Below 50 Cycles

SAUL J. WHITE*

In which the author relates some experiences with low frequencies while working toward their more realistic reproduction.

MOST HIGH-QUALITY reproducing systems terminate their *acoustic* linearity above 50 cps. Even with bass compensation and a goliath speaker-enclosure, the possibility of maintaining acoustic linearity below 50 cps is almost non-existent. While some auditory sensation can be had through exceptional equipment, the final level is so far below the mid-frequency level that ordinary bass boost cannot restore to the listener the low frequencies as they existed at the microphone position. This is because:

1. Microphone sensitivity falls off rapidly below 50 cps.
2. Losses at the low end in the modulating equipment of the broadcasting station. FCC standards require ±2 db linearity to only 100 cps.
3. Improper compensation on recording or playback equipment or failure to adhere to NAB recording standards.
4. Severe cutoff in the loudspeaker. A speaker with its low-frequency peak at 65 cps (an excellent speaker at that) may be down as much as 30 db in sensitivity at 45 cps.
5. The poor sensitivity of the human ear to low frequencies at reduced volume levels. At normal room volume the loudness sensation of the ear may be down 20 db from its mid-frequency sensation. It will require a mere 100 times more watts compensation to restore physiological linearity. This factor will cause a quality audio system to appear deficient in lows.

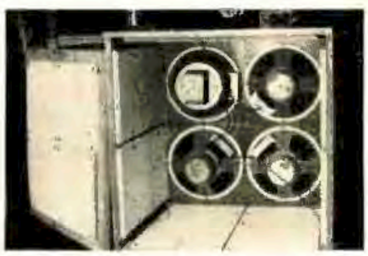
Starting with the objective of bass compensation below 100 cps, the author wound up with a low-frequency booster system with a gain of 50 db between 20 and 100 cps. This bass system is fed in cascade from the output of a conventional wide-range amplifier, which drives a woofer-tweeter system as shown in *Fig.* 1. The special bass amplifier drives a third speaker of special design which will be described later. Reproduction is thus obtained through a three-way system. Because of the excessive low-frequency gain and power output, many unexpected results followed. With reproduction capabilities down to perhaps 15 cps, observations were made of effects which contributed to greater fidelity and also served to measure the quality of broadcast equipment and technique. Certainly, sounds were reproduced never before heard over an audio system, and never intended by the broadcast stations to ever be heard. On the other hand, much flesh-and-blood program material almost lost by the transmitting equipment is restored.

The term "conventional system" when used in this article will refer to a woofer-tweeter system driven by an amplifier which is flat between 40 and 10,000 cps as measured on a resistor load. Though better than most single-speaker systems, this type of dual reproduction as yet does not give full and complete low-frequency accuracy to the original sounds. It is to this type of two-way speaker that the author has added a third speaker handling only low frequencies. (The original woofer speaker is here considered as a mid-frequency reproducer.) By cutting off the special bass system and listening only to the conventional system, an instantaneous comparison of the two types of reproduction was had. This, then, is a qualitative report of what may be heard from FM radio reception when bass compensation is lifted to ear linearity and far beyond . . upward.

Live Programs

Live programs with speech origin develop a chestiness, somewhat pleasant if the bass boost is held within moderation. If exaggerated, huffs and puffs of breath become present. Words containing "aw" sounds as in *law* or *brawn* are grotesquely deformed. Words having deep long syllables, such as *war*, *swallow*, *smoke* and *proof* are similarly distorted. Some words, with excessive boost, will start with an explosive sound, especially those starting with "p" or "b." Even the breathing of a speaker can be made audible apart from the characteristic high-frequency hiss at the tweeters. A nervous person will reveal his condition by the rapidity of his breathing, adding a realism that is not felt over the conventional reproducing system. These vocal changes are not caused by the frequency content in speech, because the deepest voice is well above the operating range of this bass system. They are the result of pressure effects caused by pulses of breath and by the opening and closing of the lips known as labial characteristics.

