History of Sound Motion Pictures

by Edward W Kellogg

Second Installment

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Our thanks to Tom Fine for finding and scanning the Kellogg paper, which we present here as a "searchable image".

John G. (Jay) McKnight, Chair
AES Historical Committee
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SECOND INSTALLMENT

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By EDWARD W. KELLOGG

For the abstract of this paper which was presented on May 5, 1954, at the Society's Convention at Washington, D.C., see the first installment published in last month's Journal.

The Motion Picture Industry Adopts Sound

Many Commercially Unsuccessful Efforts. The historical outline with which our story began contains a very incomplete account of the many efforts to combine sound and picture, some of which attained a fair degree of technical success, elicited praise and held public interest for short periods. We mentioned the work of Edison, Lauste, Rümer, and de Forest, and might add Pathé Frères and Léon Gaumont* in France.[5] Many of these were ahead of their time, for without amplifiers, the production of adequate and natural sound was practically impossible. Even after amplifiers became available the experimenters had little better success in getting picture producers seriously interested. The article by Lovette and Watkins[48] states that by the end of 1924 practically every major producer in Hollywood had rejected Western Electric's sound-picture system.

Economic Hurdles. The same authors give such a convincing statement of the financial obstacles from the producer's standpoint that I cannot do better than quote them:

"The motion picture producers had large inventories of silent films, which had cost millions to produce. They had great numbers of actors and actresses under long term contracts, most of whom knew no dramatic technique except that of pantomime. The industry was universally equipped with stages and studios suited only to the silent film technique.

"Moreover, world-wide foreign markets had been established for silent films. To serve these markets, it was merely necessary to translate the words printed upon the film from English to any language desired. Finding stars and supporting casts who spoke the various languages of the world, or finding ways to give the illusion of their speaking them, appeared to be an insuperable task.

"The art of the silent film had attained superb quality and the public was satisfied. Why then, producers asked, should Hollywood scrap the bulk of its assets, undertake staggering conversion costs, and force upon the public a new and doubtful experimental art?

"Nor were the exhibitors equipped for sound. Many, it was argued, would not be able to meet the cost of sound picture equipment."

These obstacles would not have prevented the producers from introducing synchronized sound, had they been convinced that it would give their pictures greater appeal. A factor which many developers of sound equipment probably did not fully recognize, was that to contribute to the illusion, the sound must have a degree of naturalness far surpassing that which had sufficed for simply transmitting information, or making words understood.

How It Looked in 1926–7. To many, the silent motion picture, with its freedom of action, its settings for much of its action in natural backgrounds, was better entertainment than stage drama, and when one tried to imagine what a talking motion picture would be like, one's thoughts immediately turned to examples of theater drama. I have already quoted some of Dr. de Forest's reflections. The prevailing thought at the General Electric Co. as our system began to take shape is probably typical. Many, even of the most enthusiastic advocates of the sound-picture development were not convinced that the chief function of the synchronized sound would be to give speech to the actors in plays. The art of telling stories with pantomime only (with the help of occasional titles) had been so highly developed, that giving the actors voices seemed hardly necessary, although readily possible. Such a view was actually a very high tribute to the movie makers of the silent era. However, a very large business in synchronized sound seemed assured (even without any use of the system for dialogue) in furnishing sound effects, background music, and providing voice for lectures, speeches and travelogue commentary.

As one who shared in this misjudgment, I would like to suggest to readers that it is difficult today to divest oneself of the benefit of hindsight. At that time, the principal examples of sound pictures we had seen were demonstration films, very interesting to us sound engineers working on the project, but scarcely having entertainment value. None of us had seen a talking motion picture with a good story, and picture and script well designed for the purpose. When in 1927 such a picture was shown (*The Jazz Singer*) the story, the music and the dialogue were splendidly adapted to produce a fascinating picture with great emotional appeal, in which no element could have been spared without serious loss. In short, the excellence of showmanship played no small part in making it clear to everyone who saw it that the day of "Talkies" was here.

The Jazz Singer and its predecessor *Don Juan*, it might be noted, had the benefit of a newly designed loudspeaker,[57] very much superior to those used in the Western Electric 1924 demonstrations.

Warners and Fox Take the Step. Warner Brothers committed themselves to the adoption of sound pictures in 1926, license contract being concluded in April, followed by large investments in sound stages and equipment. In July of the same year the Fox Film Corp. became committed, forming the Fox Case Corp. which took license for the Case Laboratory developments in April, and in December from Western Electric Co. for rights to use amplifiers. Both Warners and Fox operated theater chains. With two major picture producing and exhibiting organizations definitely launched on a program of making and showing pictures, could the other great picture companies remain on the sidelines?

Large Producers Agree to Choose Same System.[6] Early in 1927 the first Fox Movietone Newsreel subjects were shown. The other picture companies must by this time have become convinced that sound pictures were inevitable, for a part, if not the whole of motion-picture entertainment. In February 1927, the "big five" — M-G-M, First National, Paramount, Universal and Producers' Distributing Corp. (or PDC), jointly asked the Hays organization to study and make recommendation as to what system should be adopted. The Movietone and Vitaphone (disk) had already

* Gaumont, in addition to many inventions and other activities, was a pioneer and successful leader in the motion-picture business, and probably came nearer to success with phonograph sound than others. See account, and references given in the Theisen history[5] from which ref. 77 is taken.

become commercial systems, Western Electric was offering a sound-on-film (light-valve) system, and General Electric had made a number of demonstrations of a variable-area system (later offered to the industry with some modifications through RCA Photophone). There had as yet been no formal standardization, and those participating in the conference probably felt some uncertainty about interchangeability of recordings. It is not strange that the picture companies thought it would be advantageous for all to adopt the same system.

By far the most ambitious demonstration of sound motion pictures that had as yet (February 1927) been witnessed was the Warner Vitaphone *Don Juan* (shown August 1926),[1, 48] with performances by noted artists and score and background music for the play by the New York Philharmonic Orchestra. And the sound quality was good. But it was a demonstration of synchronized sound, and not of sound motion-picture drama. The producers, still "on the fence," continued their "watchful waiting."

The presentation of *The Jazz Singer* in October 1927 dispelled all doubts. But whether the future lay with the disk or the film system was a question not completely settled for several years.

"Big Five" Sign Contracts with ERPI.[6] With such large producers as Warners making pictures with sound on disk and Fox with Movietone releases on film, it appeared that exhibitors might be saddled with a dual system. Perhaps it was the hope that one or the other would very soon forge ahead in the race that caused further hesitancy, but in April and May of 1928 (about six months after the showing of *The Jazz Singer*) Paramount, United Artists, M-G-M, First National, Universal and several others signed agreements with Electrical Research Products Inc. (the commercial outlet for the Western Electric systems) for licenses and recording equipment.

Getting Started.[1] There followed a period of feverish activity in erection of sound stages, and procurement and installation of recording channels and equipment. Deliveries of apparatus were far behind the desires of the customers, and there was great shortage of engineers and technicians with sound-picture background. The manufacturers and associated organizations lent or lost many of their personnel. Intensive training courses and much instructive literature alleviated the situation. The Transactions of the SMPE for the fall of 1928 are little short of an encyclopedia of sound recording and reproduction by both disk and film. To this body of literature, the engineers and processing laboratory experts from the producing companies soon began making their contributions.

Scarcely a step behind the building and equipping of recording studios was the installation of sound reproducing systems in theaters. Theater chains controlled by the picture-producing companies which had already signed contracts, used sound systems of the corresponding make, but the business of furnishing sound equipment to the great number of independent theaters was competitive between ERPI, RCA Photophone and many other suppliers. An idea of the rate of growth of the sound pictures, may be had from the following figures given in Sponable's paper.[6] At the end of 1927 there were some 157 theaters in the U.S. equipped for sound, of which 55 were for both disk and film and 102 for disk only. At the end of 1928, of the 1046 ERPI theater installations, 1032 were for disk *and* film. By the end of 1929 ERPI had equipped about 4000 theaters in the U.S. and 1200 abroad, and RCA Photophone had equipped some 1200 in the U.S. and 600 abroad, most of these being for both disk and film. The SMPE Progress Report of February 1930 states that at the time, Hollywood studios were producing only 5% silent pictures. Installations by other manufacturers brought the total number of theaters equipped for sound in the U.S. to over 8700. There were at the time 234 *different types* of theater sound equipment including the large number which were designed for disk only. At the end of 1930 there were about 13,500 theaters equipped for sound, and about 8200 not equipped, according to the SMPE Progress Report of August 1931.

Contracts for Photophone Variable-Area Recording. In 1928 RCA bought the theater chain interests of B. F. Keith and of Orpheum, and the film producing company Film Booking Office or F.B.O., and organized Radio Keith Orpheum or RKO. The new company (RKO), with Photophone equipment, and drawing heavily on the RCA group for much of its initial sound personnel, made many feature and shorter pictures, using the name Radio Pictures for its product. RCA Photophone made arrangements for license and equipment with Pathé Exchange Inc., Mack Sennett, Tiffany Stahl and with Educational Pictures Corp.

One of the first feature pictures made by Pathé was *King of Kings* directed by Cecil de Mille. The Pathé Newsreels were an important item, using a number of RCA mobile recording equipments or "sound trucks."

Disney switched to the RCA Photophone system in January 1933. Republic Pictures Inc. used the RCA system beginning October 1935 and Warner Brothers in June 1936. Columbia Pictures Inc. began May 1936 to use the RCA variable-area system for part of its operations, but continued for several years to release on variable-density.

Cinephone. The Powers Cinephone system was developed by R. R. Halpenny and William Garity for Patrick A. Powers, who financed the project. It was basically similar to the system of de Forest, with whom Powers had permissive contracts. Cinephone was put on the market in September 1929 and used for several years by Walt Disney and others.

Type of Contract. Most of the initial contracts between the equipment-manufacturing companies and the picture producers were on a lease (rather than outright sale) basis, for a stipulated term of years, with equipment servicing and engineering assistance as part of the suppliers' obligation, and royalties depending on the film footage recorded.

Evolution of a New Art, Under Difficulties.* The idea that the silent motion picture would continue to have its place in theater entertainment died hard. What *The Jazz Singer* had proved was that with a suitable story and presentation, a sound picture could have an appeal far beyond what was possible without sound. It had not proved that sound would help in *all* types of presentation. In March 1929, Fox discontinued making silent pictures. In speaking of this in his historical paper[5] of 1941, W. E. Theisen calls it a daring decision, "since a large number of the leaders of the industry still felt that sound films were only a passing fad." In "The Entertainment Value of the Sound Movie" (*Trans. SMPE*, No. 35, 1928), H. B. Franklin, President of West Coast Theatres, says: "The silent motion picture is too well established. . .to vanish because of this new development."

It took time, much work and some mistakes for the industry to learn to use sound to full advantage, and the great pressure under which writers and producers worked during the years of transition was not conducive to best results. Two quotations from 1928 papers are illuminating. In "The Public and Sound Pictures" (*Trans. SMPE*, No. 35) Wm. A. Johnson, Editor of *Motion Picture News*, speaks of the great demand for sound pictures, and says: "The present hastily turned out crop of talkies are for the most part crude and disappointing." In "Reaction of the Public to Motion Pictures with Sound" (*Trans. SMPE*, No. 35), Mordaunt Hall, motion-picture editor of the *New York Times*, describes the shortcomings of many efforts as due to stories not adapted to talkies, actors who didn't articulate, or had poor voices, and misjudgments in production.

* Many excellent discussions of the requirements for the new form of entertainment have been published. One such is Chapter IX "Comments on Production," of H. B. Franklin's *Sound Motion Pictures*.[2]

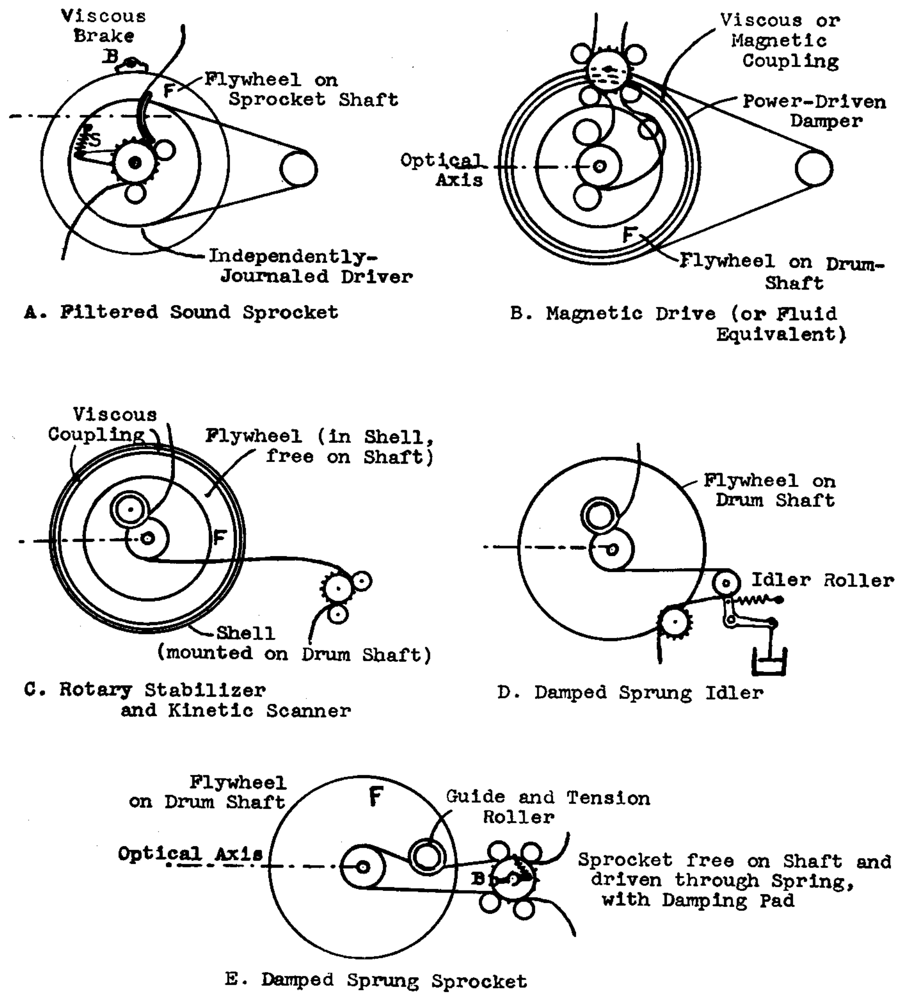


Fig. 4. Mechanical filter systems for reducing irregularities in film motion.

