

WAX CYLINDER RECORDER

In 1989(?) I was commissioned to design and build a recording machine to manufacture calibration cylinders for the U.K. National Sound Archive (now part of the British Library). Since that date, small improvements have been made to the machine, but the basic design remains the same.

Basic Concept:

The recorder consists of a rotating mandrel which carries a blank wax cylinder, a cutting tool which is moved axially with respect to the cylinder, producing a groove in the cylinder surface; and a method of vibrating the cutter in a direction perpendicular to the that surface so as to give vertical modulation to the groove.

The components to perform these function can conveniently be considered as three systems:

- 1) A lathe with mandrel, bedways and saddle.
- 2) A system of drive motors for the mandrel and leadscrew
- 3) A recording channel with amplifiers and cutterhead.

The methods used by sound recorders for generating a constant-depth groove in wax usually fall into two categories:

- a) Constant pressure on the cutter.
- b) Constant spatial relationship between the cutter and the uncut surface (advance ball).

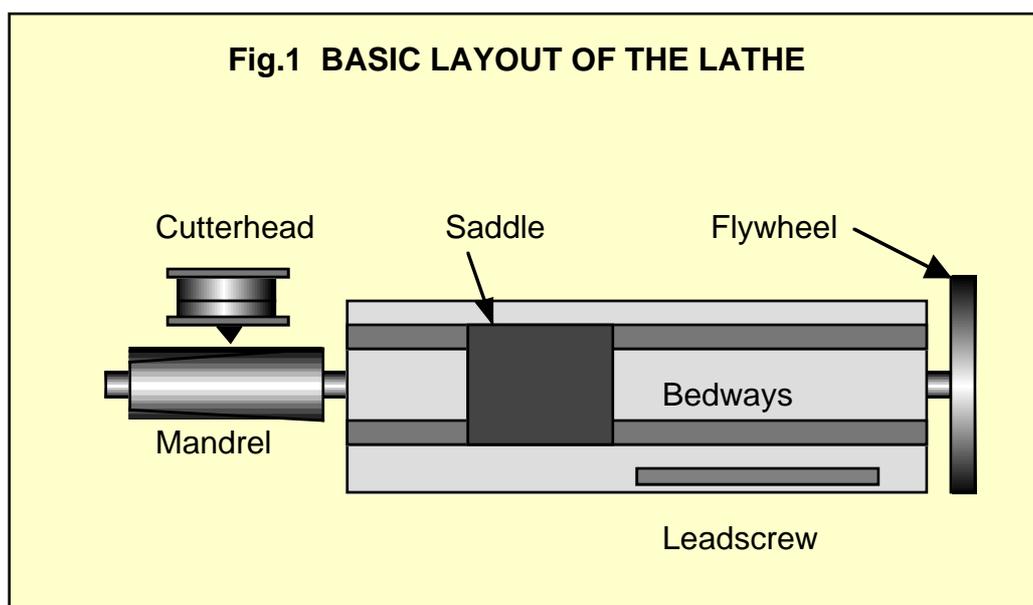
In both of these systems, the cutterhead is required to move in response to small variations in the uncut cylinder surface. The mass of the electromagnetic cutterhead used in the present design is so great that the forces needed to achieve this would be larger than the wax could sustain without damage. A servo tracking system was considered but rejected on grounds of complication.

The mean groove depth required for a 2-minute wax cylinder is 0.0007", which is less than the variation from a straight line of the tracking path of the recording stylus due to errors in the bedways.

A third method was therefore developed, whereby the wax is skimmed in-situ so as to be concentric with the mandrel axis of rotation and so that its surface already contains a copy of the unavoidable bedway errors to which the recorder will be subjected. The recording cutter tip can then be moved along a pathway which is precisely the required depth below the surface previously generated by the skimming operation.

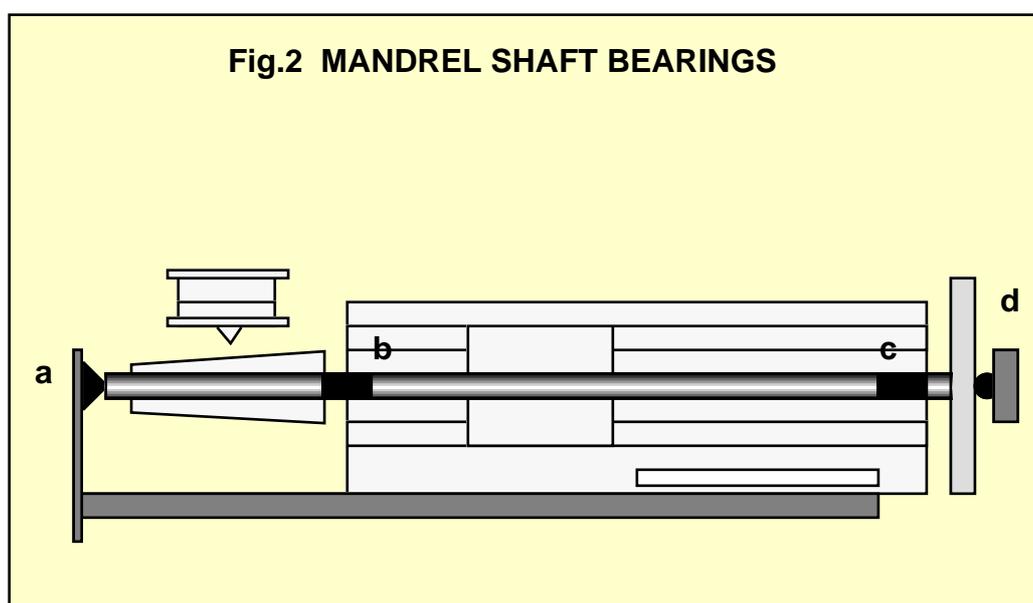
The Lathe:

The construction of the lathe is based upon the bedways, saddle and leadscrew of a Leitz microtome (a machine for cutting thin sections of tissue for histological purposes). The area where the groove cutting takes place has to be located where the cut wax shavings will not fall upon the bedways, which need to be smooth and free-running at all times.