The reproduction of live radio music with boost below 50 cps reveals the existence of much worthy material inadequately handled by the broadcasting stations. Of all live music, symphonic programs appear to be the most ill-handled, some instruments and notes not appearing at all when the special bass system is cut off to leave only the conventional woofer-tweeter functioning. Of course, if the bass boost is carried too far, bass drums, tympani, viola, contra bassoon and so on, become an overwhelming force, and the grill cloth in front of the bass speaker will flap like a sail in the breeze. However, the general character of the reproduction is never thick or muddy, as is the case with bass compensation systems that take hold at 200 or 300 cycles. Because of the extremely low frequencies at which this system functions, when judiciously handled, there is no



Rear view of bass speaker system described in text. Four 12-inch cones of similar efficiency and varying resonant frequencies are used.

*82 Elm Street, New Rochelle, N. Y.

alteration in the program bulk. This is because the time-frequency distribution of the added low frequencies is exceedingly small.

At no time is the tone boomy. When listening exclusively to the special bass speaker (pads in each speaker line permit individual attenuation), there is no recognizable melody. One hears only the true low-frequency beats. The release of a low-frequency pulse, occuring only occasionally as it does in some types of musical numbers, makes one immediately sense the improvement. Where the original conventional "flat" reproduction appeared satisfactory in handling bass, as in the percussion accompaniment of a swing number, the addition of boost brings a proud awareness to the improved quality. Furthermore, this type of boost will bring up that occasional extremely low note, below 50 cps, which otherwise could not be present. Unlike high-frequency boost with its likelihood of an increase in noise background, this bass compensation does not add any particular background or feeling of its existence while idling. However, its presence is felt with a start whenever switching of microphones or lines takes place at the station.

Compensation can be lifted to a degree where the hum level of the broadcasting station is audible. Remote pickup equipment of practically all stations is characterized by considerable 60-cps stray hum. It is possible to hear the switching of remote lines by the changes in hum levels. Even with a small amount of boost, it is possible to follow the monitoring procedure between programs. The handling of a microphone stand by a performer or announcer will easily come through. There are many unaccountable thumps tending to rupture the cone. Instrumentalists, especially guitarists, who keep time with their feet, send an unexpected rhythm along with their melody. Unfortunately it is neither precise nor clean. When first heard it was difficult to identify, sounding rough and variable in intensity. The character of certain sound effects is changed. The simulated closing of a door may sound as if the entire ceiling had fallen onto the living room floor. Pedal "thumping" never encountered on any other reproducing system can be heard on live piano numbers. Violent hand clapping carries with it a faint roar as if the mike were rocking.

Transcriptions

Programs originating with records or transcriptions need less bass compensation than live programs, although of course, they do not possess the realism of the latter. Turntable rumble can be readily turned up, and from what has been revealed, much equipment in the New York area is due for overhaul. When listening over the conventional system, bass characteristics will appear more or less uniform between various recorded numbers or between different stations. In other words, most recordings seem to possess more or less similar bass feeling, such as it is. But when the special low boost is advanced, a considerable variation in bass content is encountered. This may vary between successive dance numbers from a given station. This is probably due to differences in bass compensation of different transcriptions, and in the region below 100 cps may vary between barely audible to over-pronounced. This difference in transmitted bass level is hardly detectable over the conventional reproducer, yet these differences widen when the low frequency system is included. This wide gap in low frequencies also appears in live programs, but to a smaller extent.

This may be accounted for by (1) different microphones or positioning even in adjoining studios; (2) deliberate bass attenuation because of preference by conductor, producer or engineer; (3) poor low-frequency response of the telephone lines (even Class A) when pickup is remote or out of town; (4) inadequate low-frequency acoustic output in the station monitoring reproducer which fails to show up these variations, the unbalance between programs therefore being inadvertant.

Sometimes with low frequencies adjusted for desirable response on a certain program, the following program from the same station will have so much more bass as to throw the entire system into mechanical feedback or to develop hangover effects.

