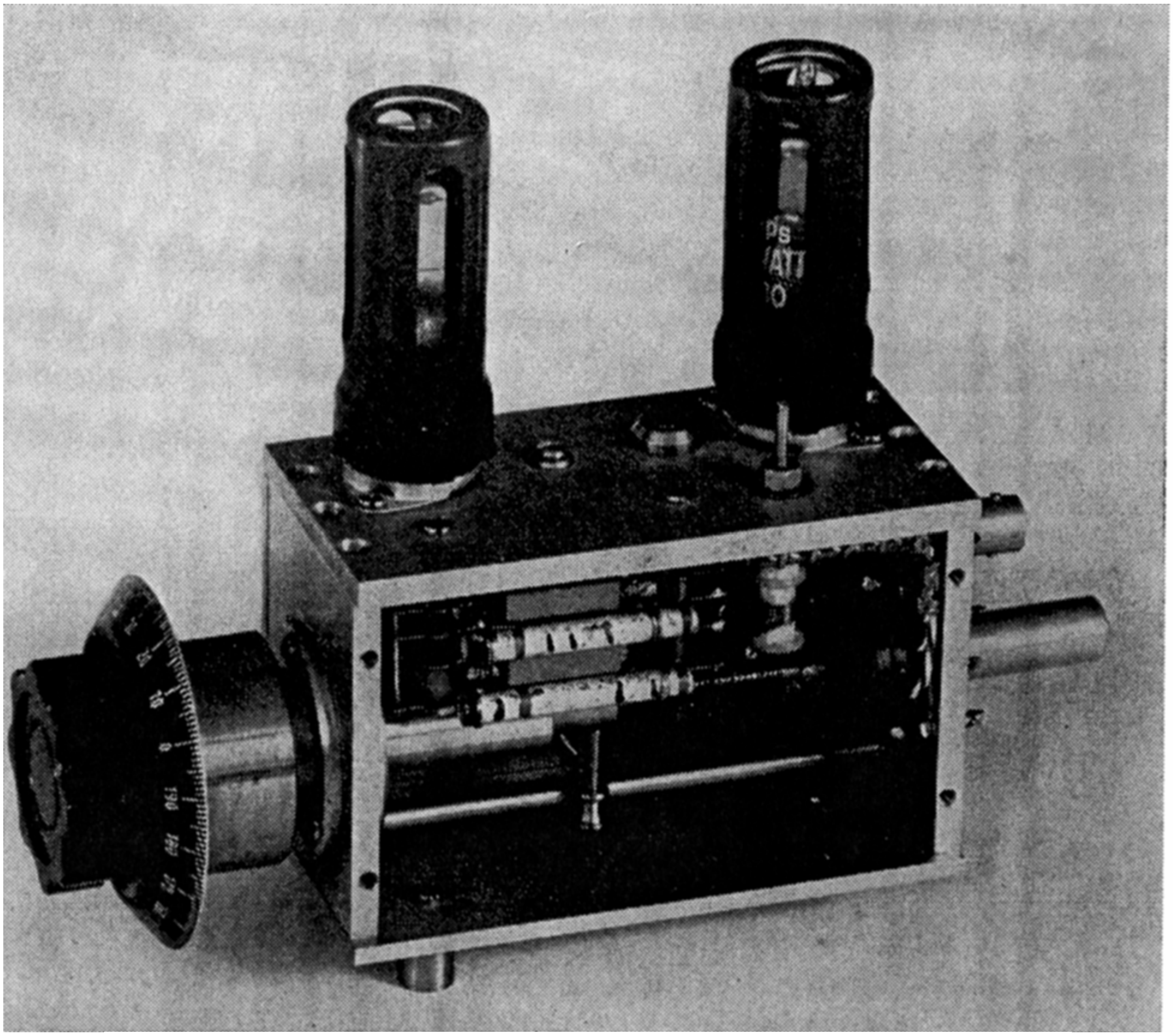


Fig. 1—The completed p.t.o. unit with one side cover removed. The rugged mechanical design is quite apparent in this photo. The small coil above the p.t.o. inductor is for setting the band limits.

A High-Precision Permeability-Tuned VFO

A Stable Unit for Receiver or Transmitter Use

BY WALTER HORN, I1MK
***QST* July 1964**

The VXO can achieve frequency stability as great as that required in CW, SSB and RTTY operation, but its range of frequency variation is insufficient for many applications. On the other hand, the stringent requirements for precise frequency control over a wide range impose highly severe design considerations on VFO circuits.

In this article we will describe a VFO showing several features believed to be unusual and which result in a high order of frequency stability and resetability with the ability to cope with changes in supply voltages, tube characteristics and component aging, along with a rigorously-linear frequency calibration.

These remarkable results have been obtained employing a well-designed electrical circuit, a very rigid mechanical layout and a high-precision tuning mechanism. One thing that must be tolerated with this VFO is its low output level (about 1 volt of RF). This may be brought up to a useful amount by means of additional amplification. Low output, of course, is by no means a limitation when the oscillator is employed in conjunction with a mixer to transpose an SSB or other kind of signal to a more suitable frequency.

The Electrical Circuit

The schematic diagram of the VFO is shown in Fig. 2.

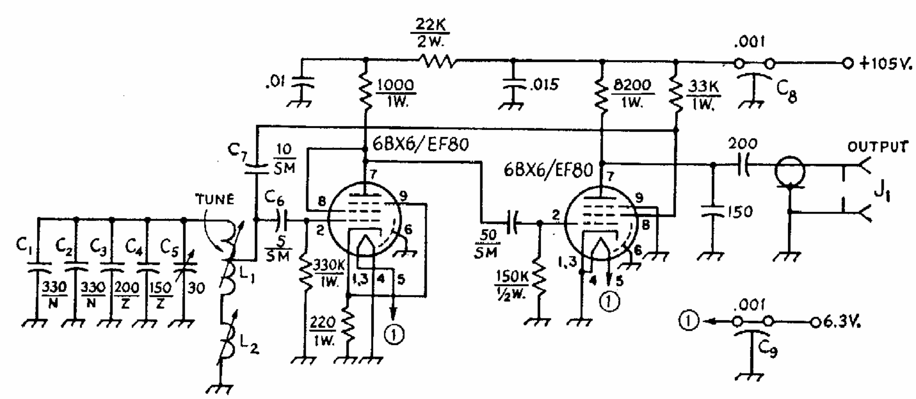


Fig. 2—The Franklin circuit used in the v.f.o. designed by I1MK. Resistances are in ohms (K = 1000). Decimal values of capacitance are in μf., others in pf. Fixed capacitors: N = N750 ceramic, Z = NPO ceramic, SM = silver mica; others not listed below are tubular or disk ceramic. Component designations not found below are for text-reference purposes.

C_1, C_2—(Centralab TCN).
C_3, C_4—(Centralab TCZ).
C_5—Air trimmer (Johnson 157-3, or similar).
C_8, C_9—Feedthrough capacitor (Centralab FT-1000).
J_1—Chassis-mounting coaxial receptacle (BNC).
L_1—See text.
L_2—0.5 μh.—5 turns No. 28 enameled close-wound on ¼-inch ceramic iron-slug form (Millen 69048 form).

Basically, it is a permeability-tuned Franklin oscillator employing two 6BX6/EF80 pentodes. The circuit shows excellent stability because of the very loose coupling existing between the resonator and driving system.

In the Franklin oscillator, the frequency determining circuit is coupled via very small capacitances to the input and output of a two stage electron tube amplifier. Because of the double phase inversion in the Class A amplifiers, the output is in phase with its input thus giving the positive feedback needed for oscillation. By making the coupling capacitances to the tuned circuit only just large enough to sustain oscillation, the effect of the amplifier on the LC circuit can be minimized, thus giving good frequency stability.

