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THE USE OF EXACT FREQUENCIES IN MODERN COMMUNICATIONS ENGINEERING

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The principal areas of use of exact frequencies in modern communications engineering are given and definitions of the qualitative indexes which such frequencies must satisfy are formulated.

Modern communications engineering is finding ever greater use for oscillations characterized by extremely high indexes of frequency or phase stability. The use of exact frequencies makes possible the creation of communications systems which permit a manifold increase in the effective power of communications channels without increasing station power and permit a considerable increase in the flow of communications, that is, in the traffic capacity and noise stability of lines of communications. Systems using exact frequencies for the above purposes are usually referred to as "synchronous."

Modern communications systems permitting proximate realization of the maximum noise stability and traffic capacity predicted by communications theory must certainly be synchronous. Hence, communications engineering-technical workers may be interested in determining the basic areas of use of exact frequencies in communications engineering and the results obtained from their use.

Single-Sideband Radio Transmission

In defining the advantages of single-sideband operation (OBP) it is usually pointed out that if transmission of the carrier frequency is eliminated, then for a given maximum transmitter power the voltage amplitude of the sidebands is doubled. This is equivalent to a power signal gain of four times (owing to best use of the output of the transmitter tubes).

A narrower frequency spectrum is required for reception of single-sideband transmission than for the usual amplitude modulation (at the most, half as wide). Hence it is possible to obtain a corresponding reduction in the bandwidth of radio receivers and thereby to decrease (by half) the noise received by the receivers. This is equivalent to doubling the signal strength. Thus, compared with conventional double-sideband transmission, the overall gain in signal strength is 4 x 2 = 8 times.

On short-wave systems this gain may be still greater, since in the propagation of amplitude-modulated signals the phase relationships between the components of the upper and lower sidebands and the carrier frequency may be disturbed, which decreases the effectiveness of the received signals. In OBP transmission this phenomenon does not occur.

In noting the advantages of OBP transmission mention of the advantage in transmitter power requirement is often omitted. Nevertheless, the gain here is still great and is explained by the decrease in power radiated by the transmitter. In fact, with 100-percent amplitude modulation the average (for power calculations) percentage of modulation in radio broadcast transmission (considering pauses and moments of transmission of faint sounds) is approximately 10 percent and, consequently, the average sideband power $P_{side} = 0.5\ m^2\ P_{carr.} = 0.005\ P_{carr.}$, that is, only about 0.5 percent of the power of the carrier wave. Thus, in conventional modulation a radio station not only radiates power approximately 20,000 percent greater than when transmitting on single sideband, but also occupies twice the bandwith and still does not insure as high a quality of reception as single-sideband transmission. In short-wave transmission the latter circumstance is due chiefly to a-m distortions arising from selective fading, and in long-wave transmission it is due to the fact that single-sideband operation permits a gain in effective power of the channel (improved signal-noise ratio).

Hence it is completely understandable that modern communications engineering is making ever wider use of single-sideband systems both for wire communications and for radiotelephone communications. Effort is being made also to solve the problem of using single-sideband transmission on long waves for the purpose of radio broadcasting.

However, single-sideband transmission, as is known, requires restoration of the carrier frequency at the receiver with a high degree of accuracy. In radio broadcasting, for example, the restored carrier frequency at the receiving station must not differ by more than one cycle from the carrier frequency of the transmitter.

Thus, one of the ever-expanding areas of application of exact frequencies is the single-sideband system of communications.

Synchronization of Broadcasting Stations

As concerns systems of broadcasting, it is necessary to mention the so-called synchronous broadcast nets in which a large number (often more than 10) of low-power transmitters (0.5-5 kw) usually operate together with high-power transmitters on a single frequency, transmitting the same program synchronously and cophasally. This method of broadcasting is widely employed in many European countries. Its use has the following advantages: in daytime, with a low total radiated power and with extremely good signal-noise ratio, it permits adequate service of a large territory in the medium-wave broadcast band (200-500 m); in the evening, in the hours when the audience is largest, it permits considerable improvement in the quality of broadcasting, since in the zones served by its propagation is chiefly by ground wave. Moreover, this method permits the use of lower frequencies for broadcasting and reduces operating costs.