Low-Frequency Booster Amplifier

The low-frequency booster amplifier shown in elemental form in *Fig.* 1 consists of what was originally a conventional three-stage amplifier modified to reproduce only from 100 cps down. Its frequency vs gain characteristic is shown on *Fig.* 2. It is a capacitance resistance coupled unit with push-pull parallel 6L6's in the output stage and having a power output of approximately 35 watts at 50 cps. Shunt capacitors with values to commence a 6 db loss at 100 cps were wired across each stage grid resistor. Coupling capacitor values of 0.1 μf are adequate where the plate-load resistors are not under 50,000 ohms. No trouble was experienced with blocking effects at high signal voltages. A triple-shielded (magnetically) input transformer is used to couple the driver to the input stage grid. Since this is a bridging arrangement, it has a pri-

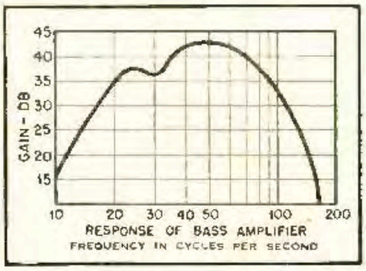


Fig. 2. Bass system amplifier of Fig. 1 provides large boost at frequencies where normal speaker response falls off.

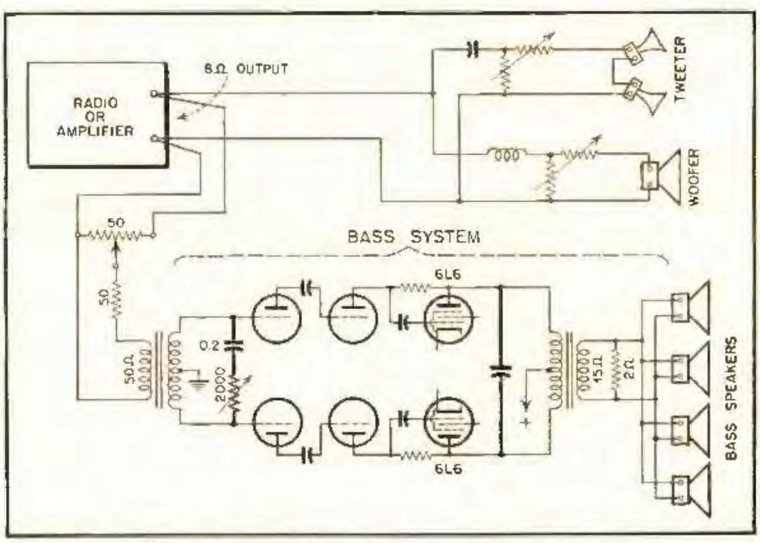


Fig. 1. Block diagram of multiple amplifier-multiple speaker arrangement used to enhance low-frequency output.

mary impedance of 50 ohms. The secondary is shunted with a 0.2 mfd capacitor and a series adjustable resistor. This forms a broadly tuned circuit at 40 cps. In operation the resistor may be adjusted to suit the character of the response sought. The output transformer primary is shunted with a capacitor to resonate at about 25 cps. The humps due to resonance are not sharp due to the low efficiency of the transformers at these frequencies. The two tuned circuits function broadly over a frequency area where the loudspeaker output would ordinarily disappear. However, this method of increasing low-frequency gain must be approached with caution since the results will vary with transformer Q. An excessive peak or trace of circuit resonance will give bad hangovers and disguise the fidelity of the original source. Needless to say, both the main amplifier and the bass amplifier must have lower-than-average hum level, or the performance will be unsatisfactory. Low line hum can be achieved by observing good design and construction technic, such as thorough shielding of all low-level wiring and components; direct current for heaters of the voltage amplifier stages, with all heater voltages about 10 to 15 per cent below nominal values; balanced push-pull tubes; well-filtered power supply with wide separation of input transformers from the power supply, large values of decoupling capacitors; and care in avoiding ground loops which pick up potential differences in the chassis and grounding leads.