The first tube is provided with a cathode resistor to increase the impedance the grid presents to C_6. This is highly desirable because the grid conductance in conjunction with the input capacitance affects the phase angle of the equivalent voltage divider, thereby affecting the frequency of the generated signal.

At frequencies near 2 MHz, where the circuit is operated, the load resistance may be made so small with respect to its associated capacitances that the phase shift in each stage is substantially 180 degrees; the operating frequency is then very nearly the natural frequency of the resonant circuit. The chosen arrangement has the remarkable advantage that tuning may be accomplished by means of a variable inductor or capacitor, one side of which is directly grounded.

In this circuit it may prove desirable (but not absolutely necessary) to use a tapped coil; this preserves the advantages of a low impedance level without requiring the use of an inordinately large capacitance. Moreover, the tap is critically located to compensate for impedance variations over the tuning range. In this way, a low RF output voltage coefficient is maintained throughout the VFO frequency range.

All usual oscillators present amplitude limiting to a greater degree or lesser degree. In this VFO, due to the coil tapping and the cathode resistor, the signal level on the control grid of the first tube is very low; the tube does not draw grid current and therefore operates as a Class A linear amplifier.

Some limiting occurs in the following tube, but to a very low extent. The output signal is therefore almost perfectly sinusoidal. By grounding the cathode of the buffer tube, noise and hum have been minimized. The screen grid of this tube is used as the anode in the feedback loop, while its plate is in an electron-coupled output circuit.

The Variable Inductor

The most critical component of the VFO is the variable inductor. The simplest mechanical arrangement for a variable inductor is the slug-tuned coil. An inductance ratio of about 4 to 1, with a uniformly high Q, may be obtained by inserting a suitable powdered-iron core into a long, slender solenoid. When such a coil is associated with a fixed capacitance, the frequency variation may be made almost linear with respect to core position. This arrangement has been used in well-known commercial receivers and transmitters, and is capable of meeting fairly exacting requirements; it also has the advantage that there are no moving contacts in the entire tuning circuit.

The starting point in designing a permeability-tuned arrangement is the selection of the slug to be used in conjunction with the coil. The chosen slug must have sufficient permeability to produce the necessary inductance variation with a reasonable longitudinal displacement. It must also be stable with temperature and aging, and free from possible troublesome effects when placed in a magnetic field.

The author removed the slug from the core of a surplus 455-KHz IF transformer. The slug is a powdered iron type, 8 mm in diameter and 19 mm in length, and has a 4 mm hole through its center.

Other high-Q ferrite cores were tried initially, but were quickly discarded because of instability resulting from a high temperature coefficient, or because they were sensitive in permeability when placed close to magnetic fields.

The second point is the design of the coil. To produce an output frequency linearly related to core travel, the coil must have a special variable-pitch winding. So many factors have influence on the resulting inductance, including unavoidable variable capacitance with respect to ground, and the variable mutual inductance between different coil sections, that a prediction of the tuning curve in advance appears almost impossible. However, by experimentally adjusting coil length, number of turns, winding pitch and core travel, the tuning curve can be made to follow exactly the desired linear shape.

Constructional Details

The VFO is so designed and constructed that it has little sensitivity to vibrations in the order of 5 G. Frequency deviation is less than ± 100 Hz under 5 G acceleration at 50 cycles. Bumping or pounding on the operating table does not cause any noticeable frequency deviation.

A factor which must be taken into account in designing the mechanical layout is the size and type of box in which the circuit is to be installed. This is of primary importance in relation to frequency stability and resetability vs. mechanical stability.

First, the box must have such a size as to permit the tuning tank to be mounted in a position which will insure that the walls are no closer to the coil than by an amount equal to three to four times the coil diameter. This will minimize deterioration of the coil Q, and the thermal excursions, which inevitably cause the sidewalls of the box to expand or contract, will produce less effect on coil inductance.

Circuit components should also be kept away from the tuning tank.

Mechanical layout of the VFO may be seen in Figs. 1 and 3.

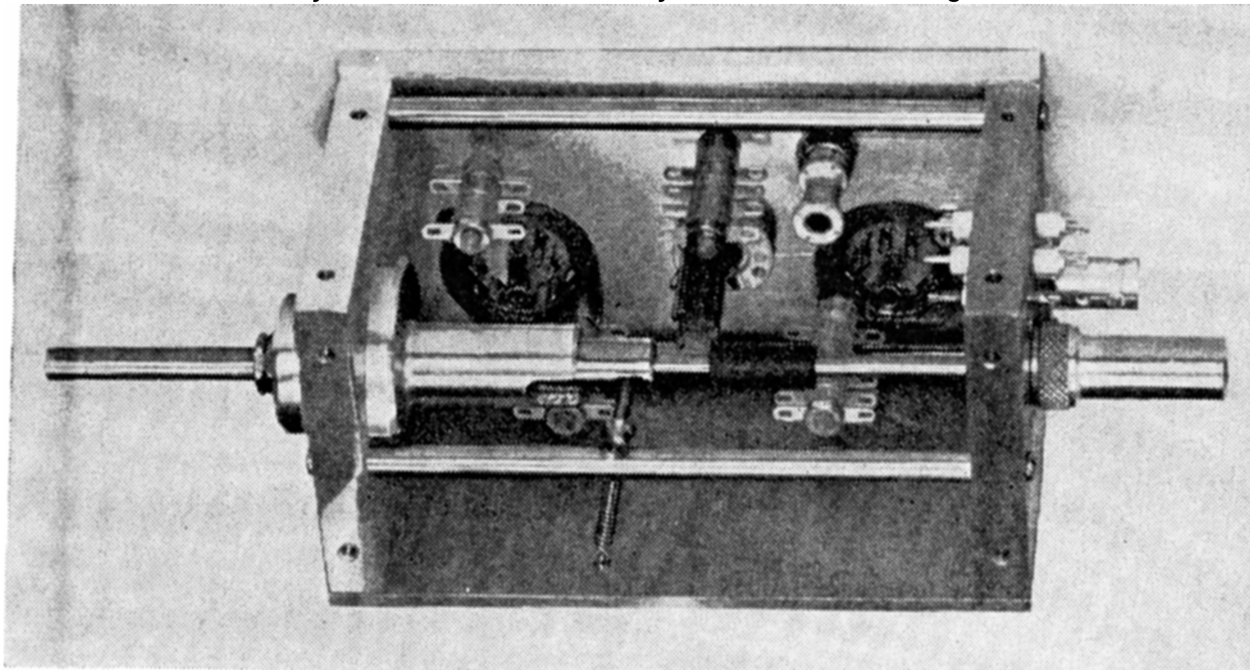


Fig. 3—In this view of the partially-assembled p.t.o. unit, the coil has been omitted to expose the tuning slug mounted on the driving shaft. The front bearing guide is notched for the arm that prevents rotation of the slug shaft to permit full lateral movement of the slug. The knurled aluminum sleeve at the left-hand end covers that end of the slug shaft and the coil spring that prevents backlash.

1. The VFO is mounted in a frame consisting of a front and a rear plate clamped together by three metal rods. For smooth action of the tuning mechanism, the two plates must be exactly parallel. To achieve this, both plates are milled from an aluminum block, and the three rods are turned down from brass stock. The end plates are 10 mm. thick and the rods are 6 mm. in diameter; their ends are tapped to fit 5-32 machine screws.

2. The frame supports an upper and a bottom plate, bolted to the end plates by a set of machine screws. The upper plate, a sheet of aluminum 5 mm. thick, supports the electrical circuit, except the tuning coil.

3. The bottom plate is provided with three ceramic pillars to fasten the VFO on a main chassis. The pillars assure thermal insulation of the VFO unit from heat-generating devices mounted on the main chassis.