We tend, fortunately, to forget the troubles that are past. Still more do we forget the troubles other people had. We who took part in the development of sound equipment may be tempted to think that we made the talking picture possible. But if we give the credit they deserve to the writers, directors, actors and their bosses, and to the patient guinea pigs who bought tickets, perhaps the only bouquet left to hand ourselves is to say that our stuff was not so bad as to make the talkies impossible.

Mechanical Systems

Of all the tell-tales that remind the listener that the sound he hears is from a record and not "live pickup," the most unmistakable is that due to speed variations — known as "wow" or "flutter," and it is probably the most painful and devastating to realism. The importance of correct and constant speed was recognized by Edison and all his successors in sound recording, but standards were not very high. Phonographs sold despite their shortcomings. But sound for pictures could succeed only by providing better entertainment than silent pictures. In those systems which gained eventual acceptance by the motion picture industry, the engineers spent much effort on providing constant speed. In his story of the development of the Fox-Case system, for example, Sponable[6] tells of having to rebuild cameras, and of mounting a flywheel on the sprocket shaft and driving the combination through damped springs.

The literature dealing with speed fluctuations has been devoted largely to discussions of measures for improving the performance of recorders and reproducers in this respect.[70] Until the recent important contribution by Frank A. Comerci,[84a] such information as has been published regarding subjective thresholds or tolerances has been limited largely to continuous tones. Further systematic quantitative studies with typical program material are very desirable. There is no question however that all the present and future improvements in equipment performance are well justified in terms of more satisfying sound reproduction. Some of the more general discussions of the subject will be found in the literature.[70,79–84a]

Wow Meters. Of prime importance toward improving recording and reproducing machines is ability to measure the departures from uniform speed. One of the first such meters was built about 1928 by M. S. Mead[85] of the General Engineering Laboratory at Schenectady. It was improved by H. E. Roys and used extensively at Camden, N.J., being the basis of the flutter-measuring equipment described by Morgan and Kellogg.[86] This meter made an oscillographic recording of the fluctuations. An extremely simple and light-weight indicating flutter bridge used in RCA servicing is described in the *Journal.*[87] Flutter-measuring instruments are described by Scoville.[88] These are of the indicating type with band filters, by which flutter at different rates can be separated. Another design is described by Herrnfeld.[89] A widely used wow meter designed by U. R. Furst of Furst Electronics, Chicago, has been commercially available since 1947 or earlier.[90]

Disk System. In the disk system the change from 78 to $33\frac{1}{3}$ rpm increased the difficulties, for at the low speed even a very heavy turntable (although very helpful toward eliminating rapid flutter) was not a practical answer. A flywheel driven through springs, or what we call a "mechanical filter," was a well-known expedient, but such a system is oscillatory and will multiply rather than reduce the speed fluctuations if the disturbances are of a frequency anywhere near that of the resonance, unless the system is damped by adequate mechanical resistance.[69,70,81,91,94,100,102,104,105] The requirement that the transient disturbance of starting shall disappear in not more than one revolution is more difficult to meet with extremely large inertia. The acceptable $33\frac{1}{3}$-rpm reproducing turntables had much more inertia than had been customary for 78-rpm machines, and were driven through springs, with enough damping to reach equilibrium reasonably quickly, and dependence was not placed on making the natural frequency low in comparison with that of the slowest disturbance (once per revolution). Damping in some designs was provided by applying friction to the springs,[52,53] and in others by a viscous drag on the turntable. In either case it was essential to have high indexing accuracy in the low speed gear or worm-wheel.

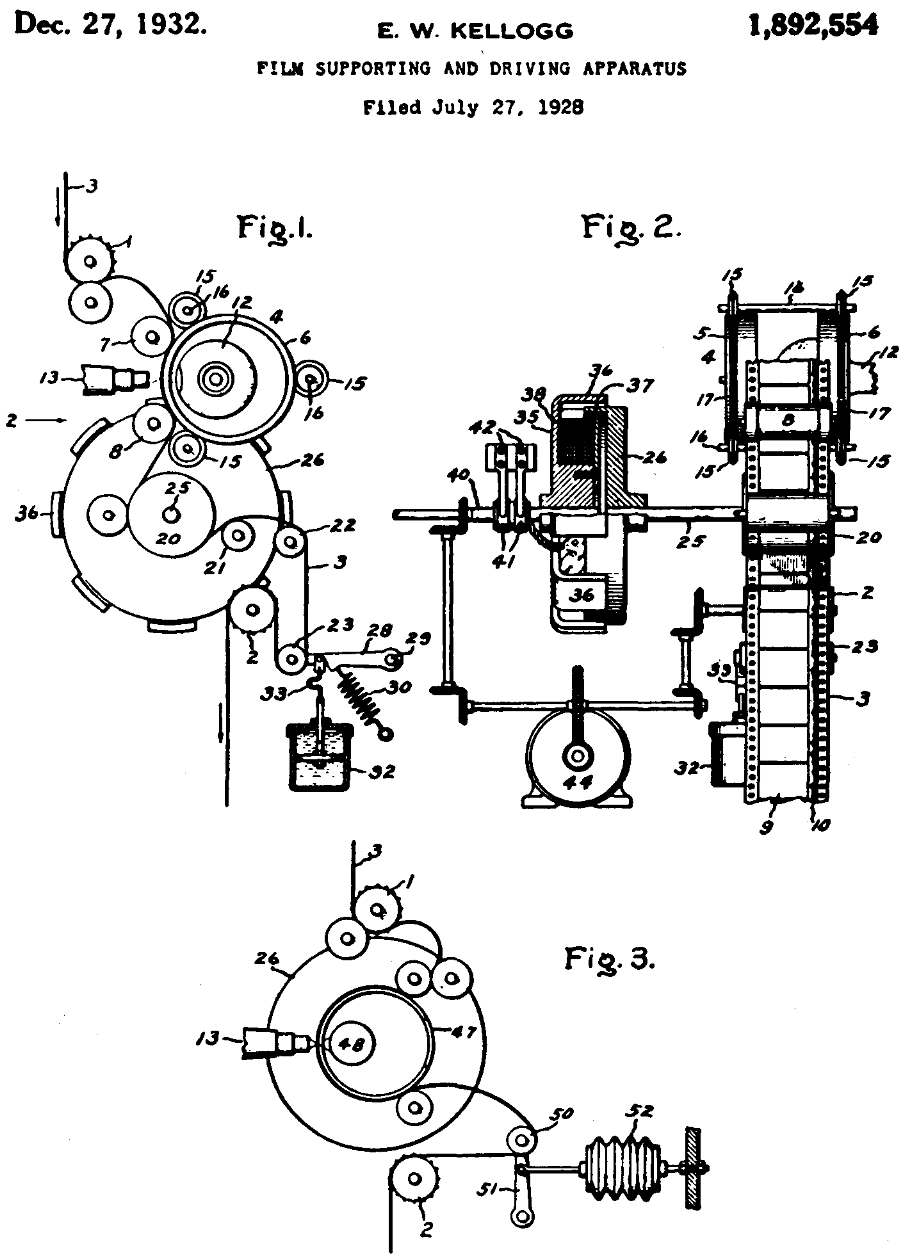
For $33\frac{1}{3}$-rpm recording turntables, the Western Electric engineers went to extraordinary refinement.[70,91] On the theory that it would not be practically possible to produce gears with no eccentricity or indexing errors, they made their $33\frac{1}{3}$-rpm worm-wheel in four laminae, all cut together in one operation. Then they separated and reassembled them, each rotated 90° with respect to its neighbor. Each had its own spring connections to the turntable. Damping was by means of vanes in oil. Four vanes were rigidly connected to the turntable, while the pot and four other vanes were driven from the gears through a system of equalizing levers (which might be compared to whiffletrees) which imparted to the pot and its vanes a rotation which was the average of that of the four gear laminae. The effect of this was to divide by four the magnitude of each disturbance due to imperfection in the cutting of the gear, but to make it occur four times per revolution instead of once, and both of these effects are helpful toward filtering out irregularities.

Filtering Systems for Film. In a very judicial appraisal of the relative advantages of film and disk, P. H. Evans[92] speaks of the disk system as giving better speed constancy. He was of course referring to the experience up to the time of writing. There can be no question that film presents a more difficult problem. Synchronous drive and the maintenance of free loops require that it be propelled by sprockets. In the earlier systems of driving the film, it seems to have been regarded as sufficient to provide constant rotational speed for the sprocket (often called the "sound sprocket") which carries the film through the point of recording or reproduction. To obtain such constant sprocket speed it was practically necessary to use mechanical filtering to take out irregularities originating in the gearing.[4,70] But the spring-driven sprocket was very sensitive to jerks from the film, so that it was necessary to employ extra sprockets with slack film between to isolate the filtered sound sprocket. It was also necessary to have an unusual degree of precision and concentricity in the sound sprocket. (Fig. 4A).

But there remained the question of what imperfections there might be in the film perforations, or how much it had shrunk since the holes were punched. Shrinkages up to 1% were not uncommon.

A sprocket can propel a film at uniform speed only when the pitch of the teeth and that of the holes match perfectly.* Otherwise there are continual readjustments of the film on the sprocket, producing in general 96-cycle flutter, plus random small variations. A paper by Herbert Belar and myself[82] shows graphically the startling breaking up of single tones into a multiplicity of side tones by a 96-cycle speed change such as might result from a shrinkage of about $\frac{1}{2}$%.

Recorders, since they are working with fresh film, may give very little 96-cycle flutter at the sprocket. The



Film 5. Schematic representation of the magnetic drive for film motion, showing also provision for damping by use of a movable roller with dashpot.

Western Electric recorders of the earlier 1930's were designed on this basis.[4,93] The large sprocket was of precise construction and a nearly perfect fit for unshrunk film. It was on the shaft with a flywheel, and driven through damped springs. Another sprocket (unfiltered) drew the film from the magazine and resisted the pulls from the take-up magazine.

The engineers who designed the recorders supplied by RCA took no chances with sprocket teeth. In the first General Electric recording machines the film was carried past the recording light on a smooth drum (with a flywheel on its shaft) and a soft-tired pressure-roller prevented slipping.[67] Between the drum and the sprocket which fed the film through the machine at synchronous speed were flexible loops of film which (so long as they remained under sufficiently low tension to retain their flexibility) would not transmit appreciable disturbances from the sprocket to the drum. Because of uncertain shrinkage the drum must be free to choose its own speed. The simplest expedient was to let the film pull the drum, like a belt. Machines built this way worked so well at times that they delayed the effort to design something on sounder principles. My own part in the development of a better machine lay originally in the recognition that the stretch of film which pulled the drum, in combination with the inertia of the flywheel, constituted an oscillatory system, although its period varied so greatly that the irregular action did not look like that of any oscillator we were accustomed to seeing. Another trouble was that the film loop

* Sprocket propulsion of the film through the light beam has certain advantages for printers, as will be explained in the section on printer improvements. This mechanical section, however, seems the logical place for a brief review of studies by J. S. Chandler and J. G. Streiffert of the Eastman Co., directed to the reduction of sprocket-tooth flutter.

