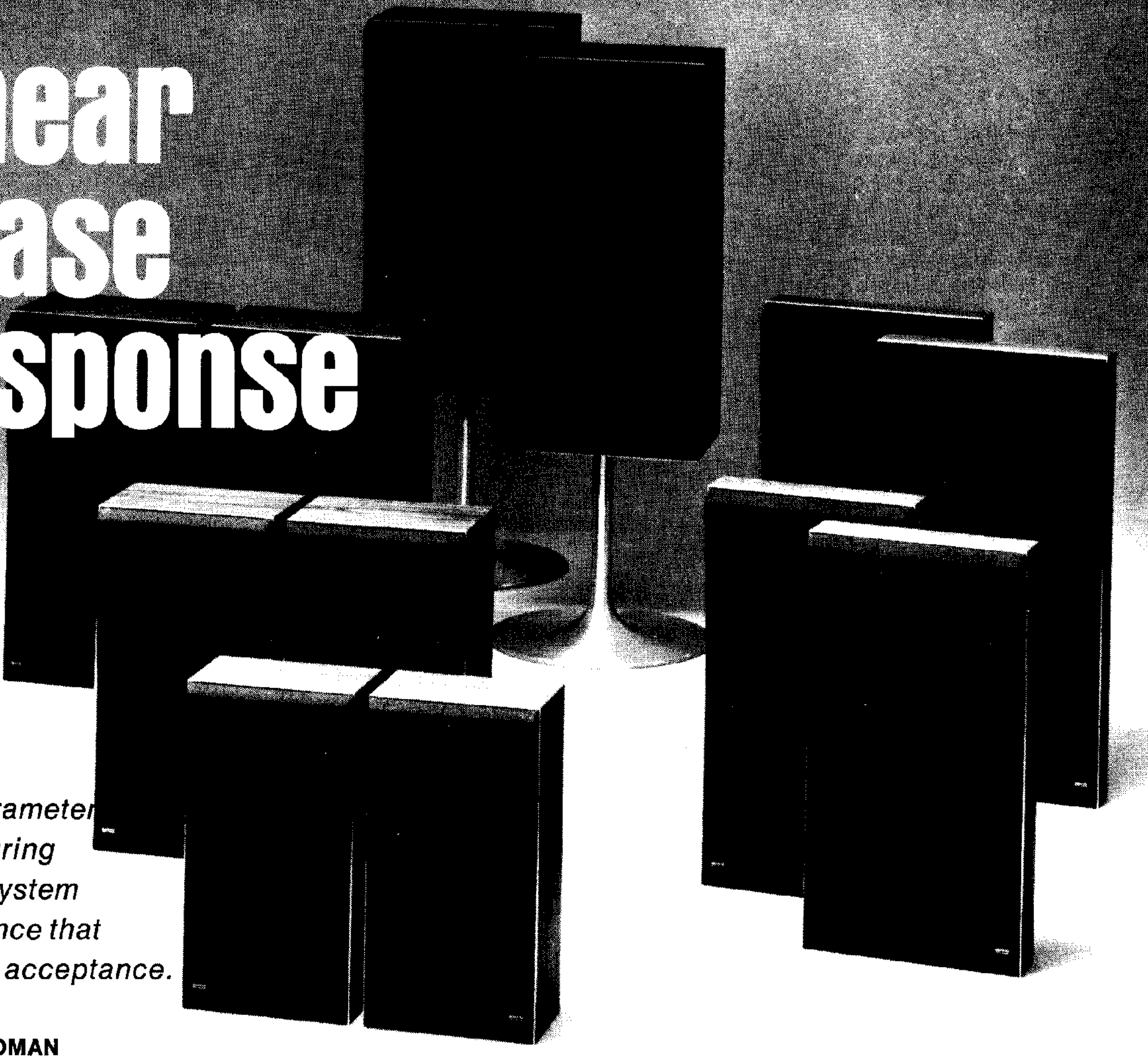
Linear Phase Response



A new parameter for measuring speaker system performance that is gaining acceptance.

by LEN FELDMAN
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ANYONE WHO HAS EVER CONNECTED A pair of speaker systems to a stereo amplifier knows they need proper phasing. If the stereo pair is connected out of phase, we know that one speaker cone (or set of cones in a multi-driver system) will "push" air while the other "pulls". The result is a combination of loss of apparent bass and of vague positioning of instruments in the stereo sound field. The reason for the loss of bass is fairly obvious. Since low, bass tones are fairly non-directional (bass sound seems to fill a listening room rather than originate from a pin-point location), when recordings are made the left channel microphone or microphones pick up as much of the bass energy as the right channel mikes. In reproduction, both speakers are expected to deliver approximately the same bass energy. If the bass tones coming from one speaker are out of phase with those coming from the other, the wave fronts tend to cancel each other and there is a noticeable absence of bass in the reproduced music.