The nominal 15-ohm output of the amplifier is shunted with a 2-ohm resistor for the purpose of damping the output, although this is attained at the expense of useful power. This achieves stiffening of the loudspeaker diaphragms at resonant frequency by electrical means. This system will be called upon to handle severe transients of high intensity and must do so without damaging the speaker. This is a stiffness controlled system, both electrically and acoustically, and while such systems are inherently insensitive at low frequencies, in this case they are driven into the speaker by brute force.

The Bass Speaker

The low-frequency loudspeaker is composed of four 12-inch cones mounted as close together as possible in an enclosure of approximately six cubic feet. No reflex ports are used, the objective being to stiffen the cones acoustically by a not-too-large airtight enclosure. The four cones tend to act as a single diaphragm of large diameter, but is should not be assumed that they will perform, in a practical sense, as a single cone of four times the area, i. e., 24-inch diameter. During early experiments, excellent results were obtained with a single 12-inch speaker in a cabinet measuring 20 x 20 x 20 inches. However, it and a replacement were shortly ruptured by these experiments. Nevertheless, models of single 12-inch speakers with proportionately smaller amplifiers give impressive results when held to room loudness levels. A two-speaker system would probably be adequate for most disciplined experimenters interested merely in high-quality musical reproduction.

The effort behind this speaker design is to reduce the resonance peak of the cone and to achieve a slow roll-off in sensitivity. A loosely loaded cone, that is, one in an excessively large cabinet, will have the lowest resonant frequency, but this will usually be in the form of a distinct peak and a steep roll-off below this peak, making smooth equalization difficult. In large cabinets at frequencies above resonance, the diaphragm is mass-controlled, and it is a characteristic of mass-controlled transducers that output falls sharply below resonance. A small enclosure adds stiffness, raising resonance and reducing low-frequency efficiency, as shown in *Fig.* 3. While the smaller enclosure will raise the resonant frequency of the speaker, seemingly giving it less bass, it is a preferable practice, since the peak is shifted to a higher point by the increased stiffening factor of the smaller rear volume and broadened by the change of mass-to-stiffness ratio. It was reasoned that amplifier power today is a cheap commodity, whereas high-efficiency, low frequency cone speakers, massive enclosures and horns are expensive. This system will surely appeal to those who wish greater bass output without placing a monstrosity in their home.

In this bass system it is important to suppress the amplitude of the speaker resonant peak, for unless this is done effectively, the whole reproducing system will develop acoustic feedback before adequate compensation is obtained. This develops because the mid-frequency speaker acts as an input transducer or microphone across the bass amplifier, and by virtue of the gain existing between the mid-frequency speaker and the bass speaker, acoustic feedback will set in. To some extent, this was overcome by attenuating the low end of the conventional amplifier and the high end of the bass amplifier so as to form an amplification crossover with a 10 db dip at the resonant frequency of the bass cones. It is clear also that it is impractical to place the two speaker groups too close together. If bass gain is carried too far, mechanical feedback may develop due to the microphonic sensitivity of the tubes and the physical coupling through the floor under low frequency stimuli, even with the speaker unit located at the opposite end of the room from the amplifier or tuner. This regeneration occurs whenever the gain of the mechanically vibrating tube-to-speaker circuit is greater than the transmission loss through the coupling medium, i. e., floor, chassis, tube elements, and so on. This regeneration is preceded by severe hangover, flutter and instability typical of all positive feedback arrangments.

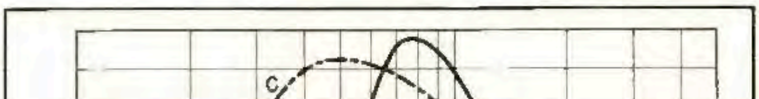


Fig. 3. Curves showing effect of adding low-frequency booster and speakers to normal system. (A) shows typical response of a so-called woofer in an enclosure of ample volume. (B) represents the same speaker enclosed in a small airtight cabinet. (C) represents speaker (B) with bass compensation added.

