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THE DEVELOPMENT OF DISC CUTTING HEADS.

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ABSTRACT

Proper restoration of historic recordings is assisted by an accurate knowledge of the characteristics of the equipment used in the recording process.
This paper traces the evolution of electro-mechanical disc cutting heads from the early 1920's to the last models. Use is made of the electrical-mechanical equivalent circuits to analyse the performance of moving iron, moving coil and feedback controlled types.

1. INTRODUCTION.

The disc cutting head is an electro-mechanical transducer used in the production of analogue disc recordings. Prior to about 1920 nearly all sound recording was by the acoustic-mechanical process. The possibility of electrical amplification consequent on the introduction of the triode valve together with the existence of adequate microphones meant that only a cutterhead was needed to achieve an electrical recording process. However, early experiments often produced results which were inferior to the existing acoustic systems. One of the reasons was that many experimenters came from the recording industry and tried to adapt acoustic-mechanical concepts: in one such design a ferrous plate was attached to the mica diaphragm of a typical acoustic recorder box. A set of coils carrying the audio current modulated the field of a permanent magnet, very similar to the telephone earpiece.

2. THE IDEAL HEAD.

The transfer function of a transducer can be defined as the attributes of a selected output parameter when another selected input parameter is maintained constant over a range of frequencies.

In the case of a cutterhead the output parameter is the motion of the cutting stylus whilst the input may be the audio signal voltage, current or power.

Given a constant input (in any of the three parameters) the stylus motion against frequency may be: i). Constant Velocity; ii). Constant Amplitude; iii) Constant Acceleration.

For commercial reasons it would be desirable that recordings made with an electric system should play satisfactorily on the acoustic gramophones then existing. (It is worth pointing out that in The UK only 25% of homes had electricity by 1931).

A constant sound pressure level from an acoustic reproducer requires a record cut to constant velocity.

However, if this relationship is maintained down to low frequencies (e.g. 50 Hz) then the resulting amplitudes would be difficult to trace and also take up too much space on the disc surface. The acoustic recording systems had a naturally deficient low frequency response so that the problem did not arise.

The ideal head should therefore have the following properties:

- 2.1 Constant stylus velocity for constant signal input to the recording amplifier;
- 2.2 Low distortion at any frequency and amplitude within its working range;
- 2.3 Parameters should not be influenced by environmental changes (temperature, humidity);
- 2.4 Stable performance over time without the need for readjustments.
- 2.5 Performance should not be influenced by the recording medium.

3. PRACTICAL DESIGNS.

There are three main types:

3.1 Electro Magnetic e.g. moving iron;

3.2 Electro Dynamic e.g. moving coil;

3.3 Piezo Electric.

The last type was popular in the 1930’s and 40’s where high sensitivity and low costs were paramount such as in portable reporting machines and domestic types. They are no longer used and will not be considered further.

3.1. Electro Magnetic.

Fig. 1 shows a simple moving iron head.

A ferromagnetic armature M1 is pivoted at C2 between the poles of a magnet (which may be permanent or energized).

A driving coil is situated between the polepieces whilst a piece of damping material terminates the upper part of the armature.

Fig. 2 is the equivalent circuit.

Clearly, the circuit will have resonance.

For a constant velocity of stylus motion the impedance of the moving system must be high compared with the load Rd presented by the disc.

Below resonance the system is stiffness controlled (stiffness is the inverse of compliance), above resonance it is mass controlled. In the latter case changes in the load impedance will have a large influence on the velocity response of the moving system. At resonance the mechanical impedance is at a minimum. The effect of varying the mass or stiffness of the system is shown in Fig.3. [1] in which the solid curves represent the compliance changing in the ratios 1, $\frac{1}{4}$, $\frac{1}{16}$, the mass and resistance being constant. It will be seen that adjusting the compliance to raise the resonant frequency one octave reduces the overall response by 12 dB. Also, with changing compliance the resonance becomes sharper. Well above the resonant frequencies all the solid curves become asymptotic at 12 dB / octave. The dotted curves show the effect of reducing the mass. So we need to place the resonant frequency above the desired working range of the head. This may be achieved by reducing the mass but then the armature may magnetically saturate at an inconveniently low level.

Above the resonant frequency the response of the head will be affected by variations in the disc load caused by cutting diameter, stylus dimensions, turntable speed, stylus heat and variations of the blank material.

What is not shown in this simplified diagram is the non linear force which attracts the armature to the polepieces according to the inverse square law.

For a given magnetic gap D the non linearity will be proportional to the ratio $\frac{\Delta d}{D}$

Where d is the momentary displacement of the armature from its central position. It is clear that greater amplitudes associated with low frequencies will make this distortion frequency as well as level dependant.