But what about the other effect? Why—when speakers are out of phase—do we find it difficult to pin-point instrument locations in the reproduced music? Despite early studies (which suggested that the human ear is not sensitive to "phase errors" in complex waveforms) an increasing amount of recent evidence suggests that, indeed, phase linearity (or, more simply, correct relative time relationships of all tones and their harmonics) is a necessary ingredient of true high-fidelity sound reproduction. It is simple enough to insure that left and right speaker systems are operating "in phase" (there's a 50-50 chance of correct connection to begin with, and if you suspect an out-of-phase connection you just reverse the wires to one of the speaker systems). But there's much more to "phase linearity" than that. Remember, most modern high-fidelity speaker systems consist of two or more drivers. We have woofers, tweeters, and in some cases mid-range drivers as well as super-tweeters, each attempting to reproduce a given portion of the audio spectrum. How about the phase relationship between these various drivers *within* a given speaker system?

Some manufacturers have come to the conclusion that the various speaker elements in a multi-driver system must be arranged so that all audio frequencies arrive at the listener's ear in correct time (or phase) relationship. The very nature of woofers and tweeters makes this difficult if all drivers are mounted on a common baffle, in a single plane, as illustrated in Fig. 1. Because the woofer cone is deeper than that of the tweeter, sounds produced by the woofer arrive at the listener's ear a fraction of a second later than those produced by the tweeter. Some manufacturers (such as Dahlquist in their DQ-10 design) have sought to compensate for this by

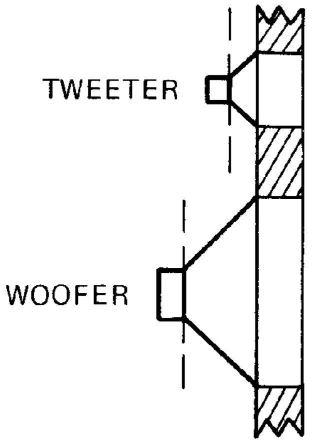


FIG. 1—DIFFERENT CONE DEPTHS of woofer and tweeter cause the two wave fronts to reach the ear at different times.

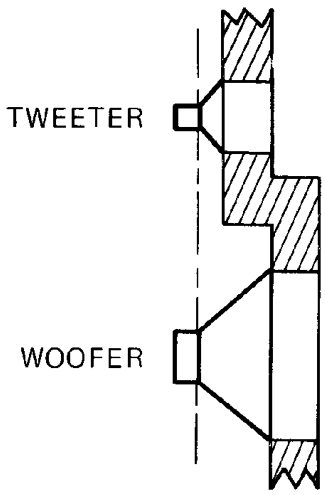


FIG. 2—OFFSETTING THE SPEAKERS is a way some manufacturers try to improve phase linearity between woofer and tweeter.

positioning the various drivers on different surfaces or planes, as illustrated in the diagram of Fig. 2.

What of the crossover network?

Recently, I had an opportunity to visit the well known Danish electronic firm of Bang & Olufsen. There, certain additional facts regarding phase distortion in speaker systems were brought to light most dramatically. Much of what follows is based upon original research by the famous acoustical engineer Erik R. Madsen who was, for many years, chief engineer at B & O and serves as a consultant to the firm these days. As he pointed out in a paper at the 1973 Audio Engineering Society convention in Rotterdam, the chief cause of phase distortion in a loudspeaker system arises not from the physical disparity between the positioning of the different drivers, but from the action of passive crossover networks that are used in the majority of today's commercially available loudspeaker systems.

A simple crossover system is shown in Fig. 3. It provides a 6-dB/octave slope in response at the selected crossover frequency (1 kHz in our example), feeding low frequencies to the woofer and high frequencies to the tweeter. Note that at the crossover point itself, relative amplitude is down 3 dB for each driver, so that the *sum* of energy delivered to the two drivers is the same as at frequencies outside the crossover region. With a simple crossover such as this, overall phase response of the system will be quite good—even in the region of crossover. If a square wave at 1 kHz were fed into such a system (and assuming that the drivers were otherwise perfect in response), the output waveform from the woofer would look like the waveform drawn in Fig. 4-a while the output from the tweeter would have the appearance of Fig. 4-b. Add these two components together and you have the waveform of Fig. 4-c —a perfect square wave with no phase distortion.