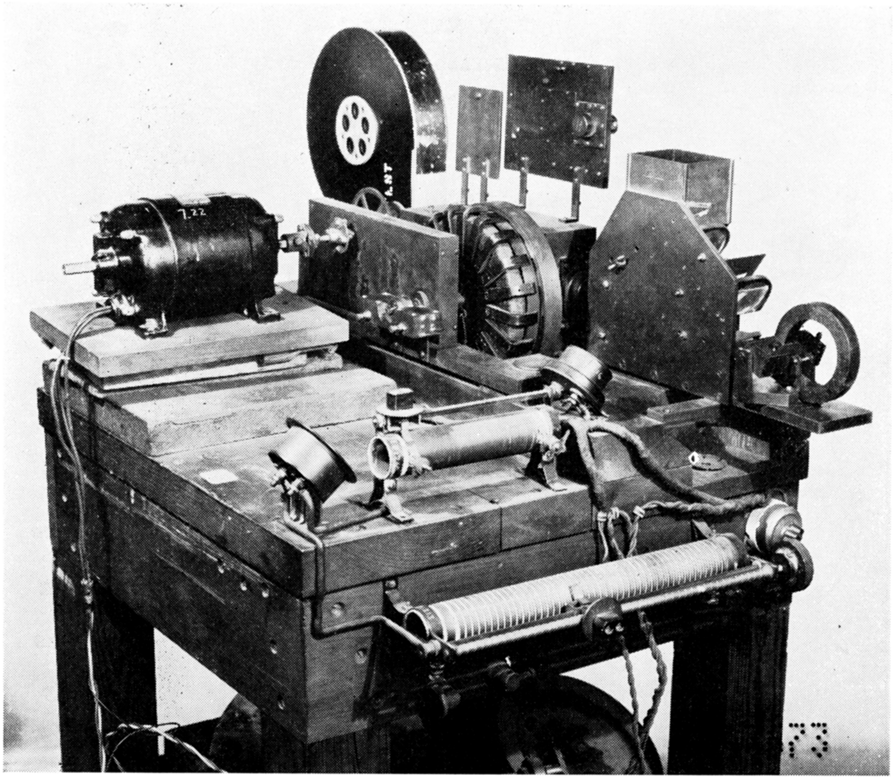


Fig. 6. Original model of magnetic-drive recorder.

was not free enough for isolating the drum. The cure for the bad effects of oscillatory action would be to provide damping. One way to provide this would be by bending the film around a flexibly supported idler roller,[105] connected to a dashpot. Another measure would be to use eddy-current damping at the flywheel by mounting a copper flange on the flywheel, spanned by a set of magnets. To use stationary magnets would provide damping but would also produce a steady drag, making a really flexible film loop impossible.[102,102a] By mounting the magnets so that they could be driven somewhat above flywheel speed, it became possible to provide a forward torque as well as damping, thereby relieving the film of all but a small part of its tension. (Figs. 4B, 5).[94–96]

The first magnetic-drive machine (an experimental model) (Fig. 6) employed both the damped idler roller and the rotating magnetic damper, but the latter was so effective that the first was superfluous. By adjusting the magnet current the film loop could be caused to run anywhere between a very slight deflection and a nearly semicircular bend. A production model (the R-4) recorder was designed in 1929 and was in production in 1930.[94] It was followed by other models (PR23 in 1933[98] and PR-31 in 1947[99]) employing the same principle.

The magnetic drive probably carried the idea of isolation of the film drum from disturbing forces farther than it has been carried in any other film-recording machine. Its extreme effectiveness as a filter system was demonstrated by Russell O. Drew and myself at the SMPE's 1940 spring convention.[96]

Although only a few were built, I should mention another recorder, the R-3,[70] designed by C. L. Heisler of the General Electric Co., which preceded the magnetic type. This had the smooth drum with flywheel to carry the film past the recording point, and the sprocket drive to hold synchronism. The drum was driven through a continuously adjustable-speed friction drive, which might be compared to a cone pulley, and the speed adjustment was automatically controlled by the length of the loop of film between the sprocket and drum, which loop was measured by the position of a movable deflecting roller.

Effect of the Tri-Ergon Patents.[35,114] Mention has been made of the development, beginning in 1918, of a sound system by Vogt, Massole and Engl, to which the name Tri-Ergon was given. They obtained very broad patents in Germany and were allowed some extremely broad claims in the United States. The patent which figured most seriously in litigation was No. 1,713,726 in which one claim covered the use of a flywheel on the shaft of the roller which carried film past the translation (recording or reproducing) point. Another claim covered carrying the film on a short roller and scanning it at the overhanging edge, and a third (based on a showing of flexibly mounted rollers pressing against and deflecting the stretches of film on either side of the drum) called for a spring-pressed roller engaging the film between the sprocket and the roller (drum). Patent attorneys in the RCA group and Western Electric felt very confident that the broad flywheel claims could be safely disregarded because anticipated in many old sound-recording and reproducing devices, but the patent departments would not approve constructions using the overhung film for scanning until after about 1930, when W. L. Douden of the RCA patent department discovered an older disclosure of the same idea in a patent application of C. A. Cawley* (to which RCA obtained rights).

Film-Transport System of Soundheads. So the first reproducing machines to be marketed avoided the overhanging film feature, and instead pulled the film through a sound gate, where the scanning light passed through it and into the photocell. Friction in the gate made this arrangement much less favorable to constant speed than the use of the overhung principle. For constancy of film speed no further measures were used than to try to provide good sprockets to pull the film through the gate, and to filter the motion of the sprocket by use of a flywheel, and driving through springs. To damp this filter, the RCA PS-1 used grease-pads acting on the flywheel (Fig. 4A) and the Western Electric used a balanced pair of oil-filled sylphon bellows which acted as a dashpot supplementing the driving springs.[53] A practical improvement over filtering the sound sprocket was to drive a heavy flywheel on the sound-sprocket shaft by multiple V belts directly from the motor, and then by gearing take from this shaft whatever power is needed to drive the projector. The heavy flywheel and tight coupling to the motor gave the sound-sprocket drive such high mechanical impedance that its speed constancy was not materially disturbed by the irregularities of the projector load.

The Rotary Stabilizer. The discovery of the Cawley patent application by Douden made the RCA Patent Department consider it safe to build machines in which the reproducing light passed through the film where its edge overhung a short roller. With this privilege the way was open to make the film motion in reproducing machines comparable with that which had been attained in the magnet-drive recorder. However a less expensive construction was very desirable. The damping in the recorder was by eddy-current coupling between the flywheel and a coaxial magnet running at nearly the same

* The Cawley application had been filed Jan. 28, 1921, but had been held up on technicalities. It was put into suitable shape and issued Sept. 29, 1931 as a parent patent, No. 1,825,438, and three divisional patents, of which No. 1,825,441 contained the claims to the overhang feature.

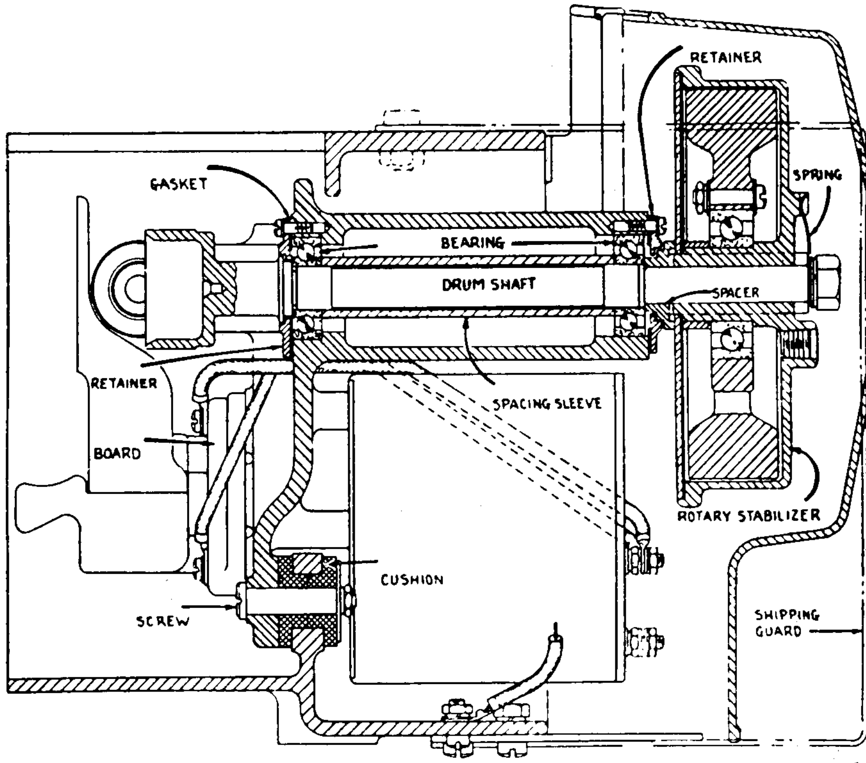
speed. The functional equivalence of eddy-current coupling and viscous-fluid coupling was well recognized. I had tried some experiments with viscous coupling to a coaxial member which was not independently driven but was free to pick up the flywheel speed. The inertia of the viscously coupled member would tend to keep its speed constant so that a change in flywheel speed would cause relative movement and hence energy loss.[100] But I gave up in view of the feebleness of the damping I obtained.

It remained for C. R. Hanna of Westinghouse to make an analysis of the system. He showed that in order to get critical damping of the mass which is rigidly connected to the drum, the viscously coupled mass must have eight times as much moment of inertia, and the coupling coefficient must have the right value.[69] In 1932 and 1933 E. W. Reynolds and F. J. Loomis of the RCA Victor Co. in Camden did the job right.[101] The directly connected mass was an oil-tight shell of aluminum alloy inside which was a heavy cast-iron flywheel supported on a ball bearing whose friction was negligibly small in comparison with the oil coupling. Small clearance between concentric surfaces and a suitable oil gave the desired coupling. The inertia ratio was less than 8:1, but damping somewhat short of critical is satisfactory. By use of high-grade ball bearings the drum with attached stabilizer was caused to run with so little tension on the film which pulled it that the loop had plenty of flexibility for effective filtering.[102, 102a] (See Figs. 4C and 7.) The rotary stabilizer introduced in 1933 proved so satisfactory that it has been retained with little change for twenty years. A device on similar principles, called the "kinetic scanner" was used in Western Electric soundheads early in 1936[103] (Type 209).

In 1941 Alberscheim and MacKenzie[81] and Wente and Müller[104] described damped flywheels in which the entire viscously coupled mass was liquid. In order that there might be sufficient viscous resistance to movement of the liquid with respect to the container, partial obstructions were placed in the annular channel. This type of damped flywheel was used in the recorders and reproducers of the stereophonic system developed and demonstrated by the Bell Telephone Laboratories. Study has been given to the problem of finding suitable fluids. A low-temperature coefficient of viscosity is desirable, and if the entire coupled mass is liquid, high density is valuable.

Filters Using Movable Idler Rollers. The use of this type of filter was avoided in this country because of the danger of infringement suits on the basis of either the Tri-Ergon patent (No. 1,713,726)[35] or the Poulsen and Peterson patent (No. 1,597,819). Both of these show rollers elastically pressed against the film to deflect it from a straight path and thereby provide flexibility. Neither patent shows or mentions provision for damping, and yet the great merit of such an arrangement is in the simplicity with which damping can be obtained and not in the extra flexibility, for plenty of flexibility can be had by simply freeing the film of too much tension.[102,102a] The flywheel may be solid and the arm on which the film-deflecting roller is mounted can be connected to a dashpot. (Even a cruder frictional device may give good results, but resistance of the viscous type is better.) A laboratory model of a soundhead using this type of filter was built about 1928 by the writer and performed very well, but did not receive patent approval (Fig. 4D).

After the patent obstacle to the use of the sprung-idler type of filter was ended, soundheads employing this principle were brought out by the Century Projector Corp. and the Western Electric Co.[105] and a recorder by Western Electric.[106] RCA adopted this film-motion system for 16mm machines and lightweight recorders R-32 and R-33,[107] but for 35mm soundheads continued to use the rotary stabilizer, the advantage of the movable-idler design being not so much a matter of performance as of lower manufacturing costs, an item which is contingent on schedules and tooling costs. Recently the flexibly mounted idler filter system has been utilized by RCA[108] and others[109,110] in soundheads for use with multiple magnetic soundtracks.



Rotary stabilizer construction of F. J. Loomis and E. W. Reynolds.

Fig. 7. Cross section, showing construction of the "rotary stabilizer."

Filter System With Drum and Sprung Sprocket. A film-motion system developed by engineers of M-G-M is described by Wesley C. Miller.[111] Recording or reproduction takes place on a drum with solid flywheel, and the drum is driven from a sprung sprocket isolated from other sprockets by loose loops. The film passes from the sprung sprocket, around the drum and back to engage the opposite side of the sprung sprocket, and this portion of the film is maintained under tension by a roller pressing against a free span of the film. The tight film affords the required traction between film and drum. Adjustable friction pads between the sprocket and its shaft cause frictional resistance whenever the deflection of the sprocket driving springs changes, thereby damping the system.

Excellent film motion was obtained in these machines (Fig. 4E).

Minimizing Sprocket-Tooth Flutter. J. S. Chandler, in 1941[112] showed it to be possible to so shape sprocket teeth that the film speed would fluctuate between a maximum and minimum value which are the same at perfect fit and spread progressively with increasing misfit, but with a net flutter which can for a moderate range of shrinkage be quite small. However the realization of the calculated flutter values demands perfect perforation uniformity and freedom from any sticking on the teeth as the film is fed on or stripped off.