This reduction in operating costs is due chiefly to the fact that the specific radiated power of low-power transmitters is considerably less than for high-power transmitters (specific radiated power being the power radiated in kilowatts per square kilometer of the served zone). This is explained by the fact that, in accordance with laws of propagation of medium waves, with a given minimum field strength the area served does not increase in proportion to the transmitter power but lags considerably behind. Moreover, low-power and medium-power broadcast transmitters are usually made for unattended operation.

These are the compelling reasons why, under the Copenhagen International Plan, frequency assignments for most of the European countries were secured by synchronous broadcast nets. Numerous researches conducted up till World War II demonstrated that in order to achieve synchronous broadcasting an extremely high degree of synchronism in the carrier-frequency radiation is desired. Over a period of hours the frequency phase of synchronous stations must not differ by more than several tenths of a degree and, in any case, the frequency deviations of synchronized radio broadcasting stations must not exceed one ten-millionth of the carrier frequency ($1 \cdot 10^{-7}$).

Hence, synchronous broadcast nets are another important area of application of exact frequencies in communications engineering.

Compositing the Spectra of Telegraph and Radiotelegraph Services

The third area of application of exact frequencies is determined by the problems of compositing the spectra of telegraph and especially of radiotelegraph services. As the simplest calculations as well as experiment will show, the use of exact frequencies opens extremely wide possibilities for further compositing the spectra. For example, in the voice-frequency carrier system of radiotelegraphy of the DChT [frequency-shift telegraphy] type transmission of a single teletype channel occupies a bandwidth of about 3,000 cycles, and with four-channel time multiplexing the bandwidth is more than 1,300 cycles per channel (with allowance for transmitter instability).

Transmission of the same intelligence with no less noise stability may be achieved with a bandwidth of no more than 400 cycles per channel, and even this can be reduced by three times if transmission is limited to the first harmonic of the telegraph signals, which, as calculations show, is wholly permissible.

Thus, in many cases ten stations may provide radio communications with high noise stability within the same frequency range now occupied by a single station. However, such a system can be achieved only if the numerous narrow bands and channels employed in radiotelegraphy remain precisely on the assigned frequencies. The relative shift of the frequency bands of the individual channels for such systems must not be more than a few cycles, that is, tenths and even hundredths of the shifts now permitted.

Thus, the possible vast improvements in radio communications, the increased traffic capacity and noise stability can be obtained only by the use of exact frequencies at transmitting and receiving stations.

Phase-modulation telegraphy is of great importance for cable trunks and long-wave radio stations, for it requires a bandwidth less than half that for frequency-modulation telegraphy with the same noise stability. However, as will be seen, the phase-modulation telegraph system requires the use of exact frequencies of especially high quality.

Special Systems

The fourth area of use of exact frequencies is in special communications with unusual noise stability. Narrowing the bandwidth by improving the system of keying and increasing frequency stability, it is possible by various methods to increase the effective channel power (to increase noise stability).

The simplest of these is the repetition of messages consecutively in time or in parallel along several channels, as well as the method of integrating telegraph pulses for definite intervals of time. These methods, permitting a considerable increase in the effective power of communications channels, require the rigid cophasal operation of the transmitting and receiving equipments, that is, the use of exact frequencies of high quality.

Time-Multiplex Systems

In the fifth area of use of exact frequencies we include the various systems permitting intermittent multiplex operation of communications channels (multiplex transmission). Such systems are well known. The 9-plex Baudot system may be cited as an example. The most generally used methods of multiplex operation of communications lines are usually divided into two classes: frequency multiplex and time multiplex operation.

The number of channels in communications lines is usually relatively small. Thus, in radio communications lines the number of channels is usually less than ten. Under these conditions, with frequency multiplexing the power of any one channel decreases rapidly as the number of channels is increased (as an approximation may be considered that the power of one channel decreases in inverse proportion to the square of the number of channels).

