produce a sideband having an amplitude-frequency characteristic like that of said signal, a band-pass filter having a pass band narrower than the bandwidth of said signal but encompassing the amplitude peak of said sideband when said sideband amplitude peak occupies a predetermined central frequency, a first frequency-sensitive means to detect any departure of said sideband amplitude peak from said predetermined central frequency, and means responsive to said first frequency-sensitive means to shift the frequency of said first carrier oscillator in the direction required to restore said sideband amplitude peak to said predetermined central

frequency, and a frequency expander at the other of said stations which includes a second carrier oscillator, means to demodulate said side band with the output of said second carrier oscillator and reproduce said signal, a second frequency-sensitive means to detect any departure of said sideband amplitude peak from said predetermined central frequency, and means responsive to said second frequency-sensitive means to shift the frequency of said second carrier oscillator in synchronism with the frequency of said first carrier oscillator.

5. An arrangement for compressing the bandwidth required for the transmission of a speech signal which comprises a plurality of sub-channels each corresponding to one of the principal formants of said speech signal, each of said sub-channels including a carrier oscillator, means to amplitude modulate the output of said carrier oscillator with at least a portion of said speech signal containing a respective one of the formants thereof and produce a sideband having an amplitude peak in its amplitude-frequency characteristic corresponding to the formant, and means to restrict the frequency excursions of the amplitude peak of said sideband by varying the frequency of said carrier oscillator, the carrier oscillators in all of said sub-channels having respectively different operating frequencies.

6. An arrangement for compressing the bandwidth required for the transmission of a speech signal which comprises a plurality of sub-channels each corresponding to one of the principal formants of said speech signal, each of said sub-channels including a carrier oscillator, means to amplitude modulate the output of said carrier oscillator with at least a portion of said speech signal containing a respective one of the formants thereof and produce a sideband having an amplitude peak in its amplitude-frequency characteristic corresponding to the formant, a band-pass filter having a pass band narrower than the bandwidth of the respective portion of said speech signal associated with the sub-channel but encompassing the amplitude peak of said sideband when said amplitude peak occupies a predetermined central frequency, frequency-sensitive means to detect any departure of said amplitude peak from said predetermined central frequency, and means responsive to said frequency-sensitive detection means to shift the frequency of said carrier oscillator in the direction required to restore said amplitude peak to said predetermined central frequency, the carrier oscillators in all of said sub-channels having respectively different operating frequencies and the band-pass filters in all of said sub-channels having respectively different pass bands.

7. An arrangement for transmitting a speech signal between two stations with reduced bandwidth comprising a frequency compressor at one of said stations which includes a plurality of sub-channels each corresponding to one of the principal formants of said speech signal, each of said compressor sub-channels including a first carrier oscillator, means to amplitude modulate the output of said first carrier oscillator with at least a portion of said speech signal containing a respective one of the formants thereof and produce a sideband having an amplitude peak in its amplitude-frequency characteristic corresponding to the formant, and means to restrict the frequency excursions of the amplitude peak of said sideband by varying the frequency of said first carrier oscillator, the carrier oscillators in all of said compressor sub-channels having respectively different operating frequencies, and a frequency expander at the other of said stations which includes a plurality of sub-channels each corresponding to a respective one of said compressor sub-channels, each of said expander sub-channels including a second carrier oscillator, means to demodulate the sideband received from the corresponding one of said compressor sub-channels with the output of said second carrier oscillator and reproduce the respective portion of said speech signal containing one of the principal formants thereof, and means to vary the frequency of said second carrier oscillator in synchronism with the frequency of the said first carrier oscillator

in the corresponding one of said compressor sub-channels, the carrier oscillator in each of said expander sub-channels having the same operating frequency as the carrier oscillator in the corresponding one of said compressor sub-channels.