A further development in improving sprocket action is described by J. G. Streiffert.[113] The driving faces of the

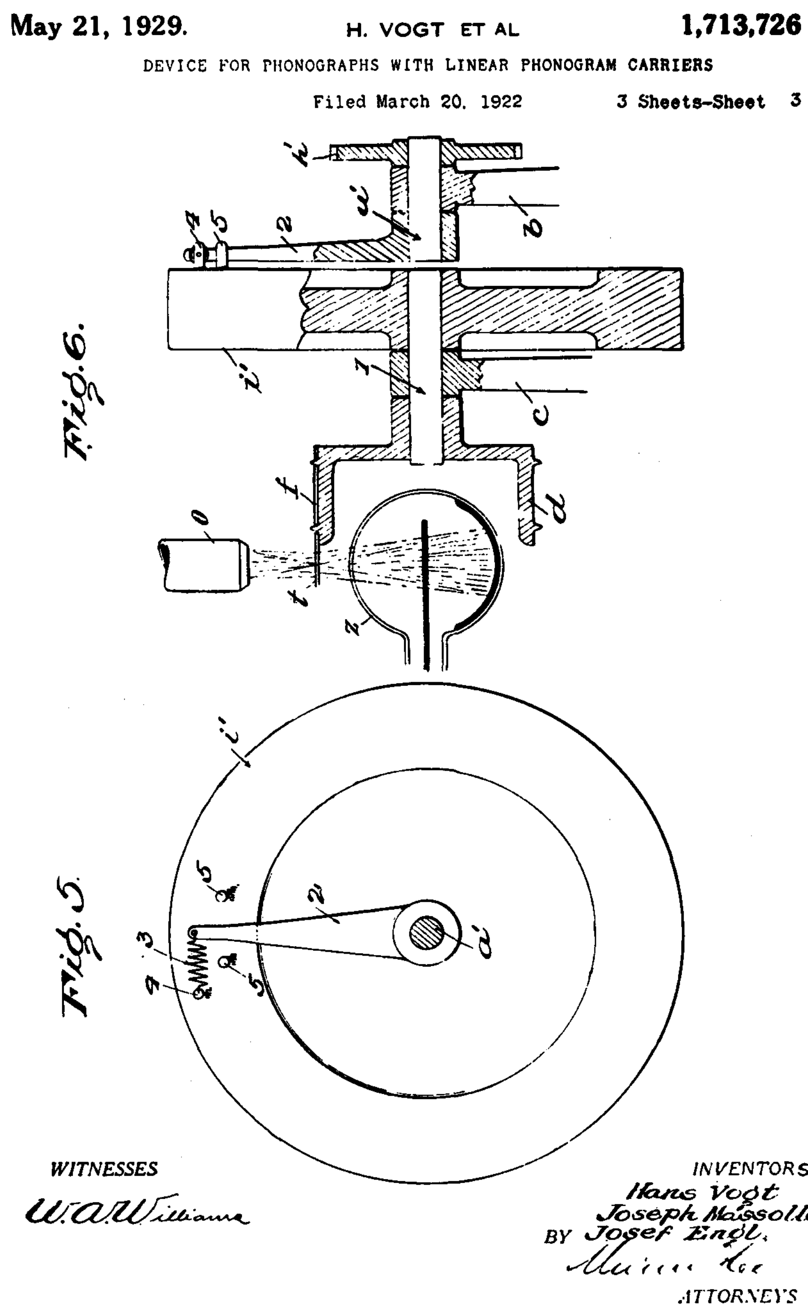


Fig. 8. Tri-Ergon showing (U. S. Pat. 1,713,726) of flexibly mounted rollers deflecting the film between sprockets and drum.

teeth are radial and the film is supported on a cylindrical surface which is slightly eccentric with respect to the sprocket. The film is fed on at a point where the teeth project only slightly above the film support, and as it travels around its arc of engagement the film gets closer to the roots of the teeth. The radius from the sprocket center to the film thus keeps decreasing, and therefore the velocity of the tooth face at the plane of the film decreases. The effect is essentially as though the tooth speed and the tooth pitch decreased correspondingly. The design is such that the tooth enters the hole with a margin of clearance and with the effective velocity (since the working radius is here near maximum) slightly greater than that of the film. The tooth face therefore gains with respect to the film, closing up the clearance, and as soon as it touches the edge of the perforation begins propelling the film. While it is doing so the next tooth is catching up. Each tooth in turn propels the film from the moment that it reaches the perforation edge until the next tooth, which at the instant is moving slightly faster, touches the edge of its perforation. Thereafter, the effective speed of this tooth, which continues to decrease, is less than that of the film, so that a gap or clearance develops between the tooth and the leading edge of the perforation. The design is such that the film is not stripped from the teeth until, in all cases, sufficient clearance has accumulated to avoid possible interference during the stripping.

Assuming that the film velocity is equal to that of the driving-tooth face at the radius where it touches the film, the film speed will fluctuate by the amount by which the effective tooth speed decreases as it travels one tooth pitch. This can be a very small change, especially if there is a large number of teeth and the eccentricity no more than needed to take care of a reasonable shrinkage range.

The region on the circumference of the sprocket where the propelling action takes place varies with the shrinkage of the film. Thus with unshrunk film the propulsion will be relatively near the place where the tooth enters the perforation, while with shrunk film it will be where the teeth are projecting farther, so that the point of contact is nearer the root of the teeth.

One way of describing the action of the system is to say that a film of any given shrinkage finds the appropriate radius where the pitch of the teeth equals the pitch of the perforations, and this is the region where propulsion takes place.

The Eastman Co. has used this system with excellent results in experimental printers. The Streiffert paper gives wowgrams of negative recordings made on such a sprocket, and also of contact prints, and for comparison wowgram (or flutter recordings) of prints made in a conventional sprocket-type printer, showing a major reduction in flutter with the new sprocket.

Litigation. Despite the efforts to avoid infringement of such claims of Tri-Ergon patent No. 1,713,726* as appeared to have any likelihood of being held valid, the American Tri-Ergon Corp. brought suit against Altoona Publix Theatres Inc., who were using an RCA Photophone (PS-1) projector attachment or soundhead. The case was tried at Scranton, Pa., in the U.S. District Court for the Middle District. The apparatus had been sold with a guarantee against patent liability, and the suit was defended by RCA, Electrical Research Products Inc. giving technical assistance in the defense. The court ruled (Feb. 10, 1933) that seven of the claims were valid and infringed. The case was appealed and reviewed by the U.S. Circuit Court of Appeals for the third circuit (in Philadelphia), which affirmed (June 13, 1934) the findings of the lower court. The defendents then appealed to the U.S. Supreme Court, which at first refused to review the case, but finally decided to do so, and on Mar. 4, 1935, ruled that the seven claims in the suit were all invalid (294 US 477).[114]

* This patent, issued May 21, 1929, was filed in the U.S. Mar. 20, 1922, and had a German filing date of Mar. 24, 1921.

This removed the threat to the equipment manufacturers of what might have been almost crippling damages, for had the findings of the lower courts been sustained the plaintiffs would have been in a position to bring suits for damages for infringement by most of the recording and reproducing equipment in this country, and covering a period of over five years.

The American Tri-Ergon Corp. applied on Feb. 18, 1937, for a reissue patent with modified claims, and this was granted Jan. 11, 1938, as Re. No. 20,621. On Oct. 25, 1946, RCA reached an agreement with American Tri-Ergon Corp. whereby it was granted rights under both the original and reissue patents.

Two other patents placed restrictions on the film-motion systems which American engineers could safely employ, namely Poulsen and Peterson No. 1,597,819 (filed July 9, 1924, and issued Aug. 31, 1926) and Poulsen No. 2,006,719 (filed Germany Sept. 1, 1930, and U. S. Aug. 19, 1931, and issued July 2, 1935). These patents to Danish inventors were owned by British Acoustic Films Ltd., which brought infringement suits against RCA Mfg. Co. and against Electrical Research Products Inc. The trial (in Wilmington, Del.) was before the U.S. District Court for the District of Delaware (43 USP–Q69). The arrangement shown in the patent comprised a drum propelled by the film, the film being passed around a flexibly mounted idler roller. Some of the claims in suit described the invention as "means contacting the film for increasing its flexibility." The apparatus in suit was the RCA PS-24 (rotary stabilizer type), which has no flexibly mounted roller, but was alleged to have the equivalent in that the film loop was so formed by the fixed rollers as to be very flexible. The court ruled Sept. 22, 1939, that the claims in suit were not infringed and not valid (the flexibly mounted idler having been disclosed in the earlier Tri-Ergon patent).

Plaintiffs appealed and the case was reviewed by the Circuit Court of Appeals of the Third Circuit which affirmed the findings of the lower court (46USP–Q107, June 27, 1940).

To forestall possible future trouble RCA obtained rights under these patents by agreement with British Acoustic Films Ltd., Dec. 21, 1944.

Immediate Requirements for Sound

Our historical story thus far has been confined almost entirely to the three fundamental elements, sound pickup (or microphone), a recording and reproducing system and loudspeakers. These represented the difficult phases of the problem, but before sound could become commercial certain items of equipment had to be made available and techniques established. Before discussing the advances in the art that followed commercialization, we shall mention some of these items.

Standard Track Position and Width.[115] Agreement between the makers of variable-width and variable-density systems was reached in 1928. The reproducing light spot must cover more than the extreme width of the clear area of a variable-area track, with both ends on black areas, but should fall entirely within the width of a variable-density track. This requirement is met with margins of safety, by recording density tracks 0.100 in. wide, while the scanning spot is 0.084 in. long. The modulated area of a variable-width track is limited to 0.071 in. with the black parts extending to the 0.100-in. width. The track center line is to be 0.243 in. ± 0.002 in. from the edge of the film.

Printers. Continuous contact printers previously used for pictures only could be adapted to sound by providing masks by which light could be confined to either the picture or the soundtrack area. Except for certain newsreel negatives, the sound and picture were on separate negatives, so that the print film had to be run through the printer twice. Even when the sound was on the same negative as the picture, the offset was not usually the required 14.5-in. and independent light controls were needed. Combination printers were soon developed which were essentially two printers in cascade, so that the print was complete with one passage through the machine.[116–120]

Bloops. The development engineer can overlook many defects so long as he knows their cause and that the apparatus he is testing is not at fault, but before sound pictures could be shown the public, these faults had to be corrected. The noise which a splice makes as it passes through the scanning beam can be made almost inaudible by cutting off the light gradually instead of suddenly. This was accomplished at first by painting a black spot with sloping edges over the splice. Later, black patches which could be quickly cemented in place where the splice crosses the sound track were made available. These are called "bloops." They are of trapezoid shape, masking off the entire sound track for a distance sufficient safely to cover the splice and with end slopes designed to change the light gradually enough to keep the noise just below noticeability at normal gain settings. The design of bloops is discussed in several papers.[121–123] To prevent a disturbance due to a printed-through negative splice, Sponable[124] described a punch which made a hole in the negative, resulting in a suitably-shaped black spot on the print.

Electrical blooping of splices in negatives has come into extensive use. When a negative splice goes through the printer an auxiliary light exposes (through the base) a suitable area of the print film, an edge notch or other means being employed to control the blooping light.

Lewin (Apr. 1947)[124a] describes a system of silencing splices in re-recording positives in which the output is momentarily suppressed in response to a punched hole.

Blimps.[125] Cameras which were entirely satisfactory for silent pictures were much too noisy for making sound pictures. Much quieter cameras were developed eventually,[126–128] but for immediate requirements it was necessary to reduce the noise radiated by existing cameras by building shells around them with thick layers of sound-absorbing material. These were called "blimps," or sometimes "bungalows." To smother the sound and still give access for the necessary operations was enough to tax the skill and ingenuity of the designer. Even with the quieter cameras it is still common to resort to partial or complete sound-insulating housing.

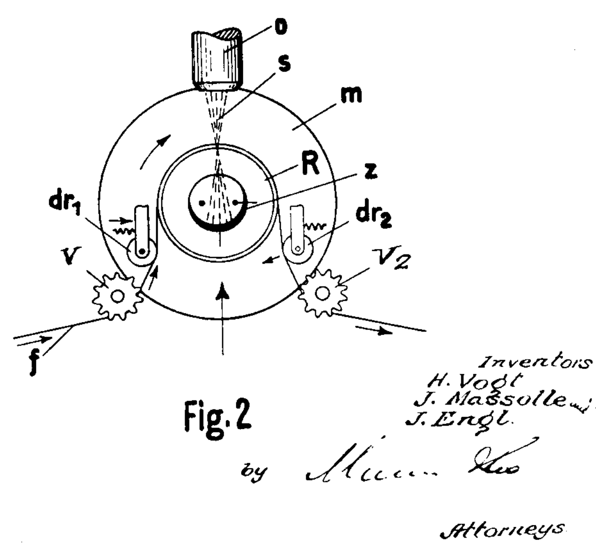


Fig. 9. Tri-Ergon showing of filtered sound-sprocket and overhanging sound-track.