A greater value of D will however increase the reluctance of the magnetic circuit leading to a reduction in head sensitivity. For linearity over a wide amplitude range the damping material must provide an exact opposing force to the inverse square whilst at the same time assist in damping the resonant frequency of the system. Good head designs separate these functions..

The first fully engineered design was due to J.P. Maxfield and H.C. Harrison of Bell Telephone Laboratories [2]

The principle innovation in the cutterhead was the termination of the armature system by a long rubber line, made of concentric tubes. This performed as a mechanical equivalent of the transmission line filter familiar to telephone engineering. By terminating the moving system impedance correctly no energy is reflected from the rubber line.
The equivalent circuit (Fig. 4) introduces a negative capacitance (- Co) to represent the inverse square armature forces, but this does not emulate non linear forces very well. This circuit otherwise follows the general arrangement of the simple head (Fig.2) with C2 representing the balancing springs, C1 and C3 the armature compliance divided because it is a balanced armature, M3 is the mass of the disc coupling the armature to the rubber line. M1 is the armature and M2 the cutting stylus.

The cutter had a constant velocity response from 200Hz to 4kHz after which it became constant acceleration to about 6kHz.
By suitable matching of the audio coils to the output of the cutting amplifier a first order curve was obtained below 200 Hz.

This design, manufactured by Western Electric was very successful and was licensed to most major record companies. The patents were very well drawn up and it was difficult to design a high quality head which did not foul some or all of the claims.

One manufacturer, Siemens and Halske even went so far as to patent a head design (The Telefunken ELP5111) in which there was no damping, it being claimed that this gave superior results! [3].
However, good as the Western Electric head was, it was sensitive to small changes in spring tensions whilst the rubber line was affected by climate changes and the rapid ageing of natural rubber.[4]

The moving iron head continued to be popular until the 1950’s because of its comparative simplicity, reasonable cost and robustness.
Other methods of damping included synthetic materials *e.g.* “Viscaloid” (The RCA MI4887) and oil as in the Neumann R12b (Fig. 5) and the BBC type B Head. [5]

3.2 MOVING COIL

The Moving coil principle is free from the problem of non linearity, also the coil cannot be saturated by magnetic flux (although it can of course be thermally overloaded).

Two important patents were granted in 1929 and 1931. The one to the British inventor P.G.A.H. Voight [6] described a moving coil head in which the coil was placed in a saddle which could ride on the surface of the disc, the magnetic field being provided by a large fixed electro magnet which had sufficient depth in the gap to allow a linear flux over the coil’s range of travel.
The very high field resulted in a large back emf which, when fed from an amplifier of sufficiently low output impedance, gave enough electro magnetic damping to avoid the use of rubber or other materials.
This design was later adopted by A. Haddy of the Crystallate company which then (1937) was absorbed by the Decca Record Co. and the head was later developed to give a range to 14 kHz (the “ffrr” system). (Fig. 6).

British Patent No. 350,998 was granted to A.D. Blumlein of the Columbia Graphophone Co.
Blumlein was employed by Columbia in 1929 principally to design a recording system which did not infringe the Bell Telephone/Western Electric patents but which would be at least as good in all respects.

The design consisted of a single turn coil, stamped from aluminium, to which was attached an arm to carry the stylus (Fig.7). The coil rotated around a magnetic core whilst two sets of external polepieces carried respectively the steady and alternating magnetic fields. The operation can be likened to a transformer with a moving secondary, and the coil/stylus arrangement like a moving coil pointer meter.

The main resonance was at 250 Hz to damp which Blumlein devised an ingenious circuit (Fig. 8).
The iterative impedance of the network when viewed from the cutterhead is at a minimum at 250Hz hence the back emf sees virtually a short circuit at this frequency.
The Blumlein head together with its associated microphone and amplifiers became the standard system for the newly formed EMI Company from 1932 onwards until the early 1940’s.

The transition from wax as a master medium to cellulose nitrate lacquer coated discs took place much earlier in the USA than in Europe; one of the reasons was that the moving iron heads popular in the USA had a sufficiently high mechanical impedance that the disc load had little influence on the response.

Moving coil heads would be loaded too heavily by lacquer to yield a satisfactory high frequency response.

The solution to this problem was to use a feedback signal derived from the motion of the cutter system. This is basically similar to an electro-mechanical servo. The first practical realization was by Vieth and Wiebusch of Bell Telephone Laboratories [7].

The head was for vertical modulation, this being the preferred method for transcription recordings. The principal is shown in Fig.9.