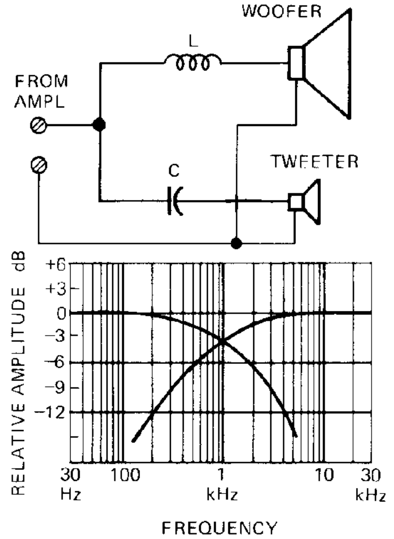


FIG. 3—CIRCUIT AND RESPONSES of a 6dB/octave standard crossover network.

The problem with using such a moderate-sloped crossover network is that it requires woofers and tweeters to operate effectively (with low distortion and flat frequency response) well outside their intended regions of best performance. Since the contribution of each driver can be heard at least until it is 12 dB below reference program level, the overlap region in a 6 dB/octave crossover arrangement extends for a full four octaves, as illustrated in Fig. 5-a.

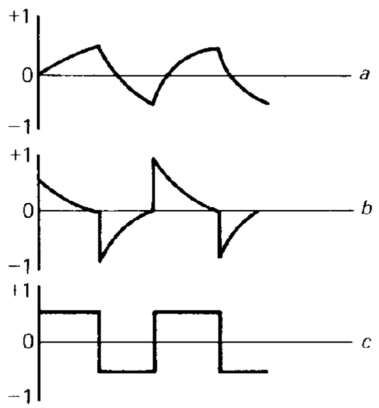


FIG. 4—WITH SQUARE-WAVE INPUT applied to a 6 dB/octave crossover, the outputs of the woofer (a) added to those of the tweeter (b) produce an accurate replica (c) of the original square-wave input signal.

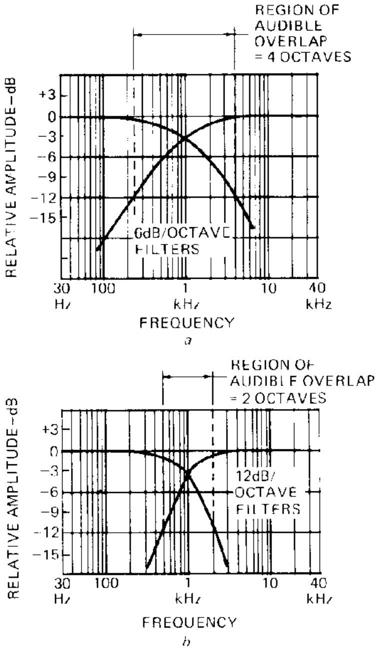


FIG. 5—COMPARING CROSSOVERS. The range over which drivers must work efficiently is twice as great (4 octaves) for 6 dB/octave networks as is the range for 12 dB/octave units (only 2 octaves).

If a steeper rate of roll-off—such as 12 dB per octave—were employed, overlap would need to extend only for a total of two octaves, as shown in Fig. 5-b and optimum performance of each driver would not have to be extended so far outside its "normal" frequency region. For this reason, most better systems do utilize 12 dB/octave crossover networks (some even employ 18 dB/octave slopes). But here is where the problem arises. When such a network is used, the phase angle of the waveform fed to the woofer goes in a negative direction as the crossover frequency is approached, while that for the tweeter goes positive, as shown in Fig. 6. Thus, although single-amplitude plots (without regard to phase) of the output voltages of a 12 dB/octave network, as shown earlier in Fig. 5-b, suggest that total energy output of the system in the

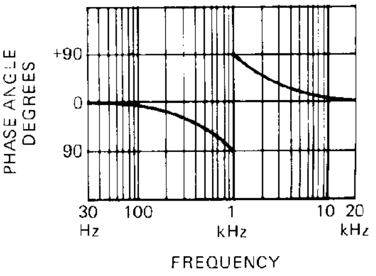


FIG. 6—PHASE RESPONSE of the high-frequency section of a 12 dB/octave unit is 180 degrees out of phase with that of the low-frequency section of the same network.

region of the crossover frequency will be "flat", yet if outputs are plotted with regard to amplitude *and* phase, the actual output energy in the crossover region appears as in Fig. 7 because of the cancelling effect of the out-of-phase outputs from the two legs of the crossover network.