Sound Stages.[129,130] The requirement of freedom from noise necessitated the building of sound stages in which extreme measures were taken to exclude noise of outside origin. Many of these had double concrete walls and double floors, with sound absorbing material between, the inner walls and floor being supported on cushion mounts to prevent transmission of earth tremors. The roof and ceiling structures were designed on the same principle.

The high absorption (or short reverberation time) desirable for recording purposes helped control noises originating inside, but so far as possible all sources of noise were eliminated. Noisy arc lights gave way to incandescent or other quiet lamps, and all mechanisms were made to operate as noiselessly as possible. Ventilating systems required extreme measures.

In recording dialogue, the better the suppression of general room reverberation, the farther (within limits) from the action can the microphone be placed, thus affording more uniform coverage and making it easier to keep the microphone out of the field of the camera. If some echoes are wanted the "set" can frequently be designed to produce enough. Artificial reverberation using echo chambers in the recording channel or equivalent devices has many applications.

In contrast to the requirements for speech, the recording of music calls in general for rooms with considerable reverberation.[131–133]

Theater Acoustical Treatment.[134,135] The acoustical treatment of auditoriums has probably received more study than any other phase of architectural acoustics, perhaps because the desired characteristics are most difficult to attain. The reverberation must be sufficient to make music pleasing and to help equalize sound intensity in the various parts of the space, but must be short enough not appreciably to impair clarity of speech. A high order of directivity in the loudspeakers plus application of absorbent materials to any large surfaces toward which they are directed has helped with this part of the problem.

In general every theater or auditorium, many of which were built before the era of sound pictures, presents its own problems and calls for individual study. For new theaters there is optimum shape to consider as well as best distribution of absorption. The multiple loudspeaker systems (discussed later) besides making new effects possible have given the acoustical designer somewhat more freedom.

Booms and Dollies. In order that microphones might be suspended as near the action as might be wanted but just above the field of the camera, and in order that their positions might be readily changed, microphone booms of various types came quickly into use. The more elaborate of these were much like derricks on platforms, with rubber-tired wheels on which they could be moved quickly and almost noiselessly.

Similarly, rubber-tired, battery-operated camera dollies enabled the cameraman rapidly and quietly to change the position or height of his camera.

Equipment of the kind just described underwent improvements through the years, but the main features were available from the start of commercial sound pictures.

Monitoring and Level Control.[136–139] Another line of equipment the essentials of which were made available as soon as recording machines, and which has been improved from time to time, was that providing for monitoring and level controls and (especially in re-recording operations) for adjusting the relative levels from several sources, or "mixing." Volume indicators[140,141] of several types were in use in broadcasting stations, and the design of mixing controls was well established.

The man responsible for recording judged the quality by means of a monitoring loudspeaker. He could check quality as represented by the current supplied to the light modulator, or by means of a photocell, in terms of the light reaching the film.[1,64,254] In the case of the RCA Photophone system there was a card on which the modulator projected a light-spot, the movements of which showed the amplitude being recorded on the sound track.[142]

It was for a time held by some that the monitoring speaker should be of the same type as a theater speaker, but high-quality monitoring speakers of the direct-radiator type were soon made available, and these were much better suited to the small rooms where the controls were located. In terms of frequency range covered, the cabinet-type monitoring speakers kept pace with the improvements in theater speakers (see section on loudspeakers). High-quality headphones have also found wide use in monitoring.[143, 211] Whatever type of listening device is used, it should obviously be designed to give the recordist about the same range and tonal balance that a theater patron would get.

Screens. Our sense of the direction from which sounds come is too keen for us to be fooled by loudspeakers placed alongside or above the screen. Sound must come from directly behind the screen to give a good illusion. This is one of the lessons that was learned early. Screens of the types developed for silent pictures caused excessive loss and distortion if placed between the loudspeaker and the audience.

Mention has been made of a sound-transmitting screen developed by E. I. Sponable in 1927.[6] One of the first papers in the SMPE *Journal* dealing with screens for sound pictures was that in 1930 by H. F. Hopkins.[144] His curves of measured transmission indicate good results with screens having perforations whose total area is 4% or 5% of the screen area, and show definite advantage in a thin (0.013-in.) screen rather than a thicker (0.030-in.) material. With such screens the loss of brightness need be no greater than the proportion of the area taken out by the holes. Allotment of about 8% of the area to holes has been common, for example about 40 holes of 0.050-in. diameter per square inch.[145]

Processing, Variable-Density.[146] In the story of the work at Western Electric and Bell Laboratories I said that it was recognized by Wente and by MacKenzie that for the correct, or linear, relation between negative exposure and print transmission, the product of the negative and print gamma* should equal unity.† This is in accordance with principles set forth in early SMPE papers by L. A. Jones[62] and by A. C. Hardy.[61] Since practice in making pictures had been to develop the print to a gamma of approximately two, and both sound and picture would receive identical development, the sound negative should be developed to a gamma of about 0.5 or slightly higher. Picture-positive film was used for a number of years for sound negatives. Developers of the types used for picture negatives tend to give low contrast and fine grain, and the use of such developers helped to give the desired low value of gamma for the sound negatives.[147,148] MacKenzie[64] gives some information about the harmonic distortion which results from departures from the unity product, and thus gives an indication of tolerances with respect to development.

With the advent of sound, with its requirement for more strict control of development, control by use of sensitometric test strips, and by specified time, temperature and developer formulas[149–152] supplanted dependence on visual judgments of operators, where that practice had prevailed.[153,154] Maintenance of developer activity received much attention,[155–158] and stop baths assumed increased importance.[159,160] Rack-and-tank methods, where these had been followed,

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* Gamma is the slope of the straight portion of a curve plotted with density $\left(\text{or log of } \frac{1}{\text{transmission}}\right)$ as ordinates and log exposure as abscissae. This is known as the Hürter and Driffield, or H & D curve. Gamma product is a measure of overall contrast as compared with that in the original exposure.

† In practice, because of some loss of contrast due to stray light in optical systems, best results with pictures had been found with somewhat higher gamma product.

gave way to continuous machine processing.[161–163]

How generally the distinctions between specular and diffuse density,[164] and between exposure modulation by varying time (light valve) and varying intensity (as by glow lamp)[165] were understood at first is a question, but these points were well covered in the literature. The Eastman Capstaff Densitometer,[166] which was developed primarily for measuring picture negatives for contact printing, reads diffuse densities. This would be appropriate for measuring the densities of sound negatives for use in contact printers, but not for densities of soundtrack prints, for it is the specularly transmitted light which reaches the photocell in a reproducer.

The widely used Eastman IIb Sensitometer, brought out about 1932,[167] which gives an accurately standardized series of test exposures in the form of a step tablet with exposure time increasing in the ratio $\sqrt{2}$ per step, and ranging from about 0.004 sec to 4 sec, has been of utmost value in maintaining controls. However, it does not simulate soundtrack recording conditions, where the intensity is extremely high and the time for average exposure was approximately 1/18000 sec (1/36000 sec with a later light-valve system and in present practice about 1/90000 sec) and still shorter for low exposures. The 1934 paper by Jones and Webb[165] gives an indication of the magnitude of the error. The Eastman Sensitometer on the other hand gives exposures which approximate sufficiently well those which a print receives, and are thus suitable for determining gamma of contact prints. For many purposes it has been satisfactory to draw conclusions by applying correction factors, if needed, to the readings of these instruments.

In the course of a few years densitometers employing photocells were developed which had the advantages of greater accuracy and much faster operation than the Capstaff visual-balance type.[168–172] For exposing sound negatives for sensitometry purposes, the light valve itself, with suitable calibration, can be used. The subject is again discussed under "Intermodulation Test."

While the conditions for low distortion were to keep both negative and positive exposures on the straight parts of the H & D characteristics, studies reported in 1931 by D. MacKenzie[172a] showed that low distortion was still possible while using the "toe" range of both films ("toe recording") or that of the positive only ("composite"). Toe recording using positive stock for the sound negative might, if the recording-system light was limited, be preferable to resorting to faster and coarser-grained recording stock. In the case of single-film systems (sound recorded on the picture negative) where the development of both the negative and positive soundtracks is fixed by picture requirements, MacKenzie found that the composite system offered best promise of low distortion. Both the toe and composite systems give higher output than a classical or straight-line system, but poorer signal-to-noise ratios.

It took a number of years to bring about the full transformation from the methods (depending much on visual judgments) which had been employed for making silent pictures, to the close controls and scientific precision needed for satisfactory and consistent sound. The constant and close checking of every element exerted a pressure for improvement along the whole front, including the manufacture of the film, in which departures from uniformity were quickly detected. The story is interestingly told by J. I. Crabtree.[146] An early account is given by J. W. Coffman.[153]

Processing, Variable-Area. Since the ideal variable-area track is part clear and part black with a sharp boundary between, there is no question of preserving correct shades of gray, but in general the higher the contrast (or gamma product) the better. As in the case of variable-density tracks it must be assumed that the print development will be that which is wanted for the picture, and that has been taken in general to give a gamma of about 2.0. Variable-area negatives as well as the prints are processed in high-contrast developers. The variable-area system is noncritical with respect to gamma product but, for a given positive emulsion and processing, there is for any given negative a best setting of printer light.

A comprehensive study of available sound-recording films and their processing was published by Jones and Sandvik.[173] Another study was made by J. A. Maurer.[174] From his curves it appeared that negative densities of 1.3 or higher were desirable, and the prints which gave maximum outputs were the ones having densities (in the dark areas) about equal to those of the negatives from which they were made. This held true for negative densities ranging from 0.6 to 1.3 and higher. The maxima however were very broad.

In November 1931, Dimmick[175] reported the results of a series of determinations of conditions for maximum output from a 6000-cycle recording, using Eastman positive 1301 for negatives and prints, and 4, 6, 8 and 10 min in D-16 developer. The study covered an adequate range of the four variables — negative (recording) exposure, negative development or gamma, printing exposure and print development. The results showed that wide ranges in each of the variables could be used with comparatively small loss of output, but for any negative there was a print density at which output was greatest. It made comparatively small difference (except near the extremes) whether a given density of either negative or print was reached with small exposure and longer development or more exposure and less development, but in general the maxima were broader with the higher values of gamma, especially that of the print. The two highest gamma values in the series, 2 and 2.18 of both negative and print, in general gave best results, with negative densities (measured in the black areas) in the range 1.5 to 2, and print densities a little less in each case than that of the negative.

While maximum high-frequency output is of less consequence than avoidance of cross-modulation (which is discussed in the section on distortion) it is of interest that recommended practices based on the test just described come very close to those found to be best in later experience and after current testing methods had become established. The cross-modulation test did not come into general use until 1938.[176]

For a number of years a print density of 1.4 or slightly higher, with appropriate corresponding negative density, was taken as a practical objective. As galvanometers and optical systems were improved and finer grain films came into use, the tendency was toward higher densities for both negatives and prints, especially for the negatives.

Evolution in a Growing Industry

Greatly Expanded Developmental Activities. The development work prior to commercialization of sound was carried on largely in laboratories supported by manufacturers of supplies or equipment, or in independent laboratories, and it was done on the basis of hope for returns which might be realized either through patent royalties or through sales of equipment or both.

Once sound pictures began to be made and shown, developmental work was on a different basis. Research and investigations of numerous incompletely solved problems took on rather the character of plowing in profits, with greatly increased total expenditures for research and participation by all the major picture-producing organizations.

Of all of the problems, the most fundamental and greatest in magnitude was learning how to use sound pictures, or the evolution of a new art. This is discussed by J. E. Abbott.[177] The expression "growing pains" aptly describes the less successful phase of this evolution. Capacity for readjustment is one of the qualities of greatness in individuals and in organizations, and the motion-picture industry came through splendidly.

When any industry becomes large, and especially if its requirements are as diverse as those of sound pictures, it provides a market for numerous special-

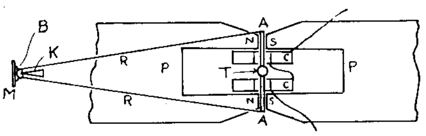

Fig. 10. Arrangement employed by G. L. Dimmick in 1929 galvanometer, for multiplying the rotation of the mirror.

ties and services. Many of these requirements are met by comparatively small organizations and others by branches of companies having many other activities and products. A few such items will serve to illustrate: special lamps, arc carbons, screens, cameras, acoustic treatment materials and service, chemicals, printers, testing equipment and studio apparatus. Many important improvements and contributions to technical advances are due to those who develop and supply such auxiliary equipment.

Mingled with the natural rivalry between picture producers has been a spirit of cooperation and sharing of experience and knowledge which has greatly accelerated progress. In 1930 this society began issuing the monthly *Journal* instead of the quarterly *Transactions*, an appropriate step to accommodate the rapidly expanding literature of sound-picture technology, covering almost every phase of the making and showing of motion pictures. The Academy of Motion Picture Arts and Sciences also played an important part in promoting interchange of information. Engineers and technicians from the sound-picture laboratories have reported experiences with various problems related to processing and controls and to sensitometry, while film and photographic suppliers have spared no efforts to enable those using their product to get the best possible results.