4. Sidewalls are simple aluminum sheets having a thickness of 3 mm.

Grounding of zero-potential tube pins is achieved by means of two silver-plated copper rings having 22-mm inside and 30-mm outside diameters, fastened against the mounting plate by the same screws which hold the sockets. In making these rings, the material is cut so as to form lugs, on the inside diameter, in a pattern corresponding to the socket pins to be grounded. This assures the shortest grounding path. To the same rings all circuit ground returns must be soldered.

All connecting leads, except those of the tuning coil, are made with No. 14 silver-plated copper wire, and the lengths are broken by standoff insulators so that no length remains unsupported for more than a half inch. This kind of lead rigidity, plus the excellent ground return, assures maximum frequency stability under mechanical vibration.

It should be noted that solid construction alone is not enough to insure short- or even long-term stability; the components must also be mounted so that there is a minimum of strain and stress on the frequency-determining parts.

On the rear frame plate are located a BNC coaxial connector, serving as an output terminal, and two feed through ceramic capacitors for connecting the VFO to its power supply.

The Tuning Mechanism

The heart of the unit is the tuning mechanism, most of the essential parts of which can be seen in the photographs of Figs. 1, 3 and 4.

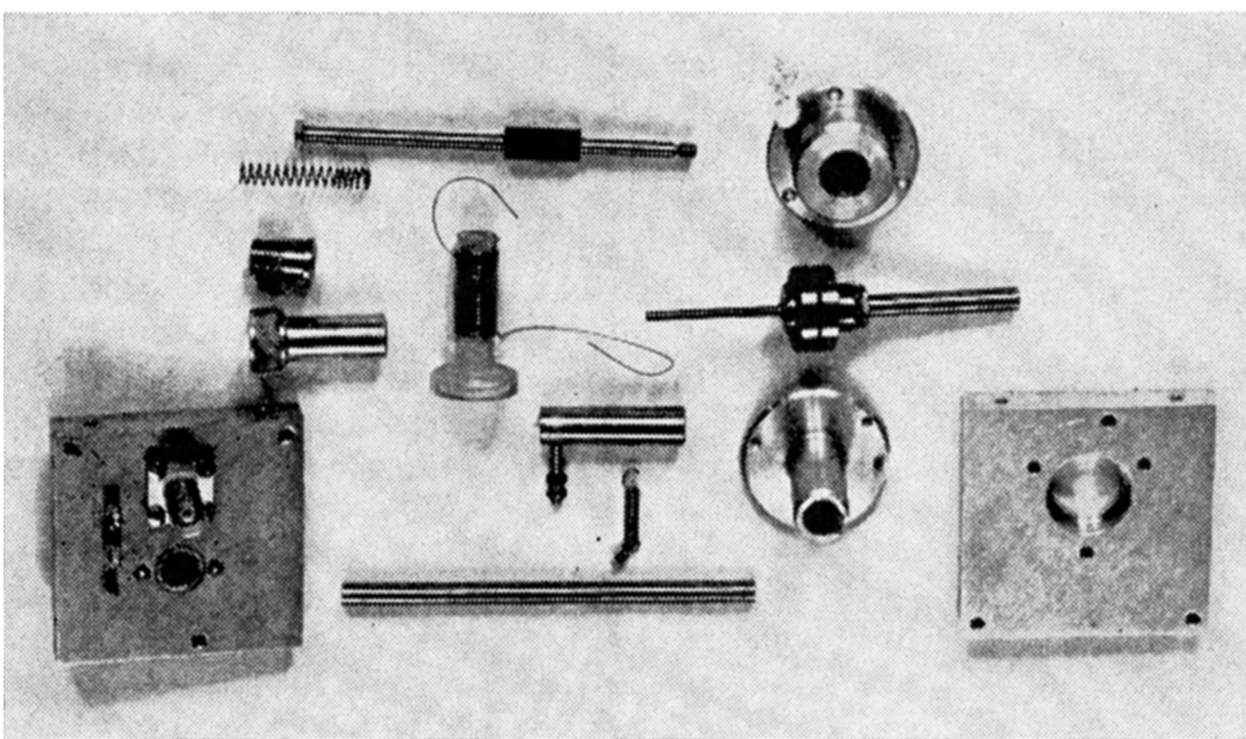


Figure 4

5. The slug is fixed on a stainless-steel rod 6 mm. in diameter. The author removed the slug from the core of a surplus 455-KHz IF transformer. The slug is a powdered iron type, 8 mm in diameter and 19 mm in length, and has a 4 mm hole through its center. To assure accurate alignment of the slug within the coil, one end of this rod is threaded into a section of stainless-steel rod of larger (10 mm.) diameter that slides back and forth through a close-fitting aluminum cylinder attached to the front end of the VFO box.

6. The opposite end of the larger rod is tapped to fit a lead screw attached to the control shaft that runs through ball bearings. The lead screw is threaded 2 threads per mm (approximately 50 threads per inch).

7. Turning of the lead screw moves the slug back and forth through the coil (not shown in Fig. 3). The core travel is limited to 12.5 mm, covered by 25 revolutions of the lead screw.

8. The rear end of the rod carrying the coil slug slides in a bearing mounted in the rear end of the VFO enclosure.

9. Turning of the slug shaft with rotation of the control shaft is prevented by a stop attached to the slug shaft. This stop carries a grooved roller that rides against one of the box-assembly rods under tension of a spring.

10. The front bearing consists of a pair of ball thrust bearings, back to back.

11. Any possible play in the threads of the lead screw is taken up by a spring at the rear end of the shaft.

12. Moving parts and bearings of the assembly must be machined to close dimensions because upon their precision depends the frequency stability and resetability of the VFO

The Tuning Inductor

13. The coil, shown in Figs. 1 and 4, is wound on a form 11 mm in diameter and 40 mm long turned down from a block of polystyrene. See the template of this part in Figure 5 and note the reference to the ‘tap 1/8’ statement on the plan view.

14. The form is bored out to a slide fit for the powdered-iron slug, and a mounting flange is turned at one end to permit fastening the form to the rear end of the box. As already mentioned, the coil has a specially developed variable-pitch winding. Core and coil are designed to work together to produce an output frequency that is a linear function of slug travel. Because core and coil must be matched together, employing a different type of slug will make it necessary to wind the coil with a little different pitch shape.

To tune the 2.5-3-MHz band with a fixed capacitance of 1000 pF, the required inductance is 4.09 to 2.82 uH (L_{MAX} / L_{MIN} = 1.44).

Leaving off 0.5 uH for the trimming inductor, L_2, the tuning coil must show a maximum inductance of 3.56 uH and a minimum of 2.32 uH.

Number 28-enameled wire is used, and the turns are proportioned as in Fig. 5.