In the case of time multiplexing the decrease in power of a single channel is somewhat slower (approximately in inverse proportion to the number of channels). Hence, in systems with a relatively small number of channels, especially in radio communications, time-multiplex systems are finding increasingly wider use. These systems require cophasal operation of the transmitting and receiving equipments, hence they also require exact frequencies of extremely high quality.

It must especially be noted that the achievement of phase synchronism of terminal telegraph apparatus permits solution of an important problem of modern communications engineering -- the electrical transit of telegrams in systems with time multiplexing.

Only the principal areas of use of exact frequencies in communications engineering are listed above. Such frequencies are also widely used in other areas -- time service, frequency control, navigation, in scientific laboratories, etc.

Qualitative Indexes of Exact Frequencies. Systems of Synchronism

It is clearly important that in the near future exact frequencies should constitute the organic basis of all the principal lines of electrical communications. Hence it is to the interest of communications specialists that they become acquainted with the principal qualitative indexes of exact frequencies. We will here dwell only on the physical determinations of qualitative indexes without touching on problems of their generation and transmission or methods of conversion.

In order to excite synchronous radio transmitters, to provide the requisite synchronism of the operation of terminal telegraph equipment, to measure the frequencies of radio stations, etc. exact frequencies, distinguished by somewhat different qualities, are necessary. In speaking of the synchronism of communications equipment using exact frequencies it is above all necessary to distinguish the states of phase synchronism and frequency synchronism, or, so to speak, phase-synchronous and frequency-synchronous systems. We shall explain these terms by example.

Let us assume that we are dealing with a phase-modulation telegraph system operating at ultrasonic frequencies, for example, at a frequency of 20 kilocycles. The period of this frequency is 50 microseconds. Telegraphing is achieved by varying the phase of oscillations in transmitting in time with the frequency of modulation, which in amplitude modulation is equivalent to transmission of the modulation sideband frequencies only (without the carrier). The "carrier wave" is restored in the proper phase at the receiving site. In this case, as is easily seen, the result is amplitude modulation with variations in the amplitude of oscillation twice as great as in the amplitude modulation achieved at the transmitting end. In fact, if in amplitude modulation the voltage at the receiver were to vary for example, from 0 to 1 millivolt, then in phase modulation in transmitting a signal in the positive phase the same transmitter will add 1 millivolt to the amplitude of the local carrier and in the negative phase it will subtract 1 millivolt. Thus, the amplitude of oscillations in the receiver will vary over 2 millivolts instead of the 1 millivolt in amplitude keying. This is equivalent to a channel power gain of four times or 6 decibels. In figures a, b, and c the vector OH represents the restored carrier wave at the receiving site; the vectors HB - [illegible]A are the resulting oscillations of the modulation sideband. The value and sign (direction) of these vectors depend on the amplitude and phase of the transmitted oscillations (HA is the fall vector, Hb is the rise vector). In Figure a the properly phased components receive a high degree of modulation from the detected oscillations. In Figure b the carrier frequency and the modulation frequency are out of phase by 45 degrees; the degree of modulation is somewhat reduced and the effective output of the channel decreased. Finally, in Figure c the carrier and the modulation frequency are out of phase by 90 degrees; in this case communication is not possible. Examining these figures, we can conclude that for phase-modulation telegraphy the phase difference of the carrier frequency and the modulation frequencies at the receiving end should not exceed one radian. If this difference is greater, as is seen from the figures, phase modulation ceases to provide any advantage in power and even becomes worse than amplitude modulation.

The phase difference may also be expressed in time. We have already noted above that at a frequency of 20 kc the duration of a cycle (2π radians) is 50 microseconds. Consequently, a phase deviation of one radian is equal to a time interval of $\frac{50}{2\pi} = 8$ microseconds. Thus, it may be said that in our example for phase-modulation telegraphy the principal requirement for exact frequencies is that the phase of the exact frequencies in transmission and reception do not differ by more than 5-7 microseconds. For phase measurements it is best to use time units (microseconds) instead of electrical degrees, since in frequency conversion schemes (multipliers, dividers) phase shifts expressed in microseconds are not changed. If the phase shifts are expressed in electrical degrees, then in multiplication and division they must be changed correspondingly.

