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A NEW METHOD OF COUNTERACTING NOISE IN SOUND-FILM REPRODUCTION

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Reproduction of the sound recorded on sound-film is usually accomplished by means of a narrow beam of light thrown upon the film in a direction perpendicular to that in which the sound track is moving. The fluctuations in the light flux passed through are converted into sound. With this method a noise results which is caused by the fact that part of the light passed through is intercepted by specks of dust, scratches, etc. on the sound track, especially when the film has already been used several times. This articles describes a method of counteracting this noise in cases where the sound is recorded as so-called amplitude writing. The beam of light is replaced by a series of equidistant light spots moving with great velocity perpendicular to the sound track. In addition to the theoretical fundamentals of the method, a practical form of application is also discussed.

The ordinary method of reproduction

The reproduction of sound recorded on sound film is usually reproduced in the following manner. A narrow beam of light is thrown on the film perpendicular to its direction of motion. Confining ourselves to the case where the sound is recorded as so-called amplitude-writing, such as for example with the **Philips-Miller** film [1], the quantity of light passing through the film depends upon the width of the sound track (and of course of the beam). The light passes through to a photocell and is converted into an electric current which may be considered as a direct current upon which an alternating current is superposed. The magnitude of this direct current depends upon the width of the so-called zero track, *i.e.* the track which is made when no sound vibrations are being recorded. The zero track is unavoidable, since otherwise modulation would be impossible. It is easy to understand that its width must be equal at least to once or twice the maximum modulation amplitude, according as the modulation takes place on one side or on both sides of the track.

The alternating current depends upon the modulation of the track and thus on the sound vibrations recorded, and if the light beam were infinitesimally narrow the trend of this current would be an exact copy of the sound vibrations. Actually the beam has a finite width Δ, but even so the relation between the sound vibrations recorded and the corresponding vibrations of the light flux can easily be determined. Let us assume that the sound track is modulated by one harmonic vibration. Such a vibration is represented in *fig. 1.* When this vibration corresponds to a tone of ν oscillations per second, and when the velocity at which the film is travelling is v cm/sec, there are ν/v vibrations per cm of film and the vibration can be represented by the equation $y = q \cos 2\pi \cdot \nu/v \cdot x$, where y is the depth of modulation and x the length of film passed, measured from an arbitrary zero point,

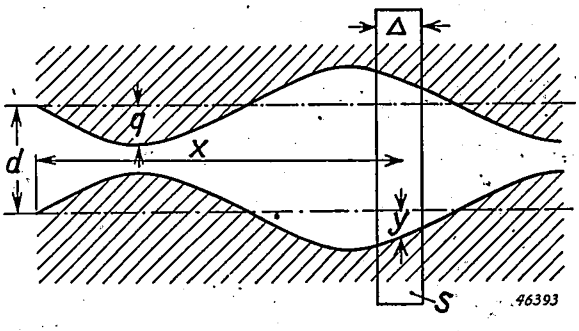

Fig. 1. Diagram of the usual method of scanning. The film with the modulated sound track travels past this beam S. The variations in the light flux passed through are registered by a photocell. In the diagram the track is modulated on both sides by a purely sinusoidal vibration. d width of the unmodulated track, q amplitude of the vibration with which the track is modulated, y depth of modulation at the point with the abscis x, Δ width of the slit.

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[1] For a description of the Philips Miller system, see Philips Techn. Rev. 1, 107, 135, 211, 1936.