So many have been the contributions to the art and science along these lines, that I find it quite beyond my ability to do more than pay this general tribute and to mention a very few developments which have seemed to me to be of outstanding importance. I trust that I may be forgiven for showing partiality to the types of development with which I am most familiar, and also if I unjustly fail to mention many important advances.

Some of the Improvements After 1930

Galvanometers for Variable-Area Recording. The galvanometers used in the first variable-area recorders supplied by RCA Photophone were practically standard oscillograph vibrators, as these had been built at General Electric. They were oil-immersed and responded well up to 5000 cycles or above. An improved smaller model was brought out in 1930,[178] completely sealed instead of having an open oil well and with no external adjustments. This used molybdenum ribbon (much stronger than the bronze) and was tuned to about 6000 cycles.

When recording was started at the RKO studios in Hollywood, one of the men from the General Engineering Laboratory who had had much experience with oscillographs, F. B. Card, joined the RKO staff. The RKO engineers soon decided that their sound would be better if the frequency range were extended. The ribbons of the oscillographs had been of phosphor-bronze. A small supply of duralumin ribbon was obtained, and with this Card succeeded in re-stringing the RKO galvanometers, with sufficient tension to tune them to nearly 9000 cycles. A thinner damping fluid was then appropriate, a change almost necessary to realize the benefits of the higher natural frequency.

G. L. Dimmick came to the General Electric Co. in 1929, and one of his first projects was the development of a new galvanometer which was promptly used in newsreel equipment.[178] He used a magnetic driving system of the balanced rocking armature type and by an ingenious mechanical arrangement, shown in Fig. 10, made his mirror rotate through about ten times the angle of the armature. The important advantage of this galvanometer was that the mirror was about ten times the area of that of the previous galvanometers. A few years later Dimmick designed a new galvanometer on the same principle (Fig. 11) but improved in numerous details.[142,179,180] This became the RCA Photophone standard for all photographic recording. These galvanometers were tuned to about 9000 cycles. Damping was by means of a block of rubber, the action of which was analogous to that of the rubber line of H. C. Harrison,*[,49] but since it had to work only at high frequency it could be of quite small dimensions. Dimmick found that he could increase the effectiveness of such damping blocks by incorporating tungsten powder in the rubber to increase its density (Fig. 12).

* See June *Journal*, p. 296, third col.

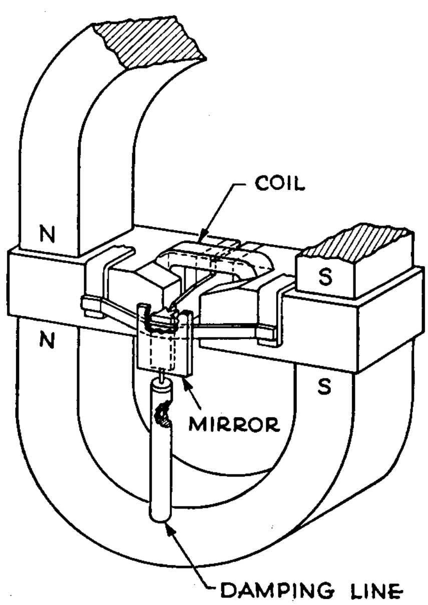

Fig. 12. Construction of RCA recording galvanometer (shown in section in Fig. 11).

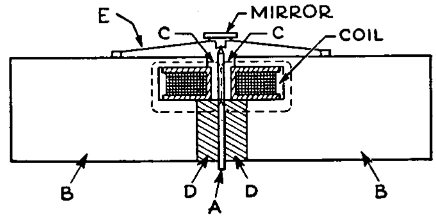

Fig. 11. Cross section of improved recording galvanometer, G. L. Dimmick. A—armature; B,B—pole pieces; C,C—working air gaps; D,D—nonmagnetic spacers; E—tensioned bronze ribbon.

Further improvements in the galvanometer were reported by Dimmick in July 1947.[181] By the substitution of better magnetic materials he was able to reduce hysteresis almost to zero, to increase the sensitivity, and to avoid a slight saturation effect which had been present in the previous design.

A More Efficient and Versatile Optical System. In order that the galvanometer in one of our experimental optical systems might be closer to the slit, and thus send more light through it, I arranged a galvanometer to work on its side, so that it would move the light spot up and down across, instead of parallel to, the slit. I used a light spot with a sloping edge at an acute angle such that the change from zero to full-length slit illumination was accomplished with a movement equal to only one-fourth of the slit length.*[,182] Dimmick improved on this by making the light spot symmetrical with respect to middle of the slit, and having two sloping edges (see Fig. 13, and in Fig. 14 compare C with B). An advantage of the transverse-movement system was that it became very simple, by changing the masks which were imaged on the slit, to produce a variety of tracks which had their special applications.[142,180,183,184]

The combination of larger mirror and reduced distance between galvanometer and slit practically eliminated the diffraction trouble that had, with the small mirrors, impaired the formation of clean, sharp, high-contrast images at the plane of the slit.

Ground-Noise Reduction—GNR.[185] Scratches and dirt on film and graininess of emulsion cause a background noise

* All galvanometers have practical limits to the angle through which they can swing the light beam. And the required light spot movement sets a minimum to the distance between galvanometer and slit. The light which a galvanometer can send through the slit is proportional to the mirror area and the inverse square of its distance from the slit, up to the point at which the objective lens is "filled."

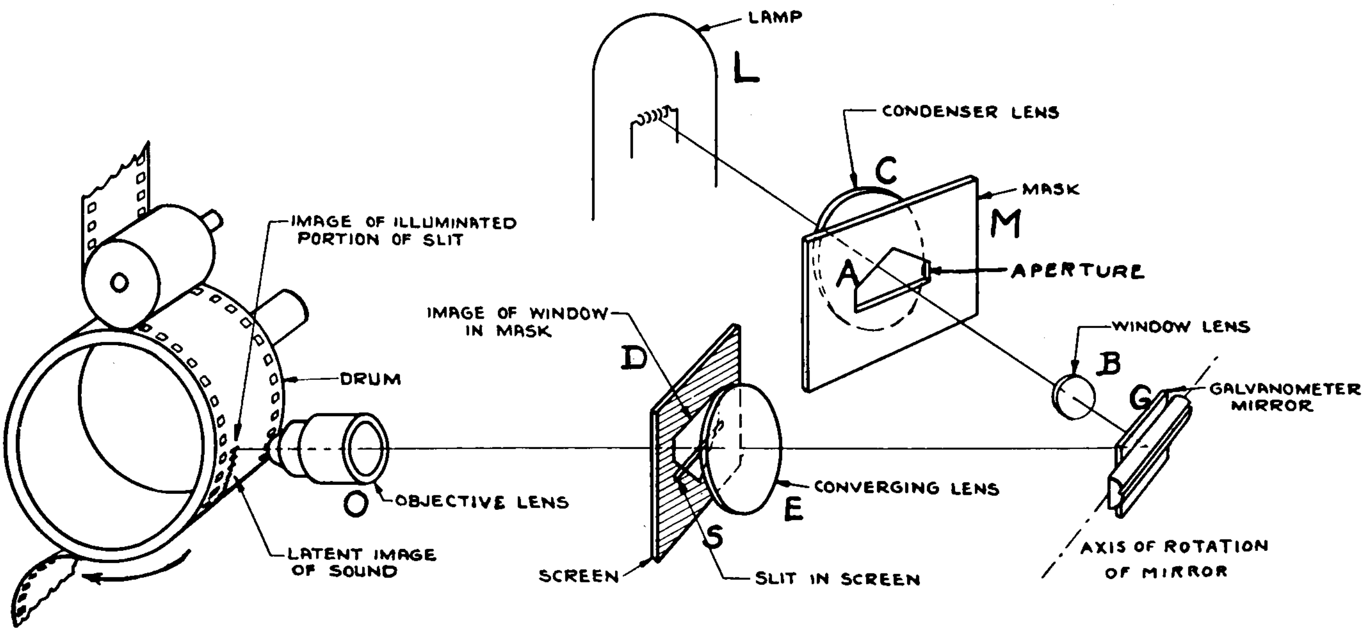

Fig. 13. Variable-area recording optical system. (Lens B images A on slit-plate D.)

which is particularly conspicuous when the modulation is low. The noise is reduced by reducing the transmitted light. At the same time, for a given modulation level there is no need for the average transmission to be more than about half the maximum. The noise may thus be reduced when the reduction is most needed, by decreasing the average light when the level of the recorded sound is low. This can be accomplished by biasing the light modulator toward zero, and then using a current derived by rectifying some of the modulation current to increase the mean light transmission when this is needed. The reduced transmission when the modulation is low means a darker track in a variable-density system, or a narrower clear area in a variable-area system, and in either case the noise is reduced. The early patent on this idea was to E. Gerlach.[186] This was assigned to Siemens & Halske, but to the best of my knowledge it occurred independently to L. T. Robinson in Schenectady and C. R. Hanna at Westinghouse,[187] and a system applicable to light valves was developed at Bell Laboratories.[188] The first trials at Schenectady with variable-area tracks did not indicate an impressively large reduction of noise, and there was an objection (in the case of the earlier, unilateral, variable-area tracks) in that the bias threw all of the low-level modulation over to one edge of the track, where many reproducing light beams were of reduced intensity. The project was revived by Hugh McDowell of RKO who got around the objection by screening off the surplus light by means of a shutter instead of biasing the galvanometer.[189] This method and the results obtained were reported to the Academy of Motion Picture Arts and Sciences by Townsend, McDowell and Clark in 1930.[190] Thereafter a commercial form of shutter was designed[191] and ground-noise reduction became standard in the RCA system (Fig. 15).

With the introduction slightly later of the symmetrical track, the objection just mentioned to depending on galvanometer bias instead of a shutter no longer applied, but there was still some danger of saturating the galvanometer. Therefore a double-vane shutter was developed to mask down the light from both sides.[192]

The Bell Laboratories system is described by Silent and Frayne.[188] In the variable-density system there is no objection to accomplishing the result by biasing the valve.

In case of a sudden increase in modulation level the rectified current would change so rapidly as to cause an audible sound. The current for the shutter or for bias is therefore passed through a filter which reduces the rate of change. Limiting the speed with which the average light can increase means some clipping of the first few modulation peaks.

The light valve is a very low impedance device, and since the bias current may have to be sustained for consider-

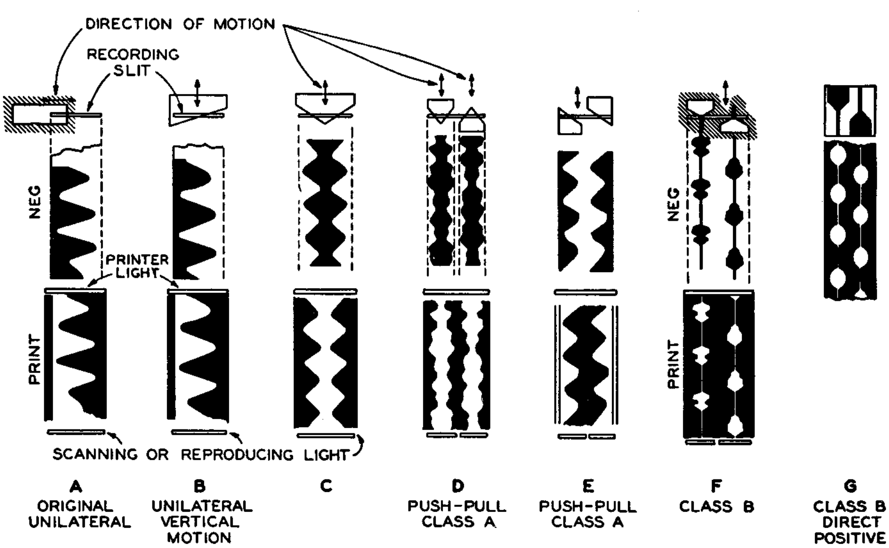

Fig. 14. Variation types of area soundtracks, and light-spot shapes which produce them.

Fig. 15. Soundtrack produced by McDowell ground-noise reduction shutter.

able periods of time transformers cannot be used for impedance match coupling to the output tube of the ground-noise reduction amplifier. In the system most widely used with light valves the modulation current is rectified, passed through the timing filter, and used to modulate a 20,000-cycle oscillator, the output of which is amplified and rectified for supply to the valve. The design of the timing filter is much simpler when it can operate at interstage impedance.[193]

As compared with variable-area, the variable-density system is characterized by ground noise which is less in the nature of "ticks" and "pops" and more a continuous hiss. Another difference is that in the density system the noise falls more rapidly with reduced light transmission, so that a given amount of noise reduction is obtained with a smaller change in transmission. The continuous hiss type of noise is especially noticeable if it comes and goes, which changing bias causes it to do. This is often called the "hush-hush" effect, and becomes noticeable if the valve opening does not immediately fall when the modulation drops to a low level. At the same time the fact that smaller changes in transmission suffice to control the ground noise makes it possible to change transmission (or bias) more quickly without causing "thump." The filters for density systems are therefore designed for much faster timing than those of area systems, particularly in closing down when modulation falls.