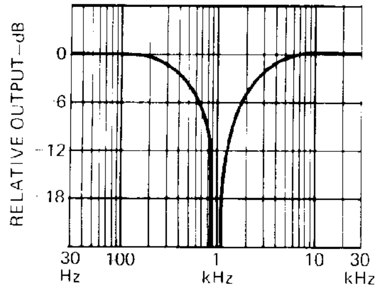


FIG. 7—PHASE ANGLES INTRODUCED by the 12 dB/octave network create a sharp cancelling null at the crossover frequency when the phases of the sections are reversed.

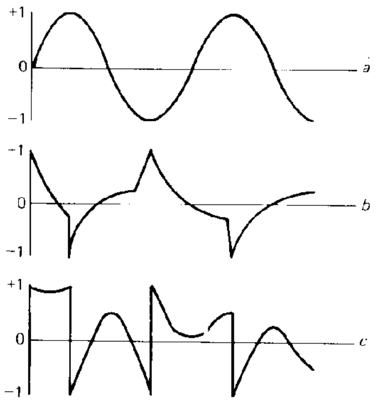
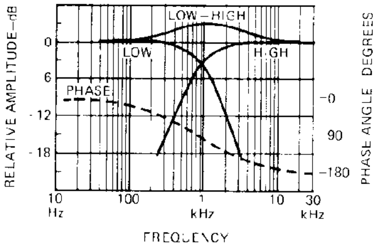


FIG. 8—MATHEMATICAL ADDITION OF woofer input waveform (a) and tweeter input waveform (b) from a 12 dB/octave crossover results in the distorted square wave of (c).

When a square wave is fed to such a system, the output from the woofer will theoretically appear as shown in Fig. 8-a, that of the tweeter as shown in Fig. 8-b, and the composite waveform will appear as shown in Fig. 8-c—not at all like the square wave input signal with which we started.

Some manufacturers have been aware of this out-of-phase problem for some time. One attempt at correction has been to reverse the phase of the tweeter with respect to the woofer (or, in the case of 3-way systems, the midrange with respect to the woofer). As can be seen from the composite diagram of Fig. 9, this produces a peak in total energy output in the frequency region of the crossover instead of a null. Because of the phase response characteristics over the entire frequency band (shown as a dotted line), application of a square wave to a system arranged in this manner would result in the woofer output shown in Fig. 10-a, the tweeter output in Fig. 10-b and the composite output shown in Fig. 10-c—still a long way from the desired square wave shape.



[illegible]G. 9—REVERSING RELATIONSHIP of phases in the tweeter and woofer of a 12 dB/octave network results in an increase of output at the crossover frequency rather than the desired and correct level output.

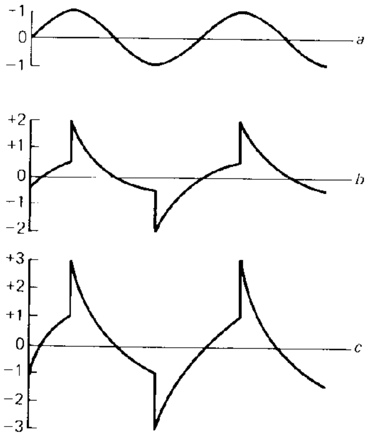


FIG. 10—SQUARE WAVE APPLIED TO the out-of-phase connected crossover network and producing conventional waveforms in the woofer (a) and tweeter (b) sections, give the distorted result of (c) when added.

Bank & Olufsen's solution

The answer to the problem of phase linearity in speaker design was discovered by Erik Baekgaard, who read a paper on his work at an AES convention in London. It is represented in a new line of speakers which were demonstrated to me while I was in Denmark. Design work on these speakers was led by Esben Kokholm, of B & O and I have since had an opportunity to evaluate them in my own laboratory.

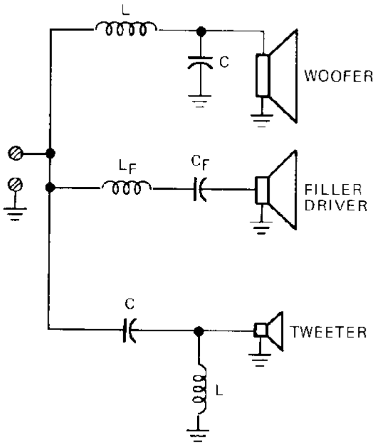


FIG. 11—A NOVEL SOLUTION of the problem is the B & O approach—a third unit with a series-connected circuit tuned to the crossover frequency to fill the null there.