Mandrel Shaft and Bearings

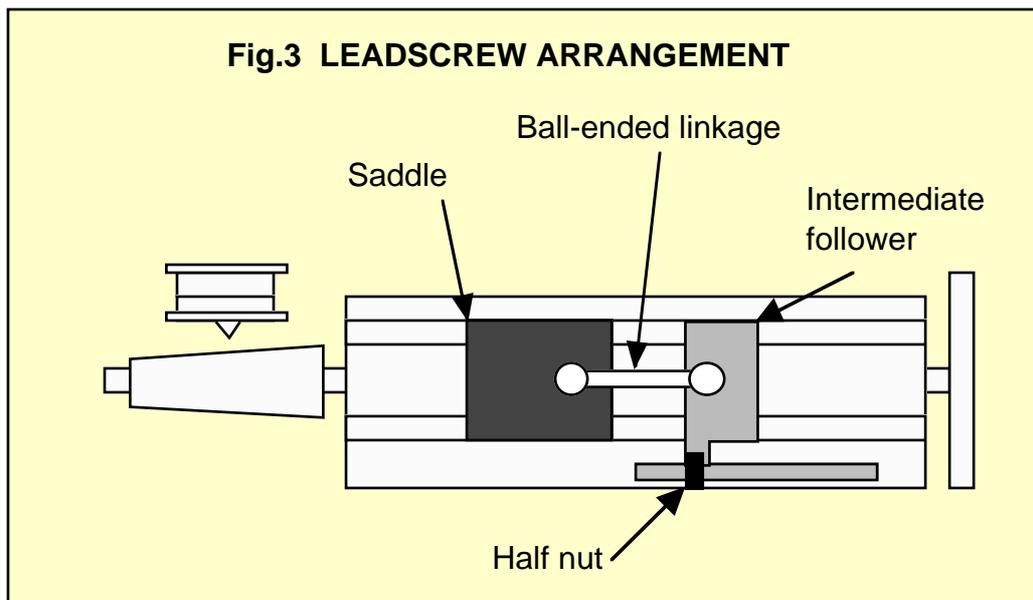
A drive shaft for the mandrel is located underneath the bedways and runs the full length of the machine. This allows the use of a large flywheel in a position which will not interfere with the location of other components.



The mandrel shaft is supported in two plain sleeve bearings located one at each end of the bedways (b & c). Sleeve bearings are necessary because ball bearings would give rise to an excessive level of rumble during the recording process. A third bearing (a) is placed so as to support the overhung end of the mandrel, but this has to be attached to a dismountable arm so as to be easily removable when changing cylinders on the mandrel. This third bearing is a cup-and-cone type. As well as locating the shaft radially, it exerts an end thrust which is resisted by an additional thrust bearing (d) located at the fly-wheel end of the shaft.

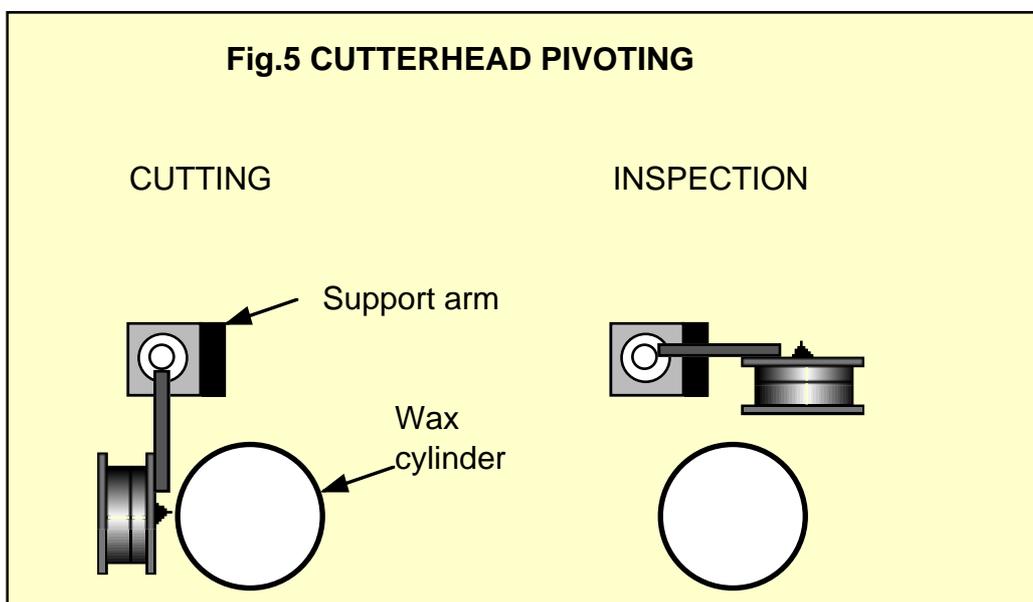
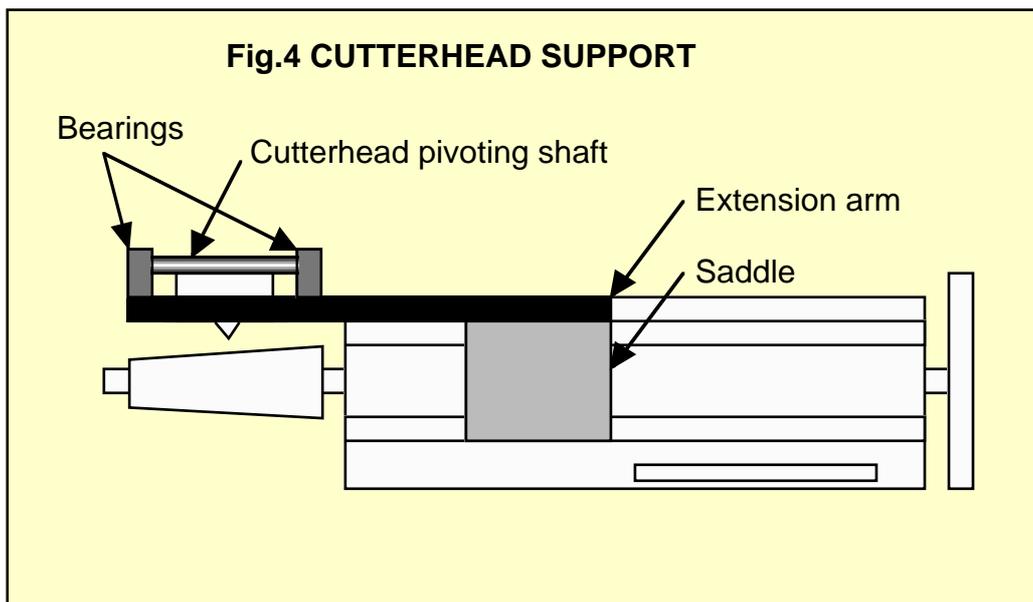
Leadscrew