The amount of light passed through is then proportional to

$$\Delta\cdot d + 2\int_{x-{}^1/_2\Delta}^{x+{}^1/_2\Delta} q\cos\left(2\pi\frac{\nu}{v}\,\xi\right)\mathrm{d}\xi = \Delta\cdot d + {} + \Delta q\cdot\frac{\sin \pi\frac{\nu}{v}\Delta}{\pi\frac{\nu}{v}\Delta}\cos 2\pi\frac{\nu}{v}x\,.$$

d representing the width of the zero track. From the result it is immediately clear that a DC and an AC component are present, while it is also clear that the amplitude of the AC component is multiplied by a factor which depends upon the frequency ν. This factor

$$\frac{\sin \pi\frac{\nu}{v}\Delta}{\pi\frac{\nu}{v}\Delta}$$

is equal to unity when $\nu = 0$, and then decreases. In order that the highest frequencies to be reproduced should not be attenuated by more than about 3.5 db compared with the lowest (such an attenuation is still permissible) it is necessary that

$$\pi\cdot\frac{\nu_{max}}{v}\cdot\Delta < 1.5\,.$$

With $\nu_{max} = 8000$ and $v = 32$ cm/sec this results in $\Delta < 0.002$ cm. The light-beam may therefore not be wider than 20 μ. [2])

When there are specks of dust or dirt on the sound track or when it has been scratched, as is particularly the case with much used sound films, these tiny specks and scratches, irregularly distributed over the surface of the film, cause a noise. They cannot, however, be observed individually, as is the case with larger particles (> 80 μ), which cause an annoying ticking or bubbling sound. It would mean a considerable improvement in reproduction if this noise could be avoided.

For some time already a system has been in use which diminishes this noise. It is based on the following principle. The noise is most annoying during the soft passages, *i.e.* when the depth of modulation is slight. In sound recording it is now arranged, by means of suitable connections, that during these passages the zero track becomes narrower, thus reducing the area upon which the troublesome specks or scratches may occur and thereby also the noise. During the louder passages the zero track again becomes wider, and thus also the noise becomes louder, but this is less troublesome here because for the greater part it is drowned out by the music or speech.

This method, therefore, does not eliminate the noise, but only reduces it during the soft passages.

Principle of high-frequency scanning

We have seen that in the scanning method described above the noise is caused by contaminations on the transparent part of the film between the two edges of the sound track. This phenomenon therefore also occurs when the edges of the track, which actually represent the sound, are ideal. With the method of high-frequency scanning, about to be discussed, only the edges of the track are scanned; the influence of the part between the edges is eliminated and thus also the noise, in so far as it is caused by specks on the transparent part of the film. Of course the noise resulting from imperfections in the edges of the sound track, to which we shall return later, still remains, just as with the method of zero track adaptation discussed above.

With this method of scanning, instead of a narrow slit of light, we have a series of light spots moving at a very high velocity and at regular intervals perpendicularly across the film. Since the sound track is also moving, the light spots actually move in an oblique direction across the film. Here, too, the light passing through falls on a photoelectric cell, which gives a current impulse during the time that the light spot is moving between the edges of the track. The image of this impulse is approximately rectangular. The intensity of the impulse is determined by the intensity of the beam of light employed. The duration of the impulse depends upon the width of the track at the point where the light spot crosses it. Thus in *fig. 2 AB* in the lower half corresponds to *ab* in the upper half, the same being true of *CD* and *cd*, etc. It is essential to note that *the beginning and end points of the blocks* are fixed by the *edges of the sound track.* (For the sake of clearness the obliqueness of the paths of the light spot across the film is exaggerated.) Contaminations on the film are manifested by variations in the beam of light passed through and consequently the image of the current impulses is not actually as shown in fig. 2b, but as in *fig. 3;* between *A* and *D* the current is not constant, variations occurring of an accidental nature. The great advantage achieved lies, however, in the fact that the disturbances are separated from the phenomenon to be reproduced, the former affecting

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[2]) *Cf.* J. F. Schouten, Synthetic Sound, Philips Techn. Rev. 4, 167, 1939.

the height of the blocks, while the latter only affects the beginning and end points of the blocks.