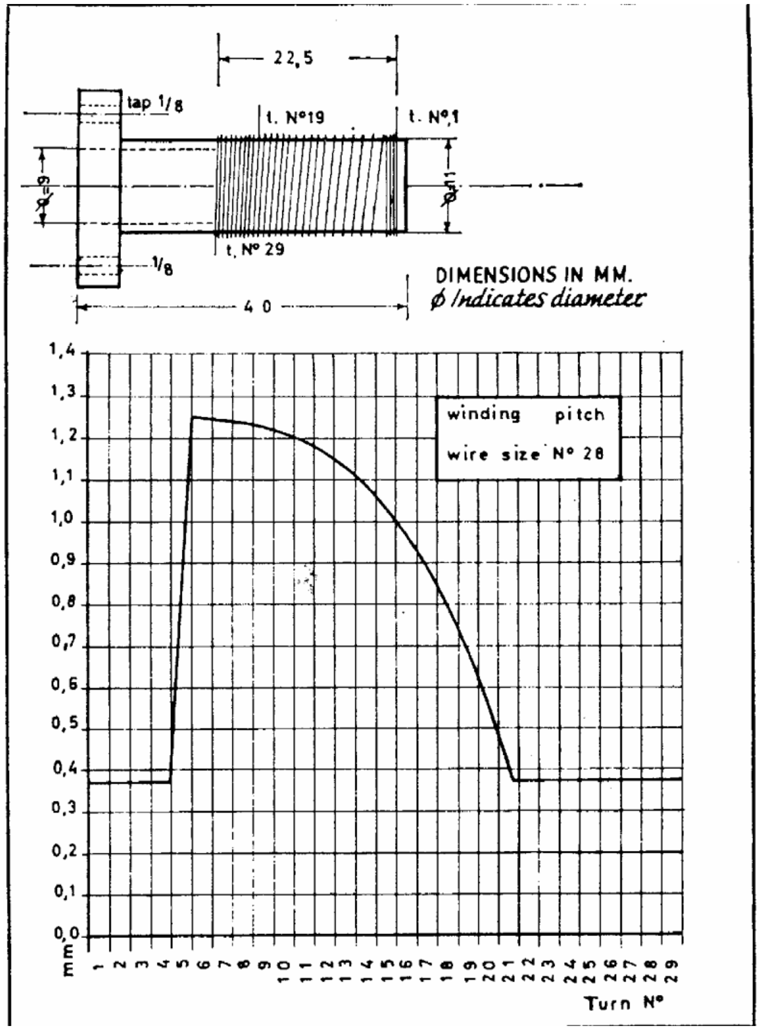


Fig. 5—The sketch at the top shows the dimensions of the coil form, and overall dimensions of the winding. "Tap 1/8" is a European approximate equivalent to 4-40. The graph (left to right) below shows the approximate distance between wire centers for each successive turn, starting at the right-hand end of the form.

- With the tuning slug removed, the coil presents an inductance of 2.1 uH and a Q of 125.
- Inserting the slug raises the Q to 160.
- In mounting the finished coil, every care should be used to align the form with the slug so that there will be absolutely no friction at any point in the travel.

Examination of Fig. 5 will show that the coil consists of three sections, from right to left:

- a first section of 4 close-wound turns,
- a second section of 17 turns wound with a variable pitch, and
- a third one of 8 close-wound turns.

The winding pitch of the intermediate section follows the contour described by the curve of Fig. 5.

Frankly speaking, winding this coil is not an easy job. To obtain a constant ratio of shaft rotation to frequency change throughout the range, the intermediate section of the coil must be wound with a smooth and continuously variable pitch and this must present no abrupt discontinuity or accidental bend. A great dose of patience and perseverance is required.

After completion, the coil must be cemented with high-grade Q-dope to hold its winding firmly and definitely in place. A number of VFO's like this have been built, and in every case the linearity obtained has been better than 0.02 per cent, despite the fact that no mechanical-correcting mechanism has been used; i.e., the actual frequency did not deviate from a straight-line calibration more than ± 450 Hz over a range of 500 KHz (see Table I).

Table I

Tuning Linearity

Rev. No.	*Cal. (kc.)*	*Measured Freq. (kc.)*	*Dev. (c.p.s.)*	*Dev. (per cent)*
1	2500	2500.000	0	0
2	2520	2520.060	+ 60	+0.002
3	2540	2540.083	+ 83	+0.003
4	2560	2559.810	−190	−0.007
5	2580	2579.900	−100	−0.004
6	2600	2600.010	+ 10	+0.0004
7	2620	2620.078	+ 78	+0.003
8	2640	2640.100	+100	+0.004
9	2660	2659.915	− 85	−0.002
10	2680	2679.729	−271	−0.010
11	2700	2699.695	−305	−0.011
12	2720	2720.046	+ 46	+0.002
13	2740	2740.003	+ 3	+0.0001
14	2760	2759.789	−211	−0.007
15	2780	2679.905	− 95	−0.003
16	2800	2800.180	+180	+0.007
17	2820	2820.071	+ 71	+0.003
18	2840	2840.320	+320	+0.0013
19	2860	2860.450	+450	+0.015
20	2880	2879.984	− 16	−0.0006
21	2900	2899.930	− 70	−0.003
22	2920	2919.941	− 59	−0.002
23	2940	2940.012	+ 12	+0.0006
24	2960	2960.036	+ 36	+0.001
25	2980	2979.982	− 18	−0.0006
26	3000	3000.043	+ 43	+0.001

The figures in the third column of this table were obtained by beating the v.f.o. output against a 20-kc. spectrum derived from a 400-kc. precision crystal oscillator (long-term stability, 10^{-7}) followed by a chain of regenerative dividers. The departure from linearity, which does not follow a precise law, may be caused more by irregularities in the threads of the actuating screw than by imperfect adjustment of coil turns.

Coil Adjustment

For calibration purposes, a trimming inductor and capacitor, L_2 and C_5, are provided; by adjusting this inductor and this capacitor, frequency end points may be reset in case tubes or components should be substituted.

Because of the small space in the final assembly, a preliminary breadboard setup is advisable.

The adjustment consists essentially in changing the number of turns in the first and third section of the coil to get the required frequency spread with a chosen travel of the tuning slug. With the slug almost out of the coil, the frequency should be at the high end of its range; if not, readjust trimmer C_5.

Then the slug is moved into the coil by making 25 revolutions of the control shaft. If the frequency is now lower than desired, move a few turns from the third section of the coil to the first one; if the frequency is higher, move one turn or two very carefully from the first section to the third.

Since the shaft can rotate more than 25 turns, a little experimenting will be necessary to find which 25 turns give the desired frequency spread together with the required calibration linearity.

When a proper tuning range has been obtained, it will be time to check the frequency at intermediate points. If the coil has been wound with appropriate care, an excellent linearity should be obtainable. Don't try to correct any nonlinearity by moving the turns spread out between the first and third coil sections; this will be only a waste of time. It is much better to discard the coil and to rewind a new one with a little different pitch. In case the circuit will not oscillate properly throughout the range with a coil of a given Q, feedback may not be sufficient. This is because the capacitance value of C_6 and C_7 that has been chosen is too small.

The Dial

As previously mentioned, the tuning range of the described VFO is 2.5 to 3 MHz. Since it takes 25 revolutions of the control shaft to cover 500 KHz, the coverage is 20 KHz per revolution. A knob with a 2.5-inch dial, marked off with 20 large and 200 small divisions, is attached to the shaft. Every large division corresponds, therefore, to 1 KHz. A string-drive system, coupling the control shaft to a slide-rule scale, indicates the 25-KHz portion of the band being covered by each revolution of the tuning knob.

Another solution, especially useful when the available panel space is small, consists in the use of a mechanical counter (speed-gauge type) marked 0-500 and coupled to the control shaft by a gear train having a ratio of 1 to 20. To obtain a direct reading in kilocycles, every revolution of the shaft, corresponding to a frequency variation of 20 KHz, must advance the counter by 20 digits.

Aside from the chosen scale system, it is strongly recommended that the rotation of the tuning shaft be limited by means of suitable end-travel stops. This will prevent any possible forcing of the tuning mechanism beyond its limits. Since the lead screw is loaded against the plunger carrying the slug rod, forcing of the control shaft can cause permanent frequency deviations. To avoid irreparable damage to the mechanism, it is also recommended that an appropriate coupler be used between the control shaft and tuning knob. The coupler, if of the constant-velocity type, will not permit end pressure to be exerted on the control shaft, and will allow for some offset between its axis and the tuning-knob rotation center. It is obvious that the coupler must be absolutely free from backlash. A coupler loaded with a set of springs is generally appropriate.