The leadscrew drives the saddle along the bedways by means of a follower half-nut, which grips the leadscrew in the manner of a spring-operated clothes peg. To avoid transmitting any side thrust to the saddle due to possible eccentricity of the leadscrew, an intermediate follower running in a groove in the bedway casting is directly connected to the half-nuts. This then drives the saddle through a linkage with ball-jointed ends, which can only transmit longitudinal thrust.

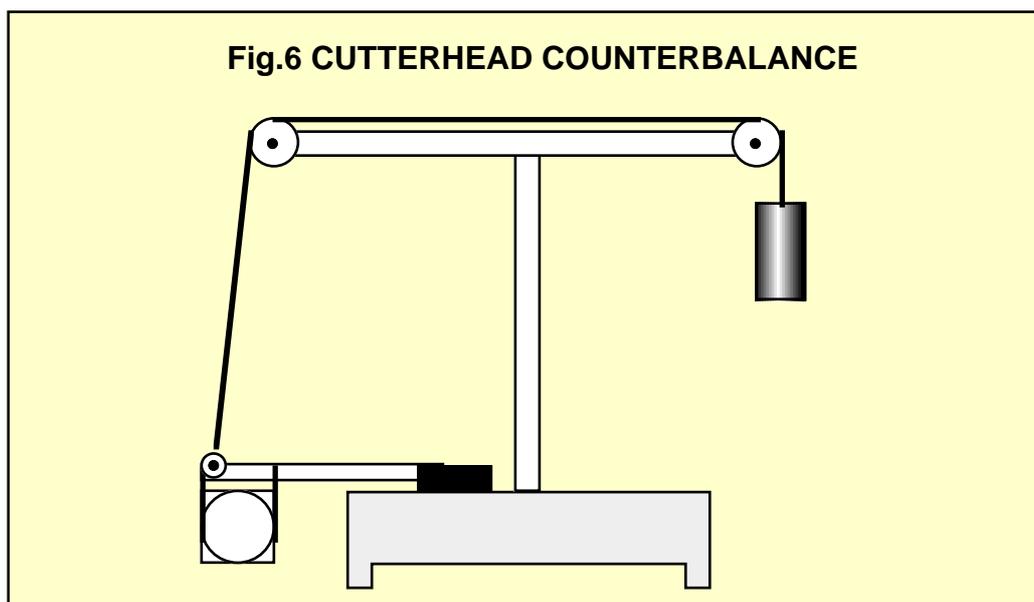


Cutterhead support

The cutterhead is mounted on an extension arm from the saddle. It is pivoted from a horizontal shaft running in pre-loaded ball bearings so as to enable it to be rotated from the cutting position into a position which allows easy inspection of the cutting tip.

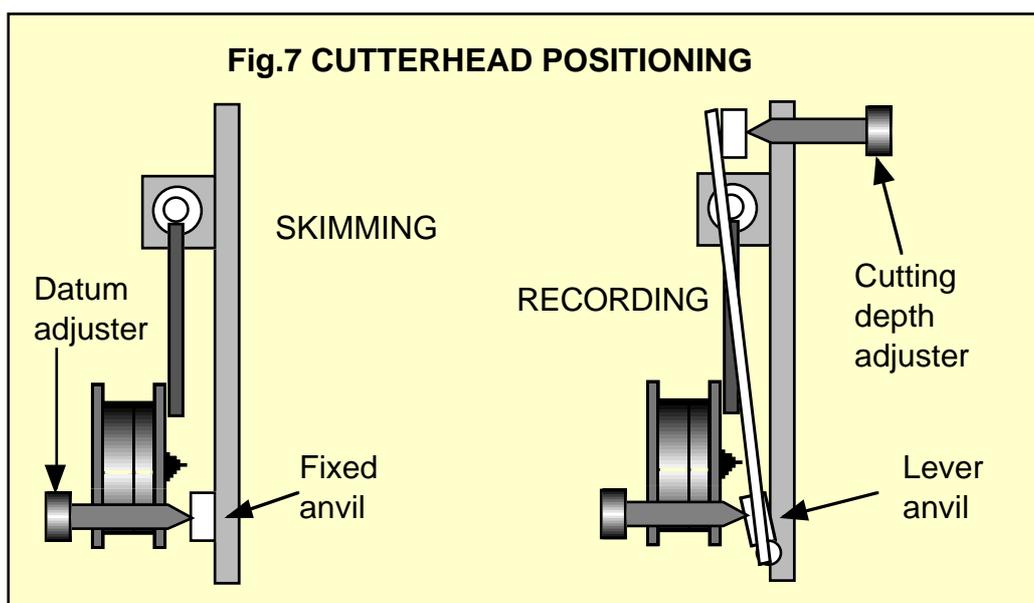


The weight of the cutterhead is more than sufficient to overbalance the saddle, so a counterbalance system has been added. This comprises a cord attached to the cutterhead at one end and to a counterbalance weight at the other, running over a pair of free-running pulleys mounted on a crane above the recorder. The changing angle of the cord, as the cutterhead moves along its cutting pathway, is accommodated by means of a small pulley wheel on the cutterhead support, which serves as the cord anchorage and avoids the jerky movement which would have resulted from a conventional hook and eye system of anchorage.