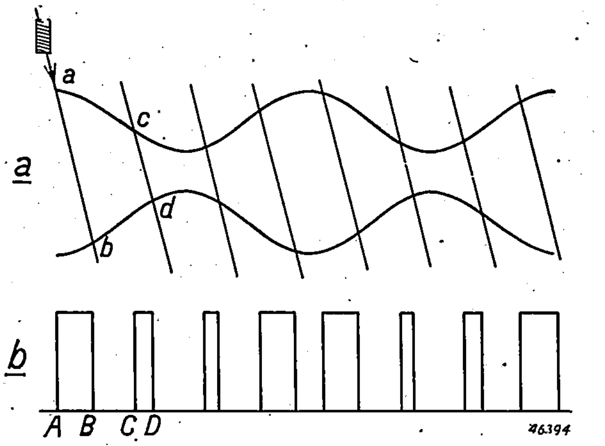

Fig. 2. Diagram of the high-frequency method of scanning. A series of equidistant spots of light travel at a high velocity across the film. Owing to the fact that the film is also travelling at the same time, the light spots describe paths which are oblique with respect to the film and which are given in fig. *a*. The slope of these paths is very much exaggerated for the sake of clearness. As long as a light spot is inside the edges of the track, a current flows in the photocell. The form of the signal leaving the photocell is shown in fig. *b*. The block *AB* corresponds to the path *ab*, etc.

Therefore the disturbances can easily be eliminated by sending the whole signal through a limiter which only passes signals up to a certain amplitude. In this way the disturbances are, as it were, cut off. For the current variation shown in fig. 3 a limitation to the level *EF* would be sufficient to bring about this elimination. If the signal is afterwards so amplified that the amplitude is increased in the ratio *BA*/*EA*, a signal is obtained which is absolutely identical with what would have been obtained if the sound track had been everywhere uniformly transparent.

We must now consider the question as to how we can derive the original sound frequencies from the block-signal. The frequency spectrum of this signal must first be investigated. This involves complicated calculations which will be further dealt with on another occasion. Suffice it here to go into a few qualitative considerations. Let us first examine the unmodulated signal. It consists of congruent blocks having a frequency μ (the scanning frequency). If a Fourier analysis is made of this signal, vibrations with the frequencies μ, 2μ, 3μ, etc. are obtained. If we now modulate the block signal with a frequency ν, secondary frequencies then appear in the spectrum: $\mu \pm \nu$; $\mu \pm 2\nu$; $\dots 2\mu \pm \nu$; $2\mu \pm 2\nu$; $\dots 3\mu \pm \nu$; etc. It is, however, quite obvious that also the frequency ν itself will occur. Let us again consider fig. 2. The blocks corresponding to the wide parts of the track are wide and consequently the wide parts give rise to relatively long current impulses with short interruptions. In the case of the narrow parts of the track it is just the reverse. If we now pass this signal through a suitable filter, *i.e.* a low-pass filter, with limiting frequency coinciding with the highest frequency that has to be passed through, the result is that the signal, roughly speaking, is replaced by a progressive average over a certain time interval approximately of the order of 1/4 of the time of vibration of the limiting frequency. Thus in each case a number of successive blocks is averaged and the result is a signal which is strong when the blocks are wide and weak when they are narrow, thus an alternating current with a frequency ν corresponding to the frequency of the vibration originally registered.

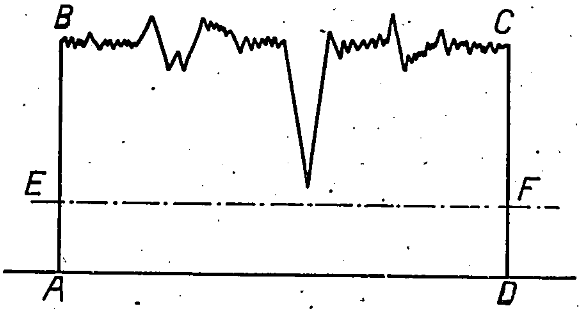

Fig. 3. Image of a current impulse from the photocell. The intensity variations are due to contaminations on the film in the path of the scanning light spot. The essence of the method lies in the fact that the influence of the contaminations can be eliminated by passing the signal through a limiter. Limitation to the level *EF* would in this case be sufficient.