In the examined case the frequencies at the transmitting and receiving ends may be relatively unstable (that is, they may vary with time). The specifications require only their relative phase stability (OSF). In practical schemes the assigned OSF index is maintained by means of automatic phase adjustment.

Let us suppose that we do not wish to make a special exact-frequency transmission channel for automatic phase adjustment. Then it is necessary to feed the transmitter and the receiver from high-stability local oscillators -- exact-frequency standards -- providing the absolute phase stability (ASF) called for by the specifications. Since the phase of one oscillator may "move forward" and the other "lag", then the ASF index of each reference generator must be expressed as a value one half that of the OSF index (that is, 4 microseconds). This means that the "time of the standard," which is defined as the product of the rated value of the period of oscillation of the standard and the number of oscillations actually completed by the standard, must never "lead" the mean solar time or "lag" behind it by more than 4 microseconds.

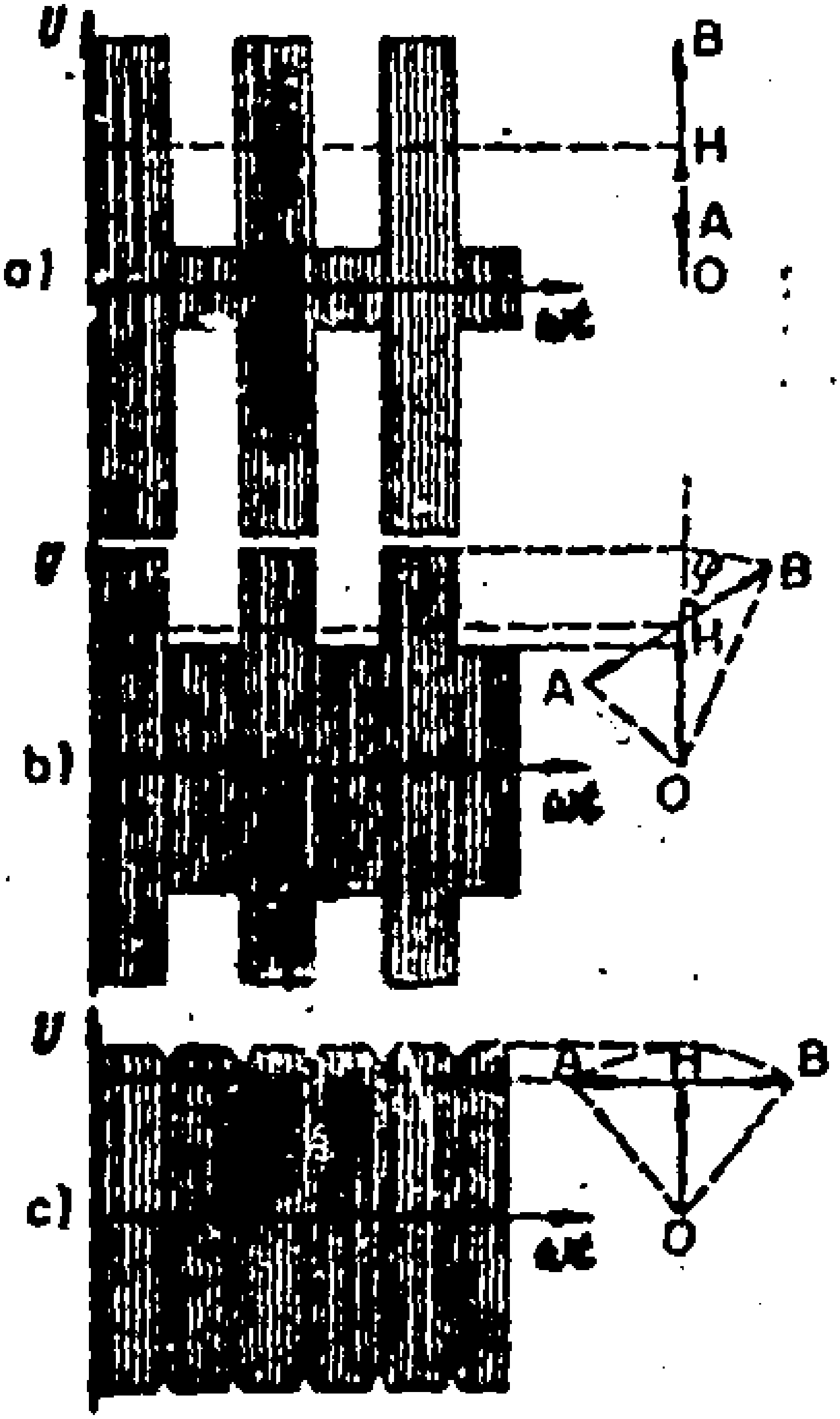
Simple calculation will show that this is an extremely rigid requirement. Indeed, if the frequency of the reference generator were to deviate one one-hundred millionth from its rated value (1×10^{-8}P, then from the formula $\frac{\Delta\tau}{\tau} = \frac{\Delta f}{f} = 1 \times 10^{-8}$ we find that over a relatively short period of time τ = 1 hour = 3,600 seconds the phase of the oscillations of the reference generator is off by $\Delta\tau = 10^{-8} \times 3600 \times 10^{-6}$ = 36 microseconds (that is, nine times greater than the value permitted for phase telegraphy). For the sake of comparison it is interesting to note that the OSF index of some modern phase-synchronized systems (synchronous broadcast nets, pulse systems of modulation, etc) is fixed within several tenths and even within several hundredths of a microsecond. Of course, in these cases special channels are provided for the transmission of exact frequencies in order to achieve automatic phase adjustment.