Cutting tip positioning

In the cutting position, the cutterhead has a tendency to swing towards the cylinder under the influence of gravity. A system of adjustable stops ensures that it skims and records at the correct depth on the wax.



In the skimming position, a tungsten carbide skimming tool (not shown) is swung into position over the cutter tip and a fixed anvil is placed so that the

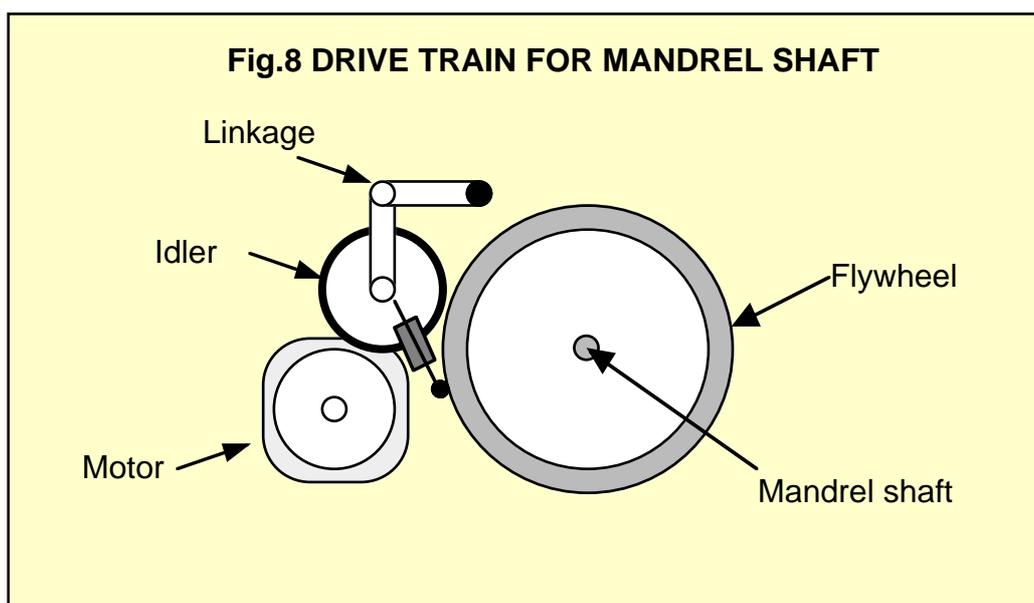
datum adjustment screw locates upon it. By means of the datum adjuster, which has a 32 tpi thread, the depth of skimming below the existing surface of the cylinder can be set to a moderate degree of accuracy.

When the cylinder has been skimmed, the skimming tool is swung out of position, to expose the cutting tip. The fixed anvil is also removed by means of a sliding lever, so as to allow the datum adjuster to bear upon another anvil which is attached to a movable lever. Without altering the setting of the datum adjuster, the position of the cutting tip relative to the position of the skimmer can now be set to a high degree of accuracy by moving the lever anvil by means of the cutting depth adjuster. The 10:1 ratio of the lever gives the cutting depth adjuster screw an effective adjustment rate of 320 tpi.

The Drive Motors

Mandrel Shaft Drive

The mandrel shaft is driven from the flywheel rim by a DC electric motor via a rubber-tyred idler wheel. The motor is mounted on a resilient rubber suspension to prevent the transmission of vibration to the structure of the lathe. The idler wheel is mounted on a jointed linkage which allows it to be pulled simultaneously into contact with both the flywheel rim and the smooth-rimmed driving pulley on the motor shaft, by a tension spring.



A lever is provided which, by means of a cam, allows the idler wheel to be disengaged from the other driving wheels when the machine is stopped. This

prevents the tyre of the idler wheel from developing 'flats' due to continuous pressure at two points when it is stationary. A switch, coupled to the cam, interrupts the current to the motor in the stopped position.

Mandrel speed

One edge of the flywheel casting is provided with a number of regularly-spaced scallops. As it revolves, these scallops and the 'lands' between them generate an alternating voltage in an electromagnetic pickup device which is converted into a stream of pulses with a frequency proportional to flywheel speed. The frequency is converted to a proportional voltage and compared with a reference voltage derived from a multi-turn dial on the control panel.

The dial is set to the required speed according to the formula:

$$\text{R.P.M.} = 50 + (\text{Dial reading} \times 2)$$

Thus for 160 RPM, a dial reading of 55 should be used.

Any discrepancy between the flywheel speed and the indicated dial speed is amplified and used to correct the motor speed.

During skimming of the cylinder in preparation for recording, a much higher mandrel speed is required. A 'SKIM' switch is provided which over-rides the speed control system and runs the motor at maximum speed.

Leadscrew Drive

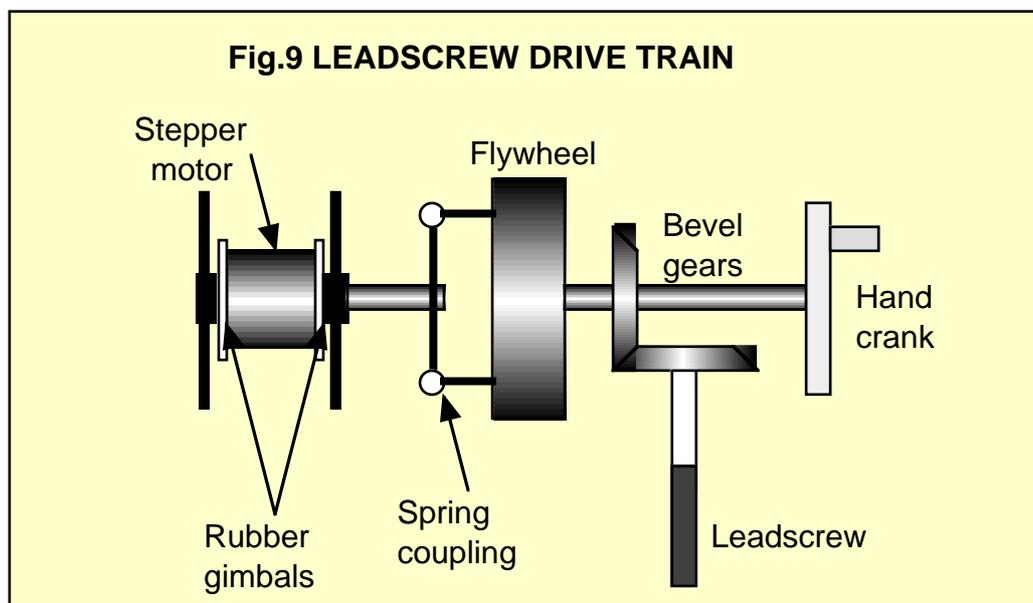
The leadscrew is driven from a stepper motor, which allows a precise relationship to be maintained electronically between the mandrel and the leadscrew positions during recording. The rotor of the stepper motor changes position rapidly between fixed angular points with relation to the stator; so both it, and the frame of the motor, are subjected to large alternating torque forces. The vibration resulting from the action of the stepper motor must be isolated from the body of the machine and from the leadscrew.