Fig.10 shows the principal circuit elements.

It can be shown that provided the loop gain is adequate the characteristics of the head and drive amplifier do not influence the transduction.

It will also be noted that the feedback signal may be used to provide audible monitoring of the signal at the head.

In 1949 the Fonofilm company of Copenhagen, under the direction of Dr.F. Schlegel produced a lateral version of a feedback head (Fig.11) [8].

Important points affecting the feedback head are:

1). The feedback voltage must be derived from the system movement as opposed to flux linkage from the drive coil;

2). The phase of the feedback voltage must be less than $\pm 180°$ for all frequencies where the loop gain is greater than unity.

3). The mechanical resonance of the moving system must be at the geometric centre of the desired frequency range.

4). Feedback control will be greatest at f_{res} : since the feedbackvoltage

$$v \approx \frac{d\Phi}{dt}$$

where Φ is the flux in the feedback coil there will be less control at low frequencies. In 1970 the Ortofon Company introduced an integrating circuit in the feedback amplifier in order to improve low frequency control. A complementary circuit in the drive section restores a level response. A basically similar approach was adopted by Neumann in their SAL74 amplifier.

5). From the analogous circuit of the simple head (Fig.2) we can see that a principal contributor to the phase response of a moving system is its mass (inductance). Thus the effective mass of the feedback head moving system largely determines the highest frequency at which feedback control can be present.

For a given total mass of the moving system the effective mass is less for a pivoted system than for a displacement system.

Above feedback control the system will be mass controlled and will be subject to the same variations as described above for the non feedback head.

On modern heads the upper boundary of feedback control is between 14 and 18 kHz.

6). The velocity of propagation within the materials of the moving system is important as this determines a delay which results in a phase shift. For this reason feedback coils must always be placed close to driving coils and parts such as the coil formers must be made of materials with high density but low mass.

3.2. THE STEREOPHONIC HEAD.

In his 1933 patent [9.] Blumlein (op.cit) published all the now familiar arrangements for two channel cutting heads. At this time the only practical models were moving iron. It was not until the late 1950’s that commercial stereophonic discs became feasible, utilizing the standardized 33 $\frac{1}{3}$ rpm L.P. format.

By this time it was clear that the feedback controlled moving coil head was the only type suited to high quality cutting at the lower speeds. Fig.12 shows the possible arrangements of driving systems: a) is the lateral-vertical in which the upper system is a displacement type with vertical motion whilst the lower is pivotal for lateral motion. The benefit of this arrangement was thought to be from the fact that most signal energy in a stereo recording is in the sum channel (*i.e.* the lateral plane) hence the lower system which needed less power for a given level would be doing most of the work. A disadvantage was that the characteristics of the two systems such as frequency response would be different. Leading to imperfect stereo imaging.

b). was an elegant theory designed by the Teldec Company of Berlin and manufactured by G. Neumann. A ceramic cone carries both drive and feedback coils for both channels thus eliminating the need for flexible couplings and ensuring that the feedback coils were very close to the actual stylus. However, the assembly was extremely difficult to make and the factory reject rate was about 70%.

Also there were difficulties in restraining the system’s degrees of freedom to those required; there was a tendency for the whole system to travel in the direction of the groove, thus smearing transients.

c) is the familiar layout used by Western Electric in their 3 series heads, also by Neumann in their SX68 and 74 types. This layout has the advantage that a given displacement of a coil system results in the same amplitude in the groove.

Disadvantages are the comparatively large amount of mechanism which is below the feedback coils and which is therefore outside feedback control, in the vertical plane the stylus describes an arc rather than a true vertical motion and there is a tendency for the stylus carrying arm to rotate upon its axis. Another problem is the provision of couplings which must allow the two systems to move independently: Western Electric used bunched wires which were tied around the middle.

The Neumann version had a very simple but ingenious method.

An austenitic spring steel rod is encased within a ceramic tube for most of its length. At the point of anchor into the coil assembly, where the deflection from the other channel is minimum, the rod is allowed to bend.

Layout type d). was used by Teldec/Neumann earlier and is still used in the Ortofon designs.

Advantages are lower mass of parts after the feedback coils, less tendency for the stylus to twist, feedback control to higher frequencies.

The main disadvantage is that a given coil displacement results in that amount multiplied by sin45 in the groove. This reduces the sensitivity by 3 dB.

4. ASSOCIATED DEVELOPMENTS.

From the beginnings of electrical recording it was recognized that a significant improvement in the signal to noise ration of the finished pressed disc could be obtained by superimposing a high frequency boost before the cutterhead and providing a mirror image attenuation in the playback system. The exact relationship is generally known as the recording curve or characteristic. Such curves were adopted in the USA particularly for broadcast recordings in the late 1930's.