While clipping of initial modulation peaks is a less serious problem in density than in area recording (because of faster opening and larger margin) engineers working with both systems have given much study to minimizing such clipping. Increased margin will decrease the frequency of occurrence of clipping, but this would be at the price of more noise. In all systems, opening (increasing light) is about as fast as it can be made without becoming audible, while the closing is much slower so that very brief reductions in level will not produce incessant closing and opening.[194]

A nonlinear characteristic has been given to RCA ground-noise reduction amplifiers, which causes the opening, as a function of modulation amplitude, to rise more steeply at first and then more slowly.[185] Relatively low-level modulation is then sufficient to cause an increase in margin and thus reduce subsequent clipping. It is when the modulation is nearly zero that close margin is urgent.

Certain characteristics of speech sounds have an important bearing on the design of ground-noise reduction systems. The positive pressure peaks are higher than the negative, and it is important to maintain correct polarity from microphone to valve, or to shutter and galvanometer.[192,195] R. O. Drew and I made an investigation to determine how often speech sounds build up rapidly.[196] Instances in which maximum amplitude was reached in less than three or four waves (voice fundamental) were surprisingly rare.

The ideal solution to the problem of avoiding initial clipping would be to anticipate increases in sound level. This is discussed by J. G. Frayne.[197]

Anticipation by use of a second microphone was used experimentally in the stereophonic system described in the October 1941 *Journal* (p. 351) for operation of the compressor.[329a] A system employing a 14-msec electrical delay network is described (March 1950) by Whitney and Thatcher.[198]

When reported it had been in use for over a year by Sound Services Inc. with very favorable results. Besides reduced clipping, advantage was taken of the system to increase ground-noise reduction in density recordings by 5 db, and in area recordings to work with a bias line only 1 to $1\frac{1}{2}$ mils wide. A low-distortion network good to 8000 cycles necessarily employs many sections (several hundred). Cost is probably the reason that this expedient has not been widely employed. A direct-positive variable-area recording system with the anticipation effect provided by means of an auxiliary exposure was designed and demonstrated by Dimmick and Blaney and has been used in the Warners' studios.[199]

In the re-recording operation anticipation should be a simple matter, involving only a double reproducing system (with scanning points a fraction of an inch apart) with separate amplifiers.* Mueller and Groves (June 1949)[200] mention use of this system at Warners. I understand however that little advantage has been taken of this possibility, presumably on account of costs. The explanation is probably that when initial clipping occurs in a well adjusted re-recording system, there was probably also some at the same spots in the original recording and the possible gain from anticipation in the re-recording operation is hard to detect. If clipping, in systems using ground-noise reduction, causes an appreciable impairment to sound quality, the ideal solution is to use for original recording a system whose ground noise is inherently so low that it needs no such expedient, and then introduce the ground-noise reduction when re-recording to the photographic tracks. Similar considerations apply to the use of compressors. Among the systems which in more or less measure meet this specification are Class B area recording, wide-track push-pull (with fine-grain film and fast-acting noise reduction) direct positives with the auxiliary exposing light,[199] and direct-playback disks. A real answer to this problem seems to have come in the recent adoption of magnetic recording.†, [200, 352–388]

* In a set-up for mixing numerous sounds, it would for practical purposes be sufficient to equip only the dialogue film-phonograph with double scanner and amplifier.

Pre- and Post-Equalization. The practice of electrically exaggerating the high-frequency components in recording, as compared with the low-frequency components, in order to compensate for inevitable losses, began early in the recording of sound. Studies of the distribution of energy in program material had indicated that this could be done without resulting in overloads in the high-frequency end of the scale. A large amount of high-frequency pre-emphasis had been employed in cutting transcription disk records. In film records as well as disk records, ground noise can be made less noticeable by decreasing the gain at high frequency. Therefore, in addition to such relative attenuation of high-frequency sounds as was caused by the imperfections of reproducing systems and loudspeakers, the practice became prevalent of producing a drooping characteristic in the electrical circuits.

In order that all films might have good balance in all theaters, a committee of the Academy of Motion Picture Arts and Sciences made recommendations for a standard reproducing characteristic.[201] With such a standard adopted, the producers of sound pictures would have incentive to use recording characteristics which would give good balance when their films were played in a theater with the typical or standard reproducing characteristic.

The problem is discussed by J. K. Hilliard[202,203] and by Morgan and Loye.[204]

Better Lamps. Among the lamps used in the late 1920's for recording were some of the ribbon-filament type. These were ideal from the standpoint of uniformity, but required an inconveniently large current (18 amp) and did not have as long life at a given temperature as was obtainable with lamps of the helical-filament type. A series of lamps for sound recording and reproduction was made available by the lamp companies. The filaments were close-wound helices, of relatively heavy tungsten wire, and to permit operation at high temperatures with satisfactory life, the pressure of the inert gas (argon) with which the bulbs were filled was increased above that employed in lamps from which less intensity was required.

In the series of lamps described by F. E. Carlson of General Electric in 1939[205] the recording lamps were rated as operating at above 3100 K (color temperature) which is several hundred degrees higher than that of common

† Some experimenting has been done with a double magnetic pickup for anticipation. Cross-talk between the two heads was a problem. The difficulties will undoubtedly soon be worked out.

incandescent lamps. Somewhat later, krypton-filled lamps were introduced, permitting still higher temperatures. The krypton, being heavier, more effectively retards evaporation of tungsten. (See the section on basic inventions.)

The light from a helical filament varies somewhat, depending on the angle from which the lamp is viewed. At the suggestion of L. T. Sachtleben of RCA, the helix of the lamp used in the variable-area recordings was curved, the convex side being presented toward the lenses. The helix with the curved axis gives definitely better uniformity.[183,205,205a]

Improvements in Light-Valves and Density Optical Systems. In June 1932 Shea, Herriott and Goehner[65] described the development of improved duralumin ribbon (stronger and with straighter edges) and better methods of adjusting and anchoring the ribbons at the ends of the free span. The new anchoring system practically eliminated the frictional hysteresis which had been found in the earlier design, thus reducing waveform distortion and making for greater stability. Stability became increasingly important as the mean spacing between the two ribbons in the valve was reduced. The ground-noise reduction system called for reducing the ribbon spacing when the modulation was low, and when it was found possible in view of required exposures to reduce the unbiased spacing from 0.002 in. to 0.001 in. this was done, while still keeping the optical reduction from valve to film at 2:1.

At high frequency and high modulation, the images of the ribbon edges move with velocities comparable with the speed of film travel. This results in a waveshape distortion which would convert a sine wave into a saw-tooth wave. Fortunately such a combination of high frequency and amplitude is not often encountered in program material, and the harmonics generated would probably not be reproduced, nor noticed if they were. However, it is desirable to minimize this "ribbon-velocity" distortion, and the reduced slit width helps in that respect and also in giving better resolution or high-frequency response.

In order that harmful effects (harm to sound quality if not to the ribbons themselves) might not result when the modulation current drives the ribbons to the point of touching or hitting each other (light-valve "clash") light valves have been built with the ribbons slightly offset, or in two planes.[207] There appears to have been difference of opinion about the necessity of this precaution. It should be remembered that in a density system the downward light modulation normally stops considerably short of zero, to avoid photographic nonlinearity. In other words touching of the ribbons would represent considerable overload. The two-plane design of valve has become generally standard for variable-density recording.

The optics of light-valve recording systems[207] have been modified by the addition of a small horizontal cylindrical lens close to the film, which results in greater optical reduction between valve and film and therefore a narrower image (0.0002 in.). This makes for improved high-frequency recording and for further reduction of ribbon-velocity distortion. One of the factors which has made the narrower image possible without sacrificing exposure is that new lamps of higher intensity have become available.

Light-valve optics have been adapted to making variable-area tracks, for example as used in the stereophonic system described in 1941.[208] The valve is turned with the ribbons vertical, or parallel to direction of film travel. The lens system, which employs cylinders, magnifies the ribbon motion ten to one. This means that the lens must be close to the ribbons, hence with little depth of focus. Therefore in this application the ribbons are in the same plane, and an electrical current-limiting expedient prevents clash.[209]

A strong magnetic field is advantageous for the sake of sensitivity and damping. In the design described by Wente and Biddulph[208] an air gap flux density of 32,000 gauss is attained, an achievement which testifies to the excellence of the permanent magnet materials and the high flux capacity of the pole-piece material. There is some further discussion of light valves in the section on variable density vs. variable area.

Microphones. While condenser microphones had excellent characteristics they were more expensive and required more servicing than magnetic microphones, and it was practically necessary to provide a stage of amplification close to the microphone. On the other hand, the electrical impedance of a magnetic microphone is such that a transformer may be used if wanted, and the output transmitted at a convenient impedance. A magnetic microphone of the flexibly mounted rigid-diaphram, moving-coil type is described by Jones and Giles in December 1931.[210,211] It is a pressure-type (rather than velocity or pressure-gradient) microphone. Damping is obtained by flow of air when the diaphram vibrates, back and forth between two cavities, through passages which are of such small dimensions as to make air viscosity effective in dissipating energy.

In June 1931 H. F. Olson described the velocity microphone,[212] consisting of a ribbon of very thin aluminum (0.0001 in.) in a magnetic field between pole pieces which are adjacent to the edges of the ribbon, so that when the ribbon moves in a direction normal to its surface a voltage is induced in the ribbon. A transformer is used to step up this voltage, which is then applied to the grid of an amplifier tube. Transverse corrugations are formed in the ribbon, which prevent it from curling and give it lengthwise flexibility. It is mounted under only such tension as is needed to keep it between the pole pieces. Olson shows that theoretically such a microphone should give uniform frequency response, and that it should have a polar directivity curve like a figure 8 (cosine law), the directivity being the same throughout the frequency range. Experimental results are also given confirming the theory. The velocity of movement of the ribbon is proportional to the velocity of air movement, so that it is often called a "velocity microphone."

Since a microphone of this type responds less and less as the direction of the sound departs from normal, it picks up much less reverberation (random in direction) than a nondirectional microphone having the same sensitivity for sound of normal incidence. The ratio of direct to reverberant sound in many cases sets the limit to how far from the source the microphone can be placed, and under such circumstances a ribbon microphone can get satisfactory pickup some 70% farther from the source than a nondirectional microphone, such as one of the pressure type.[213] Advantage has been taken of the directional characteristics of the ribbon microphone to exclude certain sounds or disturbances (for example camera noise), for it is deaf to sounds originating in the plane of the ribbon.

If the output of a pressure microphone is combined in correct phase and amount with that of a velocity microphone, the combination becomes unidirectional, having a cardioid-shaped directivity curve. It has a dead-spot 180° from the direction of maximum sensitivity. The forward directivity is much less sharp than that of a velocity microphone, and such a unidirectional microphone is better suited for picking up sound over a wide angle, as for example from a large orchestra. The cardioid directivity pattern has the same advantage as the figure 8 pattern in picking up less noise from random directions than a nondirectional microphone.

Before making a unidirectional microphone, Olson worked out an arrangement for converting a velocity microphone into a pressure microphone. He placed close behind the ribbon a combination shield and absorber consisting of an open-ended tube of the same cross-sectional area as the active area of ribbon. He distributed through the tube tufts of absorbent fiber. The length of the tube was made sufficient to dissipate wave energy. The impedance of the mouth of the tube then becomes equal to that of so much free air (to plane waves) but air in which there is no other sound to react on the ribbon. The ribbon is then actuated only by the pressure on the exposed side.[214]

Having successfully made this conversion, Olson applied the same treatment to only one half of the length of the ribbon, leaving the other half to act as a bidirectional velocity microphone, and the combination has the cardioid directional characteristics.[215]

Bell Laboratory engineers also developed bidirectional or velocity microphones, and unidirectional types, but differing from the Olson type in employing a second microphone more nearly like their standard pressure microphone. The unit and its applications were discussed by Marshall and Harry in September 1939.[216]

All studios use directional microphones for situations where the maximum ratio of direct to random sound is wanted.

Loudspeakers[4,25,73,222]

Single Range Loudspeakers. For several years after the industry had adopted sound the theater loudspeakers were of the kinds already mentioned, (1) the directional baffle-type, using a coil-driven cone, much like those used in direct radiator speakers, with a short, straight-axis exponential horn of large throat area, and (2) those using long exponential horns[217,218] with small throats, and coil-driven metal diaphragms. In view of their length the horns were coiled or otherwise bent to a form which took up less space.

Multi-Range Loudspeakers and Improved Single-Range Speakers. The idea of providing separate devices to radiate high and low frequencies is undoubtedly of early origin. When practically all radiators had strong fundamental resonances, the double or triple unit could spread the range of reasonably high response over a wider frequency band. With the advent of coil-driven, untuned diaphragms, resort to separate radiators was a measure for improving efficiency, in that the design did not have to be a compromise between what was best for low and for high frequencies. A triple-horn speaker designed with special consideration to efficiency and load capacity was advocated and demonstrated by C. R. Hanna of Westinghouse in 1927.[219]

However theater speakers of the single-unit type were so far improved (by the coil-driven unit of Wente and Thuras in 1926,[57] and by the adoption of directive baffles for the GE-RCA cone-type speakers in 1929) that they handled quite well the frequency range then obtainable from film or disk.