8. An arrangement for transmitting a speech signal between two stations with reduced bandwidth comprising a frequency compressor at one of said stations which includes a plurality of sub-channels each corresponding to one of the principal formants of said speech signal, each of said compressor sub-channels including a first carrier oscillator, means to amplitude modulate the output of said first carrier oscillator with at least a portion of said speech signal containing a respective one of the formants thereof and produce a sideband having an amplitude peak in its amplitude-frequency characteristic corresponding to the formant, a first band-pass filter having a pass band narrower than the bandwidth of the respective portion of said speech signal associated with the sub-channel but encompassing the amplitude peak of said sideband when said amplitude peak occupies a predetermined central frequency, a first frequency-sensitive means to detect any departure of said amplitude peak from said predetermined central frequency, and means responsive to said first frequency-sensitive means to shift the frequency of said first carrier oscillator in the direction required to restore said amplitude peak to said predetermined central frequency, the carrier oscillators in all of said compressor sub-channels having respectively different operating frequencies and the band-pass filters in all of said compressor sub-channels having respectively different pass bands, and a frequency expander at the other of said stations which includes a plurality of sub-channels each corresponding to a respective one of said compressor sub-channels, each of said expander sub-channels including a second band-pass filter having substantially the same pass band as the band-pass filter in the corresponding one of said compressor sub-channels, a second carrier oscillator, means to demodulate the sideband received through said second band-pass filter from the corresponding one of said compressor sub-channels with the output of said second carrier oscillator and reproduce the respective portion of said speech signal containing one of the principal formants thereof, a second frequency-sensitive means to detect any departure of the sideband peak in the corresponding one of said compressor sub-channels from said predetermined central frequency, and means responsive to said second frequency-sensitive means to shift the frequency of said second carrier oscillator in synchronism with the frequency of the said first carrier oscillator in the corresponding one of said compressor sub-channels, the carrier oscillator in each of said expander sub-channels having the same operating frequency as the carrier oscillator in the corresponding one of said compressor sub-channels.

9. An arrangement for compressing the bandwidth required for the transmission of a speech signal which comprises a plurality of sub-channels each corresponding to one of the principal formants of said speech signal, each of said sub-channels including a carrier oscillator, amplitude means to modulate the output of said carrier oscillator with at least a portion of said speech signal containing a respective one of the formants thereof and produce a sideband having an amplitude peak in its amplitude-frequency characteristic corresponding to the formant, and means to restrict the frequency excursions of the amplitude peak of said sideband by varying the frequency of said carrier oscillator, the carrier oscillators in all of said sub-channels having respectively different operating frequencies, and interlock means to prevent two adjacent ones of said sub-channels from following the same formant of said speech signal simultaneously.

10. An arrangement for compressing the bandwidth required for the transmission of a speech signal which comprises a plurality of sub-channels, each corresponding to one of the principal formants of said speech signal, each

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of said sub-channels including a carrier oscillator having a respectively different central operating frequency, means to amplitude modulate the output of said carrier oscillator with at least a portion of said speech signal containing the respective one of the formants thereof and produce a sideband having an amplitude peak in its amplitude-frequency characteristic corresponding to the formant, a band-pass filter having a respectively different pass band narrower than the bandwidth of the respective portion of said speech signal associated with the sub-channel but encompassing the amplitude peak of said sideband when said amplitude peak occupies a predetermined central frequency, frequency-sensitive means to detect any departure of said amplitude peak from said predetermined central frequency, and means responsive to said frequency-sensitive detection means to shift the operating frequency of said carrier oscillator in the direction required to restore said amplitude peak to said predetermined central frequency, and interlock means to prevent two adjacent ones of said sub-channels from following the same formant of said

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speech signal simultaneously which includes frequency-sensitive means to detect the amount and the sign of the departure of the operating frequency of the carrier oscillator of each of said sub-channels from its respective central value, and means to shift the operating frequencies of both carrier oscillators in the direction toward their own central values in response to detected departures opposite in sign from one another which exceed a predetermined limit.

References Cited in the file of this patent

UNITED STATES PATENTS

1,626,724	Demarest et al. -----	May 3, 1927
2,279,659	Crosby -----	Apr. 14, 1942
2,349,870	Koch -----	May 30, 1944
2,620,467	Donal -----	Dec. 2, 1952

FOREIGN PATENTS

463,218	Canada -----	Feb. 14, 1950
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