For reproduction it is essential that the frequency ν should occur but that 2ν, 3ν etc. should be absent. That this is indeed the case is proved by calculation, though it is not easy to imagine. It is obvious, however, that this is of importance, for, as a rule, with ν also 2ν and possibly 3ν etc. lie in the audible range.

We can now also make it clear that the scanning frequency μ must be much greater than the highest frequency ν to be reproduced, because in addition to μ owing to the modulation also the tones $\mu - \nu$, $\mu - 2\nu$, etc. occur. These tones become weaker as we get farther away from the frequency μ.

Calculation shows that the frequency $\mu - 5\nu$ is already 60 db weaker than the frequency ν. The frequency $\mu - 4\nu$ would still be strong enough to be disturbing. If we are to eliminate this by means of a filter, then it must fall outside the audible range, and this means that:

$$\mu - 4\nu_{max} > \nu_{max}, \text{ or } \mu > 5\nu_{max},$$

where ν_{max} represents the highest frequency of the audible region which is to be reproduced.

Taking $\nu_{max} = 8000$ c/sec, it follows that $\mu = 40\,000$ c/sec.

Limitations of the effect of the method

It must be pointed out that not all disturbances can be eliminated in the manner described. Two cases must be examined separately.

In the first place a contamination may be so large and consequently intercept so much light as to cause the photocurrent to fall below the value that passes through the limiter. The result is a "dent" in the corresponding block which again causes a disturbance. This is especially the case when the light is entirely cut off by the contamination, in which event one light spot produces two current impulses (blocks). However, by giving the light spot an oblong shape it is possible to ensure that this case seldom occurs. Already in the beginning of this article it was observed that the width of the light beam in the ordinary method of scanning may not be more than 20 μ, because otherwise the high tones would be weakened. This applies also for the width of the light spots, but not for their height. (By width we mean here the dimension perpendicular to the motion of the light spots and by height the dimension parallel to that motion.) An increase in the height for instance to 100 μ has by first approximation the same effect on the fluctuations of the transmitted light flux as if the zero track had been taken 100 — 20 = 80 μ wider and the height left the same. This can easily be explained: Owing to the finite height of the light spots the photocurrent impulses do not have the form of rectangles (apart from the disturbances due to contaminations), but of equilateral trapezia. During the time that the light spot is moving over the edge of the track, the intensity increases from zero to the maximum value and decreases again from the maximum to zero. In *fig. 4* two cases are depicted for different heights of the light spots. It is assumed that they begin to pass over the track at the same moment. The photocurrent impulses then begin at the same moment for both, at the point *A*. We further assume, of course, that the two light spots move at the same velocity, so that the light intensity increases in the same way and the trend of the photocurrent will be the same in both cases, for instance along *AB*. A difference occurs only when the lowest light spot is completely over the track, let us say at *B*. From that moment the corresponding photocurrent (except for disturbances) remains constant. For a short while, however, the current corresponding to the highest spot continues to increase at the same rate, until this spot is also entirely over the track, let us say at *B′*, from which moment the second current, too, is (practically) constant.

As soon as the upper edge of one of the spots has reached the other side of the track, the corresponding current begins to decrease again. Under our assumptions this will take place at the same moment for both currents and the points at which this takes place, namely *C* and *C′*, lie vertically above each other. The decrease is at the same rate as the increase and thus equal for both spots (the current curves are equilateral trapezia). The currents thus decrease according to two parallel straight lines, *CD*//*C′D′*. Therefore they do not end at the same moment. The difference *DD′*, however, is entirely determined by the difference in intensity *CC′* (and the velocity of the spots, which is however, the same for both), and this in turn depends exclusively on the difference in height of the spots. If we pass the two signals through the same limiter then from our reasoning it follows that the signals finally obtained differ only in length, but that this difference is the same for all blocks and therefore has no effect on the sound to be ultimately reproduced. It only alters the *DC* component of the photocurrent signal, just as a change in the width of the zero track would do, and this is suppressed by a filter. If the height of