The stepper motor frame is supported in rubber gimbals from a steel mounting plate fixed to the machine bed casting. This allows the motor frame to rotate through a small angle at each stepping pulse without imposing a sharp torque loading on the structure of the lathe. The rotation is limited by means of a stop peg, one end of which is rigidly fixed to the steel mounting plate, the other end is located in a rubber-lined hole in the end plate of the motor.

The stepper motor shaft is coupled to a flywheel by means of a rectangular arrangement of coil tension springs. The compliance of the springs and the mass of the flywheel act to decouple the flywheel shaft from the sharp torsional steps of the motor shaft. The springs also allow the coupling to adjust to any misalignment between its input and output shafts which may be caused by the resilient mounting arrangements of the stepper motor. To prevent excessive torsional oscillation of the coupling, the springs are filled with a bituminous

damping compound.

The drive from the flywheel is taken to the leadscrew by a right-angled arrangement of bevel gears. These gears allow for a convenient location of the stepper motor and its coupling. A hand crank is provided for manual operation of the leadscrew during setting-up operations.



Leadscrew pitch

The system of coupling between the mandrel shaft and the leadscrew needs to have a number of different selectable ratios, depending on the finished product required. Standard wax cylinders of nominal 2-minute duration are cut to a pitch of 100 tpi. Cylinders of nominal 4-minute duration are cut to a pitch of 200 tpi.

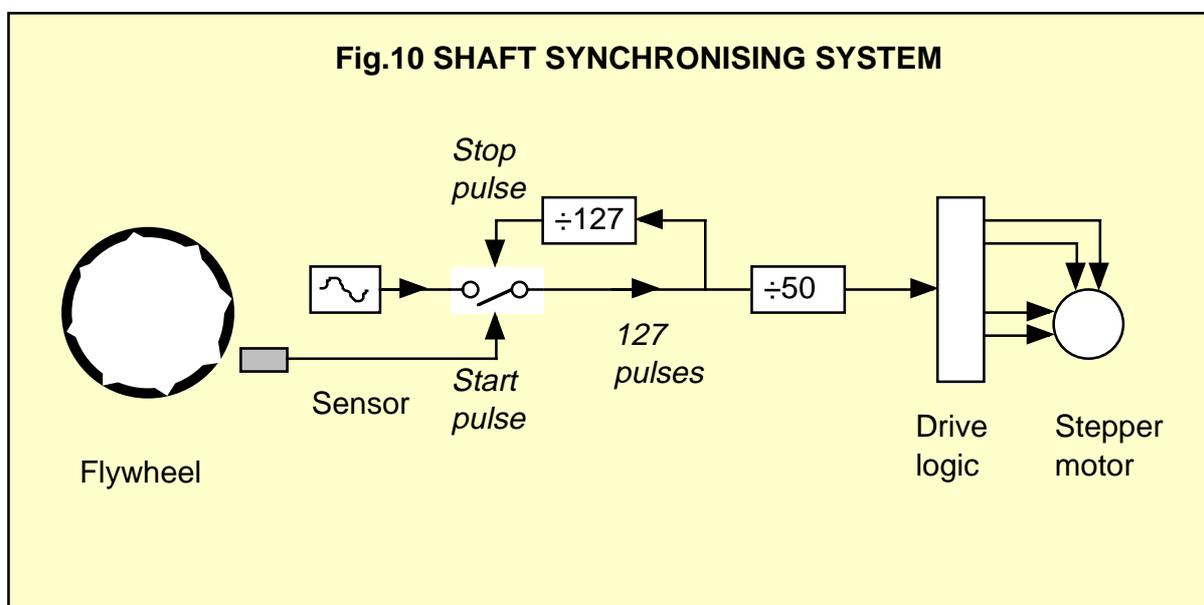
Cylinders which are intended for use as duplicating masters will subsequently be electroplated to form casting moulds. The pitch of these cylinders will differ from the standard pitch by an amount which depends on the shrinkage factor of the casting material to be used.

As well as providing for different pitches, the coupling system must allow for the fact that the leadscrew used in this machine is metric, but it must generate cylinders of imperial pitch.

The pulses from the flywheel speed control system are used to operate an electronic gate, each pulse allowing 127 pulses from a high speed oscillator to enter a counter. This counter generates one output pulse for every 50 input pulses, so the first flywheel pulse will result in two output pulses and a residual count of 27. The next flywheel pulse will cause the counter to give three output pulses because of the residual count which was already in the counter - there will now be a residual count of 4

Pulse number	Input pulses	Input + residual	Output pulses	Residual
1	127	127	2	27
2	127	154	3	4
3	127	131	2	31
4	127	158	3	8
5	127	135	2	35
6	127	162	3	12
7	127	139	2	39
8	127	166	3	16
9	127	143	2	43
10	127	170	3	20
11	127	147	2	47
12	127	174	3	24
13	127	151	3	1
14	127	128	2	28
15	127	155	3	5
16	127	132	2	32
17	127	159	3	9
18	127	136	2	36
19	127	163	3	13
20	127	140	2	40

Each output pulse is used to move on the stepper motor by one position, so it can be seen that the motor moves in a complex series of 2 and 3-pulse steps.