As recording improved, the benefits from extending the loudspeaker range became more noticeable. After various improvements in the recording system including the new galvanometer, the symmetrical track, ground-noise reduction (by galvanometer bias), ribbon microphone for sound pickup, and a film-phonograph using the magnetic drive, Dimmick and Belar gave a demonstration of extended frequency range at the SMPE 1932 Spring Convention.[179] They did not resort to two-way (divided-range) speakers, for the straight-axis, directional baffle units, which had 6-in. cone diaphragms with aluminum voice-coils, had good response even at 10,000 cycles. The range was extended downward (to 60 cycles) by using slow expansion exponential horns (of the large-throat or directional-baffle type) 10 ft long, with mouth openings 75 in. square.

Multi-Range Speakers of Bell Telephone Laboratories. A divided-range speaker system was used by H. A. Frederick in the demonstrations of vertically cut disk records in the fall of 1931.[220] The high-frequency units were of the type described by Bostwick in the October 1930 *Journal of the Acoustical Society of America*, and in the May 1931 *SMPE Journal*.[221] These were equipped with small horns better to load the diaphragms. The low-frequency units were of the direct-radiator or flat-baffle type, using (as I recall it) approximately 12-in. diameter dynamic cone units,[38] a number of units being distributed over a large baffle. A curve indicates a response within ±5 db from 50 to 10,000 cycles.

A triple-range system is described by Flannagan, Wolf and Jones,[222] whose review of the development of theater loudspeakers is comprehensive and of much interest. The system is also discussed by Maxfield and Flannagan in the January 1936 *Journal*.[222a] The mid-range units were essentially like the previous single-range speakers, using the Western Electric No. 555 driver units. The radiators for the high-frequency range (3,000–13,000) were the same as used in the Frederick demonstrations. The authors state that for the range below 300 cycles large coil-driven conical diaphragms in a large flat baffle gave better results than designs using horns.

In April 1933 the Bell Telephone Laboratories gave a demonstration of reproduction of orchestra music in "*auditory perspective*,"[223,224] the orchestra being in Philadelphia and the reproduction in Constitution Hall in Washington, D.C. Three microphones picked up the music at three well-separated positions, and at the other end the independently transmitted and amplified currents were supplied to three correspondingly placed loudspeakers.

In this demonstration no recording and reproduction entered to affect frequency range, and it was essential for the purpose to provide abundant sound power and frequency range. A dual-range system was decided on.

The low-frequency unit was designed to work from 40 to 300 cycles, and consisted in a large-diaphragm, moving-coil unit, working into the 8-in. diameter throat of a horn which expanded exponentially to a mouth 60 in. square in a total length of approximately 10 ft.

The high-frequency driver unit, which covers the range 300 to 13,000 cycles is shown in cross section as Fig. 10 in the Flannagan, Wolf and Jones paper.[222] Particular attention is given in the design to the air space and passageways leading from the diaphragm surface into the horn or group of horns.

If a single straight-axis exponential horn is used, the tones of highest frequency are radiated in a direction close to the axis, while those of lower frequency are spread through much larger angles. This defect is avoided by dividing the total cross section of the passage into a number of smaller passages each of which is a small exponential horn. In this case there were sixteen horns for each driver. These are nested with their mouths adjacent and with their axes pointed in different directions to cover a total angle of about 30° vertically and horizontally. Since the horns are of equal length, the waves, whatever their frequency, unite at the ends of the horns to form a practically continuous spherical front, which is the condition for uniform distribution throughout the 30° angle. Two of these 16-horn nests were placed side by side to give the desired total of 60° horizontal coverage.

First Commercial RCA Two-Way Theater Speakers. In the RCA line of theater equipment a dual-range loudspeaker system was briefly described by J. Frank, Jr., at the 1935 fall meeting.[225] The speakers demonstrated by Dimmick and Belar, in 1932, using 6-in. cone diaphragms with aluminum voice coils, and 10-ft horns, were not seriously lacking in frequency range and were used in a number of deluxe installations, but they had two drawbacks. There were many theaters without sufficient room to install the long straight axis horns, and in addition, the high-frequency sound components were not well distributed. When a wave front reaches a point in an exponential horn at which the dimensions of the passageway are about a wavelength, its ultimate angle of spread will not greatly exceed the angle between the walls at that place. From this consideration it follows that a rapid flare horn would distribute the high-frequency sounds through considerably larger angles. Moreover with short rapid-flare horns, it is not impractical to multiply the number of units and thereby further control the sound distribution. In the theater speaker described by Frank, there were three high-frequency horns diverging in direction, the driver units being 6-in. cones with aluminum voice-coils.

These units were rated to operate effectively from 125 to 8,000 cycles, and a separate folded horn unit took care of sounds in the 40 to 125 cycle range.

One of the practical advantages of a direct-radiator (flat baffle) loudspeaker is the small space it requires. However a horn makes it possible to radiate more sound from a given-sized diaphragm without increasing the amplitude of motion, and is therefore desirable for increasing the sound output capacity. It also affords some control of the direction of radiation. But to radiate low frequencies the rate of expansion (ratio of increase in cross section per unit distance along axis) must be small, which for a given total ratio of expansion means length. One way to provide a long passageway without requiring excessive depth of space back of the screen is to coil up the horn. Drawings of coiled horns are shown in ref. 1, p. 298, and on p. 251 of the March 1937 *Journal*. The bending of large sound passageways is objectionable. Instead of expanding continuously as in the ideal horn, short waves suffer repeated reflections by the walls, causing some irregularities in the response and making the direction of radiation of high-frequency sounds rather unpredictable.* On the other hand if the horn is to handle only low-frequency sounds, the shapes of the bends are not at all critical, and the condition is easily fulfilled that the difference between the shortest and longest paths around a bend is a small fraction of a wavelength.

In a common form of low-frequency horn (in the sense of an approximately exponentially expanding passageway) the driver unit (or units) is at the middle of the back of a box-shaped space, and the passage is forward for a short distance, dividing and forming two passages which turn back and then forward and expand to form a pair of large adjacent rectangular openings, which together form the mouth of the horn. This roughly describes the low-frequency unit of the theater speaker system reported by Frank, the drivers in that case being a pair of 8-in. coil-driven cones.

Shearer System.[226] In 1936 Douglas Shearer, sound director for M-G-M, gave demonstrations of improved sound, using loudspeakers described by J. K. Hilliard in the July 1936 *Journal*. The high-frequency radiators in this system were similar in many respects to those used for the Auditory Perspective demonstrations (see figure in Hilliard paper). The frequency range to be covered was 50 to 8000 cycles, and the division or cross-over was at 250 cycles.

The low-frequency unit was a folded horn, with four 15-in. cones in a vertical column. For simplicity of construction the expansion was all in the horizontal

* This effect can be largely reduced by careful design of re-entrant (zig-zag passage) horns.

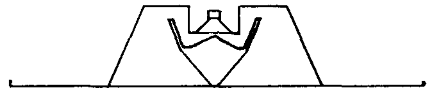

Fig. 16. Control of film speed by flexure (A. V. Bedford). Principle later utilized in nonslip printer.

plane, accomplished by suitably arranged vertical partitions. The horn cross section was divided into two expanding passageways, whose final openings together form a 68-in. square (Fig. 16). This was surrounded by a flat baffle 10 × 12 ft, to reduce end reflections and improve the loading of the units. The mean length of each passageway was 40 in. (very short as low-frequency horn designs go), nor was the expansion ratio large, the throat area being sufficient to accommodate the four 15-in. cones.

A nest of high-frequency horns, similar to that used for the Auditory Perspective demonstrations, three high by six horizontally, covered a horizontal angle of about 100°. With the lengths of the high- and low-frequency horns nearly the same, there would be little time difference in the arrival of the sounds at the plane of the mouths, thus simplifying the avoidance of a "phasing" error which has been found to have detrimental effects with transients. However, in all divided-range speaker systems the best relative positions of the high- and low-frequency units have been determined by careful trials. This problem of "phasing" is discussed by Maxfield and Flannagan,[222a] by Hilliard[226] and others. It appears to be not wholly a question of minimizing the mean time difference, although that is a part of it.

In all divided-range speaker systems, dividing networks[227] have been used to separate the high- and low-frequency portions of the amplifier output and direct each to the appropriate speaker units. The networks consist in general of simple filter sections, and their design has received much study.

Commercial Two-Way Systems. Commercial models of dual-range or "two-way" theater speakers were brought out in 1936, employing the multicell high-frequency horn system, and low-frequency units much like those described by Hilliard. The high-frequency driver units of the RCA system differed from the ERPI and Lansing designs in that the diaphragms were of molded phenolic instead of aluminum. This resulted in a more rugged, if less sensitive, device. The reduced sensitivity and greater "roll off," or falling off at high frequency, can be readily compensated electrically, and do not mean any serious increase in amplifier output power, because the high-frequency components of the sound represent only a small part of the total sound power.

The ERPI "Diphonic" speaker system is described in the Flannagan, Wolf and Jones paper.[222]

The description by Hilliard of the Shearer low-frequency unit may be taken as in general typical of the commercial speakers of 1936–7.

Divided channel or "two-way" speakers came into wide use during the several years following 1936.

In some later designs of low-frequency units, the sound passageway was not folded, and consisted only of a short flaring connection between the driver units (which presented a large total radiating surface) and the large opening in the flat baffle.* It is of interest that the evolution of low-frequency sound sources has been toward a closer resemblance to the cone and baffle speakers of 1925, but greatly magnified in size, and with some "directive baffle" effect better to control sound distribution.

Higher crossover frequencies than the 250-cycle point of the Shearer system have prevailed, 400 cycles being the choice in many of the postwar units. In 1948 Hopkins and Keith[228] described the design of a two-way theater speaker in which the crossover had been raised to 800 cycles, observations having been made that the irregularities which are apt to occur at the crossover frequency are less prejudicial if the crossover is above the frequency range of maximum energy (250 to 500 cycles for orchestra music).

A photograph of a loudspeaker designed to use with "Cinerama" is shown in the May 1954 SMPTE Progress Report, p. 343. This is more or less typical of recent practice. The horn (or directive baffle expansion passage) of the low-frequency units as well as that of the high-frequency unit is designed to give exponential expansion of the total cross section by side walls which are radial, the floor and ceiling of each passage being curved to compensate. The reflex, phase-inversion principle (mentioned under "Monitoring Speakers") is employed to utilize radiation from the backs of the diaphragms, for the extreme bass. Note in the illustration the outlet slots on either side of the horn mouth.

Alternatives to Multicellular Horns. A somewhat simpler way of achieving the directive characteristic for which the multicellular high-frequency horns were designed has been developed in the postwar period by RCA and others. Horns are used with linear expansion in the horizontal plane (i.e. walls radial with respect to the throat), while in the vertical plane the rate of expansion

* This would raise the "cutoff" frequency of the horn, but where the total expansion ratio is comparatively small that is not necessarily very significant. Below its "cutoff" frequency, an exponential horn does not impede sound transmission. It merely fails to multiply the volume displacement as it does above cutoff.

is such as to bring the total expansion of the cross section to an exponential relation.

Another expedient for gaining the desired spread of high-frequency sounds was described by Frayne and Locanthi at the May 1954 convention of this Society.[229] If the waves issuing from a straight-axis exponential horn can be made to assume a spherical instead of nearly flat front, they will spread as desired. An acoustic equivalent of a concave optical lens is placed in the mouth of the horn, in order to retard the off-axis parts of the waves relative to the central part. The reduced velocity of propagation is achieved by means of a series of closely-spaced perforated sheet-metal baffles, the number of layers being progressively greater toward the edges. This system was reported to have given smoother distribution than the multicell horns.

Monitoring Loudspeakers.[4,230,231] Wider-range monitoring speakers kept pace with theater speakers. While a single conical diaphragm can be designed so that the center portion radiates high frequencies and the outer area radiates low frequencies, best results have been obtained by using separate diaphragms and separate voice coils, or in other words resorting to the dual-range system. The upper- and lower-range units may be adjacent or concentric. In the latter case the low-frequency diaphragm becomes a directive baffle for the high-frequency radiator.

Permissible cabinet size tends to set the lower limit of the frequency range, air reaction on the back of the diaphragm creating the problem if the back is enclosed, or inadequate baffling if an open-back cabinet is used. In order to utilize the radiation from the back of the low-frequency diaphragm, a second opening is often provided (for example below the diaphragm) and the space in the cabinet used to provide a folded horn between the diaphragm and the opening, or else to serve as a simple chamber which acts in conjunction with the inertia reactance of the air at the second opening as a phase inverter. This does not greatly augment the low-frequency output except near the resonance, set by the elastic reactance of the cavity and the inertia reactance of the combination of openings (one with the diaphram and one without). Sound-absorbing material is often used in the cabinet to reduce the magnitude of other resonances. If the horn-type back-wave system is used, its augmentation of output is limited at the lower end when the phase shift through the horn becomes less than about a quarter cycle, and at the upper end by the fact that it is deliberately designed to have a low-pass filter characteristic.

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