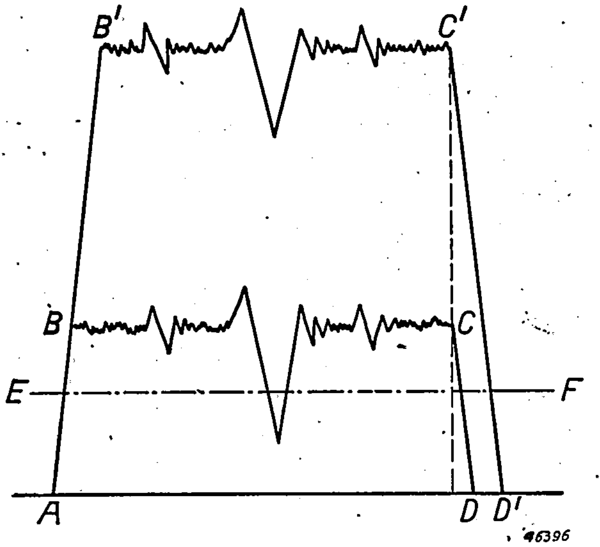

Fig. 4. Influence of the height of the light spot on the form of the photocurrent impulses excited by the light spot. Owing to the fact that the spot has a finite height, some time elapses before the whole spot is over the track. During that time the current increases continually. The impulse *ABCD* is due to a low spot, the impulse *AB′C′D′* to a higher one, the topside of both spots having reached the edge of the track at the same moment. In the second case the average current of the photosignal is larger. Limitation of the signal to the level *EF* is therefore sufficient to eliminate all disturbances in the second case but not in the first case.

the spot is greater than the width of the track, the situation is somewhat different, but a closer investigation shows that in this case too the length of the blocks of the limited signal, except for a constant, is proportional to the width of the track at the place where the light spot passed.

From the foregoing it will be clear that it is possible to choose such a height of the spot that practically speaking the transmitted light cannot be cut off by contaminations to such a degree that after limitation such disturbances still have any effect. This is in fact demonstrated in fig. 4. The absolute changes in intensity of the transmitted light beams resulting from contaminations are the same for both spots. Therefore the noise assumed to be present in this case is without influence on the limited signal with the higher spot, but with the lower spot it does leave a disturbance in the limited signal.

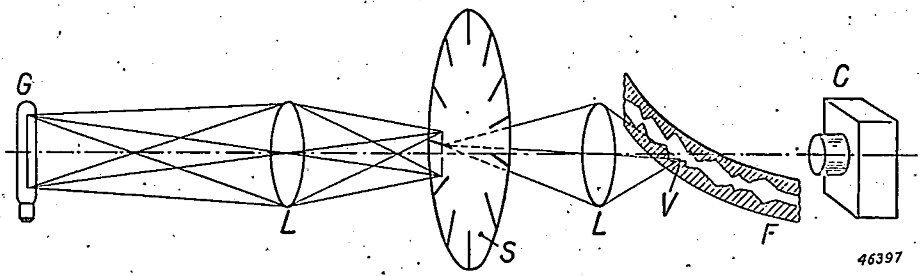

Fig. 5. Diagram of the set-up for high-frequency scanning. *G* source of light with linear filament. *L* lenses. *S* rotating disc with slits. *F* film with modulated sound track. *V* light spot. *C* photocell.

The second possibility of disturbances occurs when a contamination lies exactly tangent to or across the edge of the track. This alters the form of the limitation. The disturbance caused by such an imperfection in the edge of the track is not eliminated by the method discussed here. The chance of such a disturbance occurring, however, is slight compared with that caused by a speck elsewhere on the track. The modulated track is at least 1 mm wide, so that the chance of contaminations, even of the size of 100 μ, coming to lie at the edge is only 20%; most contaminations, however, are much smaller and there is therefore still less chance of their lying at the edge of the track.