Results

After assembling the VFO and adjusting the tuning range, it will be worthwhile to check the calibration linearity. This can be done with a frequency meter like the BC-221, by checking the VFO frequency at several intermediate points within its range. This method, of course, is a time-consuming job. A more suitable procedure consists in beating the VFO output with a 20-KHz spectrum, derived from a standard. Intervals of 20 KHz are the most useful because the VFO covers, in 25 revolutions of the tuning shaft, a band 500 KHz wide. As a consequence, the beats will appear at the zero point of every shaft revolution and the nonlinearity can be measured directly on the control dial. Divided into 20 parts, the dial will read directly in kilocycles.

In our measurements, however, we have used a counter-type frequency meter (Hewlett Packard, type 524 D), and this setup is certainly the best one to check frequency, stability, resetability and calibration linearity. A beating method, employing a crystal standard, a mixer (or receiver), an audio frequency interpolation oscillator, and a comparison oscilloscope, would be nevertheless a satisfactory setup for checking VFO performance.

Thanks to the careful temperature compensation (C_1 through C_4), our VFO showed a thermal coefficient of only 1.2 parts per million per degree Fahrenheit and this is, to our mind, a very remarkable performance.

Backlash error (the difference in frequency when resetting the VFO from opposite directions of rotation to the same angular position) is limited by mechanical design and careful adjustment to 30 parts per million. Normally such a small error is not apparent on a dial.

Changes in plate-supply voltage have very little influence on frequency (see Table II).

Table II

Output Frequency *vs.* Plate Voltage

Plate Voltage	*Measured Freq. (kc.)*	*Frequency Dev. (c.p.s.)*	*Frequency Dev. (p.p. 10^6)*
80	2700.000	0	0
82	2700.051	+51	+19
84	2700.108	+57	+20
86	2700.171	+63	+23
88	2700.226	+55	+20
90	2700.270	+44	+16
92	2700.333	+63	+23
94	2700.390	+56	+20
96	2700.412	+22	+ 8
98	2700.420	+ 8	+ 2
100	2700.401	−19	− 7
102	2700.359	−42	−16
104	2700.318	−41	−15
106	2700.270	−48	−18
108	2700.219	−51	−18
110	2700.156	−63	−20
112	2700.100	−56	−20
114	2700.049	−51	−18
116	2699.993	−56	−20
118	2699.928	−65	−24
120	2699.861	−67	−25

This table shows the change in frequency with oscillator-tube plate voltage, from an initial frequency of 2700 kc. The average deviation is 9 p.p.m. The v.f.o. plate voltage was provided by an adjustable electronically-regulated supply, and the deviation was measured by beating the v.f.o. output against a precision crystal-controlled standard (long-term stability 10^{-7}), and checking with a counter-type frequency meter.

The point of maximum flatness of the curve - showing output frequency vs. plate voltage - falls around 98 volts. For this reason, a plate-supply voltage of 105 was chosen. The frequency versus plate-voltage coefficient is about 9 parts per million per volt variation.

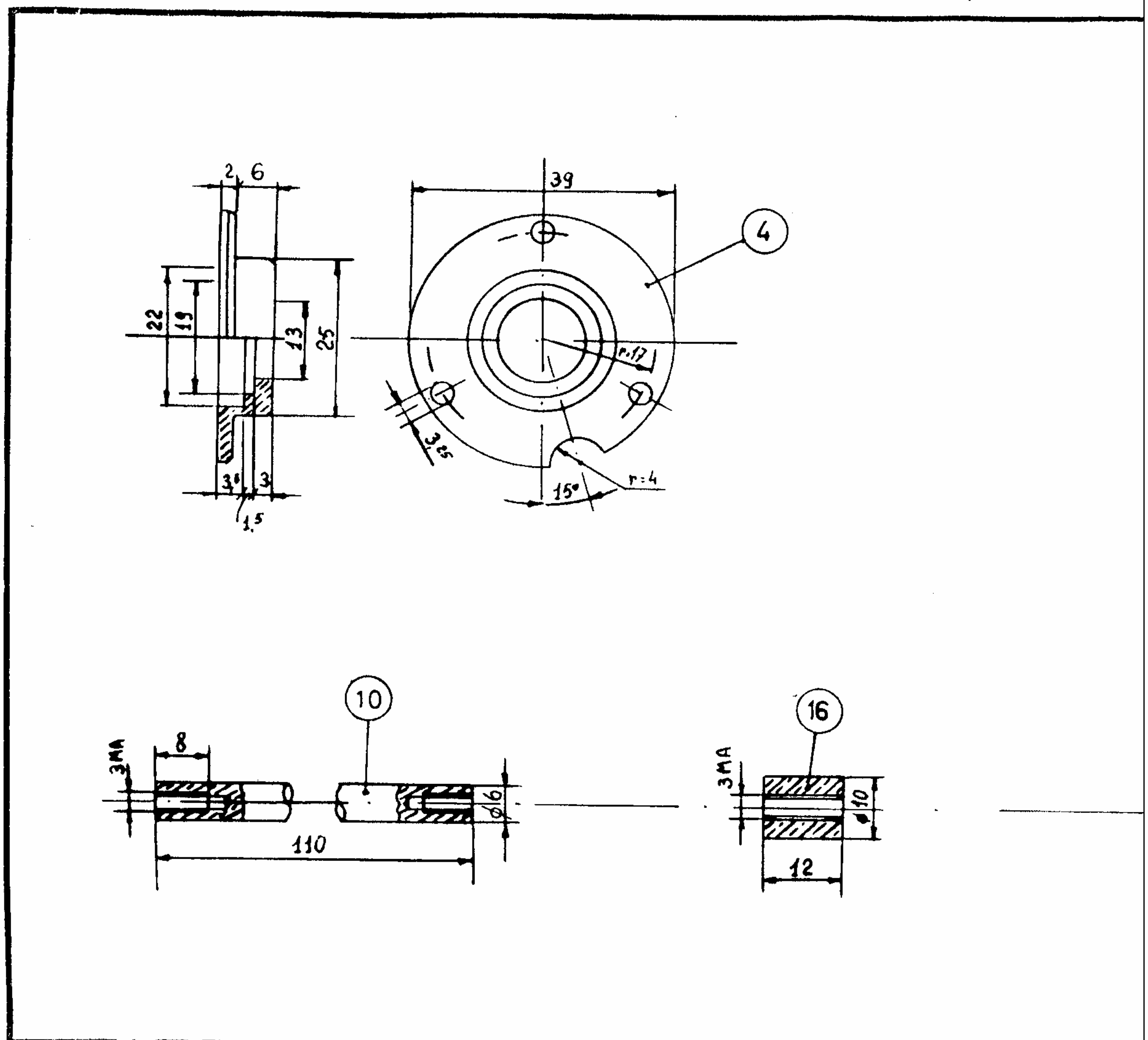
Operating the VFO from a 0B2 regulated power supply shows the average long-term (24-hour) stability to be in the order of 15 parts per million after warm-up.