When these steps are averaged-out, the ratio between the flywheel on the mandrel shaft and the stepper motor which drives the leadscrew will be in the ratio $127/50$, which is an appropriate imperial-to-metric conversion ratio. By altering the number of pulses generated for each flywheel pulse and by altering the division ratio of the counter, a wide variety of shaft ratios can be obtained.

The Recording Channel

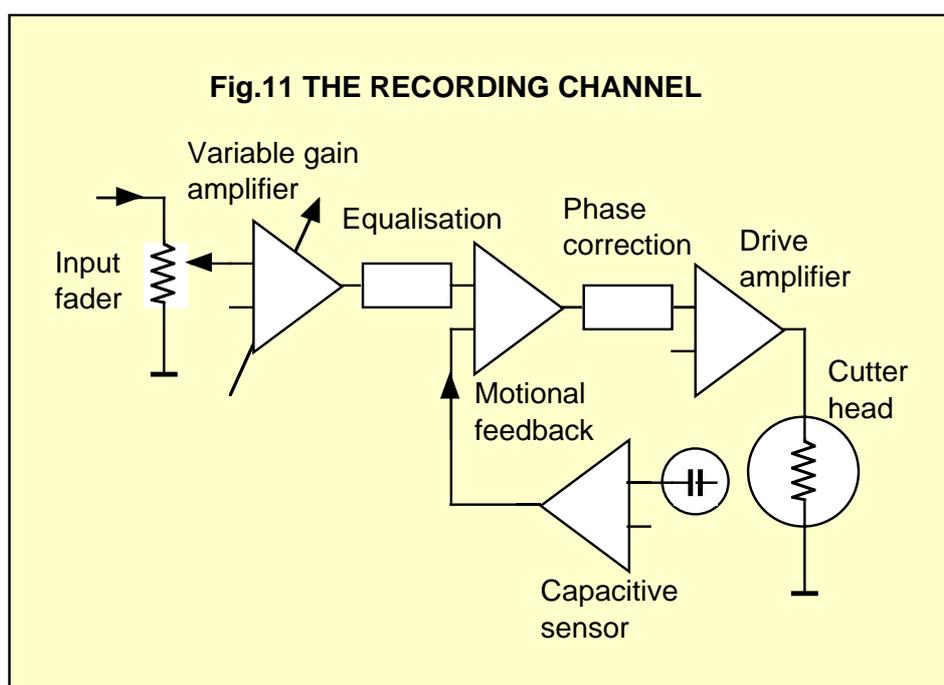
Many methods of modulating the recorded groove have been attempted in the past. Among these, the most successful have been:

- 1) Acoustic
- 2) Electromagnetic - moving iron
- 3) Electromagnetic - moving coil
- 4) Piezo-electric

The resonances of an acoustic system have no place in the manufacture of calibration recordings. Piezo-electric recording systems have proved adequate in niche recording technologies, but were deemed unsuitable for this project because of their limited amplitude capabilities. Moving iron recording is capable of very good results, especially when drive power is limited; but moving coil generally has lower distortion.

A moving coil cutterhead was adopted for this project, but it has the disadvantages of a relatively low mechanical impedance and a primary resonance within the useful frequency range. Both these disadvantages can be reduced to negligible proportions by providing the drive amplifier with a sufficient amount of motional feedback from the moving parts.

If the feedback is derived from an electromagnetic transducer, it is liable to pick up signals from the drive coil and give erroneous results (It is believed that some early Western Electric cutterhead systems were designed to do this in order to make their performance appear more favourable). The use of an electrostatic feedback transducer, based on the principles of a capacitor microphone, avoids any interference from electromagnetic fields and is easily screened against electrostatic fields.

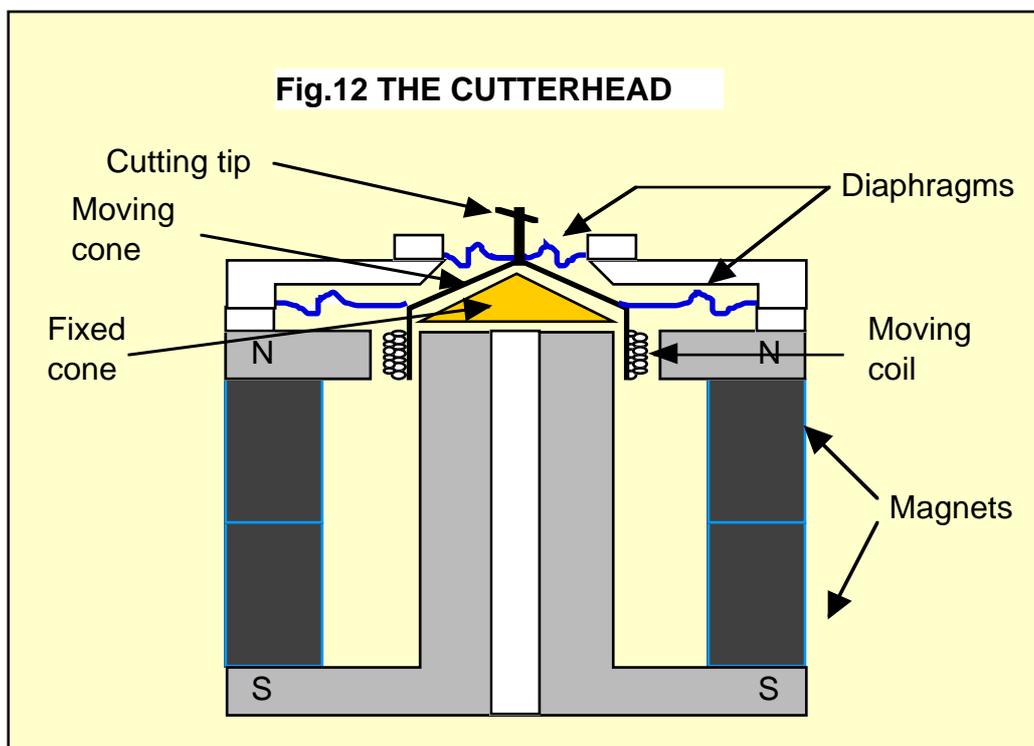


The cutterhead

For good sensitivity, the moving parts need to be of low mass, but the law of diminishing returns sets-in once the total moving mass is less than twice the mass of the coil alone. As the mass of the cutting tip and its mounting was anticipated to be difficult to reduce, it was decided to make the moving coil fairly robust. This, in turn necessitated a relatively large air gap for the coil in the magnetic circuit, so two magnets in series were used to provide the required strength of magnetic field.