One possible construction of the apparatus

The above-described high-frequency scanning can be realized in different ways. In the first place the sound track can be scanned by a moving light spot. as has been assumed in the foregoing. In principle the same results can be attained by projecting the image of the sound track and causing this image to vibrate with respect to a diaphram. In both cases we may consider the vibration as being brought about with a moving light source and a stationary optical system, but also with a stationary light source and a moving optical system. Finally the vibrations may be construed as being brought about by electrical means as well as by mechanical means. We shall here confine ourselves to the description of a method worked out by us in which the scanning is accomplished with a moving light spot obtained from a mechanically moved optical system.

In *fig. 5* a diagram is given of the arrangement employed. The light from a linear source is projected by a lens several mm from the edge of a disc which can be rapidly rotated. In this disc radial slits have been sawed beginning at the edge. When the disc is rotating rapidly, therefore, each slit allows a fraction of the light from the image to pass through. The image of the illuminated opening is focussed on the sound film by means of a second lens. The light passed through the sound track falls on a photocell and gives rise to the photocurrents already mentioned.

The practical realization of such a set-up involves a number of technical difficulties which we shall now discuss.

The choice of light source

We have already remarked that the width of the light spot on the film may not amount to more than 20 μ. Furthermore it must be very sharp (the transition from light to dark must take place within a distance of not more than a few μ) and not only when the projection is along the axis of the system, but also when the image is about 1 mm above or below it. Finally the light must be of sufficient intensity to excite a reasonably amplifiable photocurrent. These conditions make certain demands on the optical system and the source of light.

Linear light sources whose incandescent body is narrower than 80 μ are difficult to produce.

This implies that the optical system must be a reducing one. The same conclusion is reached from the requirement of sharpness of projection. A five-fold reduction suffices for both requirements. This reduction is mainly effected by the second lens. The first lens gives practically an image of 1 : 1. The requirements for sharpness of the image make it necessary to work with small opening angles.

Finally from the minimum required light intensity of the beam that falls upon the photocell and from the dimensions of the optical system it is to be deduced that the brightness of the light source employed must be at least one thousand candle power per cm^2. In order to satisfy these requirements a special lamp was constructed.

Construction of the rotating disc

The greatest difficulty lay in the construction of the disc. As already mentioned, the required frequency of the light spots is 40 000. The width of the track for Philips-Miller film can be set at a maximum of 1.6 mm, hence a velocity of the light spots of 6400 cm/sec. Since, as mentioned above, the second lens reduces by a factor 5, this leads to a peripheral velocity of the disc of 32 000 cm/sec. Now the peripheral velocity determines the stresses occurring in the disc. Similar discs of different diameters but with equal peripheral velocities exhibit exactly the same stresses at corresponding points. At a velocity of 32 000 cm/sec. these stresses are enormous and approach the yield point. It is clear that this sets an upper limit for the velocity. In fact if this limit is reached the disc flies to pieces.

Since for different materials under otherwise similar conditions the stresses are proportional to the specific weights, a material had to be found with the most favourable ratio of yield point to specific weight. Moreover, having regard to the motive power for the disc, the material had to be electrically conductive, so that practically only duraluminium and electron could be considered. Furthermore, since the highest stresses occur where the hole is drilled for the spindle, the disc was given a very slightly conical profile.

It can then be calculated that both for duraluminium and for electron the maximum stresses occurring, even at a velocity of 40 000 cm/sec, still remain below half the yield point value. This was in fact confirmed experimentally by investigating at what peripheral velocity a test disc flew to pieces. This was found to be at 60 000 cm/sec (the stresses are proportional to the square of the velocity). From *fig. 6*, which is a photograph of the fragments of the disc, it is apparent that the break began at the spindle, as was to be expected.

Furthermore, as it was desirable not to make the apparatus too cumbersome, the disc could not be made too large. Its radius was therefore fixed at 5 cm. This means that a speed of rotation of $32\,000/10\pi = 1000$ rev. per sec. is required. Since the slits have to be about $5 \times 1.6 = 8$ mm apart, $10\pi/0.8 =$ approx. 40 slits can be made on such a disc. They are 0.6 mm wide and 3.5 mm long (from this it follows that the length of the light spots on the film is 120 μ). The cutting of the slits requires much care.