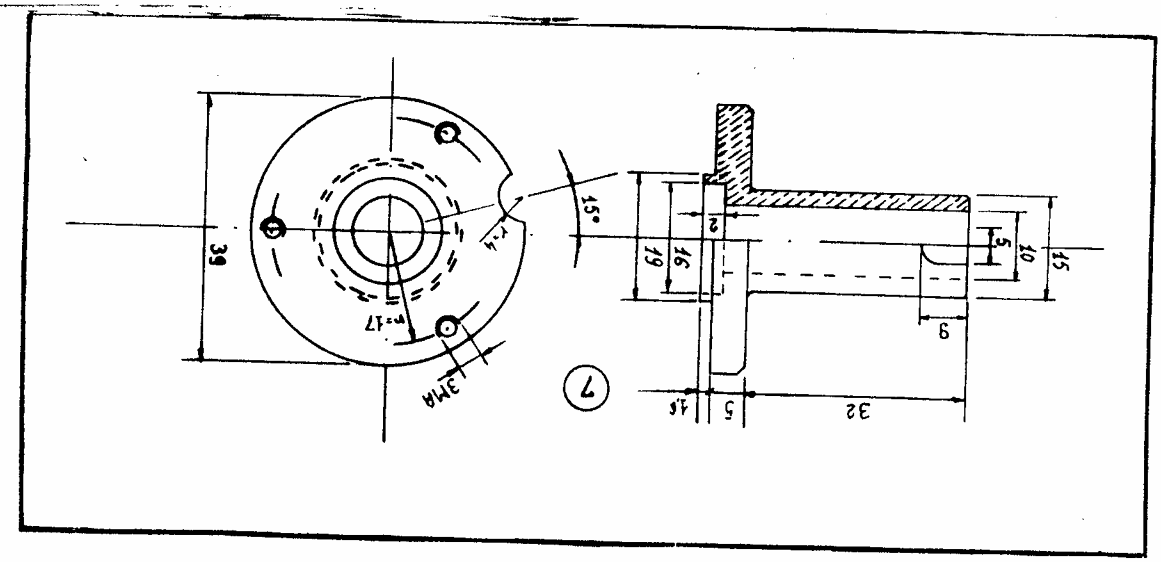
A regulated heater power source is recommended.

The frequency is for all practical purposes unaffected by loading at the VFO output terminals: shorting the output connector results in a frequency shift of less than 5 Hz.

Conclusions

The described VFO is certainly not an easy-to-build piece of equipment. Its construction cannot be carried out with simple tools, and probably is quite beyond the practical possibilities of the average ham workshop. Rather than as a description of how to build your own VFO, this article is intended as an explanation of difficulties encountered in designing a precision unit and the techniques employed to reach the final result.