In the UK and Europe most commercial discs were cut to constant velocity above c.250 Hz until the Decca ffrr system was introduced (c. 1944).

From the well known mechanical relationship

$f = m.a$ (***f*** is force, ***m,*** mass; ***a*** acceleration)

it will be clear that boosting high frequencies calls for additional power handling capacity in the cutterhead and its drive amplifier. As power doubles for every 3 dB the demands of a curve such as the RIAA which has a total boost of nearly 20 dB at 20 kHz will be severe. Pre-war cutting amplifiers for moving iron heads were adequate at powers of 20 watts; the BBC type D amplifier offered 75 watts (the BBC curve had a slope of about 2 dB/octave). Today's cutting amplifiers approach 600 watts peak for feedback moving coil heads. Such a power is fed into a coil of 10mm diameter wound with 0,1mm copper wire. Heat dissipation is improved by passing Helium gas into the drive coil magnetic gap thus providing a thermal shunt to the surrounding metalwork at a better efficiency than air.

In many ways today's cutting engineer has cause to lament the standardization of the RIAA curve: the replacement of ribbon microphones by condenser types followed by electronically generated sounds and the popularity of the 30cm "single" make a 75*u*sec curve totally unsuitable.

5. CONCLUSION

The last generation of cutterheads (it is unlikely that there will be significant new departures at this stage of the discipline) are extremely high precision products in which special materials allow a very high performance *e.g.* the drive coils of a typical head are wound with a specially insulated wire allowing operation at a temperature of $200^{\circ}c$. Special precautions are necessary to protect the moving system in such circumstances [9].

Heads exist which can offer a frequency range beyond 25 kHz, although these are not suited to the highest possible cutting levels demanded by many publishers.

5. ACKNOWLEDGEMENT

The Author wishes to thank Ms. R.Edge of EMI Music Archives for permission to reproduce Figures 7 and 8.

6. References.

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DAVIES DEVELOPMENT OF CUTTERHEADS

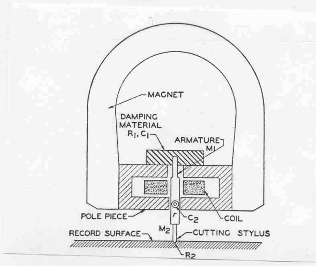
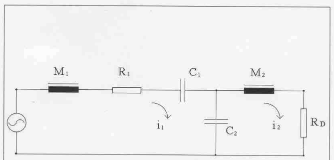


FIG.1



Simple Head

FIG.2

DAVIES DEVELOPMENT OF CUTTERHEADS

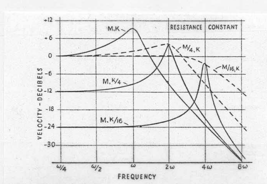
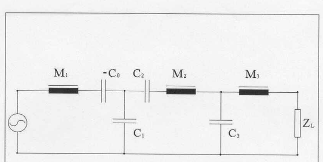


FIG.3



Western Head

FIG.4

DAVIES DEVELOPMENT OF CUTTERHEADS

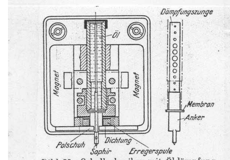


Bild 55: Schallschreiber mit Öldämpfung.