In the first place they have to be spaced at exactly equal distances and must be exactly alike, as otherwise the frequency of revolution of the disc appears in the frequency spectrum, and since this lies in the audible region there will be a whistling tone in the sound reproduced. The scanning frequency, which is 40 times as high, lies, as we know, outside this region.

In the second place very careful finishing is essential because otherwise at the high speeds of rotation the disc might crack at the slits. For that reason before the slits are cut small holes are drilled at the spots where the slits end.

Bearings and motive power of the disc.

With the above mentioned very high number of

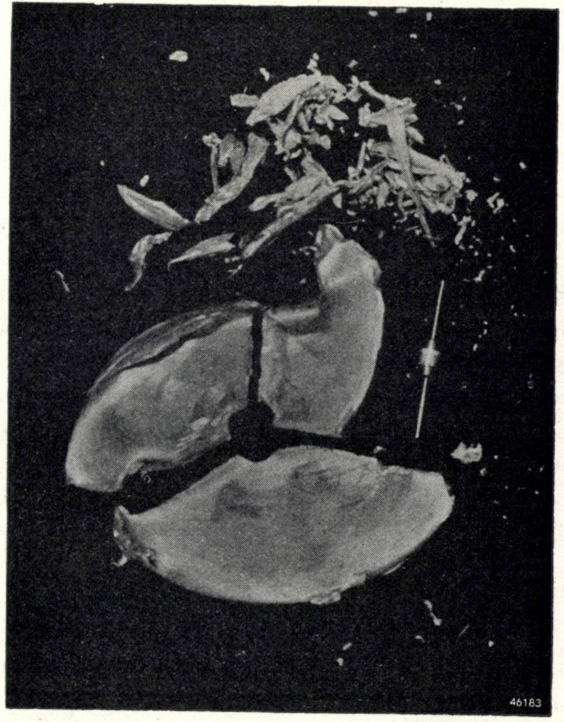

Fig. 6. Fragments of a rotating disc which flew to pieces at a peripheral velocity of about 60 000 cm/sec. The photo shows that the fracture began where the spindle passed through.

revolutions of 1000 per sec special demands are of course made of the bearings. Even a slight excentricity of the centre of gravity of the disc with respect to the centre of the bearings gives rise to enormous centrifugal forces as the speed increases, resulting in high pressures on the bearings, vibration of the motor, high friction and heavy wear. In order to avoid this the principle of the de Laval shaft was employed, with a thin flexible spindle instead of the usual rigid shaft. Due to the centrifugal force the spindle will sag already at a low number of revolutions, and this sag becomes greater as the speed of rotation increases. When a certain speed is reached, the so-called critical speed, the sag will theoretically even be infinite. Above that speed the sag decreases rapidly and at the limit for infinitely high speed the disc will rotate about its centre of gravity. When this state is reached the sag of the spindle and consequently the pressure on the bearings is very small. The bearing pressure is then mainly determined by the disc's own weight.

A difficulty in working with a de Laval spindle lies in the passing of the region of the critical frequency when starting up. It is possible to do so without breaking the spindle if that region is passed so quickly as to leave no time for the disc to assume large deflections. In our case, however, the driving couple was not large enough for this and we therefore decided to suppress the dangerously large deviations by applying a suitable damping arrangement to the spindle. For that purpose the spindle is passed through eyelets at a short distance from the disc on either side. These eyelets are connected by rods to small pistons moving up and down with a little play in small cylinders containing oil. By this means the lateral movements of the disc are damped, and by choosing suitable dimensions for this device the vibrations in the critical region can be kept sufficiently low. Once the critical region is passed, the disc runs very quietly and speeds of 1000 and 2000 revs/sec are easily attainable.

As already remarked in passing, the disc is driven electrically. It is placed in the field of two mutually perpendicular magnetic circuits activated by alternating currents with a frequency of 1500 c/sec and shifted 90° in phase with respect to each other. Each circuit consists of two pole shoes, between which air gaps of about $^1/_2$ cm have been cut. The disc is placed in these air gaps. The combination of the two alternating magnetic fields produces a rotating field which turns the disc — made of a conducting material especially for this purpose — and is able to give it sufficient velocity. In order to minimize friction the disc with the complete driving mechanism is placed in an air-tight housing, so that it can function in a vacuum.