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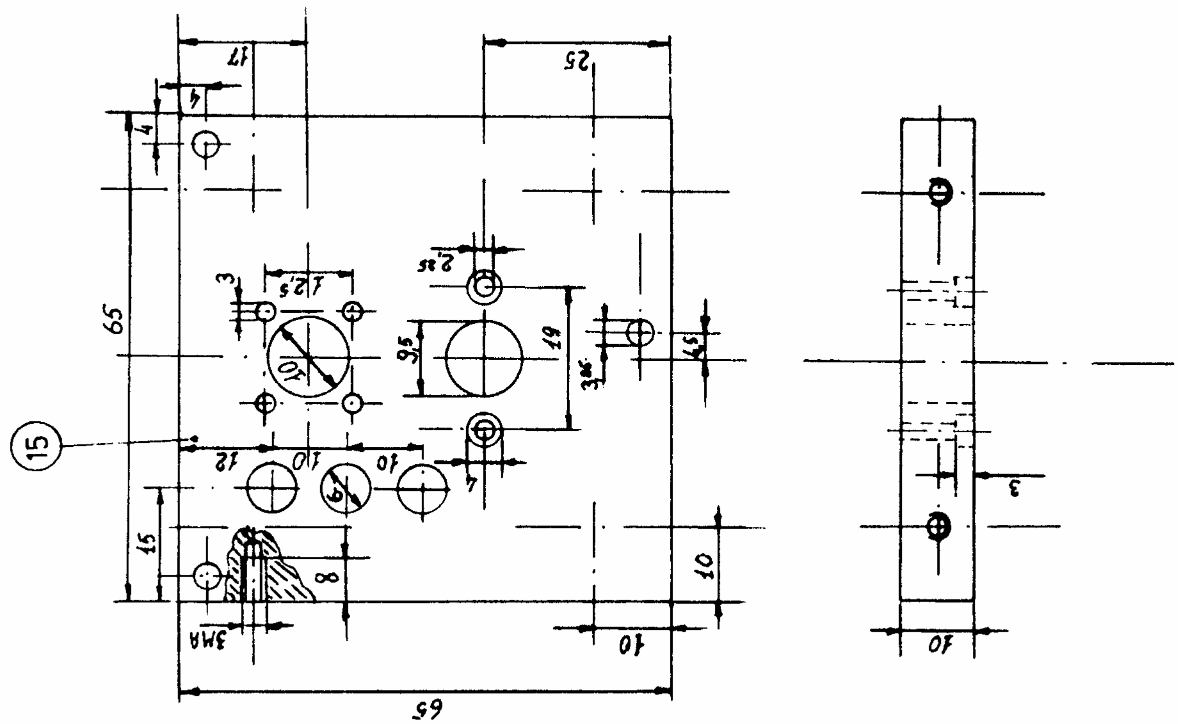
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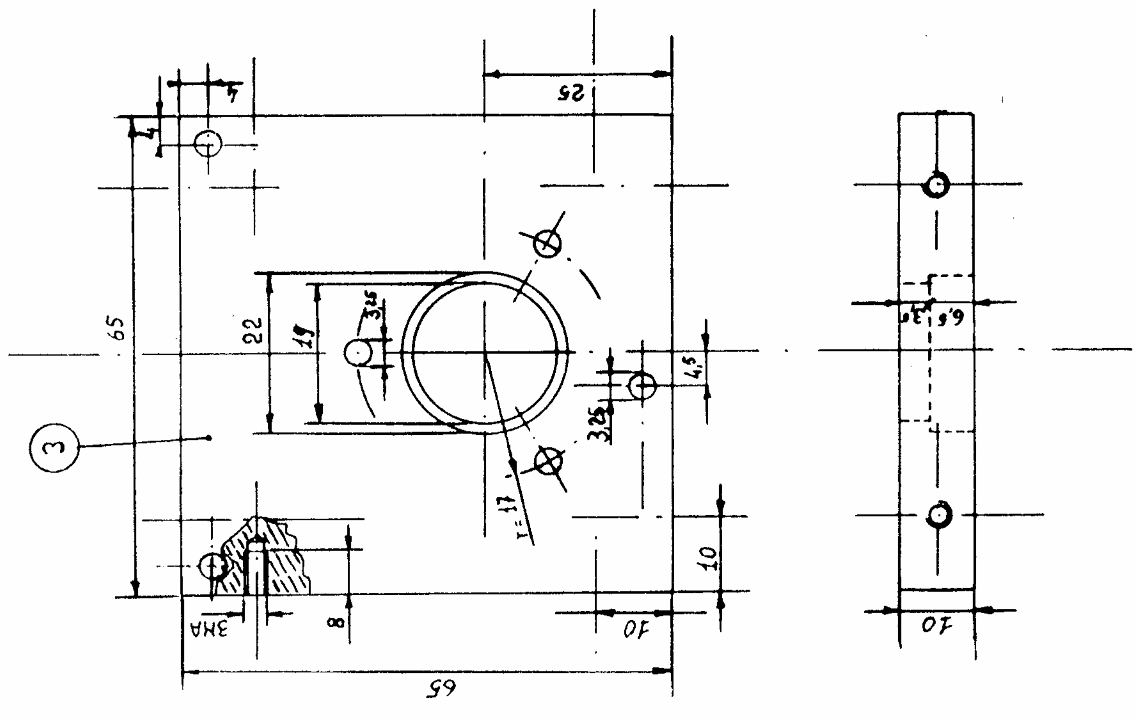
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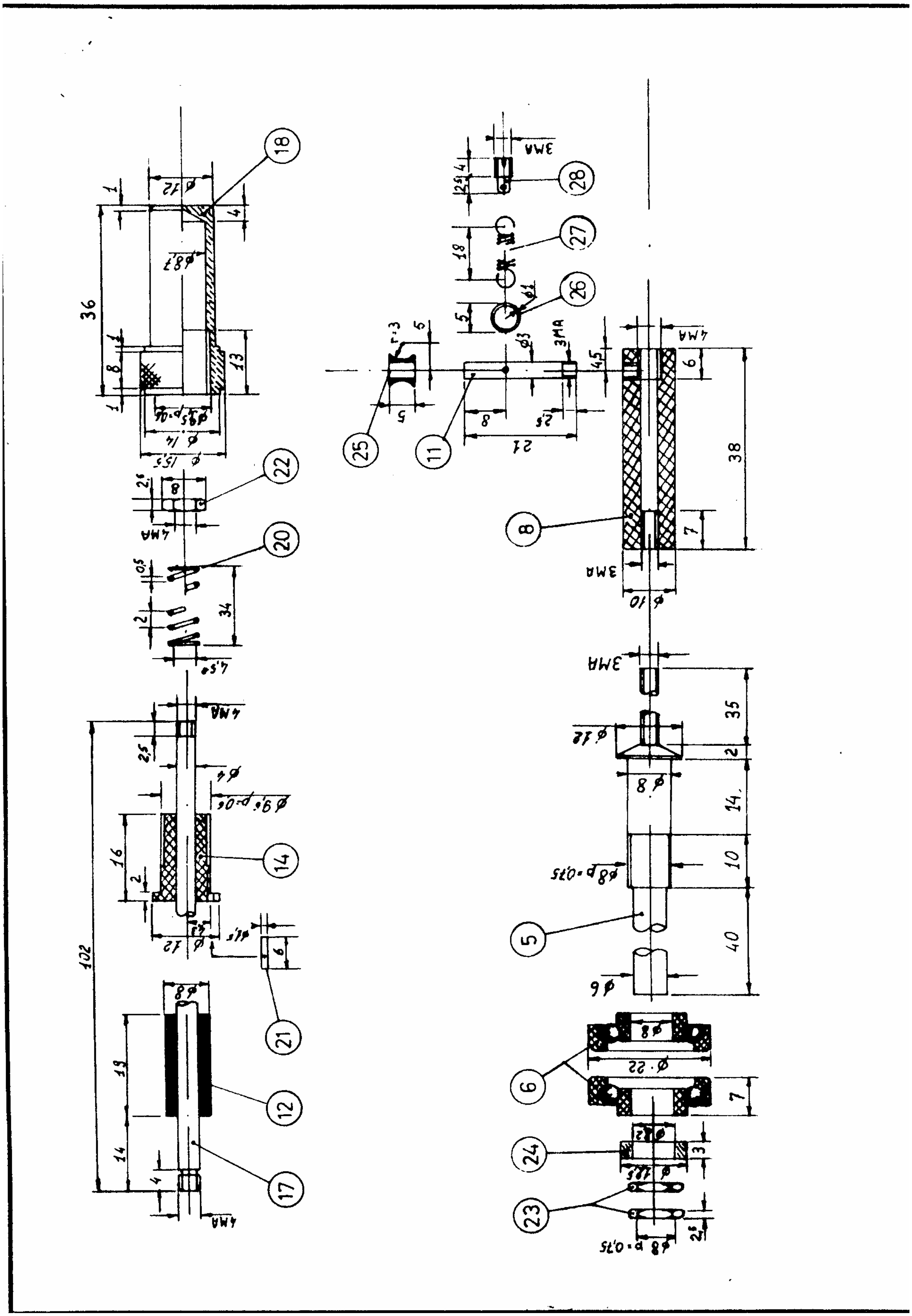