The layout of the cutterhead follows fairly conventional moving coil 'dome tweeter' loudspeaker practice except that the dome is replaced by an aluminium cone, integral with the coil former, and the tip of the cone is supported by an additional corrugated diaphragm to resist the side forces arising from cutting into the wax of the cylinder.

The central pole piece supports a brass cone of similar shape to the moving aluminium cone and located approximately 0.050" away from it. This fixed cone is electrically insulated from its surroundings and charged to a potential of approximately 600 volts from a high source resistance. It acts as one plate of a capacitor, with the moving cone forming the other, earthed, plate. Capacitance changes caused by movement of the moving cone induce small voltage changes in the fixed cone, which are amplified and used to provide motional feedback.



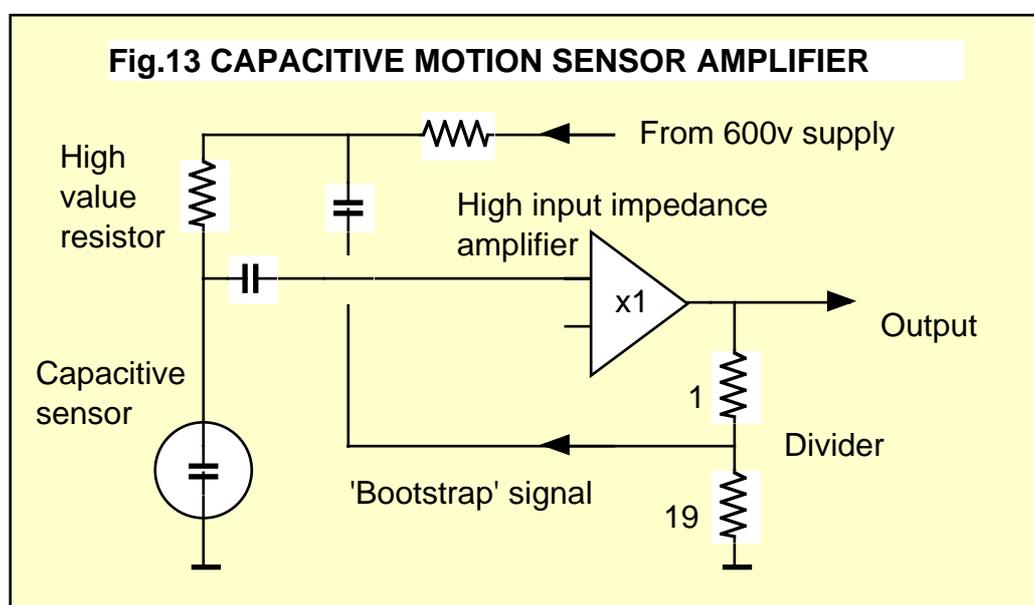
The pre-amplifier for the motional feedback signal is mounted in a die-cast screening box on the back of the cutterhead and connected to the fixed cone by a metal rod (not shown) running through the hollow centre pole piece.

If the movement of two capacitor plates is significant compared with their spacing, distortion of the electrical signal will occur. The total anticipated movement of the moving parts is less than 0.0005" RMS; for this displacement, a spacing of 0.050" between the plates has been calculated to give a distortion figure below 0.5%, which is adequate for this application.

The Feedback Amplifier

To avoid taking high voltages through flexible cables and dismantable connectors, the polarising voltage for the capacitive sensor is derived from a low voltage AC supply taken from the power supply of the drive amplifier. This is current-limited by a resistor and fed through flexible wiring to a metal box attached to the saddle of the lathe. At this point it is stepped up to around 300v by a transformer running with the magnetic circuit in saturation. A Cockroft-Walton multiplier steps this up again, to approximately 600 v, for the sensor.

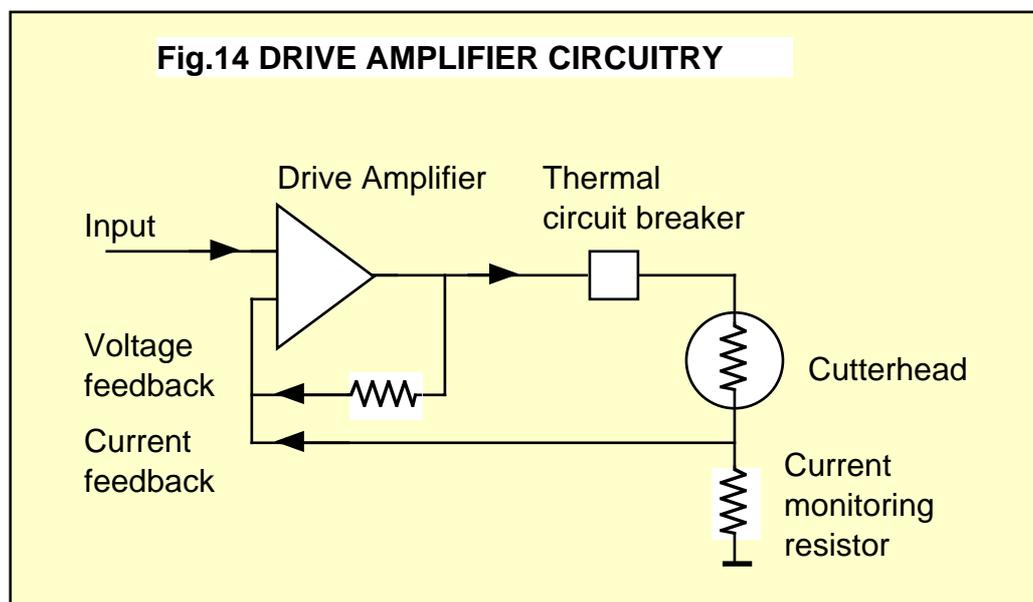
In order to achieve a good low-frequency response from a capacitive sensor, the input circuit of the amplifier must exhibit a very high impedance at the frequencies of interest. This is achieved without the need for special high-value resistors by means of a 'bootstrap' input circuit, which effectively multiplies the value of readily-available components. The 600v supply is first smoothed to remove voltage ripple, then it is coupled by a 'bootstrap' capacitor to a signal which has an amplitude of 0.95 of the sensor signal and is in phase with it. This has the effect of multiplying the value of final resistor in the feed chain by a factor of 20.