FIG.5

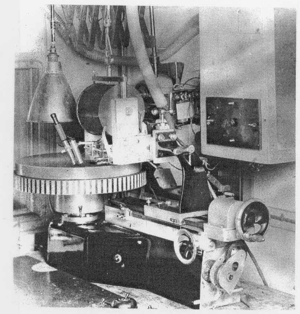


FIG.6

DAVIES DEVELOPMENT OF CUTTERHEADS

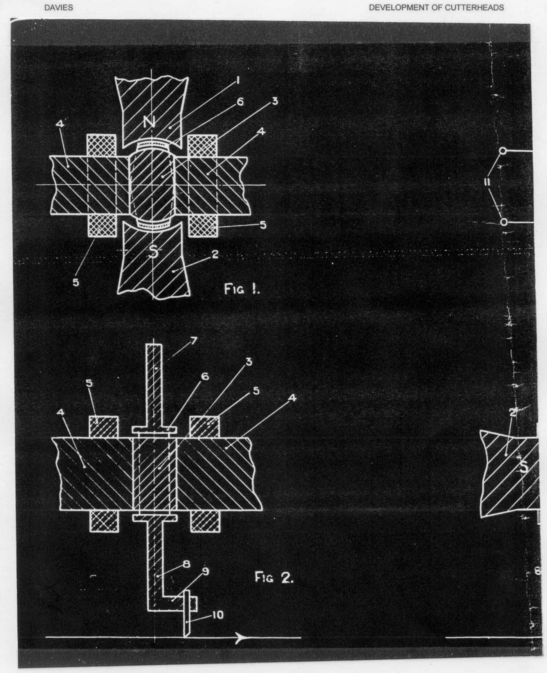


FIG.7

DAVIES DEVELOPMENT OF CUTTERHEADS

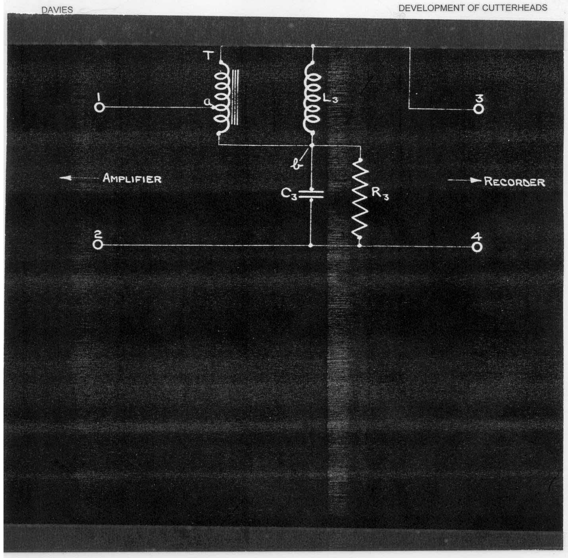


FIG.8

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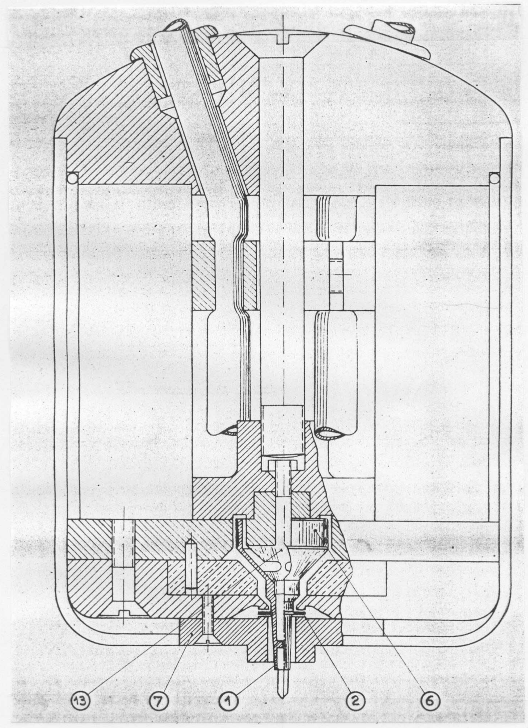
11



13

FIG.11

DAVIES DEVELOPMENT OF CUTTERHEADS

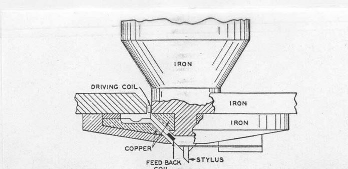


FIG.9

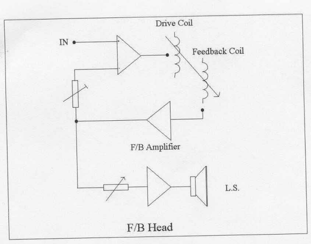


FIG.10

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12

DAVIES DEVELOPMENT OF CUTTERHEADS

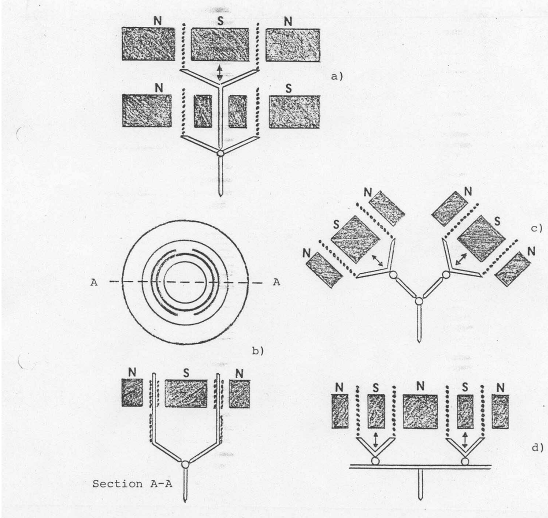

FIG.12

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14