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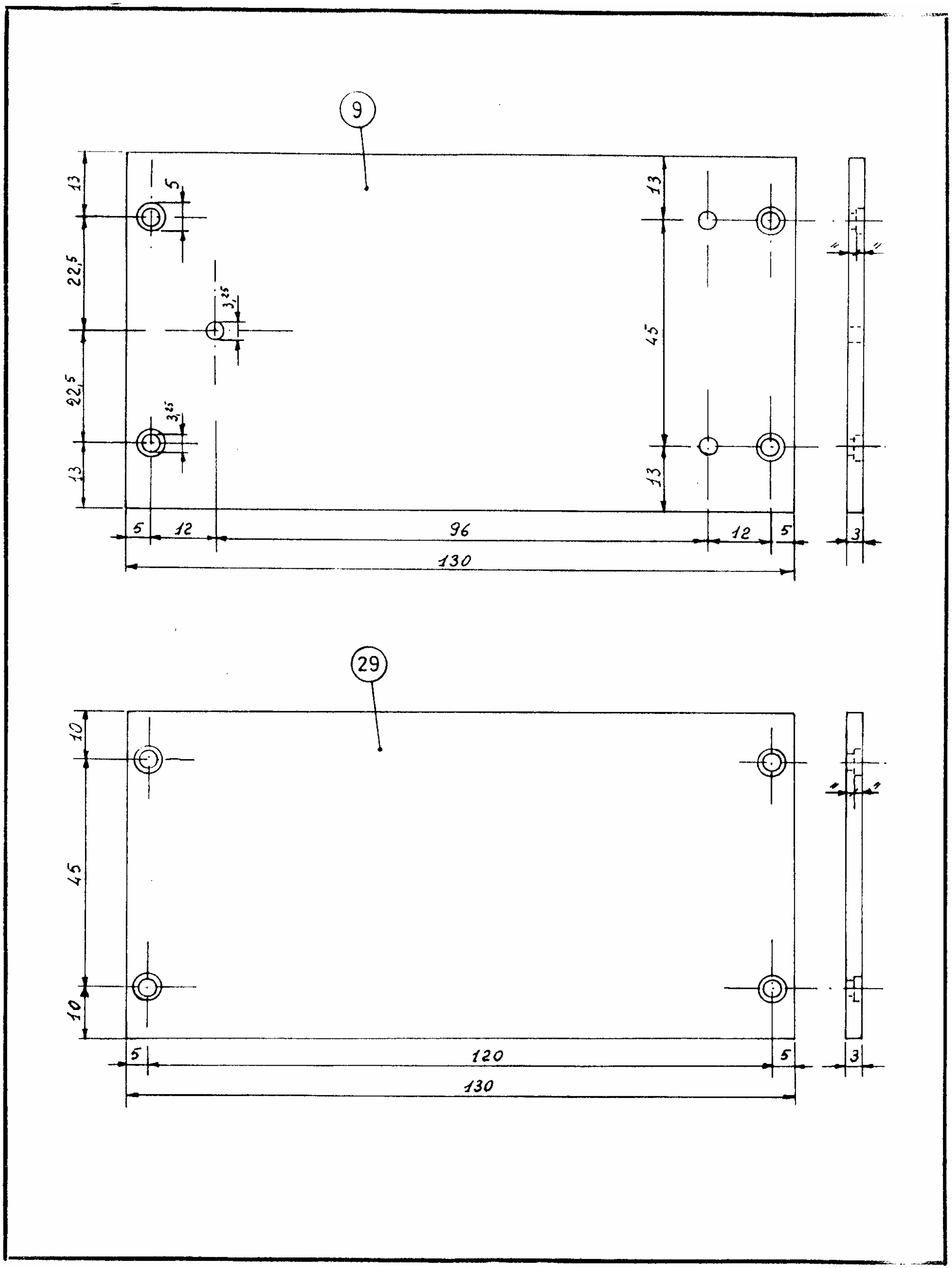
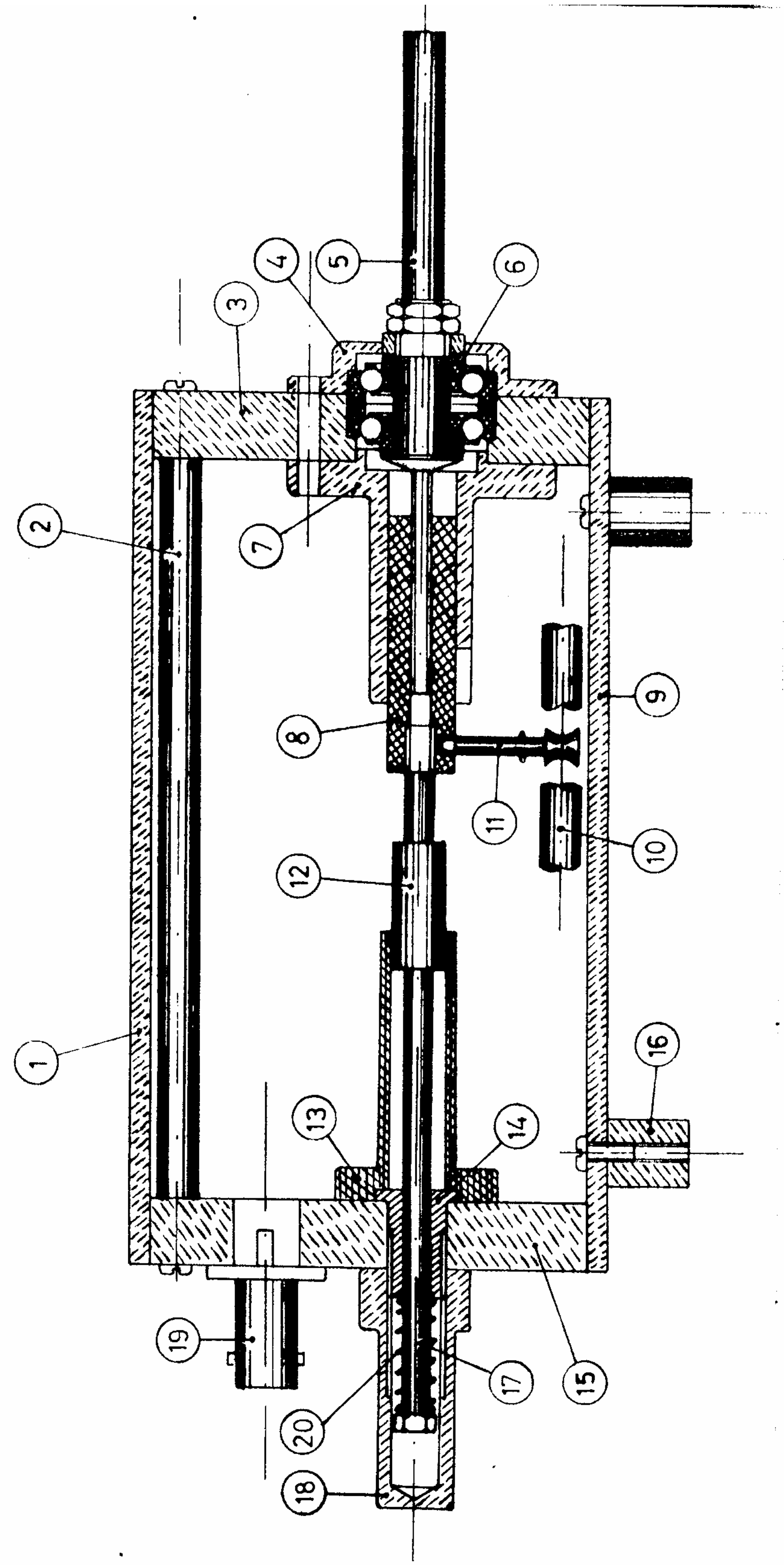
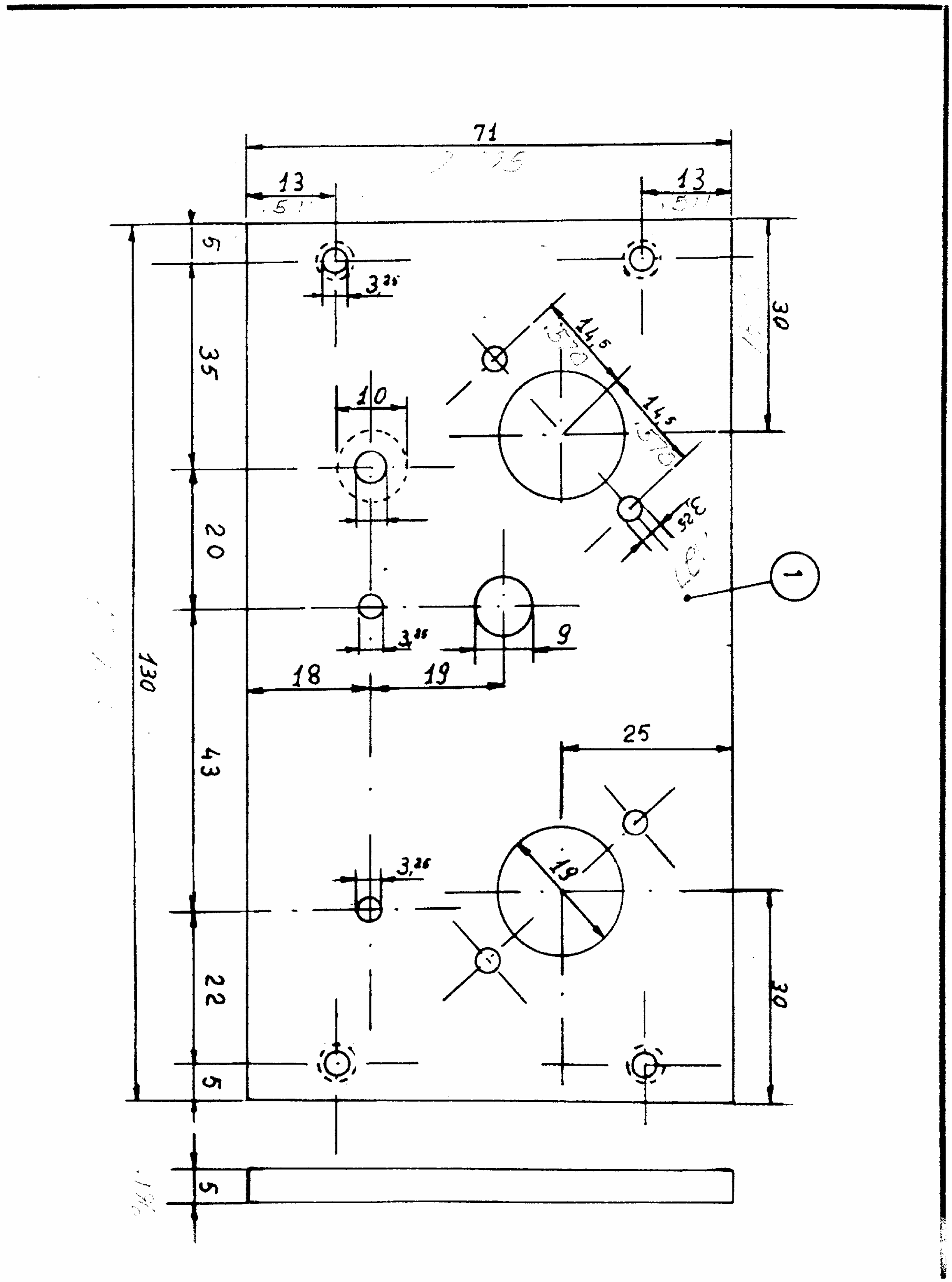


- Detailed mechanical drawing of VFO side walls.



Tuning Mechanism.



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