In addition to the usual woofer, midrange and tweeter, this family of speaker systems employs what B & O calls a "filler driver". The general form of crossover network used is that of Fig. 11. Note that the center circuit is neither a low-pass or a high-pass filter, but rather a series resonant arrangement that provides a peaked response to the filler driver (or phase-link speaker, as they call it) at the crossover frequency and a roll-off of 6 dB per octave above and below that frequency. Added to the responses of a conventional 12 dB/octave network, we have the composite crossover network response shown in Fig. 12. The theoretical outputs from the three drivers are now as shown in the three parts of Fig. 13. When these are added together graphically, we do come up with an exact replica of the original square-wave input waveform.

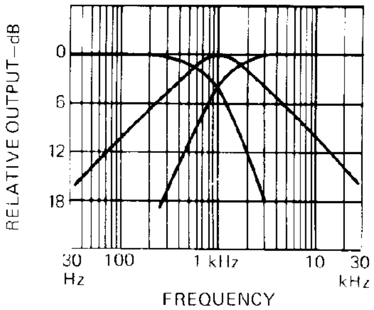


FIG. 12—THE COMPOSITE RESPONSE of the woofer, filler driver and tweeter in the new Bang & Olufsen crossover network.

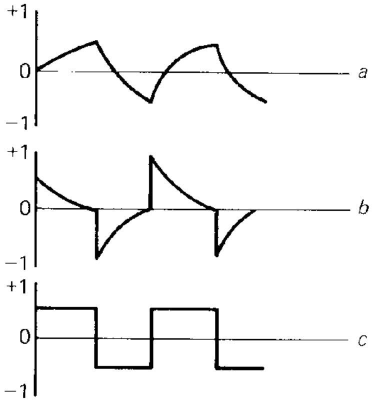


FIG. 13—APPLYING SQUARE WAVE TO the B & O network results in the response at (a) for the woofer, (b) for the filler, and (c) for the tweeter, and adding them gives the result in (d), or the original square wave.

Having achieved a solution to the crossover problem, the people at B & O were not about to ignore the driver positioning problem mentioned earlier. While they maintain that flat-baffle positioning produces less phase distortion than that introduced by conventional crossover networks, they nevertheless were looking for as near perfect a phase response characteristic as possible. Accordingly, they developed a new front-baffle shape (actually precision molded of high density foam resin which, they claim, is superior in damping and acoustic qualities to wood) which slants the woofer upward so that wavefronts produced by it arrive at the listener's ear at the same time as those produced by the other drivers. The principle is shown diagrammatically in Fig. 14. In the floor-standing versions of the new B & O speakers, a special pedestal is recommended, with which the listener can actually tilt the entire speaker box forward or back from the vertical, depending upon where he or she is seated in relation to the speakers, and even to compensate for different "ear heights". I was perfectly content with what later proved to be the somewhat vague stereo localization of music using a well-known speaker pair—until I pushed the A-B switching arrangement and listened to the linear-phase units for comparison. Suddenly, the previous pair's sound wasn't quite as gratifying.

The square-wave drawings shown in earlier diagrams are purely theoretical, and derived mathematically. I was curious to see if results could be duplicated in practice, allowing for the fact that my lab is anything but an anechoic chamber and that microphone placement would have a great bearing on the results. I therefore hooked up a square-wave generator to my system, placed a calibrated microphone at what I thought was an optimum spot in front of my regular lab speaker, and photographed what was picked up by the microphone. The results are shown in the scope photo of Fig. 15. Without moving the microphone, I carefully replaced my regular speaker with the sample M-70 model from Bang & Olufsen and repeated the experiment. The scope photo of Fig. 16 shows the results I then obtained. Maybe Bang & Olufsen has something here! **R-E**

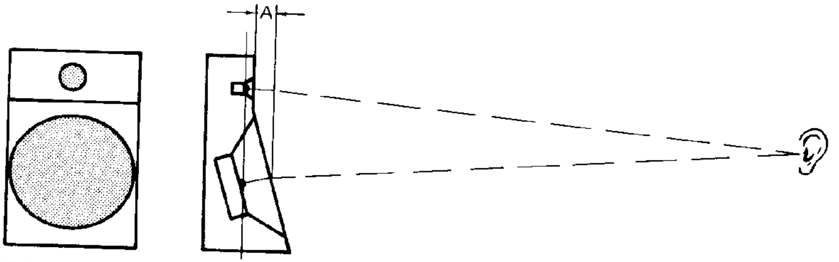


FIG. 14—ANGLED FRONT BAFFLE compensates for the phase delay caused by difference in depths of woofer and tweeter.