The limitation of the signal and its conversion into sound

The current impulses from the photocell, which are of the order of 10^{-7} A, are first very strongly amplified. For this purpose a wide-band amplifier is used which gives amplification constant within 6 db in a region from 30 to 500 000 c/sec. These voltage impulses are modulated, in the first place by fluctuations resulting from contaminations on the sound film, but in addition a noise connected with the powerful amplification is superposed on the whole signal.

As has already been mentioned in discussing the principle of the method, these disturbances are eliminated by limiting the signal. For this purpose a pentode with high anode resistance is used. As is known, by introducing a sufficiently high resistance in the anode circuit of such a valve the I_a–V_g characteristic can be made to assume the shape of the curve k in *fig. 7* 3). If, then, we apply

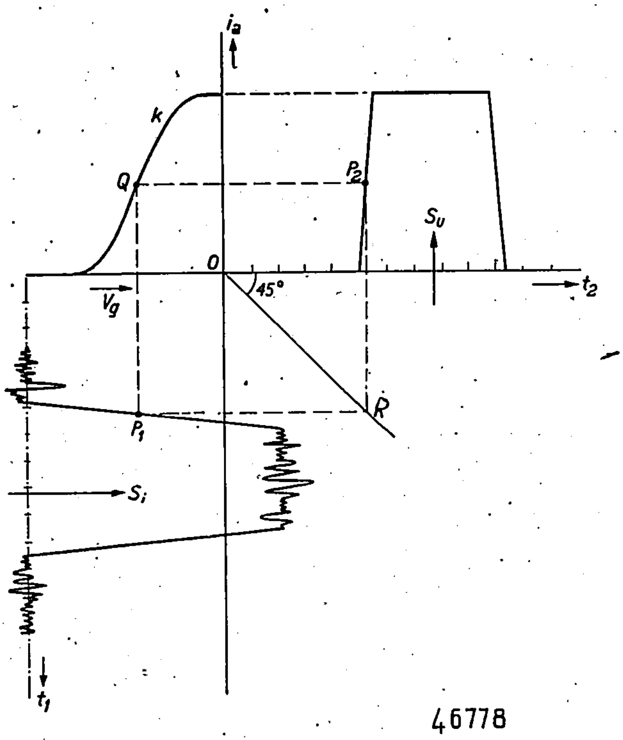

Fig. 7. Diagram of the double limitation of the photocurrent signal by means of a pentode. S_i incoming signal showing disturbances caused by contaminations on the film and disturbances due to the powerful amplification. S_u outgoing signal. k I_a-V_g characteristic of the pentode. Starting from an arbitrary point P_1 of S_u the corresponding point P_2 of S_u can be constructed with the aid of the auxiliary points Q and R. Since the time units on the t_1 and t_2 axes are similar, OR cuts the angle between the t axes through the centre.

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3) *Cf.* also Philips techn. Rev. 5, 61, 1940.

to the valve a negative grid voltage so high that $I_a = 0$ even for the most powerful disturbances occurring, in the absence of a signal, and make provision for the signal, on the other hand, to be so powerful as always to generate the maximum anode current, likewise for the most powerful disturbances, then the object has been attained (see fig. 7).

Finally the signal prepared in this manner needs only to be sent through a filter that allows the frequencies of the audible region to pass through and eliminates all the others. It may then be fed to the loudspeaker *via* a power pentode.

Conclusion

By means of the method of counteracting noise described here it is possible to obtain a perceptible improvement in quality of the sound reproduced. At the present stage of development the improvement in the case of new films, which are therefore practically free of contamination, is of no significance. In the case of films which have been used several times, however, the improvement is considerable. The method described thus makes it possible to use a film much longer than was previously possible, with retention of the original quality.