The Drive Amplifier

The drive amplifier is a straightforward Class-A design, running from + and - 24v power rails. No doubt it would have been possible to design other classes of amplifier for this application; but fault-tracing if, for instance, the feedback loop had become unstable, would have been considerably complicated if the amplifier design was at all suspect or unproven. Class-A was therefore chosen, despite its higher power consumption, so that the design effort could be concentrated on unavoidable problems, rather than unnecessary ones.

Feedback signals are derived from both the output voltage and the current through the cutterhead. This has the effect of maintaining a more constant current through the cutterhead coil at higher frequencies, despite its predominantly inductive impedance. Between the amplifier and the cutterhead is a thermally-operated circuit breaker with thermal characteristics similar to the cutterhead coil assembly. This allows the cutterhead to respond to short periods of high current such as those which result from normal programme material, but protects it in the event of a prolonged overload.



The Input Stage

A monophonic signal at nominal 0 dBm level can be fed into the recorder through a standard Gauge 'B' jack. Transformer isolation of the input avoids any possibility of hum loops. An input fader is provided, so that noise before and after the wanted recording can be eliminated. The fully-closed position of this fader operates a switch which can be used to remotely control the starting and stop-

ping of suitably-equipped signal sources. An amplifier/attenuator circuit allows control of the signal level over the range - 12 to +12 dB in steps of 1 dB.

The Equalisation Stage and Monitoring

A 'Blumlein' recording characteristic can be selected by means of the 'Equalisation' switch, which also selects the inverse of this characteristic for the playback and monitoring circuits. The time constant of the circuits can be chosen to give turnovers of 0; 300 c/s; 500 c/s and 800 c/s; and provision has been made on the switch for two additional time constants, should the need become apparent.

A monitoring output is provided at a nominal level of 0 dBm from 600 ohms, suitable for driving headphones or a self-amplified loudspeaker. As mentioned above, the equalisation of this signal is selected to match the recording characteristic in use at the time. The monitor signal can be derived from the input signal, the motional feedback sensor or a playback device (not yet fitted).

Metering

A meter is provided for monitoring signal levels. It approximates to a standard BBC PPM with nominal 0dBm at the centre of the scale and markings at 4 dB intervals. The overload point is marked at +12 dB.

The meter can be switched to check various signal levels:

- a) Input signal
- b) Cutterhead amplitude
- c) Cutterhead velocity
- d) Whichever is the greater of cutterhead amplitude or velocity
- e) Drive amplifier output power.

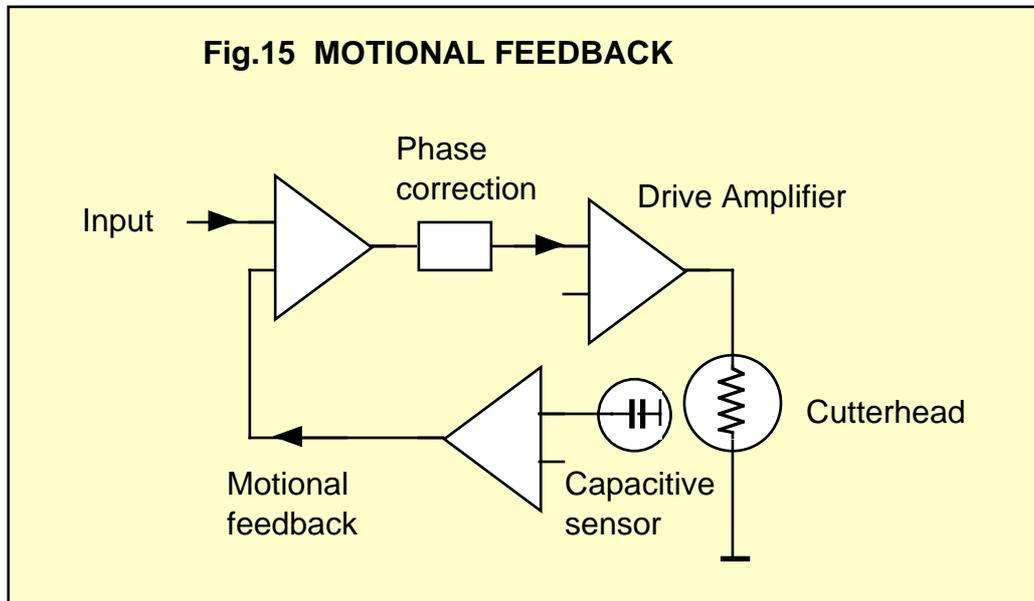
During setting-up, monitoring position d) is a useful way to check that neither the amplitude nor the velocity signals are in danger of overloading.

The Motional Feedback System

The amplified signal from the capacitive motion sensor is combined with the signal from the recording equalisation stage in such a way as to give negative feedback.

Because of the mechanical characteristics of the compliance and mass of the moving parts of the cutterhead, there are considerable phase changes within the wanted audio band and at frequencies above it. These set a limit to the amount of feedback which can be applied before instability occurs. Phase-shift networks are provided within the feedback loop, which partially counter-

act the mechanical phase changes. These allow an increase in the amount of negative feedback before instability, which gives a further improvement in the frequency response at the extremes of the required range.



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