We will now consider another, more common task -- measuring an unknown frequency by comparing it with another, exact frequency. Such measurement is usually performed with an accuracy of one millionth (1×10^{-6}) of the rated frequency value. The exact frequency used for the comparison must have a stability of approximately 1×10^{-7}. The phase stability in this case is of no interest to us. An exact frequency with a high degree of phase stability (4 microseconds, as in the above example) may, nevertheless, prove unsuitable. Indeed, if the automatic phase adjusting system corrects the phase at a rate of one microsecond (time of the standard) per second (time of adjustment), this will cause a deviation of the standard frequency from the rated value by an amount determined by the equation $\frac{\Delta f}{f} = \frac{\Delta\tau}{\tau} = \frac{1 \times 10^{-6}}{1} = 1 \times 10^{-6}$. Thus, the frequency of the standard will be ten times worse than required for the measurement. In the case under consideration we are concerned with the absolute frequency stability (ASCh) index in relative units $\left(\frac{\Delta f}{f_0}\right)$.

Finally, the communications engineer must often deal with schemes in which he is not interested in the OSF, ASF, or ASCh, but in which it is important to know the frequency deviation or relative frequency stability (OSCh). An example of such a scheme would be a single-sideband system of radiotelephone transmission. When the first systems of short-wave single-sideband transmission appeared frequency stabilization techniques were still inadequately developed and frequency conversion techniques were practically unknown. Under such conditions wide use was made of schemes for automatic frequency control (in distinction from the automatic phase adjustment mentioned previously). Automatic frequency control allows a certain deviation of the compared frequencies by a value of Δf, wherein the OSCh index may be defined as the value $\frac{2\Delta f}{f_1 + f_2}$, where f_1 and f_2 are the compared frequencies and $\Delta f = f_1 - f_2$.

Thus, operation with phase or frequency synchronism is determined by the requirements which the system must meet in regard to exact frequencies. The quality of phase synchronism is determined from the ASF and OSF indexes, expressed in microseconds; the quality of frequency synchronism is determined from the ASCh and OSCh indexes, expressed in relative units of frequency instability.

Various communications systems must meet entirely different requirements in regard to exact frequencies. With a high index of phase stability, the exact-frequency stability may be far from adequate for frequency-synchronized systems and, conversely, an exact frequency of extremely high stability may prove wholly unsuitable for use in phase-synchronized systems (phase-modulation telegraphy, pulse systems of modulation, time-multiplex systems, etc).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