Does it make a difference?

Obviously, we don't listen to square waves, and it can be argued that when listening to complex musical waveforms some of these fine points tend to be obscured. I can only tell you that in comparison tests made with three other speaker system types (all popular, well-accepted brands) I was able to sense better localization of stereo images, better transient response with certain program material, and a more natural sounding overall musical quality.

How much of the improvement is a result of the linear phase response of these new systems and how much is simply the result of otherwise excellent driver selection, enclosure design and generally good speaker system design I am not prepared to say. The fact is that "hearing memory" in humans is extremely poor. We tend to listen to our favorite speakers and to convince ourselves that we are hearing reality. This happened in my listening tests, too. I

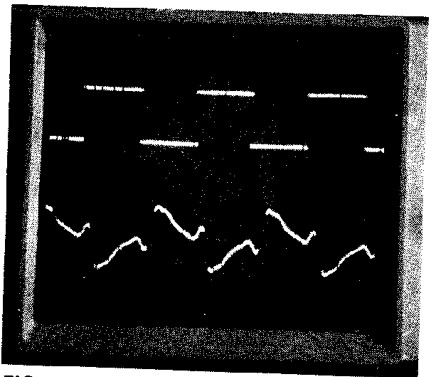


FIG. 15—SQUARE-WAVE SIGNAL IS reproduced by actual conventional speaker system much as shown in the theoretical mathematical addition of Fig. 8-c.

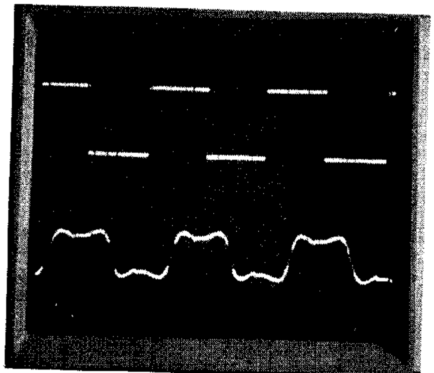


FIG. 16—TEST SETUP OF FIG. 15 with the new B & O speaker system. Output more closely resembles the square-wave input.

DON'T MISS IT!

This month's in-depth hi-fi test reports include the Marantz model 2325 stereo receiver and the Lafayette model LR-2200 stereo receiver.

RCA closes Harrison tube plant, oldest in world

"A sharp decline in demand for receiving tubes in the face of the continuing shift to solid-state devices in consumer, industrial and defense electronic systems" was given by Paul B. Garver, head of RCA's Distributor and Special Products Division, for the July closing of RCA's last tube manufacturing facility, at Harrison, NJ, July 30. Industry sales have declined almost 80 percent since 1966, he said, with replacements in older electronic equipment responsible for most of the present volume.

The Harrison plant was opened by Thomas Edison in 1882, to manufacture electric light bulbs. Ten years later, it was acquired by General Electric, who continued to manufacture lamps until 1918 when the first radio tubes were made. Throughout the 1920's, G-E continued to supply tubes to the various manufacturers of radios. In 1930 the plant was purchased by an RCA subsidiary, RCA Radiotron Co., and the tubes were called Radiotrons.

At its peak, the Harrison plant had a work force of more than 7,000 (as compared to a recent figure of 1,100 employees) and made 87 million tubes in one 12-month period. Besides mass-producing tubes for consumer use, the plant made special ones for industrial, military and aerospace equipment, some in rather small quantities.

RCA, now the sole source for about 110 types of receiving tubes, plans to meet as far as possible all future requirements for these types, and will continue to sell replacement receiving tubes

550,000 calls-per-hour on new telephone central system

The world's highest-capacity long distance telephone switching system went into action in Chicago last January 17. The new facility, No. 4 Electronic Switching System (ESS), has a peak capacity of 550,000 calls-per-hour. This works out to a little over 9,000 calls-per-minute, or *150 calls-per-second.*

BELL LABORATORIES TECHNICIAN M Haverty inserts circuit packs in the "bra of the No. 4 ESS System, the 1A central processor. The ribbon-like strips snaking down the front of the control unit are actually cables connected to test equipment.