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It is this mechanically stimulated feedback which finally limits the amount of low frequency amplification. The loudspeaker described utilizes a high value of resistance and acoustical capacitance to stiffen the vibrating cone. The load resistor shunting the speakers together with the crossover dip reduces the tendency toward feedback. Notwithstanding these measures, the full gain of the bass amplifier could never be turned up unless the speaker were located in some other building. At times during these investigations, footsteps on a thick rug caused a "thump" in the speaker. When the gain is turned just below feedback, almost any action in the room will result in a "bloop." However, for all rational and most irrational enjoyment of bass program material, the amount of gain required will be far below feedback.

On Speakers Generally

There is probably more misinformation the subject of loudspeakers than in any other branch of the communication art. In spite of manufacturers' ratings, few 12- and 15-inch cone speakers can reproduce 50-cps within 10 db of their output at 100-cps. Manufacturers' specifications for low-frequency cut-off probably means that their product will respond to this frequency within 10 of 20 db of the piston range level. Furthermore, the prevalent notion that one merely has to utilize a larger cabinet or baffle to increase lows is not strictly true. Beyond a certain volume there is insignificant improvement, as can be attested by the disappointment of those who have mounted speakers in the door of closets or even in the wall between rooms. In order to reduce the resonant frequency by one octave, the total stiffness must be reduced by a factor of four. The formula for resonant frequency shows that this varies inversely as the *square root* of all stiffness factors, the stiffness contributed by the cabinet enclosure being only one of many factors. The mechanical stiffness built into the cone rim and spider which operate below resonance is the largest factor, and over this the constructor has little control. The natural resonant frequency of a typical 12-inch cone, rated to handle 10 watts of audio, is between 70- and 80-cps as measured in a flat baffle of practically infinite size.

Speakers can be designed for 50-cps

on a flat response basis, but this usually means a severe sacrifice in power handling ability and the use of an extremely large magnet. The compliant rim of the cone must be made thinner or more flexible in order to reduce the mechanical stiffness. Hence, the power handling ability and the life of the cone are reduced. Further, it must be capable of movement to extreme amplitudes under linear force, and the voice coil must remain in a uniform high-density flux field. Speakers of 12- and 15-inch diameter, as popularly made, have a voice coil length (winding length) of approximately .300 inches. To maintain such a voice coil within a field of uniform magnetic flux means that (for 10 watts excitation and 5 per cent efficiency) the axial gap length in the magnetic circuit must be about .600 inches at 50 cps. For a given flux density, the weight of the magnet will be proportional to the *square* of the increase in gap volume. This results in a magnet so costly as to place it outside the competitive field, a disastrous prospect for most manufacturers. It is widely considered in the speaker industry that high flux density in a long axial gap is so costly as to be hardly justified by what is thought to be only a slight increase in musical value. One of the most reputable 15-inch woofers on the market today—one selling for over $100.00—has an axial gap length of only .400 in. Probably also the problem of designing a suspension system that has uniform high compliance over a .600 in. total displacement is rather formidable and discouraging, to say nothing of the need for adequate restoring force.

To the author, the logical solution was the use of a stiffness-controlled speaker system, driven by brute force to overcome the low-frequency deficiency of conventional cone speakers. By using four speakers, the input power is divided, and each speaker operates at reduced amplitudes, holding distortion to a minimum. The effective piston diameter is increased over that of a single cone, thus maintaining radiation resistance to a lower frequency and hence improving the efficiency.

In selecting speakers, it is not necessary that they be so-called woofers, assuming such can truly be found. It is only required that they have high conversion efficiency. The magnets in efficient cone speakers should weigh at least 16 ounces if Alnico V, or about 4 pounds if Alnico I or II. Actually, the grade of Alnico or other magnet material is unimportant so long as a flux density in excess of 10,000 gauss is realized in the gap. Voice coil diameter should preferably be at least two inches. Large diameter voice coils exert a more uniform driving force to all surfaces of the cone, and besides handling more input power, may possess less distortion at high amplitudes. An attempt was made to select speakers having slightly different resonant frequencies to avoid an accentuated peak. Peaks and dips, inherent in all speakers, occur at slightly different frequencies in each speaker. When such speakers are combined in a group, the final output will be characterized by smoother response, the dips virtually disappearing.